RESEARCH

IKSAD INSTITUTE

INSTITUTE OF ECONOMIC DEVELOPMENT AND SOCIAL RESEARCH

14. INTERNATIONAL EUROPEAN CONGRESS ON ADVANCED SCIENTIFIC RESEARCH

September 3–6, 2026

ZURICH, SWITZERLAND

FULL TEXTS BOOK

EDITOR

Assoc. Prof. Dr. Ethem İlhan Şahin
Assoc. Prof. Dr. İsmail TOPCU

ISBN: 979-8-89695-545-0

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18.09.2026

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CONGRESS ID

TITLE OF CONGRESS

14. INTERNATIONAL

EUROPEAN CONGRESS ON ADVANCED STUDIES IN BASIC SCIENCES

PARTICIPATION

Keynote & Invited

DATE - PLACE

September 3-6, 2026

Zurich, Switzerland

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Marmara University

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Diyarbakır Oral and Dental Health Hospital, Diyarbakır

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Türkiye, Azerbaijan, Morocco, India, Nigeria, Romania, Bangladesh, Kosova, Algeria, Croatia, Italy, Poland, Cambodia, Kingdom of Saudi Arabia, Bosnia and Herzegovina, Iran, Malaysia, Albania, Pakistan, Iraq, Palestine, Taiwan, North Macedonia, Serbia, USA, Lebanon

TOTAL PAPERS: 231

The number of papers from foreign countries: **123**

The number of papers from Türkiye: **108**

LANGUAGES

Turkish, English

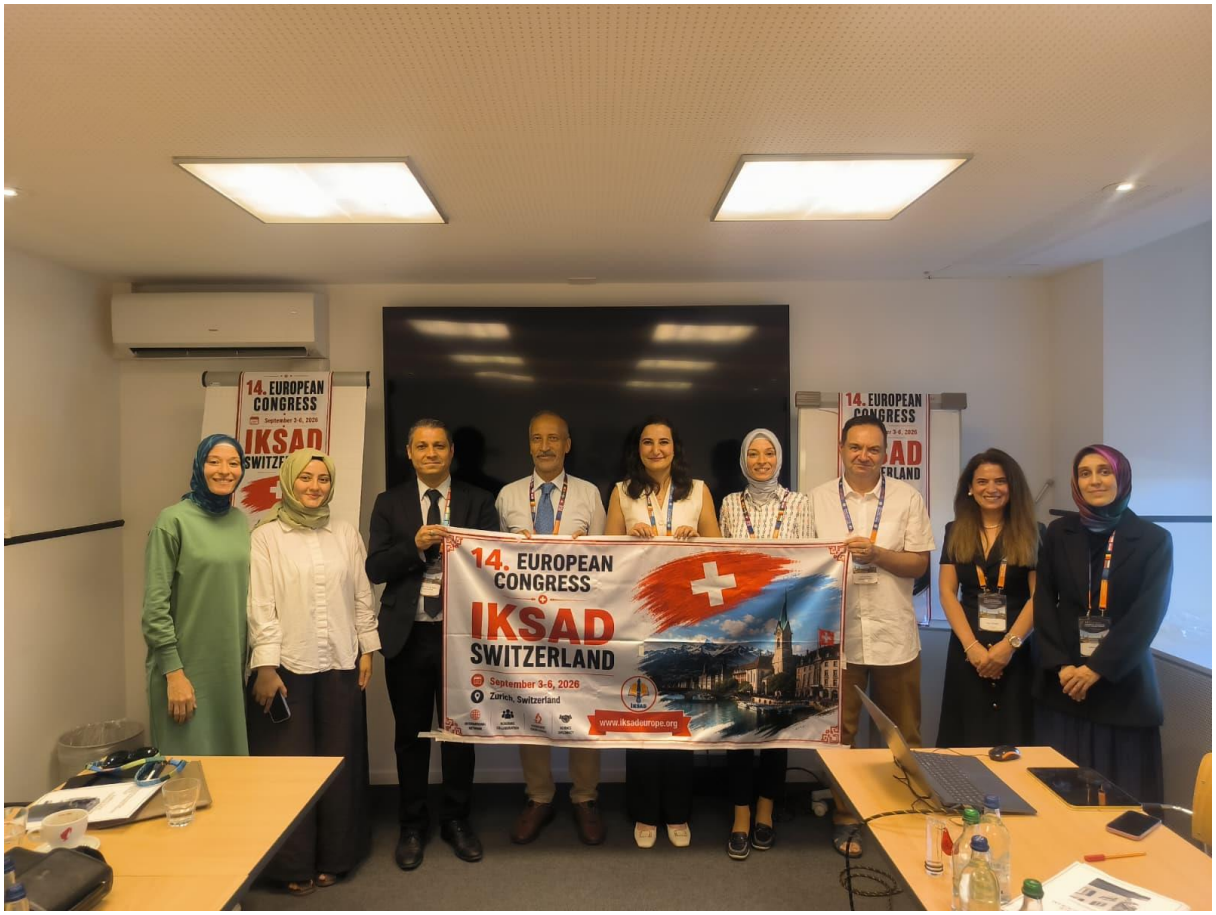
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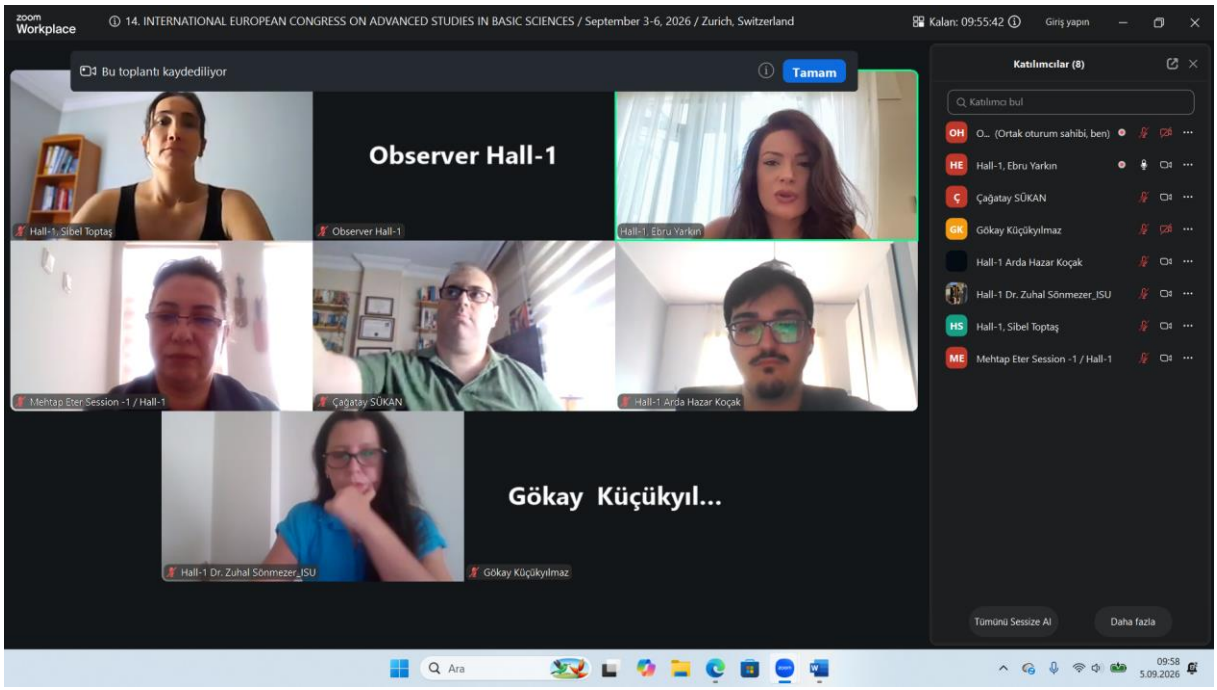

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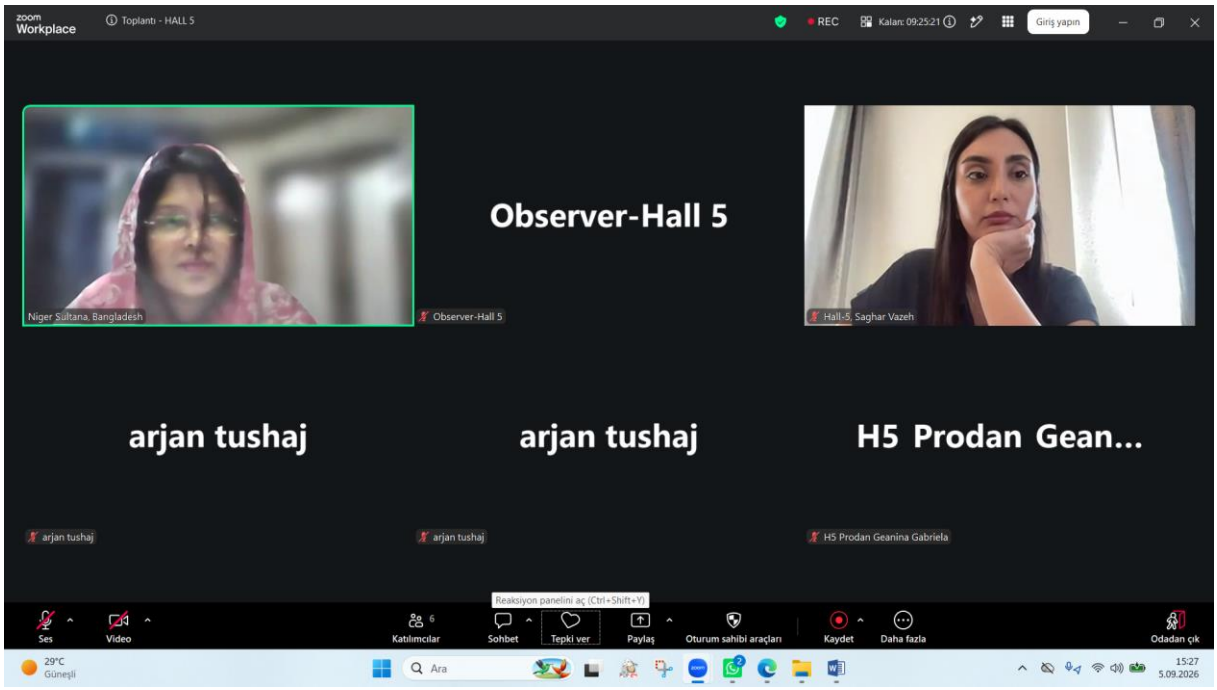

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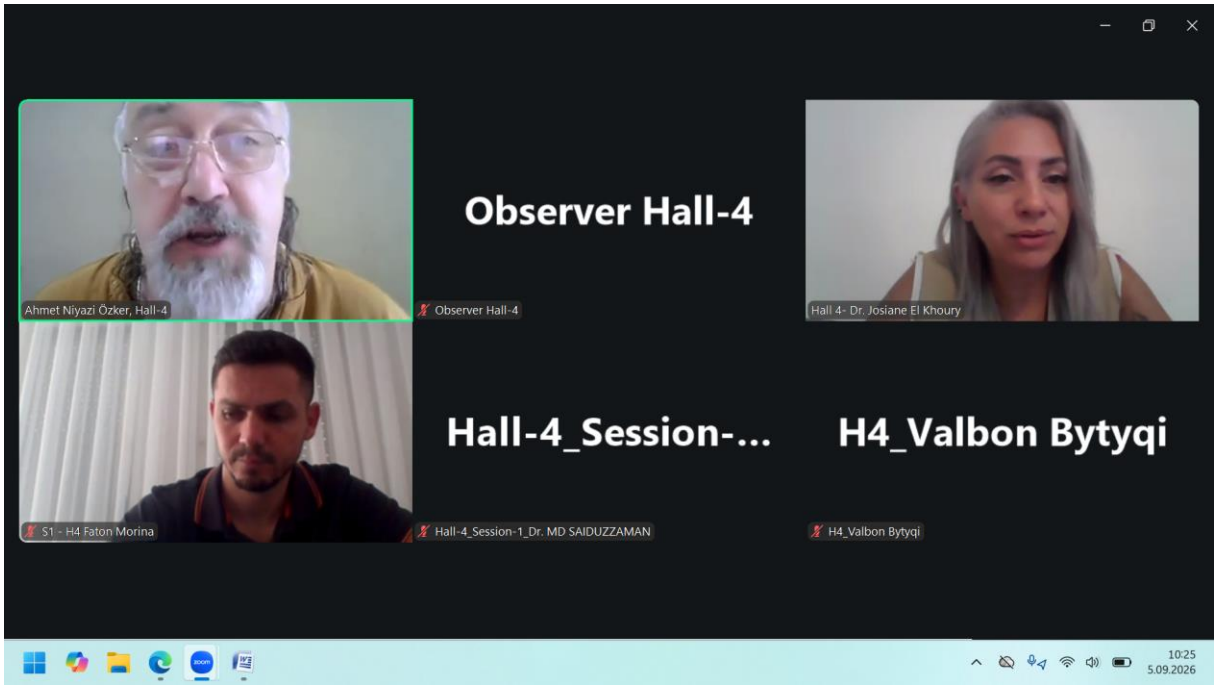

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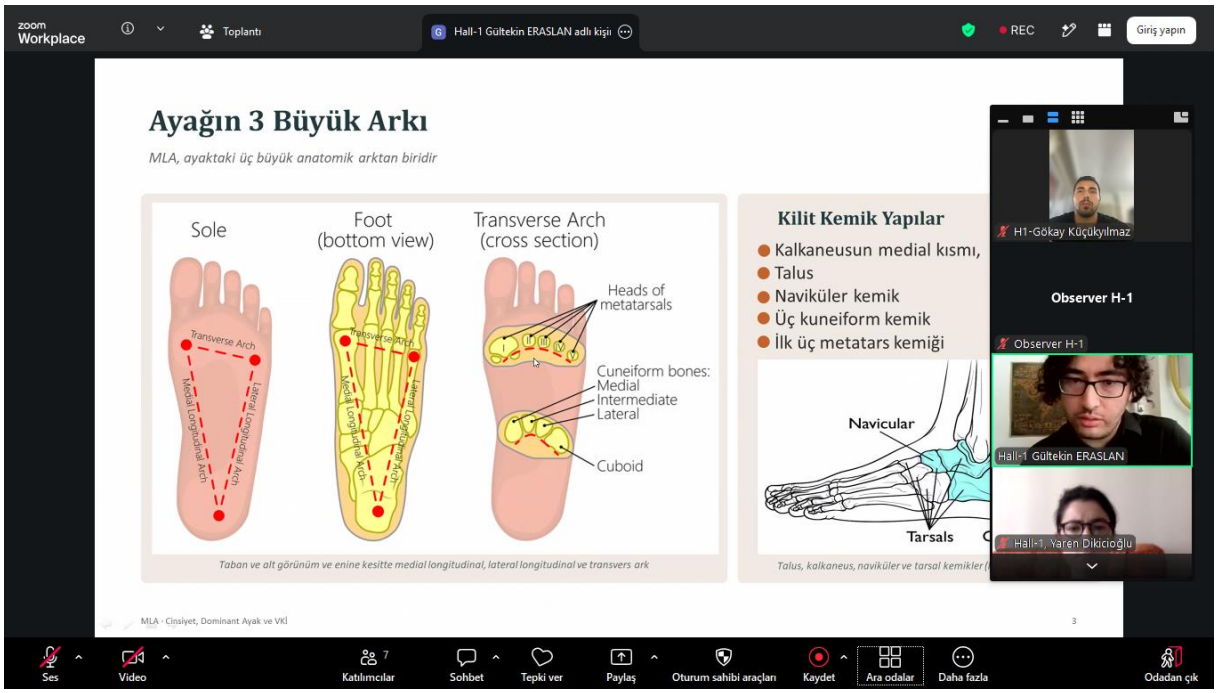

zoom Workplace
14. INTERNATIONAL EUROPEAN CONGRESS ON ADVANCED STUDIES IN BASIC SCIENCES / September 3-6, 2026 / Zurich, Switzerland
Kalan: 09:55:42
Giriş yapın
Bu toplantı kaydediliyor
Tamam
Observer Hall-1
Katılımcılar (8)
Katılımcı bul
O... (Ortak oturum sahibi, ben)
Hall-1, Ebru Yarkın
Çağatay SÜKAN
Gökay Küçükyılmaz
Hall-1 Arda Hazar Koçak
Hall-1 Dr. Zuhal Sönmezer_ISU
Hall-1, Sibel Toptaş
Mehtap Eter Session -1 / Hall-1
Gökay Küçükyıl...
Tümünü Sessize Al
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5.09.2026

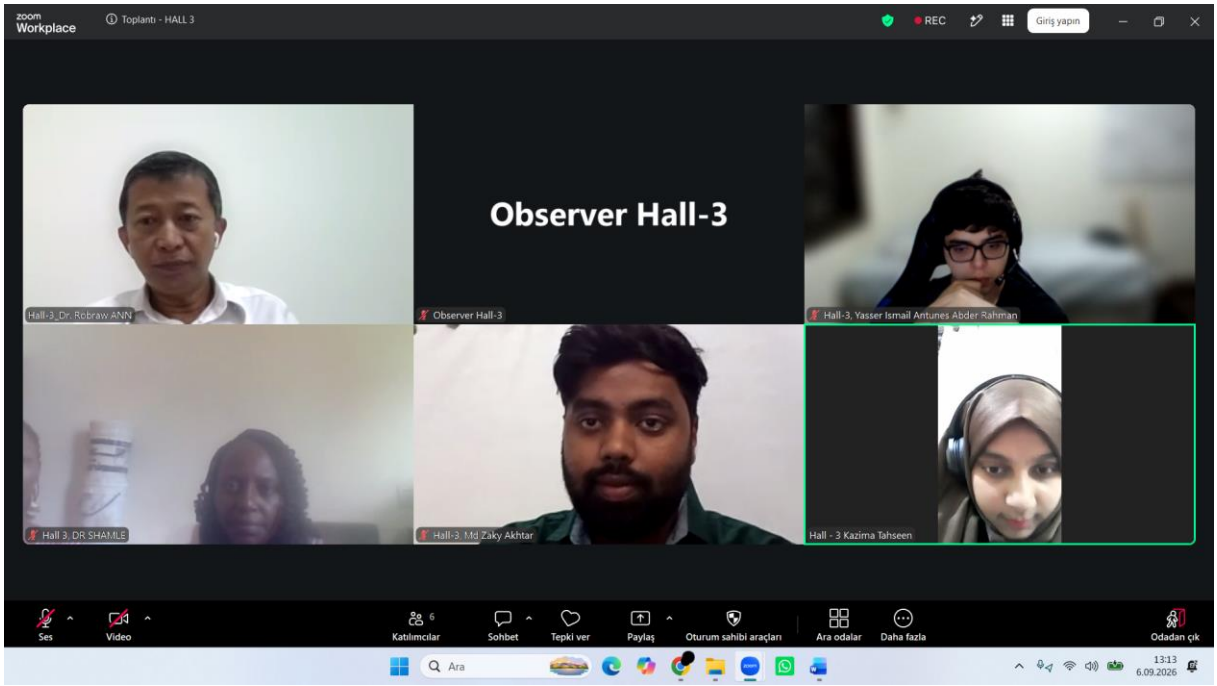

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Toplantı - HALL 5
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Kalan: 09:49:58
Giriş yapın
Observer-Hall 5
Antigoni Bullari, Hall 5
Hall-5 Bledar Kraja
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Maria Ermelinda...
HALL 5-RIAD M...
Maria Ermelinda de Sousa
HALL 5-RIAD Maroua
Ses
Video
Katılımcılar
Sohbet
Tepki ver
Paylaş
Oturum sahibi araçları
Kaydet
Daha fazla
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10:04
5.09.2026





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14. INTERNATIONAL EUROPEAN CONGRESS ON ADVANCED SCIENTIFIC RESEARCH

September 3-6, 2026
Zurich, Switzerland

FACE TO FACE CONGRESS PROGRAM

VENUE

Fred Hotel Hauptbahnhof
Limmatstrasse 5, 8005 Zürich, Switzerland



IN PERSON PRESENTATIONS

Fred Hotel Hauptbahnhof

04.09.2026

Time	Title	Author/Presenter	Affiliation
Moderator: Assoc. Prof. Dr. Ethem İlhan ŞAHİN			
13:30-13:40	THE ROLE OF GEOGRAPHICAL INFORMATION SYSTEMS (GIS) IN DETERMINING THE MOST SUITABLE TRAP SKEET SHOOTING RANGE FACILITY	Dr. Anıl Can BİRDAL Dr. Hatice GENÇ KAVAS Dr. Esra TÜRK **Prof. Dr. Tarık TÜRK**	Sivas Cumhuriyet University
13:40-13:50	LENGTH PREDICTION OF Atherina boyeri BASED ON MORPHOMETRIC MEASUREMENTS: AN ARTIFICIAL NEURAL NETWORK AND SUPPORT VECTOR REGRESSION APPROACH	**Prof. Dr. Semra BENZER** Prof. Dr. Recep BENZER	Gazi University, Türkiye Ankara Medipol University, Turkey
13:50-14:00	DEVELOPMENT OF AN ENVIRONMENTALLY FRIENDLY PAINT STRIPPING AND RAW MATERIAL RECOVERY PROCESS FOR PAINTED VEHICLE DOOR HANDLES	**Eda FERŞAT** Ersoy YILMAZ Ömer Taner SARPER **Ecem SAYAR ÖZGÜR** **Halit YİĞİT** Murat AYABAKAN Murat AKKAYA	Kocaeli University AISIN Automotive
14:00-14:10	MANUFACTURING, INTERFACIAL BONDING, AND MULTI-FUNCTIONAL PERFORMANCE OF NEXT-GENERATION FIBER-METAL LAMINATES VIA VACUUM-ASSISTED RESIN INFUSION	**Mustafa Baran TERZİ** Prof.Dr. Aziz Armağan ARICI **Eda FERŞAT** Ersoy YILMAZ Murat AYABAKAN Murat AKKAYA	Kocaeli University, Türkiye AISIN Automotive, Türkiye
14:10-14:20	THE DISCOURSE OF POWER AND TRUTH IN POETIC WORKS (LITERATURE AND ART): AN INTRODUCTION	Mas'ud Hamdan	University of Haifa, Palestine
14:20 – 14:30	REFRESHMENT BREAK		
Moderator: Assoc. Prof. Dr. Ali ORHAN			
14:30 – 14:40	İŞ HAYATININ RASYONELLEŞTİRİLMESİ: ELTON MAYO'DAN DİJİTAL DAYANIKLILIK ÇAĞINA ALGORİTMİK KÜLTÜR DÖNÜŞÜMÜ	**Tijen SÖNMEZ**	Marmara University, Türkiye
14:40 – 14:50	A SECOND-ORDER META-ANALYSIS OF THE EFFECTIVENESS OF GAME-BASED LEARNING ON ACADEMIC ACHIEVEMENT AND HIGHER-ORDER THINKING SKILLS	**Assoc. Prof. Dr. Ali ORHAN** Assoc. Prof. Dr. Murat TOPAL	Zonguldak Bülent Ecevit University, Türkiye Sakarya University, Türkiye

14:50 – 15:00	DEVELOPMENT OF ARTIFICIAL INTELLIGENCE-SUPPORTED INDIVIDUALIZED EDUCATION PROGRAMS FOR STUDENTS WITH SPECIAL NEEDS	**Dr. Aslan AYDOĞAN**	Istanbul Okan University, Türkiye
15:00 – 15:10	INVESTIGATION OF THE EFFECT OF DIGITAL GAMES ON SOCIAL COMMUNICATION SKILLS IN CHILDREN WITH AUTISM SPECTRUM DISORDER	Dr. Şenay KOCAKOYUN AYDOĞAN **Dr. Aslan AYDOĞAN**	Sinop University, Türkiye Istanbul Okan University, Türkiye
15:10 – 15:30	REFRESHMENT BREAK		
Moderator: Asst. Prof. Dr. Ayşe Semra AKSOY			
15:30 – 15:40	EFFECT OF GRAPE VARIETY ON ANTHOCYANIN DYNAMICS AND MINERAL BIOACCESSIBILITY OF HARDALIYE, A TRADITIONAL FERMENTED GRAPE BEVERAGE, DURING IN VITRO DIGESTION	**Asst. Prof. Dr. Ayşe Semra AKSOY**	Bezmialem Vakif University, Türkiye
15:40 – 15:50	DO BRANCHED-CHAIN AMINO ACIDS AND L-GLUTAMINE ALTER INTESTINAL HISTOMORPHOLOGY IN BROILER CHICKENS DURING GROWTH?	Gürkan GÜRBÜZ **Ergin ÖZTÜRK** Şerife TÜTÜNCÜ	Ondokuz Mayıs University, Türkiye
15:50 – 16:00	THE CONTRIBUTION OF ARTIFICIAL INTELLIGENCE-ASSISTED MONITORING DATA TO NURSING DECISIONS IN CHILDREN UNDERGOING MECHANICAL VENTILATION	**Rabia KOCA** Assoc. Prof. Dr. Mehmet BULDUK Assoc. Prof. Dr. Veysel CAN	Van Yüzüncü Yıl University, Türkiye
16:00 – 16:10	THE EFFECT OF ARTIFICIAL INTELLIGENCE-ENABLED DIGITAL GAMES AND VIRTUAL REALITY APPLICATIONS ON ANXIETY, FEAR AND ADAPTATION IN CHILDREN HOSPITALISED IN HOSPITALS	**Rabia KOCA** Assoc. Prof. Dr. Mehmet BULDUK Assoc. Prof. Dr. Veysel CAN	Van Yüzüncü Yıl University, Türkiye
16:10 – 16:30	REFRESHMENT BREAK		
Moderator: Assoc. Prof. Dr. Ethem İlhan ŞAHİN			
16:30 – 16:40	SIMULATION TECHNIQUES TO EMPHASIZE THE AMBIPOLAR CONDUCTION IN GRAPHENE-FIELD EFFECT TRANSISTORS	**Prof. Dr. Eng. Cristian Ravariu**	National University of Science and Technology Politehnica Bucharest, Romania

16:40 – 16:50	ART JEWELRY CREATED AND MADE IN SILVER WIRES AND SEMI-PRECIOUS STONES - THE SEAHORSE COLLECTION	Florina Ravariu **Prof. Dr. Eng. Cristian Ravariu**	Union of Professional Visual Artists of Romania Association UAPR, Romania Education Science Art SRL, Romania National University of Science and Technology Politehnica Bucharest, Romania
16:50 – 17:00	FOODS AND RITUALS OF THE RITES OF PASSAGE IN NEVŞEHİR (TÜRKİYE)	Durmuş Ali AYDEMİR **Sinem DİKME GÜL** Kader PARLAK Mehmet Emin DEDE Buse DURAN	Nevşehir Hacı Bektaş Veli University
17:00 – 17:30	CERTIFICATE CERAMONY		

14. INTERNATIONAL

EUROPEAN CONGRESS ON ADVANCED STUDIES IN BASIC SCIENCES

September 3-6, 2026 / Zurich, Switzerland

CONGRESS PROGRAM

Meeting ID: 862 1528 3413
Passcode: 030506

https://us02web.zoom.us/j/86215283413?pwd=Ri7LscrIwIFeGRDmcaqdEXNbpBphqg.1

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Meeting ID: 862 1528 3413
Passcode: 030506

Session -1 / Hall-1
05.09.2026
Moderator: Asst. Prof. Ebru YARKIN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
BEYİN DUYGU VE PAZARLAMA KAYSERİ MOBİLYA SEKTÖRÜNDE NÖROPAZARLAMA UYGULAMALARINA YÖNELİK BİR ARAŞTIRMA	*Özgür DEMİRTAŞ* *Mehtap ETER*	Kayseri University, Türkiye Elazığ Airport Health Inspection Center, Türkiye
MERKEZİ YÖNETİM BÜTÇESİNDE CARİ HARCAMALARDAKİ DÖNÜŞÜM VE FAİZ GİDERLERİNİN SEYRİ (2005–2025)	*Sibel TOPTAŞ*	Hacettepe University, Türkiye
PERSISTENT THREATS OF VIRAL SOCIAL MEDIA TRENDS TO BIOMETRIC SECURITY: DEEPFAKE EXPLOITS, LAZY BIOMETRICS VULNERABILITIES, AND REGULATORY ASYMMETRIES	*Zuhal SÖNMEZER*	Istinye University, Türkiye
STRATEGIC RISK MANAGEMENT AND MITIGATION IN INTERNATIONAL EDUCATION PROJECTS	*Elnara Mammadova*	Azerbaijan State University of Economics (UNEC), Baku, Azerbaijan
AN EXAMINATION OF WORKPLACE MOBBING IN LIGHT OF COURT OF CASSATION RULINGS: AN ANALYSIS FROM THE PERSPECTIVE OF EMPLOYEE RIGHTS AND EMPLOYER RESPONSIBILITIES	*Rahile GÜRAN GÖVEN* *Çağatay SÜKAN* *Altan DOĞAN*	İzmir Konak Vocational School Independent Researcher İstanbul University, Türkiye
THE ROLE OF DEMOGRAPHIC VARIABLES IN THE EFFECT OF SUSTAINABLE HRM PRACTICES ON WORK ENGAGEMENT	*Çağatay SÜKAN* *Rahile GÜRAN GÖVEN* *Gönen İlkar DÜNDAR*	Independent Researcher İzmir Konak Vocational School İstanbul University, Türkiye
CHANGING POLICIES IN GLOBAL WASTE MANAGEMENT: A LEGAL AND ECONOMIC ASSESSMENT OF THE EU, CHINA, AND THIRD COUNTRIES	*Öykü DEMİREL* *Arda Hazar KOÇAK*	Izmir University of Economics, Türkiye University of Turin, Italy
ARTIFICIAL INTELLIGENCE REPRESENTATION IN BRAND COMMUNICATION AND A DISCOURSE ANALYSIS THROUGH DIGITAL PLATFORMS: THE CASE OF GOOGLE, AMAZON AND SAMSUNG	*Ebru YARKIN*	İstanbul Kent University, Türkiye

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Session -1 / Hall-2
05.09.2026
Moderator: Assist. Prof. Dr. Okan ŞAHİN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
ORGANOID INTELLIGENCE AND THE PROBLEM OF CONSCIOUSNESS	*Volkan TEKİN*	University of Health Sciences, Türkiye
CLINICAL OUTCOMES OF TOTALLY IMPLANTABLE VENOUS ACCESS PORTS IMPLANTED IN THE TRAPEZIUS REGION: A SINGLE-CENTER RETROSPECTIVE STUDY	*Özhan ÖZGÜR*	Akdeniz University Faculty of Medicine, Türkiye
SMART WOUND CARE TECHNOLOGIES: CURRENT STATUS OF BIOSENSORS, FUNCTIONAL BIOMATERIALS AND CLOSED-LOOP THERAPEUTIC SYSTEMS	*Hatice POYRAZ KIZMAZ* *Fatih KAR*	Kütahya Health Sciences University, Türkiye
FROM CHRONIC WOUND EXUDATE TO PRECISION WOUND CARE: CLINICAL POTENTIAL OF MULTI-OMIC BIOMARKERS	*Hatice POYRAZ KIZMAZ* *Fatih KAR*	Kütahya Health Sciences University, Türkiye
YENİDOĞAN YOĞUN BAKIM HEMŞİRELİĞİNDE GÜNCEL ETİK İKİLEMLER VE KANITA DAYALI YAKLAŞIMLAR	*Esra AYDIN* *Duygu SÖNMEZ DÜZKAYA* *Atiye KARAKUL*	Tarsus University, Türkiye
ÇOCUKLARDA DİJİTAL EKRAN MARUZİYETİ: UYKU VE GELİŞİMSEL SONUÇLARIN ÇOCUK SAĞLIĞI VE HASTALIKLARI HEMŞİRELİĞİ PERSPEKTİFİNDEN DEĞERLENDİRİLMESİ	*Esra AYDIN* *Atiye KARAKUL* *Duygu SÖNMEZ DÜZKAYA*	Tarsus University, Türkiye
THE EFFECT OF TRANSCUTANEOUS AURICULAR VAGUS NERVE STIMULATION AND CONTROLLED BREATHING EXERCISES ON PERFORMANCE AND THE AUTONOMIC NERVOUS SYSTEM	*Okan ŞAHİN* *Ali Veysel ÖZDEN*	Istanbul Health and Technology University, Türkiye Bahcesehir University, Türkiye

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Session -1 / Hall-3
05.09.2026
Moderator:
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
BOUNDARY-AWARE ATTENTION U-NET WITH CONTROLLED MULTI-SCALE GUIDANCE FOR SMALL SURFACE DEFECT SEGMENTATION	*Mehmet Bilge Han TAŞ* *Eyyüp YILDIZ*	Erzincan Binali Yildirim University, Türkiye
INVESTIGATING THE INTERACTION BETWEEN DROPOUT AND STATIC AND DYNAMIC SPARSE TRAINING IN DEEP NEURAL NETWORKS	*Eyyüp YILDIZ* *Mehmet Bilge Han TAŞ*	Erzincan Binali Yildirim University, Türkiye
PROGRAMMABLE DAMAGE LOCALIZATION THROUGH SPATIAL TOOLPATH ENGINEERING IN 3D PRINTING	*Ibrahim ULKE*	Gazi University, Türkiye
BEYOND NEAR-PERFECT ACCURACY: A SPLIT- AND FEATURE-AWARE EVALUATION OF PHISHING URL DETECTION	*Hilal GEZGİN*	Bursa Uludağ University, Türkiye
A DEEP LEARNING APPROACH TO 3D SEGMENTATION OF TUMOR LESIONS IN BRAIN MRI	*Shabnam Aghamurad Hajiyeva*	Azerbaijan Medical University, Baku, Azerbaijan
INDUSTRIAL ARTIFICIAL INTELLIGENCE FOR SMART FACTORIES AND IIoT SYSTEMS	*Sevda AYTEL KOCABAŞ* *Tülay YILDIRIM*	Karabük University, Türkiye
THE FUTURE OF INDUSTRIAL AI: FROM LARGE LANGUAGE MODELS TO AUTONOMOUS AND SUSTAINABLE FACTORIES	*Sevda AYTEL KOCABAŞ* *Tülay YILDIRIM*	Karabük University, Türkiye
DEEP LEARNING APPLICATIONS IN WOMEN'S HEALTH NURSING: A REVIEW OF THE POST-2025 LITERATURE	*Aslı SİS ÇELİK* *İshak Metehan SİS* *Ebru SOLMAZ*	Atatürk University, Türkiye Alanya University, Türkiye
HEALTHCARE WORKERS' ANXIETY, LITERACY, SELF-EFFICACY, AND READINESS TOWARDS ARTIFICIAL INTELLIGENCE: A CROSS-SECTIONAL STUDY	*Aslı SİS ÇELİK* *Ebru SOLMAZ* *İshak Metehan SİS*	Atatürk University, Türkiye Alanya University, Türkiye

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Session -1 / Hall-4
05.09.2026
Moderator: Prof. Dr. Ahmet Niyazi ÖZKER
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
WHICH AI FOR WHICH BUSINESS PROBLEM? A SYSTEMATIC MAPPING REVIEW AND AI BUSINESS DECISION MATRIX	*İbrahim Sercan SAVCI* *Burak PAÇ* *Ayşenur BUDAK*	Gebze Technical University, Türkiye
HOW SHOULD WE COMMUNICATE WITH LARGE LANGUAGE MODELS TO GENERATE RELIABLE SIMULATION MODELS? A COMPREHENSIVE BENCHMARK	*İbrahim Sercan SAVCI* *Ayşenur BUDAK* *Burak PAÇ*	Gebze Technical University, Türkiye
BEHAVIORAL ECONOMICS AND DIGITAL CURRENCY ADOPTION UNDERSTANDING TRUST AND USABILITY IN LOW-INCOME POPULATIONS	*Mohammad Saiduzzaman* *Mehedi Morshed* *Farhana Afroz* *Zahiduzzaman Zahid*	Ministry of Textile & Jute, Dhaka, Bangladesh Ministry of Public Administration, Government of Bangladesh Rupali Bank PLC, Dhaka, Bangladesh University of the Cumberlands, Kentucky, USA
SYMBOLIC DISTINCTION IN RAMADAN LUXURY ADVERTISING: A COMPARATIVE STUDY OF L'AZURDE AND DAMAS	*Josiane El Khoury*	University of Balamand
PROMOTING TOURISM THROUGH MAPS AND CATALOGUES: CASE STUDY - MUNICIPALITY OF SUHAREKA (KOSOVA)	*Faton MORINA* *Valbon BYTYQI*	University of Tirana, Albania University of Prishtina, Kosovo
FISCAL SUSTAINABILITY IN AN ERA OF GLOBAL UNCERTAINTY: LESSONS FOR PUBLIC FINANCE	*Ahmet Niyazi ÖZKER*	Bandirma Onyedi Eylul University, Türkiye

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Session -1 / Hall-5
05.09.2026
Moderator: Prof. Bledar KRAJA
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
PATIENT-REPORTED EXPERIENCES AND OUTCOMES IN AN AMBULATORY SURGERY UNIT	*Maria Ermelinda de Sousa* *Goreti Timóteo*	Hospital Dr. Nélio Mendonça, SESARAM, EPERAM, Madeira
IMPLEMENTATION OF THE ALBANIAN DYSPHAGIA TREATMENT PROTOCOL IN NEUROLOGY WARD; TWO-CASE REPORT	*Antigoni Bullari* *Ilirjana Zekja*	University of Medicine Tirana
TRENDS IN HYPERTENSION AWARENESS IN ALBANIA: FINDINGS FROM THE MAY MEASUREMENT MONTH CAMPAIGNS 2018–2021	*Romina Hala* *Rudina Çumashi* *Gentiana Qirjako*	Institute of Public Health, Tirana, Albania University of Medicine, Tirana, Albania
KNOWLEDGE, AWARENESS, AND ATTITUDES TOWARD BREAST CANCER PREVENTION AND EARLY DETECTION AMONG SAUDI PHARMACISTS IN JEDDAH, SAUDI ARABIA: A CROSS-SECTIONAL STUDY	*Seham Saud F. Alshammari* *Hazrina Bt Hamid* *Ahmed Mohammed Aljameeli*	Lincoln University College, Petaling Jaya, Selangor, Malaysia University of Hafr Al Batin. Saudi Arabia
DENTAL INNOVATION ADOPTION AS A CATALYST FOR ALBANIAN DENTAL TOURISM GROWTH	*Orion Muçaj*	University Aleksander Moisiu, Durrës, Albania
BREAST CANCER AND DIABETES: AN EMERGING ASSOCIATION	*Maroua RIAD* *Rokaya AITLHAJ-MHAND* *Ahmad AL-SHAMI* *Jamal MABROUKI*	Mohammed V University in Rabat, Morocco
MODIFIABLE LIFESTYLE RISK FACTORS FOR PANCREATIC CANCER: A POPULATION-BASED CASE-CONTROL STUDY FROM ALBANIA	*Bledar KRAJA*	University of Medicine Tirana, Albania University Clinic of Gastro-Hepatology, University Hospital Center “Mother Teresa”, Albania

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Session -1 / Hall-6
05.09.2026
Moderator: Slobodan Divjak
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
FAMILY LAW IN THE AGE OF ARTIFICIAL INTELLIGENCE: NEW CHALLENGES FOR THE PROTECTION OF CHILDREN	*Aleksandra Nikolova Marković*	Megatrend University, Belgrade
ETHICAL ISSUES IN TECHNOLOGY & NEW BEST PRACTICES	*Keisi Bylyku*	Marin Barleti University, Albania
CITY DIPLOMACY AND THE DISAGGREGATION OF DIPLOMATIC AUTHORITY: ISTANBUL AS AN EMERGING INTERNATIONAL ACTOR IN A CENTRALIZED STATE	*Canan DEMIRCI MURSALOGLU*	Georgetown University
NIETZSCHE, BARBARISM AND VAZISM	*Slobodan Divjak*	Serbia
NON-COGNITIVE APPROACH: A HISTORICAL-DIAGNOSTIC ANALYSIS OF MATRIX DIAGONALISATION ERRORS IN 2011, 2018 AND 2025	*Lekë Pepkolaj Vasil Lino*	University Metropolitan Tirana, Albania
ENERGY SUPPLY UNCERTAINTY, ADJUDICATIVE COSTS, AND STRATEGIC EQUILIBRIUM SELECTION IN THE TÜRKİYE-GREECE EASTERN MEDITERRANEAN DISPUTE (1990-2024)	*Arzu AL Suraya BAZAROVA*	Marmara University, Türkiye

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Session -2 / Hall-1
05.09.2026
Moderator: Assoc. Prof. Dr. Ebru GÜNEREN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
İYİMSERLİĞİN GÖREV PERFORMANSINA ETKİSİNDE PSİKOLOJİK DAYANIKLILIĞIN ARACILIK ROLÜ	*Mehmet Hakan DURUKAN*	Başkent University, Türkiye
DEMAND VARIABILITY AND INVENTORY PERFORMANCE: EVIDENCE FROM RETAIL STORE OPERATIONS	*Şeyhmus ŞANLI* *Bahar TAŞAR*	İzmir Demokrasi University, Türkiye
TEKNOLOJİ YOĞUN İŞ ORTAMINDA ÇALIŞANLARIN İŞ YÜKLERİNİN İŞTEN AYRILMA NİYETLERİNE ETKİSİNDE İŞE TUTULMALARININ DÜZENLEYİCİ ROLÜ	*Özgür Nazım ÜNSAL*	Başkent University, Türkiye
THE ROLE OF WELLNESS/CLEAN BRAND VISUALS IN CONSUMER PSYCHOLOGY AND PURCHASE INTENTION: A CONCEPTUAL REVIEW	*Elif Ece Ünver*	Yeditepe University, Türkiye
CURRENT PARADIGMS IN SUSTAINABLE TOURISM: A BIBLIOMETRIC AND CONCEPTUAL DISCUSSION	*Ebru GÜNEREN*	Nevşehir Hacı Bektaş Veli University, Türkiye
DOES SUSTAINABILITY PAY OUT? ESG PERFORMANCE AND CORPORATE DIVIDEND POLICY IN THE EUROPEAN UNION AND TÜRKİYE	*Demet EVER* *Elif Nursun DEMİRCİOĞLU* *Mert DEMİRCİOĞLU*	Osmaniye Korkut Ata University, Türkiye Çukurova University, Türkiye
THE PRINCIPLE OF VULNERABILITY IN BIOLAW: A THEORETICAL FRAMEWORK FOR THE DIVERSE MANIFESTATIONS OF HUMAN VULNERABILITY	*Z. Gönül BALKIR* *Ecem KOCAOĞLAN*	Cyprus Aydın University, TRNC
THE PROBLEM OF REPRESENTATION IN THE RIGHTS OF NATURE: THE LEGAL PROTECTION OF THE SILENT SUBJECT	*Z. Gönül BALKIR* *Ecem KOCAOĞLAN*	Cyprus Aydın University, TRNC

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Session -2 / Hall-2
05.09.2026
Moderator: Assoc. Prof. Dr. Volha KORBUT SALMAN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
THE IMPACT OF FAMILY'S HIGHER EDUCATION PROFILE ON AN INDIVIDUAL'S PARTICIPATION IN HIGHER EDUCATION	*Nazlı Çağıl KÜÇÜKGÖKSEL* *Teoman AKPINAR*	T.C. Tekirdağ Namık KemaL University, Türkiye
DİJİTAL ÇAĞDA YAPAY ZEKÂ DESTEKLİ ÇOCUK EDEBİYATININ OKUMA KÜLTÜRÜ VE OKUR KİMLİĞİ ÜZERİNDEKİ ETKİLERİ	*Mahmut ÖĞ*	Ministry of National Education, Türkiye
BİRLEŞTİRİLMİŞ SINIFLARDA DİJİTAL ARAÇLARIN SINIF İÇİ YANSIMALARI: GÖZLEME DAYALI BİR DURUM ÇALIŞMASI	*Mahmut ÖĞ*	Ministry of National Education, Türkiye
EVALUATION OF ENVIRONMENTAL SUSTAINABILITY PRACTICES IN PRIMARY EDUCATION INSTITUTIONS	*Kardelen Meriç APAYDIN* *Zehra Keser ÖZMANTAR*	MEB, Türkiye Gaziantep University, Türkiye
HISTORICAL DEVELOPMENT OF THE HORN MOUTHPIECE AND THE IMPORTANCE OF MOUTHPIECE SELECTION FOR HORN PLAYERS	*F. Kübra ÇADIRCIOĞLU UYAR*	Mimar Sinan Fine Arts University, Türkiye
HEALTH ISSUES OF PEOPLE IN THE ANATOLIAN BRONZE AGE	*Serpil ÖZDEMİR ÖZBEY*	Ministry of Culture and Tourism
A FIELD STUDY ON THE PERCEPTIONS OF TURKISH YOUTH IN FRANCE REGARDING THE MORAL AND HUMAN QUALITIES OF PROPHET MUHAMMAD	*Bayram DEMİRTAŞ* *İsmail METİN*	Religious Affairs Advisor, Paris DITIB Eskişehir Osmangazi University, Türkiye
A FIELD STUDY ON THE PERCEPTION OF PROPHET MUHAMMAD AND SÎRA KNOWLEDGE AMONG TURKISH YOUTH LIVING IN FRANCE	*İsmail METİN* *Bayram DEMİRTAŞ*	Eskişehir Osmangazi University, Türkiye Religious Affairs Advisor, Paris DITIB
THE DEATH OF THE AUTHOR AND THE RESURRECTION OF THE READER IN THE AGE OF PARTICIPATORY CULTURE	*Volha KORBUT SALMAN*	Yozgat Bozok University, Türkiye
THE ANXIETY OF THE ANTHROPOCENE AND THE END OF THE NOVEL	*Volha KORBUT SALMAN*	Yozgat Bozok University, Türkiye

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Session -2 / Hall-3
05.09.2026
Moderator: Assoc. Prof. Dr. Kadir SAYGIN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
INVESTIGATING CHARGE ASYMMETRY IN LEPTONICALLY DECAYING Wγ PRODUCTION AT NNLO QCD FOR FUTURE HADRON COLLIDERS	*Kadir SAYGIN*	Düzce University, Düzce, Türkiye
NUMERICAL INVESTIGATION OF FLOW CHARACTERISTICS IN CONCENTRIC CHANNELS WITH ROTATION OF THE INNER CYLINDER	*Mustafa TURAN* *Habib UMUR*	Bursa Uludağ University, Türkiye
INVESTIGATING THE TRADE-OFF BETWEEN RECONSTRUCTION FIDELITY AND IDENTITY PRESERVATION IN DDIM INVERSION FOR FACE IMAGES	*Nazlıcan GENGEÇ ZORKUN* *Hasan Serhan YAVUZ* *Hakan ÇEVİKALP*	Eskişehir Osmangazi University, Türkiye
THERMAL-HYDRAULIC CFD OPTIMIZATION OF HIGH-CAPACITY LITHIUM-ION BATTERY PACKS FOR 1C DISCHARGE CONDITIONS	*İbrahim ÇAKICI* *Murat UYSAL*	Teksan Jeneratör, İstanbul, Türkiye
IMPROVEMENT OF THE FLAME-RETARDANT PROPERTIES OF COATED POLYESTER TEXTILE SURFACES USING WHEAT HUSK	*Kadriye KUTLAY* *Kenan YILDIRIM*	Bursa Technical University Berteks Textile, R&D and Innovation Project Coordinator
SYNTHESIS AND OPTICAL PROPERTIES OF COPPER OXIDE NANOPARTICLES USING SOL-GEL METHOD	*Feray BAYÇA* *Salih Ugur BAYÇA*	Alanya Alaaddin Keykubat University, Türkiye
PREPARATION OF SEMI-SOFT MAGNETIC COPPER OXIDE NANOPARTICLES	*Feray BAYÇA* *Salih Ugur BAYÇA*	Alanya Alaaddin Keykubat University, Türkiye
AGING EFFECT OF 316L STAINLESS STEEL WELDED JOINTS	*Burak Kadri ÇİLOĞLU* *Çiçek ÖZES* *Haşim Fırat KARASU*	Dokuz Eylül University, Türkiye
EXPERIMENTAL ASSESSMENT OF INFILL DENSITY, LAYER THICKNESS, AND WALL THICKNESS EFFECTS ON MATERIAL EFFICIENCY IN FDM	*Habip Gökay KORKMAZ* *Mevlüt AYDIN*	Niğde Ömer Halisdemir University, Türkiye Konya Technical University, Türkiye

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Session -2 / Hall-4
05.09.2026
Moderator: Dr. Priyanka Srivastava
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
EUROPEAN GREEN DEAL AND THE CARBON MARKET	*Ayşe Tuğba GÖKGÖZ*	Tekirdağ Namık Kemal University, Turkey
THE ENERGY POTENTIAL OF THE CASPIAN SEA AS AN ALTERNATIVE ENERGY SOURCE	*Sakina Badalli*	Baku State University, Azerbaijan
FIFTEEN YEARS OF POLYMER-BASED NUCLEIC ACID DELIVERY RESEARCH: A BIBLIOMETRIC ANALYSIS OF PUBLICATION DYNAMICS AND THEMATIC EVOLUTION (2010–2025)	*Mahluga HUSEYNOVA* *Roza GASIMOVA* *Laman AGHAYEVA* *Abdullah ALAKBAROV*	Khazar University, Azerbaijan Baku State University, Azerbaijan Gümüşhane University, Türkiye İzmir Institute of Technology, Türkiye
LOSS DUE TO EARTHQUAKE IN THE SOUTHERN COAST OF MINDANAO IN THE PHILIPPINES DURING JUNE 2026 AND ITS CONSEQUENCES IN THE MINDFULNESS OF THE CITIZENS	*Parrakal Satishchandra Menon* *Senbagavalli M*	SRM Institute of Science and Technology, Vadapalani Campus, India Alliance University, India
MAPPING AL GORE'S SIX DRIVERS OF GLOBAL CHANGE IN CONTEMPORARY CLIMATE FICTION	*Priyanka Srivastava* *Sandeep Kumar Pandey*	University of Allahabad, India Former Research Scholar, Banasthali Vidyapith, India
EFFICIENCY OF COLLECTING PERNA PERNA MUSSEL SPAT IN DAKHLA BAY: INFLUENCE OF SUBSTRATE ARRANGEMENT AND ENVIRONMENTAL CONDITIONS	*El Mustafa Ait Chattou* *Azedine Dergoun* *Omar Ezzabaha* *Nhhala Hassan* *Idhalla Mohamed* *Hasnaoui Mustapha*	Sultan Moulay Slimane University-FST Béni Mellal, Morocco INRH-Dakhla Aquaculture Station, BP 127Bis, Dakhla, Morocco Abdelmalek Essaadi University-FPL Larache, Morocco Freelancer Researcher, Tetouan, Morocco INRH-Aquaculture Department, Casablanca, Morocco
"DARIJA 2.0": WHEN TIKTOK AND INSTAGRAM REINVENT THE LINGUISTIC COMMUNITY OF YOUNG MOROCCANS	*Bouchra BELAOUISSI*	Sidi Mohamed Ben Abdellah University, Fez, Morocco

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Session -2 / Hall-5
05.09.2026
Moderator: Bukurie Hyseni
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
BASELINE REACTION TIME AS A PREDICTOR OF INDIVIDUAL IMPROVEMENT FOLLOWING OCULOMOTOR TRAINING IN ATHLETES	*Andromeda Lalaj* *Vjollca Shpata*	Sports University of Tirana, Albania
IMPROVING DYNAMIC BALANCE IN YOUTH FOOTBALL THROUGH AN 18-WEEK CORE TRAINING PROGRAM	*Ergys Rexha* *Ilir Cani*	Sports University of Tirana
ASSOCIATION BETWEEN BASELINE CAIT SCORE AND CHANGES IN JUMP PERFORMANCE AND ANKLE STRENGTH IN ATHLETES WITH CHRONIC ANKLE INSTABILITY	*Elizabeta Dodaj* *Dhimitraq Prifti*	Sports University Of Tirana, Albania
CHANGES IN TRUNK ROTATION, SPINAL CURVATURE, QUALITY OF LIFE, AND POSTURAL SYMMETRY FOLLOWING PHYSIOTHERAPEUTIC SCOLIOSIS-SPECIFIC EXERCISE IN ADOLESCENTS WITH SPINAL DEFORMITY	*Perli Rusi* *Agron Kasa* *Olsa Meta* *Silvio Selfo* *Rigerta Selenica*	Sports University of Tirana,Albania
CONSERVATIVE MANAGEMENT OF ADOLESCENT IDIOPATHIC SCOLIOSIS (BRACE & PSSE-SCHROTH)	*Olsa Meta* *Najada Quka* *Silvio Selfo* *Rigerta Selenica*	Sports University, Albania Aldent University,Albania
UNHEALTHY DIETARY PATTERNS AND EMOTIONAL SYMPTOM BURDEN AMONG ALBANIAN ADOLESCENTS: A SCHOOL-BASED CROSS-SECTIONAL STUDY	*Bukurie Hyseni* *Adrian Hoxha*	Specialist Drejtoria e Ofrimit te Kujdesit Shendetesor Operatori i Sherbimeve te Kujdesit Shendetesor

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Session -2 / Hall-6
05.09.2026
Moderator: Assoc. Prof. Quliyeva Ilaha
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
HIGH-PERFORMANCE DUAL-ACTIVATED SHEEP MANURE BIOCHAR FOR EFFICIENT CIPROFLOXACIN REMOVAL FROM AQUEOUS SOLUTIONS: ADSORPTION MECHANISM, THERMODYNAMICS, AND REGENERATION	*Boujemaa Soubai* *Aymane El haddoudi* *Belaid Selhami* *Smail Ait Said Ali* *Az-iddin Chham* *Mohamed Tahiri* *Josiane El Khoury*	Laboratory of Organic Chemistry, Morocco
BLIND AND NON-BLIND IMAGE DECONVOLUTION USING A TOTAL FRACTIONAL-ORDER VARIATION MODEL	*Bouchra Laaziri* *Anouar Ben-loghfyry* *Abdelilah Hakim* *Said Raghay*	Cadi Ayyad University, Marrakesh, Morocco Hassan II University, Mohammedia, Morocco
HIGH-TEMPERATURE PRODUCTION AND CHARACTERIZATION OF BIOMASS-DERIVED ACTIVATED CARBON AT 800 °C	*Egekan Erenoğlu* *Emin Emre Çalan* *Enes Çermik* *Yusuf Yıldırım* *Burcu Nilgün Çetiner* *Gülay Arslan Çene* *Zhannur Myltykbayeva*	Marmara University Al-Farabi Kazakh National University
EFFECTS OF GRAPHENE OXIDE-BASED NANOMATERIALS ON SYNDECAN GENE EXPRESSION IN TONGUE SQUAMOUS CELL CARCINOMA CELLS	*Sonia Abadini* *Firdevs Betül Tuncelli* *Zeynep Birsu Çinçin*	Istanbul Nişantaşı University, Türkiye ADAM European Center for Lifelong Learning, Research & Development, Ohrid, North Macedonia
GREEN SYNTHESIS OF ZINC OXIDE NANOPARTICLES FOR COPPER-ION DETECTION AND ENERGY STORAGE IN AQUEOUS MEDIA: AN ELECTROCHEMICAL AND DFT STUDY	*Sofia Kerouad*	Sultan Moulay Slimane University, Morocco
DEVELOPMENT, COMPREHENSIVE CHARACTERIZATION, AND PERFORMANCE EVALUATION OF STARCH-BASED BIODEGRADABLE PLASTIC FILMS	*Quliyeva Ilaha* *Eyyubov Rustam* *Abbasov Murad* *Sultanova Fakhranisa*	Azerbaijan State Oil and Industry University
A NEW INORGANIC–ORGANIC COMPOSITE COAGULANT: α-Costic acid, NATURAL SESQUITERPENOID PLANT FROM DITTRICHIA VISCOSA, AS A MODIFIER OF POLYALUMINUM CHLORIDE PROPERTIES	*Fatima Ezzahra Maaghloud* *Achraf Abdou* *Ahmed El Hakmaoui* *Jamal Jamal Eddine* *A. El Makssoudi* *Mohamed Akssira* *Mohamed Dakir*	Hassan II University of Casablanca, Casablanca, Morocco
DISPERSION OF TORSIONAL WAVES IN INITIALLY-STRESSED TRANSVERSELY ISOTROPIC HOLLOW COMPOSITE POROELASTIC CYLINDERS	*B. Sandhyarani* *P. Malla Reddy*	TGSWRDC(W), Mancherial, Telangana, India Kakatiya University, Warangal, Telangana, India
STUDY OF RADIAL NORMAL STRESSES IN A POROVISCO ELASTIC CYLINDRICAL SOLIDS EMPLOYING STRATIFIED MODEL	*Kiran Ambala* *Malla Reddy Perati*	Kakatiya University, Telangana, India

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Session -3 / Hall-1
05.09.2026
Moderator: Assoc. Prof. Dr. İlker AKYÜZ
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:14:00-16:00
Ankara Local Time: 15:00-17:00

TITLE	AUTHOR(S)	AFFILIATION
MITOCHONDRIAL BIOMARKERS AS POTENTIAL DIAGNOSTIC TOOLS IN MALE INFERTILITY	*Gamze ZENGİN* *Fatih KAR*	Kütahya Health Sciences University, Kütahya, Türkiye
SEMAPHORIN SIGNALING IN MALE REPRODUCTIVE BIOLOGY: EMERGING ROLES IN FERTILITY	*Gamze ZENGİN* *Fatih KAR*	Kütahya Health Sciences University, Kütahya, Türkiye
EPIVARIANTS AND EPIGENETIC SIGNATURES: THE ROLE OF DNA METHYLATION IN THE MOLECULAR DIAGNOSIS OF RARE DISEASES	*Yasemin OYACI* *Sacide PEHLİVAN*	Istanbul Nişantaşı University, Türkiye. Istanbul University, Türkiye
EVALUATION OF THE ASSOCIATION OF THE hTERT rs10069690 VARIANT WITH DISEASE RISK AND CLINICAL PARAMETERS IN METABOLIC SYNDROME	*Yasemin OYACI* *Naci ŞENKAL* *Tuğçe KARADAĞ* *Sacide PEHLİVAN*	Istanbul Nişantaşı University, Türkiye Istanbul University, Türkiye
THE EFFECTS OF A PERMANENT PACEMAKER ON WOMEN'S SEXUAL HEALTH	*Mevra EKSİN* *Seda KARAÇAY YIKAR* *Evşen NAZİK*	Adana City Training and Research Hospital Çukurova University, Türkiye
MANAGEMENT OF INTRAPERICARDIAL LIPOMAS: A CASE OF PROGRESSIVE GROWTH AND SUPERIOR VENA CAVA COMPRESSION	*Doğan YETÜT* *Mazlum ŞAHİN*	Istanbul Beykent University, Türkiye
FLEXITARIAN DIET ADHERENCE AND ITS ASSOCIATIONS WITH HEALTHY AND SUSTAINABLE LIFESTYLE AND AFFECTIVE STATES AMONG UNIVERSITY STUDENTS	*Sevinç EŞER DURMAZ* *Sinem KILIÇ* *Beyza Hatun BEKTAŞ*	Kırıkkale University, Türkiye
STATISTICAL ANALYSIS OF MATCH OUTCOMES AND PRE-MATCH BETTING ODDS IN SWISS PROFESSIONAL FOOTBALL LEAGUES (2013–2026)	*İlker AKYÜZ*	Karadeniz Technical University, Türkiye

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Session -3 / Hall-2
05.09.2026
Moderator: Assoc. Prof. Dr. Ertan ARSLANKAYA
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:14:00-16:00
Ankara Local Time: 15:00-17:00

TITLE	AUTHOR(S)	AFFILIATION
THE INFLUENCE OF VIENNA ON THE ARCHITECTURE OF THE REFIK SAYDAM CENTRAL INSTITUTE OF HYGIENE IN ANKARA DURING THE EARLY REPUBLICAN PERIOD	*Şule PFEIFFER-TAŞ* *Merve KÖSE*	Atılım University, Türkiye
A SINGULAR EXPERIENCE, MULTIPLE COMPONENTS: A SYSTEMATIC REVIEW OF AMBIANCE RESEARCH IN ARCHITECTURE	*Ümmü Gülsüm ŞENAY* *Dilek Yıldız ÖZKAN*	Istanbul Technical University, Türkiye
DETERMINATION OF LAND USE CONFLICT AREAS IN KIZILCAHAMAM (ANKARA) DISTRICT USING THE LUCIS MODEL	*Yasin YILDIRIMOĞLU* *Mehmet Ali ÖZDEMİR*	Afyon Kocatepe University, Türkiye
PRESENCE OF PFAS COMPOUNDS IN TEXTILE DYEING PLANT WASTEWATER IN TURKIYE AND REMOVAL ALTERNATIVES	*Melek Zeynep ÇETİNKAYA* *Ertan ARSLANKAYA*	Yıldız Technical University, Türkiye
THE EFFECT OF SEISMIC LOADS ON AN ONSHORE WIND TURBINE TOWER	*Asuman Isil CARHOGLU* *Melis AKFIRAT*	Suleyman Demirel University, Türkiye Civil Engineering, Antalya, Turkey
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Session -3 / Hall-3
05.09.2026
Moderator:
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:14:00-16:00
Ankara Local Time: 15:00-17:00

TITLE	AUTHOR(S)	AFFILIATION
COMPARISON OF THE EFFECT OF STACKING SEQUENCE ON THE QUASI-STATIC INDENTATION BEHAVIOR OF SYMMETRIC AND ASYMMETRIC CARBON/KEVLAR HYBRID DOUBLE-CURVED COMPOSITE STRUCTURES	*İlhan ÇAKIL* *Mehmet ÖZER* *Fatih BALIKOĞLU*	Balıkesir University, Türkiye
NUMERICAL INVESTIGATION OF THE AERODYNAMIC PERFORMANCE OF SGMMNS CONTAINER WAGON UNDER DIFFERENT CONTAINER LOADING CONFIGURATIONS	*Mehmet UÇAR* *Kerime ÜSTÜN* *Oğulcan ERTAL*	Epsilon Solentek Raylı Sistemler A.Ş Eskişehir
COST-BASED PRODUCTION OPTIMIZATION AND DIGITAL DECISION SUPPORT INTERFACE IN OPEN-PIT GOLD MINING	*Said İbrahim BARRY* *Serkan TÜYLÜ* *Deniz ADIGÜZEL* *İsmail DEMİR*	İstanbul University - Cerrahpaşa, Türkiye
UTILIZATION OF MARBLE WASTE AS FINE AGGREGATE AND CEMENT REPLACEMENT IN CEMENT-BASED MORTARS	*Can BODUR* *İsmail DEMİR* *Serkan TÜYLÜ* *Deniz ADIGÜZEL*	İstanbul University - Cerrahpaşa, Türkiye
EVALUATING THE IMPACT OF AI-BASED DESIGN TOOLS ON PROCESS EFFICIENCY AND DESIGN PERFORMANCE IN MODEL DESIGN	*Serkan GÜLER* *Bekir BOYACI* *Tuğçe UYSAL*	Sun Tekstil San. ve Tic. A.Ş.
PRETREATMENT OF INDUSTRIAL METALLIC WASTE FOR SECONDARY RAW MATERIAL RECOVERY	*Mustafa TEKIN* *Selenay ELBIR* *Ahmet Emre BAĞLI*	Yeditepe University, Türkiye
EFFECT OF PLASTIC SYRINGE-DERIVED PYROLYSIS LIQUID ON DIESEL ENGINE PERFORMANCE AND EMISSIONS	*Rasim BEHÇET*	İnönü University, Türkiye
THE ROLE OF BUILDING MATERIALS IN ACHIEVING ENERGY EFFICIENCY IN BUILDINGS	*Rasim BEHÇET*	İnönü University, Türkiye

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Session -3 / Hall-4
05.09.2026
Moderator: Ravana GULIYEVA
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:14:00-16:00
Ankara Local Time: 15:00-17:00

TITLE	AUTHOR(S)	AFFILIATION
THE IMPACT OF ARTIFICIAL INTELLIGENCE TOOLS ON SELF-REGULATED LEARNING AND ACADEMIC MOTIVATION	*Ravana GULIYEVA* *Nigar ALIYEVA* *Khadija RUSTAMLI* *Elnara MAMMADOVA* *Farida KHALAFOVA* *Konul GULIYEVA*	Baku State University, Baku, Azerbaijan Khazar University, Baku, Azerbaijan Azerbaijan University of Languages, Baku, Azerbaijan
INCLUSION OF NEW HUMAN RESOURCES IN EDUCATION: A LIFELONG LEARNING PERSPECTIVE IN ALBANIA	*Blerina Dhrami*	Universiteti Metropolitan Tirana
THE EMERGENCE AND DEVELOPMENT OF BIOETHICAL THEORY IN THE PHILOSOPHICAL SCHOOLS OF THE EAST AND WEST	*Gamar Khanim JAVADLI*	Deputy Chair, Caucasus Muslim Board
ARTIFICIAL INTELLIGENCE'S EFFECT ON BIOLOGY EDUCATION: PROSPECTS, DIFFICULTIES, AND FUTURE PERSPECTIVES	*Nilufar Bayramli*	Baku Engineering University, Baku, Azerbaijan
FROM STANDARDIZED BENCHMARKS TO CURRICULUM DESIGN: THE 2016 SAT ESSAY FORMAT: IMPLICATIONS FOR ANALYTICAL WRITING INSTRUCTION	*Greta Përgjegji*	Faculty of Defence and Security Studies, Department of Communication Sciences and Foreign Languages

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Session -3 / Hall-5
05.09.2026
Moderator: Geanina Gabriela PRODAN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:14:00-16:00
Ankara Local Time: 15:00-17:00

TITLE	AUTHOR(S)	AFFILIATION
COMPARATIVE ANALYSIS OF SUSTAINABILITY STANDARDS IN THE TOURISM SECTOR	*Saghar VAZEH* *Deniz DOLGEN*	Dokuz Eylul University, Türkiye
DETERMINANTS OF ACQUISITION PREMIUMS: THE CENTRAL ROLE OF TARGET FIRM VALUE	*Geanina Gabriela PRODAN* *Mihaela ONOFREI*	Alexandru Ioan Cuza University
LEGAL LEVERAGES THAT WILL DEFINE THE ECONOMIC ENVIRONMENT DURING REPUBLIC OF MOLDOVA ACCESION TO THE EUROPEAN UNION	*Mihai SUSANU* *Corneliu TUNI*	Republic of Moldova
CROSS BORDER CONFLICT MEDIATION DURING REPUBLIC OF MOLDOVA ACCESION TO THE EUROPEAN UNION	*Corneliu TUNI* *Mihai SUSANU*	Republic of Moldova
THE EFFECT OF FISCAL GOVERNANCE ON THE FISCAL SUSTAINABILITY DURING SHOCKS: CASE OF ALBANIA	*Arjan Tushaj* *Desantila Muja* *Valentina Sinaj*	University of Tirana, Albania
RETHINKING PUBLIC SECTOR BANKING THROUGH RESPONSIBLE ARTIFICIAL INTELLIGENCE AND ETHICAL FINANCE: A CONCEPTUAL FRAMEWORK FOR SUSTAINABLE FINANCIAL INCLUSION	*Niger Sultana* *Shahed Alamm*	Sonali Bank PLC, Bangladesh Islamic Banking and Finance Professional, Bangladesh
ASSESSING THE IMPACT OF MANAGERIAL FACTORS ON TOURISM BUSINESS PERFORMANCE IN RELATION TO COST STRUCTURE: THE CASE OF VLORA REGION	*Dorina RESMELIU* *Edmond KADIU*	University of Elbasan “Aleksandër Xhuvani” University of Tirana “Agricultural”

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Session -3 / Hall-6
05.09.2026
Moderator: Dr. Latif Hoxha
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:14:00-16:00
Ankara Local Time: 15:00-17:00

TITLE	AUTHOR(S)	AFFILIATION
MULTISCALE COMPUTATIONAL MECHANOPHENOTYPING OF TUBULINOPATHY-ASSOCIATED CYTOSKELETAL DYSFUNCTION IN MICRO-TENN MODELS	*Bengisu Arslantaş* *Zeynep Birsu Çinçin*	ADAM European Center for Lifelong Learning, Research & Development, Ohrid, North Macedonia
CULTURAL COMPETENCE MODELS AND THE PECHA KUCHA METHOD IN NURSING EDUCATION: A NARRATIVE REVIEW	*Cansu YAŞAR* *Betül ÖZEN* *Zeliha KAYA ERTEN*	Nuh Naci Yazgan University, Türkiye Erciyes University, Türkiye
GENOMIC IMPRINTING DEFECTS IN THE 15q11-q13 REGION: BIOMEDICAL IMPLICATIONS OF PRADER-WILLI AND ANGELMAN SYNDROMES	*Ayla Huseynova*	Baku State University
CRISPR-CAS SPACER ACQUISITION AS A BIOMARKER OF PHAGE-DRIVEN GENE FLUX IN ENVIRONMENTAL AND CLINICAL ISOLATES	*Zenah Hadi Saeid* *Zainab Abdullah Waheed*	Middle Technical University, Baghdad, Iraq
THE SARDINIA FILTER: A PATIENT SAFETY MODEL FOR TECHNOLOGY-ASSISTED CLINICAL INTERVENTIONS	*Viviane DaSilva*	University of Parma, 43126 Parma, Italy
TREATMENT OF A COMPLEX GLIOBLASTOMA USING THREE-DIMENSIONAL CONFORMAL RADIOTHERAPY: A CASE REPORT	*Blerina Myzeqari* *Dhurata Kuqi* *Artur Xhumari*	University Hospital Centre "Mother Teresa", Tirana, Albania UPT, Tirana, Albania University of Medicine, Tirana, Albania
THE NEED FOR SCHOOL PSYCHOLOGICAL SERVICES AND THE ROLE OF THE SCHOOL PSYCHOLOGIST: A QUALITATIVE STUDY IN KOSOVO	*Latif Hoxha*	Clinical Psychologist Specialist, Kosovo

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Session -1 / Hall-1
06.09.2026
Moderator: Assist. Prof. Dr. Tarık GÜNEŞ
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
CHANGING MATERNAL AGE PROFILE IN IVF PATIENTS: A 12-YEAR RETROSPECTIVE COHORT STUDY	*Seda KARABULUT* *Oya KORKMAZ* *Pelin MACIT*	Istanbul Medipol University, Türkiye Malatya Turgut Özal University, Türkiye Istanbul Okan Hospital, Türkiye
EVALUATION OF THE MEDIAL LONGITUDINAL ARCH IN YOUNG ADULTS BY SEX, FOOT DOMINANCE, AND BODY MASS INDEX	*Cem KOPUZ* *Ömer ELDİVEN* *Gültekin ERASLAN* *Alper BOZAK* *İrem YAŞAR*	Kütahya Health Sciences University, Türkiye
COMPARISON OF THE EFFECTS OF VIRTUAL REALITY-BASED WALKING EXERCISE AND TREADMILL EXERCISE ON BALANCE, FEAR OF FALLING, MOTOR AND RESPIRATORY FUNCTIONS, AND FATIGUE IN PATIENTS WITH CHRONIC STROKE	*Gökay KÜÇÜKYILMAZ* *Vedat GÖKEN*	Istinye University, Türkiye Marmara University, Türkiye
A COMPARATIVE ASSESSMENT OF FEDERATED, IMA AND DIMA AVIONICS ARCHITECTURES FROM A MODEL-BASED SYSTEMS ENGINEERING PERSPECTIVE	*Nur Hilal ÇILOĞLU* *Tarık GÜNEŞ*	İskenderun Technical University, Türkiye
EVALUATING THE REDUCED CREW CONCEPT IN THE TRANSITION TO FUTURE FLIGHT DECK OPERATIONS: A HUMAN FACTORS AND PILOT TRAINING PERSPECTIVE	*Yaren DIKICIOĞLU* *Tarık GÜNEŞ*	İstanbul Okan University, Türkiye İskenderun Technical University, Türkiye
THE NEUROPROTECTIVE POTENTIAL OF BORON AND BORIC ACID: MOLECULAR MECHANISMS, PRECLINICAL EVIDENCE AND FUTURE PERSPECTIVES	*Sevde Nur ÇİFTÇİ* *Fatih KAR*	Kütahya Health Sciences University, Türkiye
PREVOTELLA COPRI AND SHORT-CHAIN FATTY ACIDS: METABOLIC AND NEUROIMMUNE REGULATION VIA MICROBIAL METABOLITES	*Sevde Nur ÇİFTÇİ* *Fatih KAR*	Kütahya Health Sciences University, Türkiye

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Session -1 / Hall-2
06.09.2026
Moderator: Lect. Tuba YALÇIN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
HEMŞİRELERİN SESSİZ İSTİFASININ ÖRGÜTSEL SAPMA DAVRANIŞLARINDA ETKİSİ VE ÖRGÜTSEL ÖZDEŞLEŞMENİN ARACI ROLÜ: KESİTSEL BİR ÇALIŞMA	*Tuba YALÇIN*	Doğuş University, Türkiye
TEAR INFLAMMATORY BIOMARKERS IN KERATOCONUS	*Esra BAHADIR CAMGÖZ* *Fatih KAR*	Kütahya City Hospital, Türkiye Kütahya Health Sciences University, Türkiye
TEAR INFLAMMATORY BIOMARKERS IN DRY EYE DISEASE	*Esra BAHADIR CAMGÖZ* *Fatih KAR*	Kütahya City Hospital, Türkiye Kütahya Health Sciences University, Türkiye
THE EFFECTS OF CORRECTIVE EXERCISE AND KINESIO TAPING APPLICATIONS ON PERFORMANCE AND FUNCTIONAL MOBILITY IN YOUNG BASKETBALL PLAYERS	*Vedat GÖKEN* *Seha Nedret NECAN* *Nazlı YILDIZ* *Deniz Zeynep AKINER* *Nida Nur EKİM* *Nazlı YILDIZ* *Gufran Raed Abdulhaleem ALANI* *Berrak VARHAN*	Istinye University, Türkiye
THE RELATIONSHIP BETWEEN PRESSURE ULCER DEVELOPMENT AND SOCIODEMOGRAPHIC AND CLINICAL CHARACTERISTICS IN HOME HEALTHCARE AND PALLIATIVE CARE PATIENTS	*Murat ZENCIRKIRAN* *Adem DURMAZ*	Kütahya Health Sciences University, Türkiye
GENOMIC AND PHENOTYPIC CHARACTERIZATION OF TWO PROPOSED NOVEL EQUINE-ASSOCIATED RHODOCOCCUS SPECIES RESEMBLING RHODOCOCCUS EQUI	*Zeynep YERLİKAYA*	Fırat University, Türkiye

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Session -1 / Hall-3
06.09.2026
Moderator: Bogdan-Catalin SERBAN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
MAILLARD REACTIONS IN FOOD CHEMISTRY: MECHANISMS, BENEFITS, AND SAFETY CHALLENGES	*Bogdan-Catalin SERBAN* *Matei-Gabriel URSACHESCU* *Vlad DIACONESCU* *Caterina Maria ZETU* *Maria Ruxandra SALAGEAN* *Diana DUMITRAŞCU* *Octavian BUIU* *Marius BUMBAC*	National Institute for Research and Development in Microtechnologies–IMT Bucharest, Voluntari, Romania National College “B. P. Hasdeu”, Buzau, Romania University of Medicine and Pharmacy “Carol Davila”, Bucharest, Romania International Theoretical High School of Computer Science, Bucharest, Romania National College “Saint Sava”, Bucharest, Romania Valahia University of Târgovişte, Romania
POROUS ORGANIC CAGES: SYNTHESIS, PROPERTIES AND APPLICATIONS	*Bogdan-Catalin SERBAN* *Matei-Gabriel URSACHESCU* *Vlad DIACONESCU* *Caterina Maria ZETU* *Maria Ruxandra SALAGEAN* *Diana DUMITRAŞCU* *Octavian BUIU* *Marius BUMBAC*	//-//
HYPERCROSSLINKED POLYMERS: SYNTHESIS, PROPERTIES, AND EMERGING APPLICATIONS	*Bogdan-Catalin SERBAN* *Matei-Gabriel URSACHESCU* *Vlad DIACONESCU* *Caterina Maria ZETU* *Maria Ruxandra SALAGEAN* *Diana DUMITRAŞCU* *Octavian BUIU* *Marius BUMBAC*	//-//
THE CHEMISTRY OF CORAL BLEACHING: MECHANISMS, SUNSCREEN POLLUTION AND PREVENTION	*Bogdan-Catalin SERBAN* *Matei-Gabriel URSACHESCU* *Vlad DIACONESCU* *Caterina Maria ZETU* *Maria Ruxandra SALAGEAN* *Diana DUMITRAŞCU* *Octavian BUIU* *Marius BUMBAC*	//-//
HIDDEN HAZARDS IN HONEY: NATURAL TOXINS, ACCIDENTAL CONTAMINANTS AND DELIBERATE ADULTERATION	*Bogdan-Catalin SERBAN* *Matei-Gabriel URSACHESCU* *Vlad DIACONESCU* *Caterina Maria ZETU* *Maria Ruxandra SALAGEAN* *Diana DUMITRAŞCU* *Octavian BUIU* *Marius BUMBAC*	//-//

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Session -1 / Hall-4
06.09.2026
Moderator: Nishtman Zamani
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
CIRCULATING EXOSOMAL MIRNAS AS BIOMARKERS FOR SUBCLINICAL INFLAMMATION SERONEGATIVE RHEUMATOID ARTHRITIS	*Muhammad Amar Gul*	University of Gujrat, Gujrat, Pakistan
SOCIOECONOMIC, DEMOGRAPHIC AND CULTURAL DETERMINANTS OF ACCEPTANCE OF CAESAREAN SECTION AMONG PREGNANT WOMEN IN FEDERAL MEDICAL CENTRE, BIRNIN KEBBI, KEBBI STATE, NIGERIA	*Rasheed Adebayo Yinusa*	Federal University Birnin Kebbi, Kebbi State, Nigeria
IDENTITY AND PSYCHOLOGICAL ADAPTATION IN LIVING WITH DEMENTIA	*Chien Ju Chen*	Hsuan Chuang University Taiwan
PARENTAL ABSENCE: CHILDHOOD INSECURITY, ABANDONMENT, AND PSYCHOLOGICAL REPAIR	*Chien Ju Chen*	Hsuan Chuang University Taiwan
NEUROPROTECTIVE EFFECTS OF CAFFEINE AGAINST ROTENONE-INDUCED PARKINSONIAN MOTOR DEFICITS, OXIDATIVE STRESS, AND DOPAMINERGIC DYSFUNCTION IN DROSOPHILA MELANOGASTE NEUROPROTECTIVE POTENTIAL OF CAFFEINE IN A ROTENONE-INDUCED DROSOPHILA MODEL OF PARKINSONISM	*Omodesola Oluwafisayo Ogunruku* *Amos Rotimi Joshua* *James Busayo Agboola*	Obafemi Awolowo University, Ile-Ife, Nigeria
TOTAL PHENOLIC, FLAVONOID AND SAPONIN CONTENTS, AND GC-MS PROFILE OF THE METHANOLIC EXTRACT OF LEAVES OF CROSSOPTERYX FEBRIFUGA	*Theresa Ibibia Edewor* *Fayomi Joseph Abidemi* *Mutiu Olasunkanmi Amuda* *Igbayilola Yusuff Dimeji*	Ladoke Akintola University of Technology, Nigeria Federal University of Health Sciences, Nigeria
PHASE OF NEOVASCULARIZATION IN WOUND REPAIR: TOPICAL IMPACT OF LOW-LEVEL LASER THERAPY WITH CONVENTIONAL TREATMENT IN RABBIT MODEL	*Muhammad Asif* *Satheesh Babu Natarajan* *Muhammad Ahmed Azmi*	Lincoln University College, Malaysia Al-Tibri Medical College Isra University Karachi Campus
MATERNAL VITAMIN D DEFICIENCY AND CARDIOMETABOLIC RISK IN HYPERTENSIVE DISORDERS OF PREGNANCY	*Ramona Elena DRAGOMIR* *Daniela Oana TOADER* *Ion PETRE* *Florina BULEU* *IZABELLA PETRE*	"Alessandrescu-Rusescu" National Institute for Mother and Child Health, Bucharest, Romania „Carol Davila" University of Medicine and Pharmacy, Bucharest, Romania "Victor Babes" University of Medicine and Pharmacy Timisoara, Romania
EMERGING TRENDS IN BIOSENSOR TECHNOLOGIES FOR REAL-TIME FOOD SAFETY MONITORING: A REVIEW	*Nishtman Zamani*	Tehran University of Medical Sciences, Tehran, Iran
EMERGING TRENDS IN BIOSENSOR TECHNOLOGIES FOR REAL-TIME FOOD SAFETY MONITORING: A REVIEW	*Nishtman Zamani*	Tehran University of Medical Sciences, Tehran, Iran

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Session -1 / Hall-5
06.09.2026
Moderator: Dr. Pragnesh B. Dalwadi
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time: 09:00-11:00
Ankara Local Time: 10:00-12:00

TITLE	AUTHOR(S)	AFFILIATION
RETHINKING ISLAMIC HEALTH FINANCING FOR INCLUSIVE HEALTHCARE ACCESS THROUGH DIGITAL FINANCE	*Niger Sultana* *Md. Shahed Alamm*	Senior Principal Officer, Sonali Bank PLC, Bangladesh Islamic Banking and Finance Professional, Bangladesh
CULTURAL HERITAGE AND NATIONAL TRANSFORMATION IN NIGERIA: A STUDY OF DEWEY'S AESTHETIC PHILOSOPHY	*Ayobami Oluwasegun ADIGUN*	Federal University Oye – Ekiti
LOGISTICS RELIABILITY AS A FACTOR OF TRADE INTEGRATION IN THE WESTERN BALKANS: AN EMPIRICAL PERSPECTIVE ON BOSNIA AND HERZEGOVINA	*Nebojsa Savanovic* *Stojan Aleksic* *Gordana Blagojevic*	University of Novi Sad The university "Economics Academy" Brcko District of Bosnia and Herzegovina International University Brcko District of Bosnia and Herzegovina
ENVIRONMENTAL ACCOUNTING REPORTING AND FINANCIAL PERFORMANCE OF LISTED OIL FIRMS IN NIGERIA	*Akaninyene Akpan Arthur*	Akwa Ibom State Polytechnic, Nigeria
COMPARING FRAUD-AS-A-SERVICE BUSINESS MODELS AMONG NIGERIA, EASTERN EUROPE, AND SOUTHEAST ASIA: SEQUENTIAL EXPLANATORY MIXED METHODS DESIGN	*Hassan ABDULAZEEZ* *J.A. OJENIYI*	Federal University of Technology, Nigeria
SOCIAL ENTERPRISE MANAGEMENT AND ITS IMPACT ON SUSTAINABLE COMMUNITY DEVELOPMENT: EVIDENCE FROM ROMANIA IN A EUROPEAN PERSPECTIVE	*Elena Denisa MATEEVİCİ* *Assoc. Prof. Dr. Ivona RĂPAN* *PhD. Volodea Mateevici*	National Institute for Economic Research "Costin C. Kirițescu", Romania Institute of National Economy, Romanian Academy, Bucharest, Romania Sus Ramnicul LAG Association, Ramnicu Sarat, Romania
THE ROLE OF CAPITAL STRUCTURE IN ENHANCING PROFITABILITY: A PERSPECTIVE STUDY OF GREEN WORLD COMPANIES IN EASTERN GHANA	*Stephen Ofori Yeboah*	
DIGITAL FORENSIC ACCOUNTING: AN INTEGRATED APPROACH TO FRAUD DETECTION, INVESTIGATION AND FINANCIAL INTEGRITY	*Dr. Pragnesh B. Dalwadi* *Dr. Deepa C. Chandwani*	Government Arts and Commerce College R J Tibrewal Commerce College

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Session -2 / Hall-1
06.09.2026
Moderator: L. O. Salaudeen
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
MATHEMATICAL MODELLING OF SICKLE CELL ANAEMIA IN NIGERIA: POPULATION GENETICS, COMPARTMENTAL DYNAMICS, AND OPTIMAL CONTROL OF INTERVENTIONS	*L. O. Salaudeen*	Federal University Oye-Ekiti, Nigeria
FLOATING HYDROKINETIC TURBINES: POTENTIAL, CHALLENGES AND DEVELOPMENT DIRECTIONS	*Aneta Nycz* *Przemysław Szulc* *Witold Lorenz* *Artur Machalski* *Adam Góralczyk* *Artur Olszewski*	Instytut Optymalizacji Technologii sp. z o.o., Warsaw, Poland
PRODUCTION AND DECAYS OF AN EXOTIC CHARGED LEPTON AT AN ELECTRON–POSITRON COLLIDER	*Marlon Yesid Cuastumal Tarapues*	Universidad Nacional de Colombia
AERODYNAMIC LIMITATIONS OF LIFT-TYPE ROTORS IN GRAVITATIONAL VORTEX TURBINES: THE CURVATURE EFFECT AND ITS IMPACT ON ENERGY CAPTURE	*Alejandro Ruiz Sánchez* *Jorge Andrés Sierra Del Rio*	Institución Universitaria ITM, Medellín, Colombia
EFFECT OF THE OUTLET-TO-TANK DIAMETER RATIO ON AIR-CORE STABILITY AND KINETIC ENERGY TRANSFER IN GRAVITATIONAL VORTEX TURBINES	*Alejandro Ruiz Sánchez* *Jorge Andrés Sierra Del Rio*	Institución Universitaria ITM, Medellín, Colombia
PRIMORDIAL BLACK HOLES: QUANTUM HORIZON EFFECTS, BARROW ENTROPY, AND THERMODYNAMIC EVOLUTION	*Ritabrata Biswas*	The University of Burdwan, India
MODELING AND ANALYSIS OF A BLDC MOTOR FOR INDUSTRIAL APPLICATIONS	*Prof. Kavish G. Gaurkhede* *Dr. Umesh E. Hiwase*	Priyadarshini College of Engineering, Nagpur
COMPARATIVE AERODYNAMIC PERFORMANCE OF SG6043 AND NACA 4415 AIRFOILS FOR SMALL-SCALE HORIZONTAL-AXIS WIND TURBINES USING BLADE ELEMENT MOMENTUM THEORY AND COMPUTATIONAL FLUID DYNAMICS	*Ezeani David Onyebuchi* *Lamid Kazeem*	Air Force Institute of Technology, Kaduna, Nigeria

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Session -2 / Hall-2
06.09.2026
Moderator: L. O. Salaudeen
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
ANTIHYPERTENSIVE EFFECTS OF CROSSOPTERYX FEBRIFUGA METHANOL LEAF EXTRACT IN RAT AORTA	*Isah Otaru Audu* *Idu MacDonald* *Amaechina Fabian*	Federal University Lokoja, Nigeria University of Benin, Nigeria
INDIGENOUS ECOLOGICAL KNOWLEDGE AS A PATH FORWARD: REIMAGINING CLIMATE FUTURES IN LOUISE ERDRICH'S THE MIGHTY RED	*U. Katheeja Ramzia* *Dr, T. P. Anupama*	Deemed to be University, Kanathur, Chennai
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IDENTIFICATION OF A-TOCOSPIRO A AND B: AN ECONO-ANTIMICROBIAL AND CYTOTOXIC TOCOPHEROIDS FROM DEINBOLLIA PINNATA (SAPINDACEAE) LEAVES	*Yakubu Rufai* *Abdulrazak Jinadu Otaru* *Isyaka M. Sani* *Suleiman kabiru* *Sami F. Khalil*	Universiti Teknologi Malaysia (UTM), MALAYSIA Federal College of Education (FCE), NIGERIA North-Eastern University, NIGERIA King Faisal University, SAUDI ARABIA Curative Organic Herbal Enterprise Ltd, Kogi State, NIGERIA
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B.SUBTILISWASSCREENING AND ISOLATION OF CHITOSAN-PRODUCING BACTERIA	*Ayobami Josiah Aderemi* *Abdulrazaq Izuafa* *Oluwafemi Adebayo Oyewole*	Federal University of Technology, Minna, Niger State, Nigeria Federal University of Birnin Kebbi, Kebbi State, Nigeria
PHYTOGENIC FEED ADDITIVES AS ALTERNATIVES TO ANTIBIOTICS: A PATHWAY TOWARDS SUSTAINABLE, SAFE AND RESILIENT ANIMAL PRODUCTION	*Oluwafemi Abel Agbetuyi* *Emmanuel Kehnide Asaniyan* *Taiwo Oladoye Akande*	Federal University, Nigeria Olusegun Agagu University of Science and Technology, Nigeria Obafemi Awolowo University, Nigeria

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Session -2 / Hall-3
06.09.2026
Moderator: Dr. Robraw ANN
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

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URBAN DEVELOPMENT, SEISMIC VULNERABILITY AND PUBLIC HEALTH RESILIENCE: ASSESSING EARTHQUAKE RISK IN DHAKA, BANGLADESH	*Shahriar Hasan Mridha Ratul* *Latifa Sultana* *K. M. Shakik Ahmed Walid* *Haimonty Sarker* *Moukuri Mohim* *Mahjabin Tamanna Moury* *S M Monirul Islam* *Arafat Chowdhury*	Comilla University (CoU), Bangladesh Jahangirnagar University (JU), Bangladesh Southeast University (SEU), Bangladesh
PERFORMANCE OF DRY DETENTION BASINS (GREY INFRASTRUCTURE) IN MITIGATING URBAN FLOOD VOLUMES UNDER EXTREME RAINFALL EVENTS: A CALIBRATED SWMM-BASED DIGITAL TWIN ANALYSIS	*Yasser Ismail Antunes Abder Rahman* *Johannes Gerson Janzen*	Universidade Federal de Mato Grosso do Sul (UFMS)
INTEGRATING VIDEO INTO FRENCH LANGUAGE TEACHING IN CAMBODIA: PRACTICES, CHALLENGES, AND PEDAGOGICAL PERSPECTIVES	*Dr. Robraw ANN*	National Institute of Education, Phnom Penh, Cambodia
A STUDY OF THE PERCEPTION OF TEACHERS TOWARDS MULTILINGUAL EDUCATION	*Md Zaky Akhtar* *Prof. Harjeet Kaur Bhatia*	Jamia Millia Islamia
WHO DECIDES WHAT IS SCIENTIFICALLY VALID? LEARNERS' EPISTEMIC ENGAGEMENT WITH GENERATIVE AI IN SCIENCE EDUCATION	*Kazima Tahseen* *Dr. Aerum Khan*	Jamia Millia Islamia
EFFECTS OF PROJECT METHOD ON SENIOR SECONDARY STUDENTS' INTEREST IN PHYSICAL GEOGRAPHY IN JOS NORTH LOCAL GOVERNMENT AREA, PLATEAU STATE, NIGERIA	*Hannah Nathaniel Shamle* *Cecilia Isaac*	University of Jos
THE IMPACT OF AI ON FINANCE, ECONOMY AND DEVELOPMENT: BALANCING TECHNOLOGICAL ADVANCEMENTS WITH ETHICAL, EMPLOYMENT AND OPERATIONAL CHALLENGES	*Shahriar Hasan Mridha Ratul* *Laila Arzumand Banu* *Moukuri Mohim* *Sabya Sachi Chanda Antor* *Piyas Ranjan Biswas* *Foysal Khan* *Sharmin Akter* *K. M. Shakik Ahmed Walid*	Jahangirnagar University, Bangladesh
MOROCCAN HIGH SCHOOL STUDENT MOTIVATION IN LIFE AND EARTH SCIENCES: ANALYZING DETERMINANTS AND PEDAGOGICAL INNOVATION PERSPECTIVES	*Fadma El Abdellaoui* *Youssef Haouazine* *Hassan Bentaleb*	Regional Centre for Education and Training Professions (CRMEF), Morocco Ibn Tofail University, Kenitra B.P 242, Morocco.
A COMPARATIVE ANALYSIS OF SOCIO-CULTURAL BARRIERS TO FEMALE EDUCATION AND WOMEN'S EMPOWERMENT IN WOMAN AT POINT ZERO AND THE JOYS OF MOTHERHOOD	*Maman Kégni Salifou* *ALOU Yacoubou*	Université André Salifou (UAS) de Zinder

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Session -2 / Hall-4
06.09.2026
Moderator: Said ELANZAOUI
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
A GREEN MAGNETIC ACTIVATED CARBON FOR EFFICIENT CRYSTAL VIOLET REMOVAL	*Said ELANZAOUI*	University IBN ZOHR, Morocco
INFLUENCE OF EXTRACTION METHOD ON THE PHYTOCHEMICAL AND ANTIOXIDANT PROPERTIES OF NIGELLA SATIVA SEED PRODUCTS	*CHEKROUN-BECHLAGHEM Nadjat* *Zitouni Amel*	University Abou-Bekr Belkaid, Institute of Applied Sciences and Technologies, Department of Sciences, Tlemcen, Algeria
EFFECT OF ROOTSTOCK (CITRUS MACROPHYLLA AND CITRUS VOLKAMERIANA) ON PHOSPHORUS UPTAKE DYNAMICS IN CITRUS GROWN ON CALCAREOUS SOIL AT DIFFERENT PHENOLOGICAL STAGES	*BRITAL Rania* *MRABTI Imane* *EL Bahja Fatima* *IBRIZ Mohammed* *ABAIL Zhor*	Sidi Mohammed Ben Abdallah University, Fez
THE CELL UNDER THE PEDAGOGICAL MICROSCOPE: UNDERSTANDING AND TEACHING THE CELL CONCEPT IN MIDDLE SCHOOL	*Hassan BENTALEB* *Youssef HAOUAZINE* *Fadma EL ABDELLAOUI*	Ibn Tofail University, Kenitra, Morocco Regional Center for Education and Training Professions (CRMEF), Morocco
COMPARISON OF CHEMICAL COMPOSITION AND ANTIMICROBIAL ACTIVITY OF ESSENTIAL OILS OBTAINED FROM WILD AND CULTIVATED THYMUS ZYGIS FROM MOROCCO	*EL BRAHIMI Rajae* *BARI Amina*	Sidi Mohammed Ben Abdallah University, Fez
THE EFFECT OF FERMENTATION PROCESS ON THE ANTI-NUTRITIONAL FACTORS IN THE SUGARCANE TOPS	*Ibrahim Aisha Labaran* *Sakinatu Almustapha* *Aliyu Ibrahim Yar'adua* *Muhammad Isma'il* *Khadija Isma'il*	Umaru Musa Yar'adua University, Katsina, Nigeria
THE INFLUENCE OF DEFOAMERS ON CEMENTITIOUS MATRIX MATERIALS INCORPORATING INDUSTRIAL WASTES	*Phd. Student Mihai VRABIE* *Prof. Dr.Eng.Habil. Maria HARJA*	Gheorghe Asachi Technical University of Iasi, Romania
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Session -2 / Hall-5
06.09.2026
Moderator: Dr. Sabah Mahmoud Mahran
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
THE RELATIONSHIP BETWEEN INNOVATIVE LEADERSHIP AND NURSES' WORK ENGAGEMENT IN PRIMARY HEALTH CARE CENTERS IN MAKKAH, SAUDI ARABIA	*Dr. Sabah Mahmoud Mahran* *Dr. Ahlam Eidah Al-Zahrani* *Fajer Abdullatif Alqurashi*	King Abdul-Aziz University, Kingdom of Saudi Arabia
SCREENING AND ISOLATION OF METHIONINE-PRODUCING BACTERIA AND THEIR FERMENTATION OF ENZYMATICALLY HYDROLYZED AGRICULTURAL WASTES	*Olayemi Felicia Amole* *Mordecia Gana* *Oluwafemi Adebayo Oyewole*	Federal University of Technology, Minna, Niger State, Nigeria
A MULTISYSTEM FRAMEWORK OF EMOTIONAL EXHAUSTION RECOVERY: EMOTION REGULATION FLEXIBILITY, AUTONOMIC AND ENDOCRINE LOAD, AND NETWORK-LEVEL NEUROPHYSIOLOGY	*Franciele Maftum* *Viviane DaSilva*	EHCM Institute University of Parma, 43126 Parma, Italy
UNIVERSAL SOCIAL SECURITY IN THE GLOBAL SOUTH: INDIA'S CODE ON SOCIAL SECURITY, 2020 AS A CASE STUDY	*Dr Richa Srivastava*	GGSIP University, Delhi
ANALYSIS OF OBSTACLES RELATED TO THE READING AND INTERPRETATION OF GRAPHS IN LIFE AND EARTH SCIENCES: THE CASE OF TWO MOROCCAN QUALIFYING HIGH SCHOOLS	*Fadma El Abdellaoui* *Houda El Yacoubi* *Youssef Haouazine* *Atmane Rochdi*	Regional Centre for Education and Training Professions (CRMEF), Morocco Ibn Tofail University, Morocco
THE IMPACT OF TRAUMA ON MEMORY AND IDENTITY IN RICHARD POWERS' BEWILDERMENT	*Mukesh Kumar* *Dr. Sharanpal Singh*	Lovely Professional University, Punjab

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Session -2 / Hall-6
06.09.2026
Moderator: Assoc. Prof. Marija Šiško Kuliš
Meeting ID: 862 1528 3413/ Passcode: 030506
Zurich Local Time:11:30-13:30
Ankara Local Time: 12:30-14:30

TITLE	AUTHOR(S)	AFFILIATION
CHARACTERIZATION AND PERFORMANCE EVALUATION OF A BIO-BASED FILM DERIVED FROM CARROT BY-PRODUCTS FOR FOOD CONTACT APPLICATIONS	*Ph.D., Asmae SMAILI* *Asso. Prof. Dr. Omar TANANE* *Latifa EL FARISSI*	Mohammed V University in Rabat, Morocco University of Hassan II – Casablanca Technical Center for Plastics and Rubber, Casablanca
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PREPARATION OF SEMI-SOFT MAGNETIC COPPER OXIDE NANOPARTICLES

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ABSTRACT

This study investigated the synthesis, characterization, and magnetic properties of copper oxide (CuO) nanoparticles. In the experimental study, copper oxide nanoparticles were synthesized using the sol-gel method with copper nitrate trihydrate, citric acid, sodium hydroxide, and pure water. The particles appearance, shape, and size of the synthesized nanoparticles were determined by FESEM analysis. Phase analysis and crystal size of these nanoparticles were determined by XRD analysis. The saturation and remanent magnetization and coercivity of the copper oxide nanoparticles were also determined. The results showed that high-purity copper oxide nanoparticles were successfully synthesized, as confirmed by XRD analysis. Nanoparticles with a crystal size of 48 nm and pentagonal and hexagonal shapes according to FESEM and XRD analysis were synthesized. As a result of magnetic analysis of copper oxide nanoparticles, it was determined that they have saturation magnetization of 0.68 emu/g, remanent magnetization of 0.12 emu/g and coercivity values of 120 Oe. The synthesized CuO nanoparticles can be described as semi-soft magnetic materials.

Keywords: CuO nanoparticle synthesis, magnetic properties, Sol-gel method, semi-soft magnetic materials

INTRODUCTION

Nanomaterials have physical, chemical, and biological properties that differ significantly from bulk materials. The magnetic properties of copper oxide particles are highly dependent on synthesis conditions, temperature, and particle size. Therefore, there is no single constant value for the saturation magnetization and coercivity of copper oxide nanoparticles. While the magnetic saturation and coercivity of copper oxide (CuO) nanoparticles vary considerably depending on particle size, temperature, and surface defects, they generally exhibit weak ferromagnetic/superparamagnetic behavior, a low saturation magnetization (typically between 0.01 and 0.2 emu/g), and a wide range of coercivity of 20 – 300 Oe at room temperature (Kayani et al., 2015).

CuO nanoparticles synthesized by co-precipitation methods have shown ferromagnetic properties. The origin of ferromagnetism can be attributed to the presence of oxygen vacancies on the surface or at the interface between particles. These vacancies contribute to spins arising from unpaired electrons and unbalanced Cu^{2+} ions on the surface. It has been reported that surface oxygen vacancies and unbalanced spins are a significant factor in the emergence of ferromagnetism in pure CuO nanoparticles at room temperature (Zou et al., 2012; Gao et al., 2011; Straumal et al., 2011; Wu et al., 2010; Bhushan et al., 2019).

The aim of this study is to synthesize, characterize, and investigate the magnetic properties of copper oxide nanoparticles. The presence of peaks belonging to the CuO phase in the synthesized nanoparticles was confirmed by XRD analysis. The appearance and shape of the nanoparticles were determined by

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FESEM analysis. Saturation, remanent magnetization, and coercivity values were measured to determine the magnetic properties of the synthesized nanoparticles.

MATERIALS AND METHODS

In this study, $Cu(NO_3)_2.3H_2O$ (Carlo Erba), NaOH (Isolab), and citric acid monohydrate (Isolab) were used. In this experimental study, CuO nanoparticles were synthesized using the sol-gel method. A citric acid solution was added to a copper nitrate trihydrate solution. The pH of this solution was adjusted to 7.0 with NaOH solution. The resulting precipitate was washed several times with deionized water and dried. These samples were kept in furnace at 600°C for 3 hours.

Characterization studies were performed using XRD analysis of the synthesized samples in the 1-90° scanning range. The morphology of the samples was determined using a FESEM instrument at 25000 and 50000 magnifications.

RESULTS AND DISCUSSION

XRD analysis

XRD analysis of CuO nanoparticle samples is given in Figure 1. The standard card number of CuO nanoparticles, JCPDS 01-088-8871 well matched the XRD analysis. This confirms the formation of monoclinic CuO nanoparticles. All XRD diffraction peaks belonged to CuO nanoparticles, and no impurities were detected in the XRD patterns.

XRD analysis of copper oxide nanoparticles revealed lattice parameters of a = 4.6868, b = 3.4253, and c = 5.1327 A°. These lattice parameters are consistent with the standard JCPDS 01-088-8871 card number for CuO nanoparticles. They are also consistent with lattice parameters reported in the literature for monoclinic CuO nanoparticles (Basith et al., 2014).

Using XRD analysis, the crystal size (D) of CuO nanoparticles was determined to be 48.16 nm using the Debye-Scherrer equation (Equation 1) (Bayça, 2024).

$$D = \frac{\lambda K}{\beta \, Cos\theta} \qquad (1)$$

Since the crystal size of the synthesized samples was 48.16 nm, nanoscale copper oxide was successfully produced.

In the literature, the crystal sizes of CuO nanoparticles were 27.8 nm (Gupta et al., 2018), 3 nm (Said et al., 2021), 4 nm (Wang et al., 2002), 5 nm (Dagher, et al., 2014), 6 nm (Verma et al., 2018), 7 nm (Bhushan et al. 2019), 11 nm (Rehman et al., 2011), 14 nm (Rashad et al., 2018), 19 nm (Yakout et al., 2016),19 nm (Basith et al., 2014), 24 nm (Harshapriya et al., 2023), 25 nm (Karthik et al., 2011), 40 nm (Yakout, 2021).46 nm (Chen et al., 2011), 48 nm (This study), 48 nm (Aiswarya Raj et al., 2017),70 nm (Dar et al., 2008), 80 nm (Rashad et al., 2015), and 93 nm (El Sayed et al., 2022).

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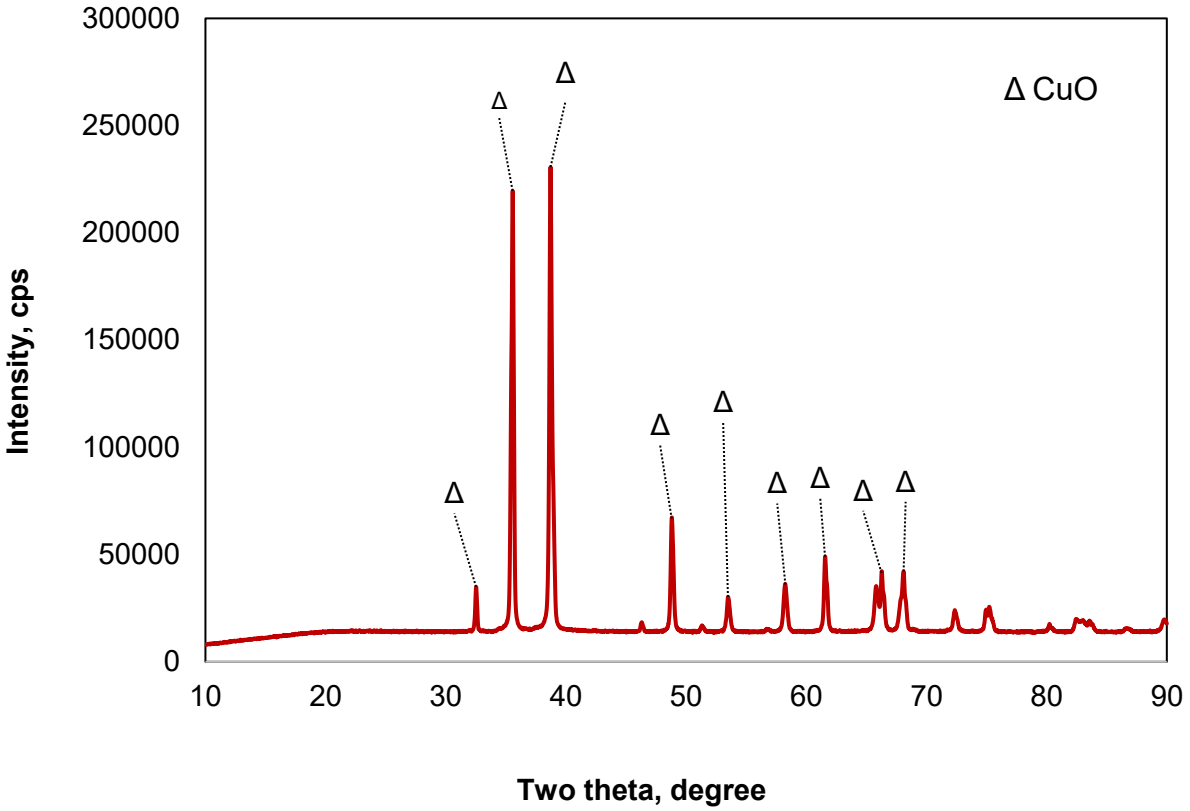


Figure 1. XRD analysis of CuO nanoparticles

The crystal size of CuO nanoparticles has been observed to be between 3 and 80 nm, in the literature. These crystal size differences may be due to the synthesis method, calcination temperature, and starting materials.

FESEM analysis

Figure 2 shows the FESEM analysis of the samples. The FESEM image shows that the CuO nanoparticles have a particle size larger than 200 nm. The particles were observed to be angular, pentagonal, and hexagonal in shape. Although particle boundaries were visible, the particles were adhered to each other. The particle size distribution consisted of mixed particles, ranging from coarse to fine, between 250 and 700 nm.

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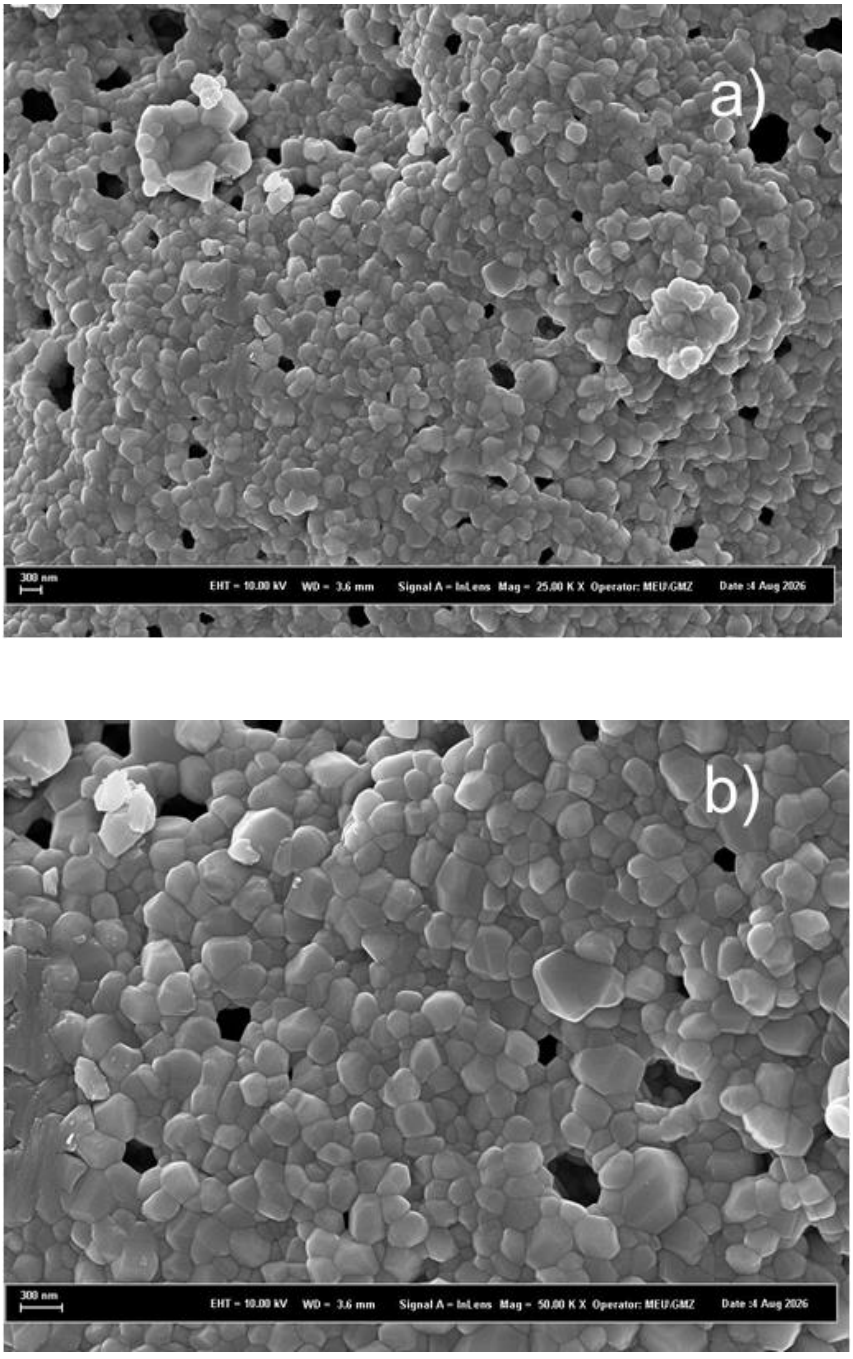


Figure 2. FESEM analysis of copper oxide nanoparticles a) 25 kx and b) 50 kx magnification

Magnetic properties

Hysteresis loops of CuO nanoparticles are shown in Figure 3. Magnetic analysis of copper oxide nanoparticles revealed a saturation magnetization of 0.68 emu/g, a remanent magnetization of 0.12 emu/g, and a coercivity of 120 Oe.

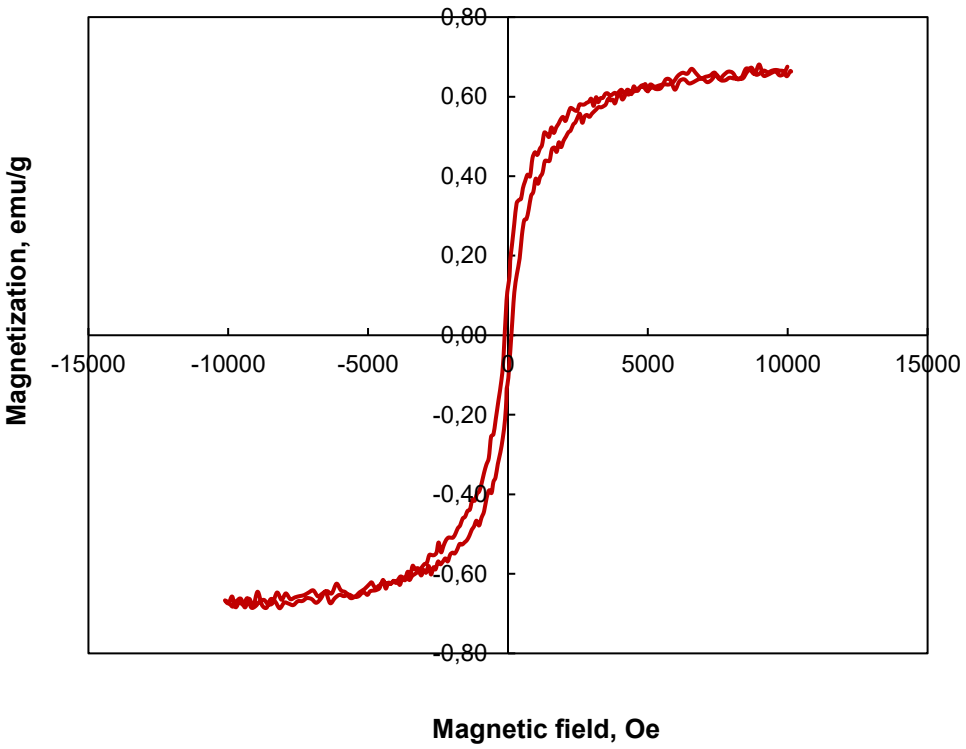


Figure 3. Histeresis loops of CuO nanoparticles

The saturation magnetization (Ms) found for CuO nanoparticles in the literature is reported below. The saturation magnetizations found for CuO nanoparticles were 0.004 emu/g (Chen et al., 2011), 0.018 emu/g (Gao et al., 2010), 0.028 emu/g (Ibrahim et al., 2025), 0.034 emu/g (Kayani et al., 2015), 0.107 emu/g (Yakout et al., 2016), 0.143 emu/g (Mohamed et al., 2014), 0.270 emu/g (Singh et al., 2013), 0.420 emu/g (Sreeju et al., 2019), 0.680 emu/g (This study), and 0.820 emu/g (Nasrallah et al., 2023). Saturation magnetization (Ms) has been reported in the literature to be between 0.004 and 0.82 emu/g. The saturation magnetization value of 0.68 emu/g found for CuO nanoparticles in this study is consistent with the literature.

The coercivity (Hc) values of CuO nanoparticles in the literature are given below. In the literature, the coercivity (Hc) values of CuO nanoparticles were 47 Oe (Kayani et al., 2015), 93 Oe (Mohamed et al., 2014), 273 Oe (Singh et al., 2013), 95 Oe (Bhushan et al., 2019), 119 Oe (Ramya et al., 2016), 120 Oe (Gao et al., 2010), 120 Oe (This study), 126 Oe (Nasrallah et al., 2023), 134 Oe (Karthik et al., 2011), 153 Oe (Sreeju 2019), 155 Oe (Harshapriya 2023), 178 Oe (Yakout 2016), 183 Oe (Yakout 2021), and 200 Oe (Chen et al., 2011). In the literature, the coercivity (Hc) values of CuO nanoparticles have been reported to be between 47 and 273 Oe. In this study, the coercivity value of CuO nanoparticles was found to be 120 Oe, which is consistent with the literature. The magnetic analysis results of the CuO nanoparticles synthesized in this study suggest that they can be evaluated as semi-soft magnetic materials.

The magnetic behavior of CuO nanoparticles depends not only on the size of the material but also on its shape. Coercivity values for spherical CuO nanoparticles have been reported as 47 Oe (Kayani, et al., 2015) and for spherical CuO nanoparticles as 183 Oe (Yakout et al., 2021). A large specific surface area/volume ratio of CuO nanoparticles leads to more unstable surface spin. The shape of the hysteresis loop is essentially influenced by both the surface area of the nanoparticles and the magnetic anisotropy of the nanoparticles. Unlike spherical nanoparticles, existing CuO nano archs exhibit shape anisotropy, which leads to coercive reinforcement (Mohamed et al., 2014; Rao et al., 2005; Xiao et al., 2007; Cullity et al., 2008).

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CONCLUSIONS

In this study, CuO nanoparticles were successfully synthesized using the sol-gel method. XRD analysis revealed that the resulting nanoparticles belonged to the CuO phase. The crystalline size of the synthesized CuO nanoparticles was determined to be 48.16 nm. Magnetic analysis of the copper oxide nanoparticles showed a saturation magnetization of 0.68 emu/g, a remanent magnetization of 0.12 emu/g, and a coercivity of 120 Oe. The higher coercivity value compared to the literature may be due to the pentagonal and hexagonal shapes of the synthesized CuO nanoparticles. Based on the magnetic analysis results, the CuO nanoparticles synthesized in this study can be considered as semi-soft magnetic materials.

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SYNTHESIS AND OPTICAL PROPERTIES OF COPPER OXIDE NANOPARTICLES USING SOL-GEL METHOD

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ABSTRACT

This study aims to synthesize copper oxide nanoparticles using the sol-gel method and experimentally investigate their optical properties. Analytical grade copper nitrate, citric acid, and sodium hydroxide were used as starting materials. Phase analysis and characterization of the nanoparticles were performed using XRD analysis. The particles shape and size of the nanoparticles were determined by FESEM analysis. The optical properties of the copper oxide nanoparticles were investigated using the Kubelka-Munk Theory. The results showed that pentagonal copper oxide nanoparticles were successfully synthesized using the sol-gel method. XRD analysis revealed peaks belonging to high-purity CuO nanoparticles in the synthesized samples. No peaks belonging to other phases were observed in the XRD analysis besides copper oxide peaks. The crystal size of the synthesized CuO nanoparticles was found to be 41 nm. FESEM analysis revealed that the particles shapes of the samples were pentagonal. The bandgap energy of the synthesized copper oxide nanoparticles was determined to be 3.97 eV. These copper oxide nanoparticles have been determined to have a wide band gap.

Keywords: CuO nanoparticle synthesis, Bandgap energy, Optical properties, Sol-gel method

INTRODUCTION

The size, shape, morphology, structure, and composition of nanoparticles affect their physical and chemical properties compared to bulk particles. Copper oxide (CuO) particles are a natural p-type semiconductor material. The optical band gap of pure bulk copper oxide is generally accepted in the literature as being in the range of 1.2 – 2.1 eV (narrow band). Thanks to the quantum confinement effect resulting from reducing the size of copper oxide particles to the nanoscale, the band gap can be extended to very wide values such as 5.37 eV (Ahmed et al., 2025; Mohammed, et al., 2022; Harshapriya et al., 2023).

CuO nanoparticles are used in gas sensors, solar cells, biosensors, photodetectors, light emitters, permanent storage devices, and magnetic storage devices (Hansen et al., 2008; Ahmed et al., 2025). They have been synthesized using microwave-assisted sol-gel autoignition (Shaalan, et al., 2016; Liu et al., 2004), sol-gel (Hai-yan et al., 1993), hydrothermal synthesis (Outokesh, et al., 2011; Sonia, et al., 2015; Liu et al., 2024; Jadhav, et al., 2023; Hung et al., 2023), and co-precipitation (Ali et al., 2024; Banu et al., 2023) methods.

The aim of this study is to synthesize, characterize, and investigate the optical properties of copper oxide nanoparticles using the sol-gel method. Phase analysis and characterization of CuO nanoparticles were performed using XRD analysis. The particle structure, shape, and size of the nanoparticles were determined using FESEM analysis. The optical properties of copper oxide nanoparticles were investigated using Kubelka-Munk theory.

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MATERIALS AND METHODS

Copper oxide nanoparticles were synthesized using the sol-gel method. In experimental studies, $Cu(NO_3)_2$.$3H_2O$ (99% purity), NaOH (99% purity), and citric acid (99% purity) were used. The precursor was added dropwise to a copper nitrate solution and then to a citric acid solution. The pH of this solution was adjusted to 7 with NaOH solution. The resulting precipitate was washed several times with deionized water and dried. The dried samples were kept in an oven at 500°C for 3 hours.

RESULTS AND DISCUSSION

XRD ANALYSIS

The XRD analysis of the synthesized nanoparticles is given in Figure 1. All diffraction peaks observed in Figure 1 match the standard card number of the CuO phase, JCPDS 01-088-8871. All XRD diffraction peaks were determined to belong to monoclinic copper oxide nanoparticles, and no other impurities were detected in the XRD analysis. Pure copper oxide nanoparticles were successfully synthesized using the sol-gel method.

XRD analysis of copper oxide nanoparticles revealed lattice parameters of a=4.6853, b=3.4267, c=5.1320 A°. The lattice parameters of the unit cell (a≠b≠c) are distinct. These lattice parameters are consistent with the JCPDS 01-088-8871 card number of the CuO phase. In the monoclinic crystal system, two of the angles intersect at exactly right angles, while the third angle is oblique.

The average crystal size (D) of CuO nanoparticles was determined using XRD analysis and the Debye-Scherrer equation, Equation 1 (Bayça, 2024).

$$D = \frac{\lambda K}{\beta \, Cos\theta} \qquad (1)$$

where D is the crystallite size (nm), β is the full width at half of the maximum intensity, and K is the shape factor.

Using the Debye-Scherrer equation, the average crystal size of the synthesized CuO samples was determined to be 41.61 nm. Thus, it was confirmed that the obtained copper oxide particles are nano-sized.

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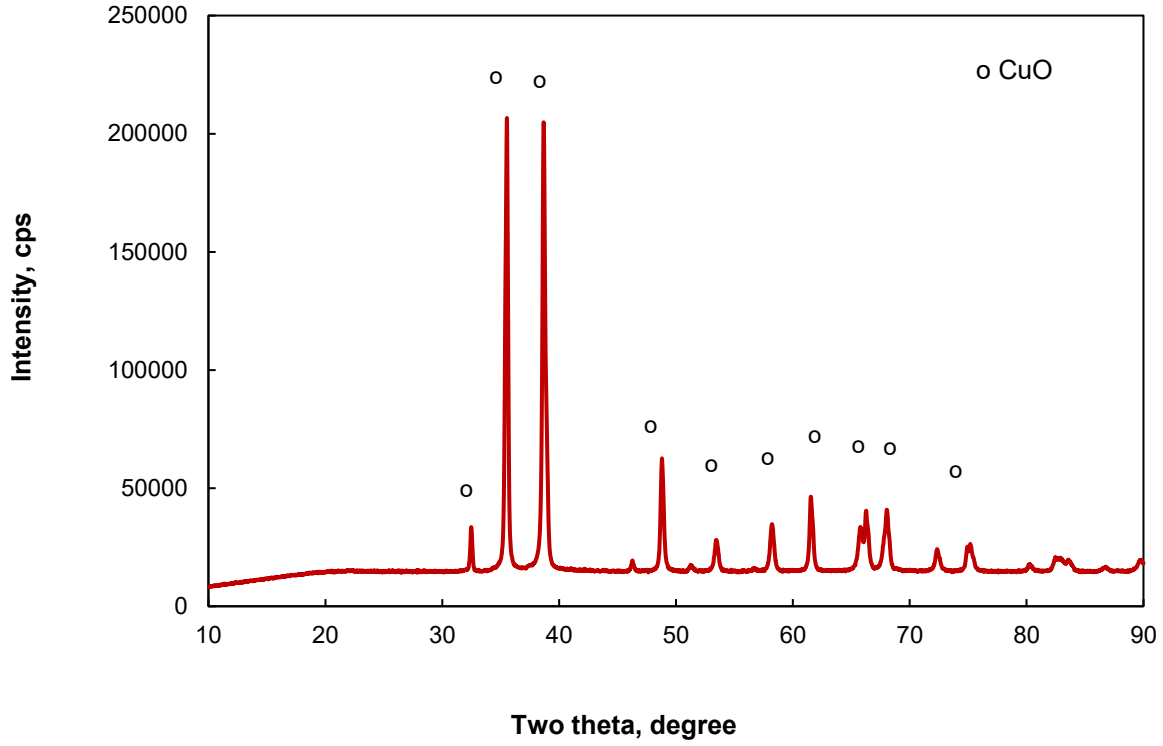


Figure 1. XRD analysis of CuO nanoparticles

FESEM ANALYSIS

Figure 2 shows the FESEM analysis of the samples. The FESEM image shows that the maximum particle size of CuO nanoparticles is approximately 300 nm.

The particles consist of mixed particles with a particle size distribution of 50–300 nm. The particles were observed to have a nearly pentagonal shape. Despite having distinct particles boundaries, the particles agglomerated to each other.

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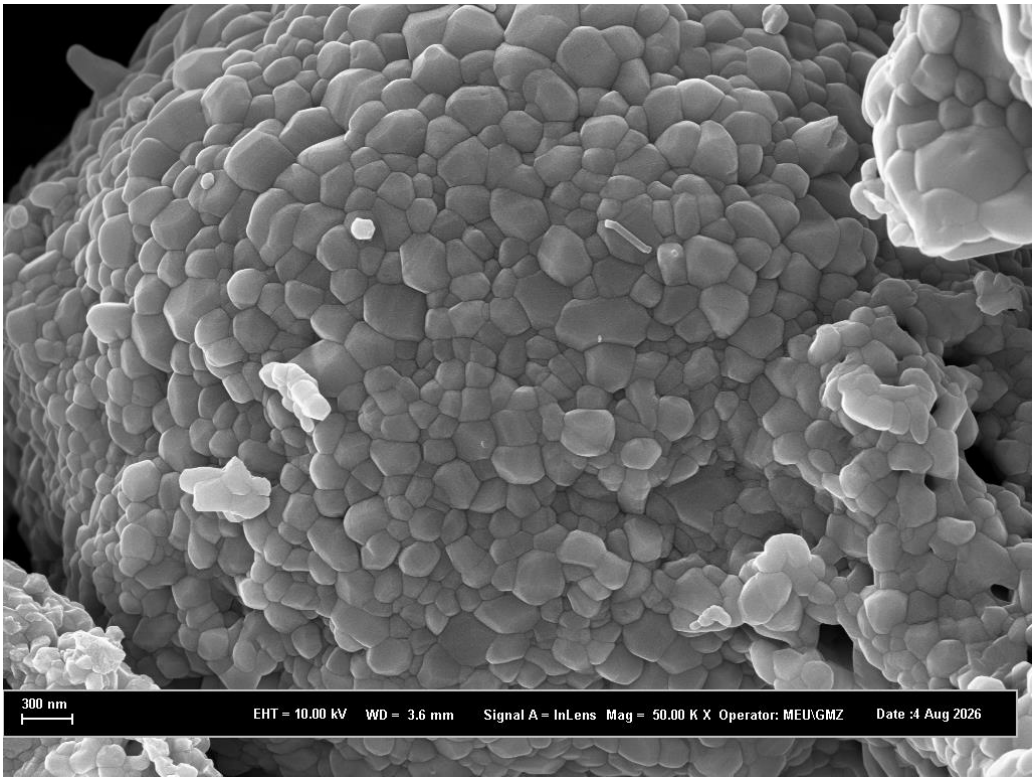


Figure 2. FESEM image of CuO nanoparticles **a)** 25 kx and **b)** 50 kx magnification

OPTICAL PROPERTIES

The bandgap energy of the samples was calculated using the Kubelka-Munk equation (equation 2) (Makula et al., 2018).

$$(\mathrm{F(R)}.\mathrm{hv})^2 = \mathrm{B}\left(\mathrm{hv} - E_g\right) \qquad (2)$$

where *F(R)* is the Kubelka-Munk function, *hv* is the photon energy, *R* is the reflectance coefficient, *B* is a constant related to the material and *Eg* is the bandgap energy.

The optical properties of the synthesized nanoparticles are shown in Figure 3. In the analysis performed, the bandgap energy of CuO nanoparticles at 41.61 nm was found to be 3.97 eV.

The following results have been reported in studies on the synthesis of copper oxide nanoparticles in the literature: The bandgap energy for a crystallite size of 27.8 nm using the sol-gel method is 1.43 eV (Gupta et al., 2018), for a crystallite size of 4 nm using the microwave co-precipitation method it is 2.43 eV (Wang et al., 2002), for a crystallite size of 3 nm using the co-precipitation method it is 3.61 eV (Said et al., 2021), for a crystallite size of 0.20 nm using the precipitation-pyrolysis route method it is 3.72 eV (Rehman et al., 2011), for a crystallite size of 5 nm using the microwave co-precipitation method it is 3.80 eV (Dagher, et al., 2014), for a crystallite size of 6 nm using the magnetron sputtering technique it is 3.90 eV (Verma et al., 2018), and for microwave sol-gel combustion. The bandgap energy for a crystallite size of 19 nm was found to be 3.90 eV using the precipitation-pyrolysis route method (Basith et al., 2014), and for a crystallite size of 11 nm, it was found to be 4.00 eV using the precipitation-pyrolysis route method (Rehman et al., 2011) and for crystallite size of 24 nm, it was found to be 5.37 eV (Harshapriya et al., 2023).

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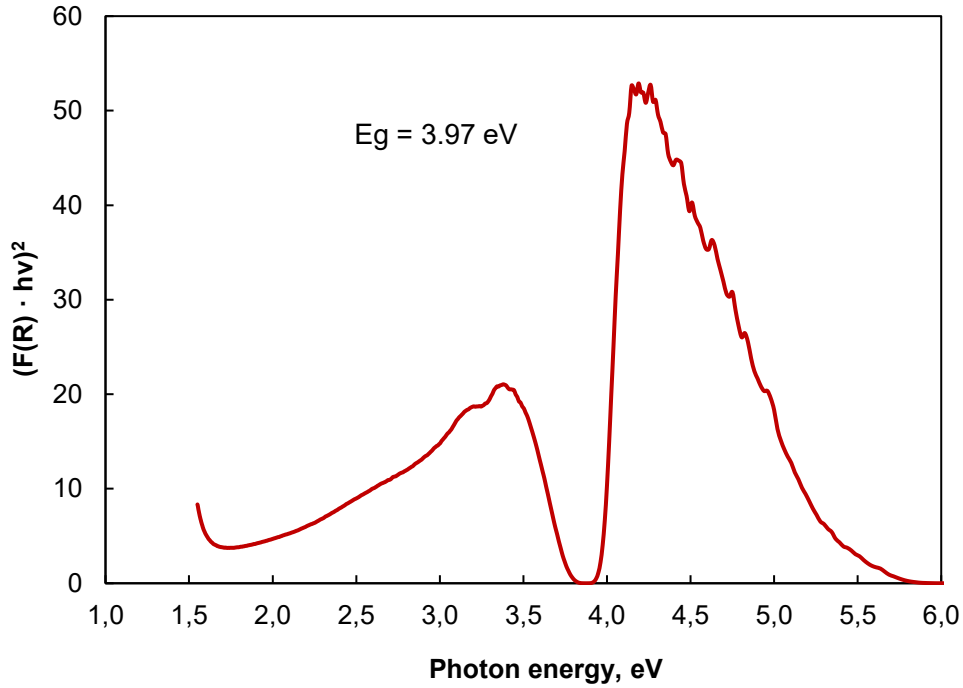


Figure 3. Optical analysis of CuO nanoparticles

In the literature, the bandgap energy values found for CuO nanoparticles in studies range from 1.43 to 5.37 eV. The bandgap energy values reported in the literature for copper oxide nanoparticles vary depending on the synthesis method and crystal size. While the bandgap energy value for bulk CuO material is 1.2 eV (Zhang et al., 2006), it was found to be 3.97 eV for copper oxide nanoparticles in this study. The found bandgap energy value has a wide band gap. This wide band gap is due to the quantum size effect. In addition, a blue shift was observed with a high bandgap energy compared to the bandgap energy of bulk copper oxide material. Although the bandgap energy value found in this study is higher than that of bulk copper oxide, it is consistent with the bandgap energy values of copper oxide material reported in the literature.

CONCLUSIONS

In this study, copper oxide nanoparticles were successfully synthesized using the sol-gel method. XRD analysis revealed peaks in the synthesized samples that correspond to high-purity CuO nanoparticles. The crystal size of the copper oxide nanoparticles was found to be 41 nm. FESEM analysis showed that the particle shapes of the samples were pentagonal. The bandgap energy of the synthesized CuO nanoparticles was determined to be 3.97 eV. These copper oxide nanoparticles can be described as semiconductor materials with very wide bandgap.

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THE PROBLEM OF REPRESENTATION IN THE RIGHTS OF NATURE:THE LEGAL PROTECTION OF THE SILENT SUBJECT

DOĞA HAKLARINDA TEMSİL SORUNU: SESSİZ ÖZNENİN HUKUKİ KORUNMASI

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ABSTRACT

In recent years, the concept of the Rights of Nature has moved beyond the traditional anthropocentric understanding of environmental protection by recognizing natural entities such as rivers, forests, mountains, and ecosystems as independent subjects of rights. Constitutional developments and judicial decisions granting legal status to nature in several jurisdictions have generated significant theoretical debates extending far beyond the boundaries of environmental law. Nevertheless, despite the recognition of legal rights for nature, fundamental questions remain unresolved regarding who may speak on behalf of nature, who is entitled to assert its rights, and according to which principles legal representation should be exercised. Accordingly, the principal challenge within the Rights of Nature discourse concerns not merely the legal personality of nature but its legal representability. This study reconsiders the Rights of Nature not through the traditional debate on legal personality but within the framework of the **Silent Subject** approach. It argues that, irrespective of whether nature is recognized as a legal person, it constitutes a silent subject requiring legal representation because it cannot express its own will or assert its own rights. Consequently, the protection of nature should be understood not only as an environmental issue but also as a broader problem of legal theory concerning the visibility and protection of entities incapable of representing themselves within the legal order. The study first examines the legal development of the Rights of Nature doctrine and then distinguishes theories of legal personality from theories of legal representation. It further discusses the limits of legal representation, the source of representative authority, and the legitimacy of representatives in protecting nature. Comparative legal perspectives on representative models involving states, local communities, civil society organizations, and independent guardians are also analyzed. The paper argues that the future of the Rights of Nature depends less on expanding legal personality than on developing a coherent theory of legal representation. In this context, it proposes the Legal Protection of the Silent Subject as a new theoretical framework. Within this model, legal representation becomes a constitutive element of legal protection by enabling entities that cannot express their own will or claim their own rights to participate in the legal order through representatives. By placing the problem of representation at the center of the Rights of Nature debate, the study reinterprets the protection of nature through a new paradigm that enhances the legal visibility of silent subjects. This framework has the potential to provide a common theoretical foundation not only for the Rights of Nature but also for discussions concerning animal rights, the protection of future generations, and representation in biolaw.

Keywords: Rights of Nature, Silent Subject, legal representation, legal personality, environmental law, ecological justice, representation-based protection.

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ÖZET

Son yıllarda doğa hakları, çevrenin yalnızca insan yararına korunması anlayışını aşarak nehirler, ormanlar, dağlar ve ekosistemler gibi doğal varlıkların bağımsız hak süjeleri olarak tanınmasını sağlamıştır. Özellikle anayasal düzenlemeler ve yargı kararlarıyla bazı ülkelerde doğaya hukuki statü tanınması, çevre hukukunun sınırlarını aşan önemli teorik tartışmaları da beraberinde getirmiştir. Doğaya hak tanınmasına rağmen, doğa adına kimin konuşacağı, hakların kim tarafından ileri sürüleceği ve hukuki temsilin hangi esaslara göre yürütüleceği sorunu bütünüyle çözülememiştir. Doğa haklarının en temel tartışma alanlarından biri, doğanın hukuki kişiliğinden çok temsil edilebilirliği konusunda yaşanmaktadır.

Çalışmamız, doğa haklarını hukuki kişilik tartışmaları üzerinden değil, sessiz özne yaklaşımı çerçevesinde yeniden değerlendirmekte ve doğanın hak sahibi olup olmamasından önce, kendi iradesini açıklayamayan ve haklarını bizzat ileri süremeyen bir varlık olması nedeniyle temsil edilmeye ihtiyaç duyan sessiz bir özne niteliği taşıdığına odaklanmaktadır. Böylece doğanın korunmasının yalnızca çevresel değerlerin korunmasına ilişkin bir konu olmadığı; aynı zamanda temsil edilemeyen varlıkların hukuk düzeni içindeki görünürlüğü ve korunmasıyla ilgili genel bir hukuk teorisi problemi olduğu gösterilmektedir.

Çalışmamızda öncelikle doğa hakları yaklaşımının hukuki gelişimi incelenmekte, ardından hukuki kişilik teorileri ile temsil teorileri arasındaki ayrım ortaya konularak doğanın hukuki korunmasında temsilin sınırları, temsil yetkisinin kaynağı ve temsilcinin meşruiyeti tartışılmaktadır. Bu kapsamda devlet, yerel topluluklar, sivil toplum kuruluşları ve bağımsız koruyucu kurumlar tarafından gerçekleştirilen temsil modelleri karşılaştırmalı hukuk perspektifinden değerlendirilmektedir.

Doğa haklarının geleceği, hukuki kişilik tartışmalarından ziyade temsil teorisinin geliştirilmesine bağlıdır. Bu doğrultuda Sessiz Öznenin Hukuki Korunması yaklaşımı önerilmektedir. Doğanın korunmasının, irade açıklayamayan ve kendi hakkını ileri süremeyen varlıkların temsil yoluyla hukuk düzenine katılmasını sağlayan yeni bir koruma modeli olarak değerlendirilmesiyle temsil, hukuki korumanın kurucu unsurlarından biri hâline gelmektedir.

Çalışma, doğa hakları tartışmalarının merkezine temsil sorununu yerleştirerek doğanın korunmasını sessiz öznelerin hukuk düzenindeki görünürlüğünü sağlayan yeni bir temsil paradigması çerçevesinde yeniden yorumlamaktadır. Bu yaklaşımın yalnızca doğa haklarına değil, hayvanların korunması, gelecek kuşakların korunması ve biyohukuk alanındaki temsil tartışmalarına da ortak teorik bir zemin sağlayabileceği ileri sürülmektedir.

Anahtar Kelimeler: Doğa hakları, sessiz özne, hukuki temsil, hukuki kişilik, çevre hukuku, ekolojik adalet, temsil temelli koruma.

GİRİŞ

Doğa hakları yaklaşımı, çağdaş çevre hukukunun en dikkat çekici dönüşümlerinden birini oluşturmaktadır. Geleneksel çevre hukuku doğal çevreyi büyük ölçüde insan yaşamı, sağlığı, mülkiyeti veya gelecek kuşakların menfaatleri bakımından korurken, doğa hakları yaklaşımı doğal varlıkların kendi varlıklarını, bütünlüklerini ve ekolojik süreçlerini sürdürmeye ilişkin bağımsız korunabilir menfaatlere sahip olabileceği düşüncesinden hareket etmektedir. Böylelikle çevrenin yalnızca insan yararına korunan bir hukuki nesne olduğu anlayışından, doğanın kendi başına normatif değer taşıdığı daha ekomerkezci bir hukuk anlayışına doğru geçiş söz konusu olmaktadır (Stone, 1972; Cullinan, 2011; Borràs, 2016; Kotzé & Villavicencio Calzadilla, 2017).

Ekomerkezci bir hukuk anlayışına doğru yaşanan dönüşüm, Christopher D. Stone'un 1972 yılında sorduğu "Ağaçların dava hakkı olabilir mi?" sorusuyla hukuk teorisinin gündemine güçlü biçimde girmiştir. Stone'un temel katkısı, doğal varlıklara hak tanınmasının yalnızca çevre korumasına ilişkin teknik bir öneri olmadığını; hukuk kişiliğinin ve hak sahipliğinin sınırlarının tarihsel olarak değişebilir olduğunu göstermesidir. Hukukun şirketler gibi biyolojik olmayan varlıklara belirli haklar ve hukuki statüler tanıyabilmesi, doğal varlıkların da belirli hakların taşıyıcısı olarak kabul edilip edilemeyeceği

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sorusunu gündeme getirmiştir (Stone, 1972). Stone'un makalesinin bibliyografik bilgileri de son denetimde doğrulanmıştır. Bu teorik tartışma zaman içinde pozitif hukukta önemli karşılıklar bulmuştur. Ekvador Anayasası doğanın haklarını anayasal düzeyde tanımış; Yeni Zelanda'da Te Urewera ve Te Awa Tupua özel hukuki statülere kavuşturulmuş; Kolombiya Anayasa Mahkemesi Atrato Nehri'ni hak öznesi olarak kabul etmiştir. Bu gelişmeler, doğanın yalnızca çevre hukukunun koruma nesnesi olarak değil, kendi varlığı bakımından hukuken dikkate alınabilir bir varlık olarak görülmesine yönelik önemli örnekler oluşturmaktadır (Kauffman & Martin, 2017; O'Donnell & Talbot-Jones, 2018; Tănăsescu, 2020; Kauffman & Martin, 2021).

Doğa hakları, hukuki kişilikler ve doğal varlıklara ilişkin diğer hukuki tanıma biçimleri birbirine özdeş değildir. Hukuk kişiliği, doğanın korunması amacıyla kullanılabilecek hukuki tekniklerden biridir; ancak doğal varlığın korunmasının zorunlu olarak tam bir kişilik statüsüne bağlanması gerekmez. Kurki'nin doğrudan ve dolaylı hukuk kişiliği ayrımı üzerinden geliştirdiği eleştiri, doğal varlıkların hukuk kişisi olarak kabul edilmesinin kavramsal bakımdan sanıldığından daha karmaşık olduğunu göstermektedir (Kurki, 2022, ss. 525–552).

Yaşanan bu gelişmeler doğa hakları tartışmasının ikinci ve belki de çok daha zor bir aşamasını görünür hâle getirmiştir. Bir doğal varlığa hak veya hukuki statü tanınması, onun hukuk düzeninde kendi adına hareket edebilmesini sağlamamaktadır. Nehir dilekçe yazamaz; orman kendisine yönelen zararı hukuki iddiaya dönüştüremez; ekosistem kendi temsilcisini seçemez veya temsilcisinin kararını denetleyemez. Bu nedenle doğa haklarının etkili olabilmesi, hak sahipliği sorunundan farklı fakat onunla doğrudan bağlantılı başka bir kurumsal sorunun çözülmesine bağlıdır: Bu hukuksal kurum mekanizması ise temsil ve temsiliyet kurumudur.

Doğal varlıkların insan merkezli hukuk sistemlerinde kendi haklarını usulî olarak ileri sürememeleri, vasilik, yöneticilik, vesayet kurumları veya diğer temsil mekanizmalarını önemli hâle getirmektedir. Nitekim en yeni doğa hakları literatüründe de tartışmanın giderek "doğa adına kim konuşabilir?" ve bu temsilin hangi epistemik ve meşruiyet temellerine dayanacağı sorularına yöneldiği görülmektedir. Gurman ve Kieser'in 2026 tarihli çalışması, doğa hakları girişimlerinde temsil ve guardianship modellerinin meşruiyetini doğrudan bu soru üzerinden incelemektedir (Gurman & Kieser, 2026). Bu gelişmeler, doğa hakları tartışmasının merkezindeki soruyu değiştirmektedir. Asıl mesele artık yalnızca: "Doğa hak sahibi olabilir mi?" sorusu değildir. Bunun ardından mutlaka;"Doğa hak sahibi kabul edildiğinde, bu hakkı kim ve hangi meşruiyetle ileri sürecektir?" sorusu gelmek zorundadır. Çalışmamızın odağındaki en temel problem ve soru budur. Bu doğrultuda çalışmada sessiz özne kavramı önerilmektedir.

Sessiz özne, korunabilir hukuki menfaati bulunan veya hak sahibi olarak tanınabilen; fakat bu menfaati kendi adına hukuk düzeninin tanıdığı bir talebe dönüştüremeyen varlığı ifade etmektedir. "Sessizlik" burada biyolojik konuşma yetisinin yokluğu yerine, öznenin kendi korunabilir menfaatini doğrudan hukuk düzenine taşıyamaması anlamındaki hukuki sessizliği ifade etmektedir.

Sessiz özne yaklaşımı, doğayı yeniden pasif bir hukuki nesneye dönüştürmemekte ve doğanın bağımsız korunabilir menfaatinin bulunduğunu kabul edilerek, hak sahipliği ile hakların etkili biçimde kullanılmasını birbirinden ayırmaktadır. Böylelikle doğanın hukuki statüsünden ziyade, bu statünün hangi kurumsal mekanizma aracılığıyla gerçek korumaya dönüştüğü sorusu öne çıkmaktadır.

Çalışmamızın temeli, doğa haklarında temsilin, mevcut bir hakkın kullanılmasına yardımcı olan ikincil bir usul mekanizması yerine; kendi menfaatini bizzat hukuk düzenine taşıyamayan sessiz öznenin, etkili hukuki korunmasının kurucu unsurlarından birisi olduğuna dayanmaktadır. Bu sav, doğa hakları ve vesayet literatüründen kopuk değildir. Mevcut literatür doğal varlıkların temsil edilmesi gerektiğini ve vesayet yapılarının doğa haklarının uygulanmasında önemli rol oynadığını ortaya koymaktadır (O'Donnell & Talbot-Jones, 2018; O'Donnell, 2018; Macpherson, 2019; Wesche, 2021; Cribb ve Ark., 2024; Gurman & Kieser, 2026). Bu noktada, Atrato kararının uygulamasını inceleyen Wesche'nin çalışması özellikle önemlidir; araştırma doğa haklarının etkisinin yalnızca standing veya mahkemeye erişimle değil, kamu politikaları ve kurumsal uygulamalarla da değerlendirilmesi gerektiğini göstermektedir (Wesche, 2021).

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Çalışmamız, temsil meselesinin yalnızca "vasi kim olmalıdır?" sorusuyla sınırlı tutulmaması gereğinden yola çıkarak, temsil eksikliğini temsil boşluğu, temsilin hukuki sonucunu ise hukuki görünürlük kavramları üzerinden daha genel bir hukuki koruma teorisine bağlamaktadır. Çalışmanın kavramsal zinciri şu şekilde kurulmaktadır: Sessiz özne → temsil ihtiyacı → meşru temsil → hukuki görünürlük → etkili koruma. Öte yandan etkili veya meşru temsil mekanizmasının bulunmadığı durumlarda kavramsal zincir: Sessiz özne → temsil boşluğu → hukuki görünmezlik → koruma eksikliği şeklinde ortaya çıkmaktadır. Çalışmadaki sessiz özne yaklaşımımızın amacı, hak temelli korumayı terk etmek yerine, sessiz özneler bakımından, hakların neden temsil mekanizması olmaksızın eksik işleyebileceğini göstermektir. Böylelikle hak temelli koruma ile temsil temelli koruma arasında tamamlayıcı bir ilişki kurulmuş olacaktır.

DOĞA HAKLARININ DÖNÜŞÜMÜ

Antropomerkezci Çevre Korumasının Sınırları

Çevre hukukunun klasik yapısında doğa, çoğu zaman insan yararı üzerinden korunmaktadır. Temiz hava, temiz su, sağlıklı çevre, doğal kaynakların devamlılığı ve biyolojik çeşitliliğin korunması insan yaşamı ve toplumsal refahla ilişkilendirilerek hukuki koruma konusu yapılmıştır. Bu yaklaşım çevrenin korunması bakımından önemli kazanımlar üretmiş olmakla birlikte, doğal varlığın değerini büyük ölçüde insana sağladığı yarar üzerinden tanımladığı gerekçesiyle eleştirilmiştir (Cullinan, 2011; Borràs, 2016; Boyd, 2017; Boulot & Sterlin, 2022,).

Doğa hakları yaklaşımının normatif kırılması, tam da burada ortaya çıkmakta, doğanın ekolojik bütünlüğünün korunması, yalnızca bu bütünlüğün insanlara hizmet etmesi nedeniyle değil, doğal varlığın kendi varoluşuna ilişkin bir menfaat olarak değerlendirilmesi gerektiğini göstermektedir. Bu yaklaşımla çevre korumasının temel sorusu da değişmekte ve klasik çevre hukukunda: "Çevresel zarar insan menfaatini nasıl etkilemektedir?" sorusu merkezde yer alırken; doğa hakları yaklaşımında buna ek olarak, "Doğal varlığın kendi ekolojik bütünlüğüne hangi zarar verilmiştir?" sorusu gündeme gelmektedir. Bu dönüşüm, doğaya hukuk kişiliği tanınmasını zorunlu kılmasa da doğanın bağımsız korunabilir menfaatinin hukuk düzeninde tanınması demektir. Bu yüzden hukuk kişiliği ile hak sahipliği ve hukuki koruma arasında otomatik bir özdeşlik kurulmamalıdır. Kurki'nin eleştirel çalışması, doğal varlıklara doğrudan hukuk kişiliği atfedilmesinin teorik güçlüklerini ortaya koymaktadır (Kurki, 2022).

Stone'un Hak Sahipliğinde Temsil Problemi

Stone'un doğal varlıklara dava açma hakkı tanınması önerisi, çalışmamızda temsiliyet kurumu üzerinden yeniden okunabilir. Stone'a göre doğal varlığa hukuki dava hakkı tanınmasının anlamlı olabilmesi için, doğal varlığın kendi adına hukuki sürecin konusu olabilmesi, uğradığı zararın mahkeme tarafından ona verilmiş zarar olarak dikkate alınması ve sağlanan giderimin doğal varlığın yararına kullanılması gerekir (Stone, 1972). Dava açma hakkı tanınması, kaçınılmaz biçimde temsil sorununu ortaya çıkarmaktadır.

Doğal varlık "kendi adına" dava sürecinin öznesi olacaksa, ona insan hukukunda görünür kılacak bir aktör gerekmektedir. Bu nedenle Stone'un yaklaşımının içinde dahi iki farklı hukuki mesele bulunmaktadır: hak sahipliği ve hakların temsili. Bunlar aynı şey değildir. Hak sahipliği doğal varlığın belirli normatif menfaat veya hakların taşıyıcısı olduğunu ifade eder. Temsil ise bu normatif konumun hukuk düzeninin karar süreçlerinde fiilen kullanılmasını mümkün kılar. Böylece doğa hakları teorisinin içindeki kurumsal sorun ortaya çıkmaktadır. Hak tanıma, sessiz özne bakımından hukuki korumanın son aşaması değil; tam tersine temsil sorununun başlangıcıdır.

DOĞA HAKLARINDA HUKUKİ KİŞİLİĞİN SINIRLARI

Doğa haklarına ilişkin tartışmalarda hukuki kişilik, doğal varlıkların hukuk düzenindeki konumunu dönüştüren en güçlü araçlardan biri olarak öne çıkmaktadır. Bir nehrin, ormanın veya ekosistemin hukuk kişisi olarak tanınması, onun yalnızca mülkiyetin veya idari düzenlemenin nesnesi olarak görülmesinden önemli bir kopuş yaratmaktadır. Bununla birlikte hukuk kişiliği, doğa haklarının tek mümkün modeli olmadığı gibi, doğal varlığın etkili biçimde korunmasını kendiliğinden sağlayan yeterli bir mekanizma da değildir. Hukuk kişiliği ile hak sahipliği, hukuki ehliyet, temsil ve etkili koruma birbirleriyle bağlantılı olmakla birlikte kavramsal olarak farklı sorunlara karşılık gelmektedir (Gordon, 2018;

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Tănăsescu, 2020; Kurki, 2022). Kurki'nin hukuki kişiliğe ilişkin eleştirisine bakıldığında; Kurki, doğal varlıklara hukuki kişilik atfedilmesinin teorik olarak sanıldığından daha karmaşık olduğunu; bir doğal varlığın belirli haklarla ilişkilendirilmesi ile onun teknik anlamda doğrudan hukuk kişisi olması arasında ayrım yapılması gerektiğini göstermektedir. Bu yaklaşım, doğa haklarının hukuki kişilik kategorisine indirgenmemesi gerektiğini de ortaya koymaktadır (Kurki, 2022). Bu ayrım, çalışmamızda, temsiliyet bakımından daha ileri bir sonuç doğurmaktadır. Bir doğal varlığa hukuk kişiliği tanınmış olsa bile doğal varlık kendi hukuki statüsünü bizzat kullanamaz. Hukuk kişiliği, doğal varlığın hukuk düzenindeki normatif konumunu değiştirebilir; fakat bu statünün hukuki süreçlerde harekete geçirilmesi ayrıca bir temsil mekanizmasını gerektirir.

Hukuki statü ile hukuki eyleyebilirlik arasında temsil aracılığıyla doldurulması gereken kurumsal bir alan bulunmaktadır (O'Donnell & Talbot-Jones, 2018; O'Donnell, 2018; Macpherson, 2019).Yeni Zelanda örnekleri, bu ayrımı açık biçimde göstermektedir. *Te Urewera Act 2014*, Te Urewera'yı kendi başına bir hukuki varlık olarak tanımakta ve hukuk kişisinin hak, yetki, görev ve yükümlülüklerine sahip olduğunu kabul etmektedir. Bununla birlikte aynı düzenleme, Te Urewera'nın adına hareket edecek Te Urewera Board'u kurmaktadır. Benzer biçimde *Te Awa Tupua (Whanganui River Claims Settlement) Act 2017*, Te Awa Tupua'yı hukuk kişisi olarak kabul ederken, Te Pou Tupua'yı nehrin "insan yüzü" olarak düzenlemekte ve nehir adına hareket etme görevini ona vermektedir (*Te Urewera Act 2014*; *Te Awa Tupua Act 2017*). Bu örnekler hukuki kişilik ile temsil arasındaki işlevsel farkı, ortaya koymaktadır: Kişilik statü verirken, temsil bu statünün hukuki etkinliğini sağlar.

Doğa haklarının geleceği yalnızca daha fazla doğal varlığın hukuk kişisi olarak tanınmasına bağlı değildir. Asıl mesele, tanınmış statünün hangi kurumsal mekanizmalar aracılığıyla karar süreçlerine taşınacağı ve doğal varlığın korunabilir menfaatinin nasıl temsil edileceğidir. O'Donnell ve Talbot-Jones'un karşılaştırmalı nehir hakları incelemesi de hukuki kişilik tanınmasının uygulamada yeni sorunlar yaratabileceğini ve özellikle temsil ile yönetişim yapısının belirleyici olduğunu göstermektedir (O'Donnell & Talbot-Jones, 2018). Hukuki kişilik sessiz öznenin hukuk düzeninde tanınmasını sağlayabilir; fakat hukuki görünürlüğünü tek başına garanti etmez.

SESSİZ ÖZNE YAKLAŞIMININ KURAMSAL YAPISI

Doğanın kendi adına hukuki talepte bulunamaması, yeni bir tespit değildir. Doğa hakları literatüründe vasilik, vesayet ve temsil mekanizmaları uzun süredir tartışılmaktadır. Özellikle Te Urewera, Whanganui ve Atrato örnekleri, doğal varlıkların haklarının insan veya kurumsal temsilciler aracılığıyla kullanılması gerektiğini açık biçimde göstermektedir (Morris & Ruru, 2010, ss. 49–62; O'Donnell & Talbot-Jones, 2018; Macpherson & Clavijo Ospina, 2018; O'Donnell, 2018; Wesche, 2021). Bu nedenle çalışmamız, mevcut literatürde farklı kurumsal modeller bağlamında ele alınan temsil sorununu daha genel bir hukuki koruma problemi içinde yeniden kavramsallaştırmaya çalışmakta ve bu amaçla sessiz özne kavramı kullanılmaktadır.

Sessiz özne, korunabilir menfaati bulunan veya hukuk tarafından belirli hakların taşıyıcısı olarak tanınan; ancak bu menfaati kendi adına hukuk düzeninin tanıdığı bir talebe dönüştüremeyen varlığı ifade etmektedir. Buradaki "sessizlik" fiziksel veya biyolojik değildir. Hukuki sessizliktir. Bir nehir fiziksel olarak vardır. Ekolojik süreçlere sahiptir. Kirlenebilir. Akış rejimi bozulabilir. Biyolojik çeşitliliğini kaybedebilir. Fakat uğradığı zararı kendi başına hukuki iddiaya dönüştüremez. Doğal varlığın maddi varlığı ile hukuki görünürlüğü arasında zorunlu bir özdeşlik bulunmamaktadır. Sessiz özne yaklaşımının ilk katkısı bu ayrımı görünür hâle getirmektir.

Sessiz özne kavramı, doğayı yeniden pasif bir koruma nesnesine dönüştürmemelidir. Klasik çevre hukukunda doğal varlık çoğu zaman insanın sağlığı, mülkiyeti veya yaşam kalitesi bakımından korunmaktadır. Böyle bir durumda doğanın korunmasının normatif nedeni insan menfaatidir. Sessiz özne yaklaşımında ise hareket noktası farklı olup, doğal varlığın kendisine ait, korunabilir menfaatinin bulunduğu kabul edilmektedir.

Temsilcinin görevi, insanın doğaya ilişkin menfaatini değil, mümkün olduğu ölçüde doğal varlığın bağımsız korunabilir menfaatini hukuk düzenine taşımaktır. Bu yönüyle sessiz özne yaklaşımı, doğanın içsel değerine ve insan dışı varlıkların normatif statüsüne ilişkin daha geniş ekomerkezci hukuk tartışmalarıyla ilişkilidir (Borràs, 2016; Tănăsescu, 2020; Boulot & Sterlin, 2022). Ancak sessiz özne

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kavramı, doğal varlığa insan benzeri irade atfetmemektedir. Doğa "istemek", "seçmek" veya "talimat vermek" zorunda değildir. Burada korunması gereken, varsayımsal bir insanlaştırılmış irade değil, belirlenebilir ekolojik menfaattir.

Sessiz özne kavramı, üç temel unsur üzerinden tanımlanabilir. Birinci unsur, korunabilir menfaatin varlığıdır. Sessiz özne olarak nitelendirilen varlığın hukuk tarafından korunmaya değer bir menfaatinin bulunması gerekir. Doğa bakımından bu menfaat; ekolojik bütünlük, biyolojik çeşitlilik, yenilenme kapasitesi, habitat sürekliliği veya ekosistem işlevlerinin devamı gibi değerlerle ilişkilendirilebilir. İkinci unsur, hukuki tanınabilirliktir. Menfaatin mutlaka subjektif hak biçiminde tanınmış olması şart değildir. Hukuk kişiliği, anayasal hak, statüsel haklar, koruma statüsü veya başka hukuki teknikler söz konusu olabilir. Önemli olan doğal varlığın menfaatinin hukuk düzeni bakımından dikkate alınabilir olmasıdır. Üçüncü unsur, öznenin menfaatini bizzat hukuki talebe dönüştürememesidir. Sessiz özneyi temsil teorisi bakımından özel kılan unsur budur. Sessiz özne kavramının üç temel kurucu unsuru birlikte değerlendirildiğinde; sessiz özne, korunabilir ve hukuken tanınabilir bir menfaati bulunan, fakat bu menfaati kendi başına hukuk düzeninin karar süreçlerine taşıyamayan varlık olduğu ortaya çıkmaktadır.

SESSİZ ÖZNE YAKLAŞIMINDA TEMSİL SORUNU

Bağımsız Bir Hukuki Koruma Eksikliği ve Temsil Boşluğu

Hakların tanınması, hukuki korumanın vazgeçilmez araçlarından biridir. Bununla birlikte bir hakkın hukuk metninde bulunması ile etkili biçimde korunması aynı şey değildir. Hak tanınmış olabilir fakat başvuru yolu bulunmayabilir; başvuru yolu mevcut olmakla birlikte giderim etkisiz olabilir; kurumlar gerekli kaynaklardan yoksun olabilir veya sessiz özne de olduğu gibi bu hakkı harekete geçirecek aktör bulunmayabilir. Burada bağımsız bir hukuki koruma eksikliği bulunmaktadır. Doğal varlık, kendi hakkını bizzat harekete geçiremiyorsa, tanınmış hakkın etkili biçimde uygulanabilmesi temsil mekanizmasına bağlıdır. Atrato deneyimi, bu açıdan öğreticidir. Wesche'nin kararın uygulamasına ilişkin ampirik incelemesi, hakların ve guardian yapısının tanınmasının önemli olmakla birlikte uygulamanın kurumsal kapasite, kamu politikaları ve yerel aktörlerin sürece katılımıyla yakından ilişkili olduğunu göstermektedir (Wesche, 2021).

Temsil boşluğu, korunabilir menfaati veya tanınmış hakkı bulunan sessiz öznenin, bu menfaat veya hakkı hukuk düzeninin karar süreçlerine etkili ve meşru biçimde taşıyabilecek yeterli temsil mekanizmasından yoksun olmasıdır. Temsil boşluğu yalnızca temsilcinin hiç bulunmadığı durumda ortaya çıkmaz. Bir vasi atanmış, bir kurul oluşturulmuş olabilir. Bir kamu kurumu temsil yetkisine sahip olsa da temsil işlevsiz kalabilir. Bu nedenle temsil boşluğu niceliksel değil, niteliksel bir kavramdır.

Wesche'nin Atrato incelemesi ile daha yeni vasilik literatürü, doğal varlık adına hareket eden kurumların yetki, kaynak, bilgi, koordinasyon ve meşruiyet sorunları yaşayabildiğini göstermektedir (Wesche, 2021; Choi, 2025; Gurman & Kieser, 2026). Bu nedenle bir temsil kurumunun hukuken kurulmuş olması, temsil boşluğunun ortadan kalktığını tek başına göstermemektedir. Temsil boşluğunun en az beş görünümünden söz edilebilir. Yetki Boşluğunda temsilci bulunmakta, fakat doğal varlığın menfaatini etkileyen bütün önemli süreçlere katılma veya gerekli hukuki başvuruları yapma yetkisine sahip bulunmamaktadır. Bu durumda temsil biçimsel olarak mevcut, fakat hukuken sınırlıdır. Kapasite Boşluğunda temsilci yeterli mali kaynak, personel, hukuki uzmanlık veya kurumsal desteğe sahip olmayabilir. Bu durumda yetki vardır, fakat yetkinin kullanılmasını mümkün kılacak kapasite yoktur. Epistemik Boşlukta, temsilci doğal varlığın korunabilir menfaatini belirlemek için gerekli ekolojik, bilimsel veya yerel bilgiye erişemeyebilir.

Doğanın temsil edilmesi yalnızca hukuki bir faaliyet değildir; aynı zamanda bilgiye dayalı bir değerlendirmedir. Bu nedenle epistemik kapasite temsilin temel bileşenlerinden biridir (Tănăsescu, 2020; Cribb ve ark., 2024; Gurman & Kieser, 2026). Bağımsızlık Boşluğunda temsilci, temsil ettiği doğal varlığın menfaatiyle çatışabilecek ekonomik, idari veya siyasal menfaatlerin etkisi altında bulunabilir. Özellikle aynı kamu kurumunun hem doğal kaynağın ekonomik kullanımını teşvik etmesi hem de onun haklarını temsil etmesi durumunda yapısal çıkar çatışmaları doğabilir. Hesap Verebilirlik Boşluğunda, doğa kendi temsilcisini seçemediği, görevden alamadığı veya temsil faaliyetini denetleyemediği için temsilcinin dışsal denetimi özel önem taşır. Temsilci kararlarını açıklamak veya

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gerekçelendirmek zorunda değilse temsil yetkisi zaman içinde temsil edilenin menfaatinden uzaklaşabilir. Bu beş görünüm, temsil boşluğunun yalnızca "temsilci var/yok" ikiliğiyle çıklanamayacağını göstermektedir. Bu nedenle doğru soru: "Doğanın temsilcisi var mıdır?" sorusu yerine artık, "Doğanın korunabilir menfaatini etkili, bağımsız, bilgiye dayalı ve hesap verebilir biçimde temsil eden bir mekanizma var mıdır?" sorusu sorulmalıdır.

Temsilin Asıl İşlevi Olarak Hukuki Görünürlük

Bir doğal varlığın hukuk tarafından hak sahibi veya hukuk kişisi olarak tanınması onun normatif görünürlüğünü artırabilir. Ancak normatif tanınma ile doğal varlığın menfaatinin somut karar süreçlerinde dikkate alınması aynı şey değildir. Bu nedenle hukuki görünürlük, normatif tanınmadan daha geniş bir kavram olarak ele alınmalıdır. Hukuki görünürlük, sessiz öznenin korunabilir menfaatinin, hukuk düzeninde; tanınabilir, ileri sürülebilir, karar süreçlerinde dikkate alınabilir ve ihlal edildiğinde giderime konu edilebilir hâle gelmesini ifade etmektedir.

Temsilin sessiz özne bakımından kurucu işlevi tam burada ortaya çıkar. Nehir restorasyon talep edemez. Temsilci bu talebi hukuki ve idari sürece taşır. Orman kendisini etkileyen ruhsat kararına itiraz edemez. Temsil mekanizması ormanın ekolojik bütünlüğünü ruhsat değerlendirmesinin unsurlarından biri hâline getirir. Ekosistem kendisi için bütçe talep edemez. Vesayet veya temsil kurumu restorasyon ve koruma için kaynak ayrılmasını talep edebilir. Bu nedenle temsilin başarısını yalnızca kaç dava açıldığı veya kaç karar kazanıldığı üzerinden ölçmek yetersizdir. Doğal varlığın korunabilir menfaati, onu etkileyen hukuki ve yönetsel kararların ne kadarında görünür hâle gelmektedir? Şeklindeki sorunun cevabı önem taşımaktadır. Bu nokta da Atrato örneği, önemlidir. Wesche'nin çalışması, T-622/16 kararının etkilerinin yalnızca mahkemeye erişim veya dava hakkı üzerinden değerlendirilemeyeceğini; kararın kamu politikaları, toplumsal mobilizasyon ve nehrin korunmasına ilişkin yönetişim süreçleri üzerinde de etkiler yarattığını ortaya koymaktadır (Wesche, 2021).

Whanganui deneyimine ilişkin ampirik çalışmalar da benzer biçimde, Te Awa Tupua düzenlemesinin öneminin yalnızca nehre hukuk kişiliği tanınmasından kaynaklanmadığını göstermektedir. İş birliği, hukuki çoğulculuk, Māori toplumunun bilgi ve normlarının yönetişim sistemine dâhil edilmesi ve yerel aktörlerin karar süreçlerindeki konumunun güçlendirilmesi de bu düzenlemenin önemli unsurlarıdır (Cribb ve Ark., 2024). Choi'nin karşılaştırmalı nehir incelemesi de hukuki statünün tek başına etkili nehir korumasını garanti etmediğini; yönetişim kapasitesi, temsil mekanizmaları, kaynaklar ve kurumsal yapıların belirleyici olduğunu göstermektedir (Choi, 2025). Hukuki görünürlük, yalnızca yargısal görünürlük değildir. Hukuki görünürlüğün, yargısal görünürlük, idari görünürlük, yönetişimsel görünürlük ve normatif görünürlük olmak üzere en az dört boyutu bulunmaktadır. Böyleliklerle temsil, yalnızca sessiz öznenin mahkemeye ulaşmasını sağlayan bir usul aracı olmaktan çıkar ve temsili, sessiz öznenin korunabilir menfaatini hukuk düzeninin görebileceği, değerlendirebileceği ve koruyabileceği bir hukuki talebe dönüştürür.

Literatürdeki ampirik ve kuramsal çalışmalar temsilin ve yönetişimin önemini desteklemekte; ancak burada kurulan sessiz özne – temsil – hukuki görünürlük bağlantısı, çalışmamızın kendi teorik mimarisini oluşturmaktadır. Bu nedenle artık ana zincirin iki yüzü açık biçimde ortadadır: Sessiz özne → temsil ihtiyacı → meşru temsil → hukuki görünürlük → etkili koruma ve bunun karşısında, eski düzende: Sessiz özne → temsil boşluğu → hukuki görünmezlik → koruma eksikliği.

Karşılaştırmalı Hukukta Doğanın Temsili

Doğa haklarının karşılaştırmalı gelişimi, doğal varlıkların temsil edilmesine ilişkin tek bir kurumsal model bulunmadığını göstermektedir. Ekvador, Yeni Zelanda ve Kolombiya örnekleri farklı temsil mekanizmaları geliştirmiştir. Bu farklılıklar, doğa haklarının yalnızca hakların içeriği bakımından değil, hakların kim tarafından ve hangi kurumsal yapı içerisinde ileri sürülebileceği bakımından da karşılaştırılması gerektiğini ortaya koymaktadır (Kauffman & Martin, 2017; O'Donnell & Talbot-Jones, 2018; Macpherson & Clavijo Ospina, 2018; O'Donnell, 2018; Macpherson, 2019).

Ekvador: Açık Dava Hakkı ve Toplumsallaştırılmış Temsil

Ekvador 2008 Anayasası'nın 71. maddesi, doğanın veya *Pacha Mama*'nın varlığını sürdürme ve yaşam döngülerini, yapısını, işlevlerini ve evrimsel süreçlerini devam ettirme ve yenileme hakkını

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tanımaktadır. Aynı hüküm, her kişi, topluluk, halk veya ulusun doğa haklarının uygulanmasını kamu makamlarından talep edebilmesine imkân vermektedir (Constitution of the Republic of Ecuador, 2008, arts. 71–74). Bu modelde doğal varlığın temsili, belirli tek bir guardian veya kamu kurumuna özgülenmemiştir. Temsil olanağı toplumsallaştırılmıştır. Modelin önemli üstünlüğü erişim genişliğidir. Doğa haklarının ileri sürülmesi devlet kurumlarının harekete geçmesine bağlı değildir. Bireyler ve topluluklar doğanın haklarını yargısal sürece taşıyabilirler. Kauffman ve Martin'in Ekvador davalarına ilişkin incelemesi, anayasal hakların farklı davalarda nasıl harekete geçirildiğini ve başarı üzerinde dava stratejisi ile kurumsal bağlamın etkisini göstermektedir (Kauffman & Martin, 2017). Ancak model aynı zamanda temsil meşruiyetine ilişkin başka bir sorunu ortaya çıkarmaktadır. Herkes doğa adına talepte bulunabiliyorsa; hangi talebin doğal varlığın korunabilir menfaatini daha doğru temsil ettiği nasıl belirlenecektir? Burada çok geniş olan dava hakkı, temsil sorununu ortadan kaldırmamaktadır.

Düzenleme, temsilin kim tarafından yapılacağı sorununu azaltırken, temsilin niteliği ve doğruluğu sorununu devam ettirmektedir. Ekvador Anayasa Mahkemesi içtihadının gelişimi bu nedenle önemlidir. Murray ve Martínez-Moscoso'nun on altı kararı inceleyen çalışması, doğa haklarının uygulanmasında mahkemelerin giderek belirli standartlar geliştirdiğini, fakat doğanın korunabilir menfaatinin ve hak ihlalinin belirlenmesinin bağlamsal değerlendirmeler gerektirdiğini göstermektedir (Murray & Martínez-Moscoso, 2025).

Te Urewera: Kurumsallaştırılmış ve Sürekli Temsil

Yeni Zelanda'daki *Te Urewera Act 2014*, Te Urewera'yı kendi başına hukuki varlık olarak tanımakta ve ona hukuk kişisinin hak, yetki, görev ve sorumluluklarını vermektedir. Düzenleme, aynı zamanda Te Urewera adına hareket etmek üzere Te Urewera Board'u öngörmektedir (*Te Urewera Act 2014*). Bu modelde, hukuki kişilik ile temsil kurumsal olarak birbirinden ayrılmıştır: Te Urewera hukuki varlıktır; Te Urewera Board onun adına hareket etmektedir.

Bu yapı Ekvador'un açık dava hakkı modelinden farklı olarak sürekli bir kurumsal temsil mekanizması oluşturmaktadır. Kurumsallaştırılmış temsilin temel üstünlüğü sürekliliktir. Temsil yalnızca zarar gerçekleştikten sonra açılan bir davayla başlamaz. Doğal varlığın yönetimi, korunması, planlanması ve geleceğine ilişkin karar süreçlerinde devam eder. Böylece temsil, reaktif korumadan önleyici korumaya genişlemektedir. Bu ayrım sessiz öznenin hukuki görünürlüğü bakımından önemlidir. Etkili koruma, yalnızca zarar meydana geldikten sonra sessiz öznenin hakkının ileri sürülmesini değil, zarar doğmadan önce onun korunabilir menfaatinin karar süreçlerinde dikkate alınmasını da gerektirir.

Whanganui Nehri: İlişkisel ve Çoğul Temsil

Te Awa Tupua (Whanganui River Claims Settlement) Act 2017, Te Awa Tupua'yı dağlardan denize kadar uzanan fiziksel ve metafizik unsurlarıyla bölünmez ve yaşayan bir bütün olarak tanımlamakta ve ona hukuk kişiliği vermektedir. Düzenleme Te Pou Tupua'yı Te Awa Tupua'nın "insan yüzü" olarak kurmakta ve onun adına hareket etme görevini vermektedir (*Te Awa Tupua Act 2017*). Te Pou Tupua'nın yapısı temsil teorisi bakımından özellikle önemlidir. Temsil iki farklı meşruiyet kaynağını bir araya getirmektedir: Whanganui Iwi ve Crown. Bu model sessiz öznenin temsilinde tek aktörlü yapı yerine çoğul temsil olasılığını göstermektedir.

Whanganui modelinin önemi yalnızca kurumsal çoğullukla sınırlı değildir. Māori dünya görüşünde nehir, insan topluluğundan tamamen ayrı ve dışsal bir nesne olarak görülmemektedir. İnsan ile nehir arasındaki ilişki, "Ko au te awa, ko te awa ko au" — "Ben nehirim ve nehir benim" ifadesinde görünür hâle gelen ilişkisel bir anlayışa dayanmaktadır. Bu nedenle Whanganui düzenlemesi, Batılı hukuk kişiliği kategorileri ile Māori ontolojisi arasında özgün bir hukuki yapı oluşturmaktadır (Morris & Ruru, 2010; Macpherson, 2019; Tănăsescu, 2020).

Cribb, Macpherson ve Borchgrevink'in uygulamaya ilişkin çalışması, Te Awa Tupua rejiminin öneminin yalnızca legal personhood kavramından kaynaklanmadığını; iş birliği, hukuki çoğulculuk ve Māori normlarının yönetişim süreçlerine dâhil edilmesinin uygulamanın merkezinde bulunduğunu göstermektedir (Cribb ve Ark., 2024). Bu örnek sessiz özne yaklaşımı bakımından önemli bir ilkeyi desteklemektedir. Sessiz öznenin menfaati tek bir bilgi veya meşruiyet kaynağının tekeline bırakılmamalıdır.

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Atrato Nehri: Müşterek Koruyuculuk

Kolombiya Anayasa Mahkemesi, T-622/16 sayılı kararında Atrato Nehri'ni korunma, muhafaza, bakım ve restorasyon haklarının öznesi olarak tanımıştır. Mahkeme aynı zamanda nehrin temsili ve guardianship'i bakımından devlet ile havzada yaşayan etnik toplulukların birlikte rol üstleneceği bir yapı öngörmüştür (Constitutional Court of Colombia, Judgment T-622/16). Atrato modeli hak sahipliği ile temsil arasındaki ilişkiyi açık biçimde göstermektedir. Mahkeme yalnızca: "Nehir hak sahibidir." demeyiş; aynı zamanda: "Bu hakkın kim tarafından korunacağı" sorusuna da cevap vermeye çalışmıştır. Kararın normatif yapısı şu şekilde okunabilir: Hak sahipliği → temsil → koruma. Ancak Atrato örneğinin asıl önemi, uygulama aşamasında ortaya çıkmaktadır. Wesche'nin ampirik incelemesi, kararın önemli toplumsal ve kurumsal etkiler doğurduğunu, fakat vesayet sisteminin uygulanmasında kaynak, koordinasyon ve kurumsal kapasite sorunlarının devam ettiğini göstermektedir (Wesche, 2021). Bu bulgu, temsil boşluğu kavramı bakımından özellikle önemlidir: Temsilcinin varlığı temsil boşluğunun bulunmadığını göstermez; etkili temsil kapasitesinin bulunması gerekir. Atrato aynı zamanda yerel toplulukların temsil sistemine katılması bakımından da önem taşımaktadır. Nehrin ekolojik durumuna ilişkin yerel bilgi ile devletin hukuki ve idari kapasitesinin birlikte kullanılması, temsilin yalnızca hukuki değil, aynı zamanda epistemik bir kurum olduğunu göstermektedir.

DOĞA ADINA TEMSİLİN MEŞRUİYETİ

Doğa adına kim konuşabilir? Doğanın temsilcisi, kendi yetkisini doğadan alamaz. Doğa temsilcisini seçemez, ona talimat veremez veya temsil faaliyetini sonradan denetleyemez. Bu nedenle sessiz özne temsilinin meşruiyeti, klasik vekâlet ilişkisindeki temsil edilenin iradesine dayandırılamaz. Meşruiyetin başka ölçütlerden türetilmesi gerekir. Doğanın temsilinde bazı temel ölçütlerin birlikte değerlendirilmesini önermektedir: korunabilir menfaat, bağımsızlık, çoğulluk, epistemik yeterlilik, hesap verebilirlik ve ekolojik sadakat. Bu ölçütlerin ortak işlevi, temsilcinin kendi tercihlerini veya kurumunun çıkarlarını doğal varlığın menfaati yerine geçirmesini sınırlamaktır.

İlk olarak temsilin dayandığı korunabilir menfaat belirlenmelidir. Doğa adına hareket eden temsilcinin görevi, kendi politik veya ahlaki tercihini doğanın "iradesi" gibi sunmak değildir. Temsil, doğal varlığın ekolojik bütünlüğü, devamlılığı, yenilenme kapasitesi, biyolojik çeşitliliği ve ekosistem işlevleri gibi hukuken korunabilir menfaatlerine dayanmalıdır. Bu yönüyle temsil, soyut bir savunuculuk faaliyetinden farklıdır; temsil edilen menfaatin nesnelleştirilebilir ölçütlere bağlanmasını gerektirir.

Doğanın temsilinde bağımsızlık önem taşır. Devletin doğayı temsil ettiği modellerde aynı devletin enerji, madencilik, altyapı veya ekonomik kalkınma politikalarını da yürütmesi yapısal çıkar çatışmaları yaratabilir. Bu nedenle temsilcinin temsil ettiği doğal varlığa zarar verebilecek ekonomik veya siyasal menfaatlerden mümkün olduğunca bağımsız olması gerekir. Bu bağımsızlık mutlak olmak zorunda değildir; ancak çıkar çatışmalarının açık biçimde tanımlanması ve denetlenmesi gerekir. Doğanın temsilinde çoğulluk ilkesi, sessiz öznenin menfaatinin tek bir aktörün yorumuna bırakılmasını sınırlayabilir. Whanganui ve Atrato örneklerinde görüldüğü üzere, devletin kurumsal kapasitesi ile yerel toplulukların ekolojik ve kültürel bilgisi aynı temsil yapısında bir araya getirilebilir. Böyle bir model karar süreçlerini karmaşıklaştırabilir; fakat temsil meşruiyetini ve denetlenebilirliği artırabilir (Macpherson & Clavijo Ospina, 2018; Cribb ve AArk., 2024; Wesche, 2021).

Doğanın temsilinde bir başka unsur epistemik yeterliliktir. Doğanın temsil edilmesi yalnızca hukuki yetki meselesi değildir. Temsilci neyi koruduğunu ve hangi müdahalenin doğal varlığın bütünlüğünü nasıl etkileyeceğini anlayabilecek bilgi kaynaklarına erişmelidir. Bu nedenle ekolojik bilim, uzun dönemli çevresel veri, yerel ve yerli bilgi sistemleri ile gerektiğinde ihtiyat ilkesi temsil faaliyetinin bilgi temelini oluşturmalıdır (Tănăsescu, 2020; Cribb ve Ark., 2024; Gurman & Kieser, 2026). Doğanın temsilinde beşinci unsur, hesap verebilirliktir. Sessiz özne temsilcisini doğrudan denetleyemediği için, temsilcinin dışsal denetimi klasik temsil ilişkilerine göre daha güçlü kurulmalıdır.

Temsilcinin kararlarını gerekçelendirmesi, belirli aralıklarla raporlaması, çıkar çatışmalarını açıklaması, yargısal veya idari denetime tabi olması ve gerekli durumlarda görevden alınabilmesi bu çerçevenin parçalarıdır. Bu noktada çalışmanın daha genel normatif önermesi şöyle ifade edilebilir: Temsil edilenin temsilci üzerindeki doğrudan denetim kapasitesi azaldıkça, temsilcinin hesap verme ve kararını gerekçelendirme yükümlülüğü artmalıdır. Doğanın temsilinde altıncı unsur ise ekolojik sadakattir.

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Temsilci, kendi kurumsal veya siyasal hedeflerinden bağımsız olarak temsil edilen doğal varlığın korunabilir ekolojik menfaatini esas almalıdır.

Bu nedenle temsil faaliyetinin temel sorusu: "Temsilci neyi tercih ediyor?" değil; "Temsil edilen doğal varlığın korunabilir menfaati neyi gerektiriyor?" olmalıdır. Bu unsurlar birlikte değerlendirildiğinde; temsil, basit bir vekâlet ilişkisi olmaktan çıkıp sessiz öznenin hukuk düzenindeki görünürlüğünü güvence altına alan kurumsal bir koruma mekanizmasına dönüşmektedir.

Doğanın Menfaatinin Belirlenmesi

Doğanın menfaatinin belirlenmesi için, irade yerine korunabilir menfaatin belirlenmesi gerekir. Sessiz özne yaklaşımının en önemli metodolojik güçlüğü, temsil edilen varlığın kendi iradesini açıklayamamasıdır. Klasik temsil ilişkilerinde temsil edilen kişi temsilciye talimat verebilir, çıkarını ifade edebilir veya temsil faaliyetini denetleyebilir. Doğa bakımından bu tür bir iradi bağlantı kurulamaz. Bu nedenle doğanın temsili, varsayımsal irade üzerinden kurulamaz. Bir nehrin veya ormanın insan benzeri tercihlere sahip olduğunu varsaymak, iki önemli risk yaratır. Birincisi, doğanın antropomorfize edilmesidir. İkincisi, temsilcinin kendi tercihlerini doğal varlığın "isteği" olarak sunabilmesidir. Bu nedenle temsilin nesnesi doğanın varsayımsal iradesi değil, korunabilir menfaatidir.

Doğanın korunabilir menfaati, ilk olarak ekolojik bilim aracılığıyla belirlenebilir. Bir nehrin akış rejimi, su kalitesi, biyolojik çeşitliliği, habitat bütünlüğü, yenilenme kapasitesi ve ekosistem bağlantıları, belirli bir müdahalenin doğanın menfaatine uygun olup olmadığını değerlendirmede kullanılabilir. Bununla birlikte ekolojik sistemler dinamik ve karmaşıktır, tek bir bilimsel ölçütün bütün bu durumları çözmesi mümkün değildir. Bu noktada yerel ve yerli bilgi sistemleri önem kazanır. Te Awa Tupua modeli, Whanganui Iwi'nin tarihsel ve ilişkisel bilgisini yönetişim yapısının içine yerleştirmesi bakımından öğreticidir. Cribb, Macpherson ve Borchgrevink'in çalışması da bu yapının yalnızca hukuk kişiliğine değil, iş birliği ve çoğul bilgi biçimlerinin kurumsallaştırılmasına dayandığını göstermektedir (Cribb ve Ark., 2024).

Benzer biçimde Atrato örneğinde de yerel toplulukların temsil sistemine katılması yalnızca demokratik katılım bakımından değil, nehrin ekolojik durumuna ilişkin uzun dönemli yerel bilgi bakımından da önem taşımaktadır (Wesche, 2021). Bu nedenle sessiz öznenin temsili epistemik çoğulluk gerektirir. Temsilcinin kararları: bilimsel veri, yerel ve yerli bilgi, uzun dönemli çevresel gözlem, ve gerektiğinde ihtiyat ilkesi üzerinden gerekçelendirilmelidir. Böylece temsilcinin meşruiyeti yalnızca hukuki yetkiye değil, bilgi temeline de bağlanmış olur. Temsilci doğanın ne istediğini söylemez ve bu yüzden mevcut en iyi bilgiye dayanarak doğanın korunabilir menfaatinin neyi gerektirdiğini gerekçelendirmeye çalışır.

Antropomorfizm ve İnsanmerkezcilik İtirazı

Doğa hakları yaklaşımına yöneltilen en temel eleştirilerden biri, doğal varlıkların "hak sahibi", "kişi" veya "temsil edilen özne" olarak tanımlanmasının doğayı insan hukukunun kategorilerine hapsettiği iddiasıdır. Bu eleştiriye göre doğa hakları, antropomerkezci hukuktan kurtulmaya çalışırken doğayı yeniden insan benzeri kavramlarla açıklamaktadır. Sessiz özne yaklaşımı bu eleştiriyi tamamen ortadan kaldırmaz. Çünkü doğal varlıkların hukuk düzeninde temsil edilmesi yine insan kurumları aracılığıyla gerçekleşmektedir.

Burada iki farklı insanmerkezcilik biçimini birbirinden ayırmak gerekir. İlk biçim menfaat insanmerkezciliğidir. Doğa yalnızca insan yararı nedeniyle korunur. İkinci biçim ise kurumsal insanmerkezciliktir. İnsan tarafından kurulan hukuk sistemi doğal varlıkların korunmasını insan kurumları aracılığıyla yürütür. Sessiz özne yaklaşımı, menfaat insanmerkezciliği biçimini aşmayı hedeflemektedir ve kurumsal insanmerkezciliğini bütünüyle ortadan kaldırma iddiasında değildir. Asıl sorun, temsilcinin insan olması değil, insan menfaatini doğanın menfaati yerine koyup koymamasıdır. Doğanın temsiline yönelik doğru soru: "İnsan doğa adına konuşabilir mi?" sorusu yerine; "İnsan doğa adına hangi koşullarda meşru biçimde konuşabilir?" sorusu olmalı ve bu sorunun koşulları da bağımsızlık, epistemik yeterlilik, çoğulluk, hesap verebilirlik ve ekolojik sadakat üzerinden belirlenmelidir.

Temsilcinin Doğanın Yerine Geçmesi Riski

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Sessiz özne temsilinin önemli risklerinden biri, temsilcinin zaman içinde temsil edilen varlığın yerine geçmesidir. Doğa temsilcisini azledemez, talimat veremez veya temsilcinin kendi çıkarlarını izlediğini doğrudan ortaya koyamaz. Bu nedenle temsil kurumunun hukuken sınırlandırılması gerekir. Temsilci, doğanın sahibi değildir, doğanın kendisi değildir, doğanın iradesi değildir. Temsilci yalnızca doğal varlığın korunabilir menfaatini hukuk düzeninde görünür hâle getiren kurumsal aracıdır.

Temsilcinin doğanın yerine geçmesi riski yüzünden, vasilik veya temsil kurullarının görev süreleri, yetki alanları, karar gerekçelendirme yükümlülükleri, raporlama usulleri, çıkar çatışması kuralları ve denetim mekanizmaları açık biçimde düzenlenmelidir. Aksi hâlde "doğaya ses verme" amacıyla kurulan yapı, sessiz öznenin sesi olmaktan çıkarak kendi kurumsal çıkarlarını sürdüren bağımsız bir aktöre dönüşebilir. Bu nedenle temsilin sınırı şu formülle ifade edilebilir: Temsil, temsil edilenin yerine geçme yetkisi değil; onun korunabilir menfaatini hukuk düzeninde görünür kılma görevidir.

Demokratik Meşruiyet ve Temsil

Doğa adına hareket eden vasi veya bağımsız temsilcilerin geniş yetkiler kullanması, demokratik meşruiyet sorunu yaratabilir. Doğal varlığın korunması, enerji, ulaştırma, tarım, madencilik, altyapı veya ekonomik kalkınma gibi demokratik karar alanlarıyla çatışabilir. Bu durumda seçilmiş olmayan bir temsilcinin ne ölçüde kamu politikasını sınırlayabileceği sorusu ortaya çıkar. Bu itiraz temsil temelli korumanın ciddi sınırlarından biridir.

Ancak sessiz özne temsilcisinin rolü demokratik kararın yerine geçmek olarak tanımlanmamalıdır. Asıl işlevi: demokratik karar sürecinde sistematik olarak temsil edilmeyen menfaati görünür hâle getirmektir. Bu nedenle doğa temsilcisi: karar süreçlerine katılabilir, ekolojik etki değerlendirmesi sunabilir, ihlale karşı yargıya başvurabilir, restorasyon talep edebilir, planlama ve ruhsatlandırma süreçlerinde doğal varlığın menfaatini ileri sürebilir. Buna karşılık nihai karar demokratik, idari veya yargısal kurumlar tarafından verilebilir. Bu yapı, temsilcinin mutlak karar yetkisi kullanmasını önlerken sessiz öznenin karar süreçlerinde görünür olmasını sağlar.

Whanganui modelinin uygulamasına ilişkin çalışmalar da çoğulculuk ve iş birliği üzerinden kurulan bu tür yönetişim modellerinin, temsil ile demokratik meşruiyet arasındaki gerilimi azaltabileceğini göstermektedir (Cribb ve Ark., 2024). Bu nedenle sessiz özne temsili demokratik sistemin alternatifi değildir. Demokratik kararın görmediği menfaati karar sürecine ekleyen tamamlayıcı bir kurumdur.

SESSİZ ÖZNENİN TEMSİLİNDE HUKUKİ KORUMA

Sessiz Öznenin Hukuki Koruma Modeli

Çalışmamızın teorik çerçevesi, sessiz öznenin hukuki korunmasının tek aşamalı değil, çok aşamalı bir süreç olduğunu göstermektedir. İlk aşama, korunabilir menfaatin belirlenmesidir. İkinci aşama, bu menfaatin hukuk tarafından normatif olarak tanınmasıdır. Bu tanınma da hak, hukuk kişiliği, anayasal statü, koruma statüsü veya başka bir hukuki teknik aracılığıyla gerçekleşebilir.

Üçüncü aşama, temsil mekanizmasının kurulmasıdır. Dördüncü aşama, temsil aracılığıyla doğal varlığın menfaatinin hukuki görünürlüğe kavuşmasıdır. Son aşama ise etkili koruma ve giderimdir. Sessiz öznenin etkili korunması, aşamalı bir zincir üzerinden kurulabilir: Korunabilir menfaat → normatif tanınma → meşru temsil → hukuki görünürlük → etkili koruma ve giderim. Bu süreçte her aşamanın ayrı bir işlevi bulunmaktadır. Korunabilir menfaat, neyin korunacağını belirler.

Normatif tanınma, bu menfaate hukuki statü verir. Temsil, menfaati hukuk düzeninin karar süreçlerine taşır. Hukuki görünürlük, menfaatin dikkate alınmasını sağlar. Etkili koruma ve giderim, ihlalin önlenmesi veya sonuçlarının ortadan kaldırılmasını amaçlar. Bu zincirin temsil halkasında ortaya çıkan eksiklik ise temsil boşluğudur. Çalışmamızda, hakların yerine temsil seçili değildir. Zira sessiz özne bakımından hakların etkili olabilmesi, temsil aracılığıyla hukuki görünürlüğe kavuşmalarına bağlıdır. Temsil temelli koruma, hak temelli korumanın alternatifi değil, sessiz özneler bakımından kurumsal tamamlayıcısıdır. Sessiz Öznenin Hukuki Korunması Modeli, kendi korunabilir menfaatini hukuk düzeninin tanıdığı biçimde doğrudan ileri süremeyen varlıkların, bağımsız, epistemik olarak yeterli, çoğul, hesap verebilir ve denetlenebilir temsil mekanizmaları aracılığıyla hukuk düzeninin karar

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süreçlerinde görünür hâle getirilmesini amaçlayan temsil temelli koruma modelidir. Sessiz öznenin hukuki korunması model olarak kabul edilirse, beş kurucu unsurdan oluşmaktadır.

Öncelikle korunabilir menfaat unsuruyla temsil edilen varlığa ait ve hukuk tarafından korunmaya değer bir menfaat bulunmalıdır. Temsil İhtiyacında, özne kendi menfaatini bizzat hukuki talebe dönüştüremediği için temsil yapısal bir gereklilik hâline gelir. Meşru Temsil unsurunda, temsilci yalnızca hukuken yetkili değil; bağımsız, bilgiye dayalı, çoğul ve hesap verebilir olmalıdır. Hukuki Görünürlük unsuru; temsil edilen menfaat yalnızca mahkemede değil, idari, planlama, ruhsatlandırma ve yönetişim süreçlerinde de görünür hâle getirmelidir. Etkili Koruma ve Giderim unsurunda ise, temsil sonucunda ihlalin önlenmesi, durdurulması veya doğal varlığın restorasyonuna yönelik sonuçlar üretilebilmelidir.

Sessiz öznenin hukuki korunması modeli, aynı zamanda temsil mekanizmalarının karşılaştırmalı değerlendirilmesi için analitik bir araç sağlayabilir. Bir doğa temsil sistemi şu sorular üzerinden incelenebilir: Temsil edilen doğal varlığın korunabilir menfaati belirlenebilir mi? Temsilci kimdir? Yetkisinin kaynağı nedir? Hangi bilgiye dayanır? Bağımsızlığı nasıl sağlanır? Çıkar çatışmaları nasıl önlenir? Kararları nasıl denetlenir? Temsil yalnızca yargısal mı, yoksa yönetişimsel mi? Giderim doğal varlığın restorasyonuna yöneliyor mu? Bu sorular, modelin soyut hukuk teorisinden, karşılaştırmalı hukuk analizine taşınmasını mümkün kılmaktadır.

Sessiz Özne Yaklaşımının Genişlemesi

Sessiz özne yaklaşımı doğa hakları üzerinden geliştirilmiş olmakla birlikte başka hukuk alanlarında da teorik açıklama gücüne sahip olabilir. Bununla birlikte bu genişleme dikkatli yapılmalıdır. Doğa, hayvanlar, gelecek kuşaklar, çocuklar veya biyohukuktaki bazı varlıklar aynı ontolojik ve hukuki statüye sahip değildir. Sessiz özne kavramı bu farklı varlıkları tek bir kategori içinde özdeşleştirmemelidir. Ortaklaştırılan unsur statü değil, temsil problemidir.

Hayvanların duyarlılık, acı çekme ve refah menfaatleri doğanın ekolojik menfaatlerinden farklıdır. Bununla birlikte hayvanlar da kendi hukuki iddialarını ileri süremezler. Bu nedenle hayvan hukukunda da temel soru şu olabilir: Hayvanın menfaatini kim ve hangi meşruiyetle temsil edecektir?

Gelecek kuşaklar henüz mevcut olmadıkları için bugünün karar süreçlerine katılamazlar. Buna rağmen iklim değişikliği, nükleer atıklar, biyolojik çeşitlilik kaybı ve kalıtsal genetik müdahaleler onların yaşam koşullarını etkileyebilir. Bu alanda sessiz özne yaklaşımı zamansal temsil problemine işaret etmektedir.

Çocuklar sessiz özne yaklaşımının sınırlarını göstermektedir. Çocuk tamamen sessiz değildir; gelişen özerklik kapasitesine sahiptir. Bu nedenle çocuk bakımından temsilin amacı onun yerine sürekli biçimde konuşmak değil, yaş ve olgunluk arttıkça temsili azaltmak ve doğrudan katılımı artırmaktır.

Karar verme kapasitesini kaybetmiş hastalar veya gelecek kuşakları etkileyebilecek genetik müdahaleler bakımından da temsil sorunları ortaya çıkabilir. Ancak bu alanların kendi etik ve hukuki yapıları bulunmaktadır. Sessiz özne yaklaşımı, tek tip temsil modeli değil; farklı hukuk alanlarında temsil boşluğunu teşhis etmeye yarayan ortak teorik soru olarak kullanılmalıdır.

SONUÇ

Doğa haklarının gelişimi, çevre hukukunun insan merkezli yapısında, önemli bir dönüşüm yaratmıştır. Doğal varlıkların yalnızca insan yaşamı ve refahı bakımından korunması gereken nesneler olmadığı; kendi ekolojik bütünlükleri, süreklilikleri ve yenilenme kapasiteleri bakımından bağımsız korunabilir menfaatlere sahip olabilecekleri düşüncesi, çağdaş hukuk teorisinin özne ve hak sahipliği anlayışını genişletmiştir.

Ekvador'daki anayasal doğa hakları, Yeni Zelanda'daki Te Urewera ve Te Awa Tupua düzenlemeleri ve Kolombiya Anayasa Mahkemesi'nin Atrato Nehri kararı, bu dönüşümün pozitif hukuktaki önemli örneklerini oluşturmaktadır. Karşılaştırmalı deneyimler aynı zamanda doğa haklarının yalnızca hukuk kişiliği veya normatif tanınma üzerinden açıklanamayacağını; temsil ve yönetişim mekanizmalarının bu hakların gerçek hayatta işleyebilmesi bakımından belirleyici olduğunu göstermektedir (Kauffman & Martin, 2017; O'Donnell & Talbot-Jones, 2018; Wesche, 2021; Cribb ve Ark., 2024).

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Sessiz özne, korunabilir hukuki menfaati bulunan veya hak sahibi olarak tanınabilen; fakat bu menfaati kendi adına hukuk düzeninin tanıdığı biçimde ileri süremeyen varlıktır. Doğa bu bakımdan paradigmatik bir sessiz öznedir. Bir nehir kirlenebilir. Bir orman geri döndürülemez biçimde zarar görebilir. Bir ekosistem biyolojik çeşitliliğini kaybedebilir. Ancak doğal varlık bu zararı kendi başına hukuki talebe dönüştüremez.

Doğanın hukuki korunması bakımından hak sahipliği ile etkili koruma arasında yapısal bir boşluk bulunmaktadır. Bu boşluğu temsil doldurmaktadır. Çalışmanın temel savı bu nedenle şöyledir: Doğa haklarında temsil, mevcut hakkın kullanımını kolaylaştıran tali bir usul mekanizması değil, sessiz öznenin etkili hukuki korunmasının kurucu unsurlarından biridir.

Ancak temsilcinin yalnızca bulunması yeterli değildir. Temsilci hukuken yetkili olduğu hâlde gerekli kaynaklardan yoksun olabilir. Ekolojik bilgiye erişemeyebilir. Başka kurumsal menfaatlerle çıkar çatışması yaşayabilir. Hesap vermez biçimde çalışabilir. Bu nedenle çalışmada temsil boşluğu, yalnızca temsilcinin yokluğunu değil, etkili ve meşru temsil kapasitesinin eksikliğini ifade edecek biçimde kullanılmıştır. Temsil boşluğu: yetki, kapasite, epistemik yeterlilik, bağımsızlık ve hesap verebilirlik boyutlarında ortaya çıkabilir. Bu nokta da doğru soru: "Doğanın temsilcisi var mıdır?" sorusu yerine; "Doğanın korunabilir menfaatini etkili biçimde hukuk düzenine taşıyabilecek meşru temsil mevcut mudur?" sorusu olmalıdır.

Doğa haklarıyla ilgili olarak hukuki görünürlük kavramı ve hukuki görünürlüğün sağlanarak doğaya haklar tanınması, doğa haklarının normatif olarak tanınmasını da sağlayabilir. Ancak doğal varlığın menfaatinin gerçek karar süreçlerinde dikkate alınması için, bu menfaatin; yargısal, idari, planlama, ruhsatlandırma ve yönetişim süreçlerine taşınması gerekir. Bu yüzden temsilin temel işlevi yalnızca dava açmak değildir. Temsil, sessiz özneyi hukuk düzeninin görebileceği hâle getirmektir. Bu çerçevede etkili koruma aşamaları, bir süreç üzerinden şöylece koruma sağlamaktadır: Korunabilir menfaat → normatif tanınma → meşru temsil → hukuki görünürlük → etkili koruma ve giderim. Oysa mevcut düzende bu süreç: Korunabilir menfaat → temsil boşluğu → hukuki görünmezlik → koruma eksikliği şeklinde ortaya çıkmaktadır.

Sessiz öznenin hukuki korunması modelinin teorik omurgasını oluşturan bu yapı; temsilin meşruiyetini şu ölçütlerle ilişkilendirmektedir: Korunabilir menfaat, bağımsızlık, çoğulluk, epistemik yeterlilik, hesap verebilirlik ve ekolojik sadakat. Özellikle temsil edilenin temsilciyi denetleyemediği durumlarda temsilcinin hesap verebilirlik ve gerekçelendirme yükümlülüğünün güçlendirilmesi gerekir. Temsil edilenin temsilci üzerindeki doğrudan denetim kapasitesi azaldıkça, temsilcinin hesap verme ve kararını gerekçelendirme yükümlülüğü artmalıdır. Bu önerme, doğa haklarının ötesinde hukuk teorisi bakımından da açıklayıcı olabilir.

Hayvanlar, gelecek kuşaklar, çocuklar veya biyohukuktaki bazı temsil sorunları doğayla aynı değildir ve aynı hukuki statüye sahip değildir. Ancak ortak bir soru bulunmaktadır: Kendi korunabilir menfaatini hukuk düzenine taşıyamayan varlığın hukuki görünürlüğü nasıl sağlanacaktır? Sessiz özne yaklaşımının daha genel hukuk teorisine açıldığı nokta burasıdır. Doğa haklarının geleceği bakımından ise sonuç daha sınırlı fakat nettir. Hukuki kişilik önemlidir. Hak tanınması önemlidir. Fakat bunlar tek başına yeterli olmayabilir. Kişilik statü verir. Hak normatif koruma alanı yaratır. Temsil bu normatif statüyü hukuk düzeninin karar mekanizmalarına taşır. Doğa hakları tartışmasının bir sonraki aşaması yalnızca: "Doğa hak sahibi olabilir mi?" sorusu değildir. Artık: "Doğanın hakkını kim, hangi bilgiye dayanarak, hangi meşruiyetle ve hangi hesap verebilirlik rejimi içinde temsil edecektir?" sorusuna cevap vermek gerekmektedir. Doğaya hukukta yer vermek önemli olsa da sessiz öznenin gerçek korunması için, bundan fazlasına ihtiyacımız bulunmaktadır. Zira hukuk yalnızca doğaya hak tanımamalı; o hakkın duyulabileceği meşru kurumsal sesi de kurmalı ve oluşturmalıdır.

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THE PRINCIPLE OF VULNERABILITY IN BIOLAW: A THEORETICAL FRAMEWORK FOR THE DIVERSE MANIFESTATIONS OF HUMAN VULNERABILITY

BİYOHUKUKTA KIRILGANLIK İLKESİ: İNSAN KIRILGANLIĞININ FARKLI GÖRÜNÜMLERİNE İLİŞKİN BİR KURAMSAL ÇERÇEVE

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ABSTRACT

Developments in biotechnology, gene-editing technologies, artificial intelligence-assisted healthcare, neurotechnologies, and the processing of personal biological data have significantly expanded the scope of legal intervention into human life. These developments not only generate new legal challenges but also require a fundamental reconsideration of the concept of the human being and the model of legal protection underlying contemporary biolaw. At present, biolaw is largely structured around the principles of human dignity, bodily autonomy, informed consent, and biological integrity. However, rapid advances in the life sciences have made increasingly visible the multidimensional vulnerability inherent in the biological, genetic, and mental dimensions of human existence. Rather than merely cataloguing legal issues arising in different fields of biolaw, this study adopts the premise that vulnerability is not an exceptional condition affecting only particular groups but a universal characteristic of human existence rooted in biological life itself. From this perspective, the diverse legal problems encountered in biolaw are examined as different manifestations of human vulnerability. The study first traces the development of the concept of vulnerability within ethics, political philosophy, and legal theory. It subsequently proposes a systematic framework encompassing bodily vulnerability (medical interventions and organ transplantation), genetic vulnerability (gene editing and genomic data), mental vulnerability (neurotechnologies and neurorights), digital vulnerability (biometric and health data), and relational vulnerability (children, older persons, persons with disabilities, and individuals with limited decision-making capacity). The study argues that vulnerability may serve as a common explanatory concept across the various branches of biolaw. It maintains that contemporary legal challenges in biolaw cannot be adequately understood solely through a technology-centered perspective, since they ultimately arise from different manifestations of the vulnerability inherent in human biological existence. Accordingly, vulnerability is presented as one of the fundamental conceptual frameworks for determining the scope of legal protection in biolaw and as a unifying theoretical concept capable of connecting its diverse fields. Such an approach has the potential to move beyond the classical autonomy-centered model of protection and contribute to a more comprehensive understanding of the legal protection required against biological and technological interventions affecting human beings.

Keywords: Biolaw, vulnerability, human dignity, bodily autonomy, genetic vulnerability, neurolaw, biotechnology, legal protection.

ÖZET

Biyoteknoloji, gen düzenleme teknikleri, yapay zekâ destekli sağlık uygulamaları, nöroteknolojiler ve kişisel biyolojik verilerin işlenmesine ilişkin gelişmeler, insan yaşamına yönelik hukuki müdahale alanlarını önemli ölçüde genişletmiştir. Bu gelişmeler yalnızca yeni hukuki sorunlar ortaya çıkarmamakta; aynı zamanda biyohukukun temel aldığı insan düşüncesinin ve koruma anlayışının

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yeniden değerlendirilmesini de zorunlu kılmaktadır. Günümüzde biyohukuk, büyük ölçüde insan onuru, bedensel özerklik, aydınlatılmış rıza ve biyolojik bütünlük ilkeleri çerçevesinde şekillenmektedir. Ancak yaşam bilimlerindeki hızlı gelişmeler, insanın biyolojik, genetik ve zihinsel açıdan taşıdığı çok katmanlı kırılganlığın hukuki koruma bakımından daha görünür hâle gelmesine neden olmaktadır.

Biyohukukun farklı alanlarında ortaya çıkan sorunları kırılganlık kavramı ekseninde değerlendirmeyi amaçlamayan çalışmamızda, kırılganlığın yalnızca belirli kişi gruplarına özgü istisnai bir durum olmadığı, insanın biyolojik varoluşundan kaynaklanan evrensel bir özellik olduğu yaklaşımıyla biyohukukta karşılaşılan hukuki sorunların, insanın farklı biçimlerde ortaya çıkan kırılganlığıyla doğrudan ilişkili olduğu gösterilmek istenmektedir.

Çalışmada öncelikle kırılganlık kavramının etik, siyaset felsefesi ve hukuk kuramındaki gelişimi ele alınarak biyohukuk bağlamında bedensel kırılganlık (tıbbi müdahaleler ve organ nakli), genetik kırılganlık (gen düzenleme ve genom verileri), zihinsel kırılganlık (nöroteknolojiler ve nörohaklar), dijital kırılganlık (biyometrik ve sağlık verileri) ile ilişkisel kırılganlık (çocuklar, yaşlılar, engelliler ve karar verme kapasitesi sınırlı bireyler) sistematik bir çerçevede incelenmektedir.

Çalışmamızda kırılganlığın biyohukukun farklı alt alanlarında ortak bir açıklayıcı kavram olarak işlev görebileceği ortaya konularak, biyohukukta ortaya çıkan güncel hukuki sorunların yalnızca teknoloji merkezli bakış açısıyla açıklanamayacağı; bu sorunların ortak noktasının insanın biyolojik yaşamına ilişkin kırılganlığın farklı görünümleri olduğuna odaklanılmıştır. Çalışmada kırılganlık, biyohukukta, hukuki korumanın kapsamını belirlemede dikkate alınması gereken temel kavramsal çerçevelerden biri olarak ele alınmış ve kırılganlık kavramının biyohukukun farklı alanlarını ortak bir teorik zeminde buluşturma potansiyeline sahip olduğu gösterilmeye çalışılmıştır. Böylece bu yaklaşımın, biyohukukta korumanın yalnızca bireysel özerkliği esas alan klasik anlayışın ötesine geçerek, insanın biyolojik ve teknolojik müdahaleler karşısındaki korunma ihtiyacını daha bütüncül biçimde değerlendiren yeni tartışmalara katkı sağlayacağı ileri sürülmektedir.

Anahtar Kelimeler: Biyohukuk, kırılganlık, insan onuru, bedensel özerklik, genetik kırılganlık, nörohukuk, biyoteknoloji, hukuki koruma.

GİRİŞ

Biyoteknolojideki gelişmeler, insanın biyolojik varlığının anlaşılmasını, değiştirilmesini, izlenmesini ve öngörülmesini sağlayan teknik kapasiteyi önemli ölçüde artırmıştır. Gen düzenleme teknolojileri genom üzerinde müdahale imkânı yaratmakta; nöroteknolojiler beyin faaliyetlerine ilişkin daha önce erişilmesi güç olan verileri kullanılabilir hâle getirmekte; yapay zekâ destekli sağlık sistemleri teşhis ve tedavi süreçlerinde olasılık ve risk hesapları yapmakta; biyometrik, genomik ve sağlık verilerinin büyük veri sistemlerinde işlenmesi ise insan bedenini giderek daha kapsamlı bir veri kaynağına dönüştürmektedir. Bu gelişmeler insan sağlığının korunması ve hastalıkların tedavisi bakımından önemli olanaklar yaratırken, aynı zamanda insan bedenine ve yaşamına müdahalenin sınırlarını belirleyen klasik hukuki kavramların yeniden değerlendirilmesini gerekli kılmaktadır (Beauchamp & Childress, 2019; WHO, 2021a).

İnsan genomunun düzenlenmesi, bunun en belirgin örneklerinden biridir. Gen düzenleme teknikleri belirli kalıtsal hastalıkların tedavisi bakımından önemli bir potansiyel taşımakla birlikte özellikle germ hattı ve kalıtsal genom düzenlemeleri, müdahalenin sonuçlarının mevcut bireyin ötesine geçerek gelecek kuşakları etkileyebilmesi nedeniyle yeni etik ve hukuki sorunlar ortaya çıkarmaktadır. Dünya Sağlık Örgütü bu nedenle insan genomu düzenlemesinin bilimsel yarar potansiyelinin yanında etik, sosyal ve hukuki riskler taşıdığını ve bu teknolojiler bakımından güçlü yönetişim ve gözetim mekanizmalarına ihtiyaç bulunduğunu vurgulamaktadır (WHO, 2021a, 2021c).

Benzer biçimde yapay zekânın sağlık alanında kullanılması teşhis, tedavi, risk tahmini, sağlık araştırmaları ve ilaç geliştirme bakımından önemli imkânlar sunmaktadır. Bununla birlikte algoritmik sağlık sistemlerinin kullandıkları verilerdeki yanlılıklar, belirli gruplar bakımından farklı hata oranları, karar süreçlerinin açıklanabilirliği, mahremiyet, sorumluluk ve insan denetiminin devam ettirilmesi gibi sorunlar, teknolojik etkinliğin tek başına hukuki meşruiyet için yeterli olmadığını göstermektedir.

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WHO'nun sağlık alanındaki yapay zekâya ilişkin etik ve yönetişim rehberi de insan özerkliğinin korunması, şeffaflık, açıklanabilirlik, hesap verebilirlik, eşitlik ve sürdürülebilirlik gibi ilkeleri ön plana çıkarmaktadır (WHO, 2021b). Bu gelişmeler karşısında biyohukukun temel sorusu yalnızca hangi teknolojinin hukuken kullanılabileceği değildir. Daha temel düzeyde, hukuk düzeninin hangi insan düşüncesini esas aldığı sorusu gündeme gelmektedir.

Modern hukuk, özellikle liberal hukuk düşüncesinin etkisi altında, kişiyi irade sahibi, kendi yaşam planını oluşturabilen ve kendi yaşamına ilişkin kararları verebilen özerk bir özne olarak kavramaya eğilimlidir. Biyoetik ve tıp hukukunda bu anlayışın en açık karşılığı kişisel özerklik ve aydınlatılmış rıza ilkeleridir. Kişinin bedeni üzerinde gerçekleştirilecek tıbbi müdahaleye kendisinin karar vermesi, paternalist hekim modelinden kişi merkezli tıp hukukuna geçişin temel kazanımlarından biridir (Beauchamp & Childress, 2019).

İnsanın yalnızca kendi kaderini belirleyebilen özerk bir özne olarak kavranması, insan varoluşunun başka bir temel özelliğini arka plana itme tehlikesi taşımaktadır. İnsan aynı zamanda kırılgandır. İnsan bedeni hastalanabilir, yaralanabilir ve yaşlanabilir. İnsan başkalarının bakımına ihtiyaç duyabilir. Bilgi ve güç asimetrileri altında karar vermek zorunda kalabilir. Biyolojik özelliklerini ve genetik mirasını seçemez. Zihinsel süreçleri nöroteknolojik müdahalelerin konusu hâline gelebilir. Biyolojik verileri kendisinden ayrılarak dijital sistemlerde saklanabilir, çoğaltılabilir, yeniden analiz edilebilir ve kişinin öngörmediği amaçlarla kullanılabilir. Bu özellikler insanın yalnızca özgür ve özerk değil, aynı zamanda zarar görebilir bir varlık olduğunu göstermektedir.

Kırılganlık yalnızca kişinin biyolojik veya psikolojik özelliği değildir. Aynı zamanda hukuk, teknoloji, sosyal ilişkiler ve kurumlar tarafından artırılabilen veya azaltılabilen bir durumdur. Çalışmamız, kırılganlıkla ilgili olarak, kırılganlığın; biyohukukun farklı alanlarında ortaya çıkan sorunları, ortak bir kuramsal zeminde açıklayan ve hukuki korumanın yoğunluğunu belirlemeye yardımcı olan tamamlayıcı bir normatif ilke olarak işlev görebilme olanağına odaklanmıştır.

Kırılganlığın insan onuru, özerklik veya adaletin yerine geçirilmesi yerine, daha sınırlı, daha işlevsel bir normatif öneri gösterilmeye çalışılmıştır. Kırılganlık, mevcut biyohukuk ilkelerinin hangi koşullarda daha yoğun ve farklılaştırılmış koruma gerektirdiğini belirleyen tamamlayıcı bir normatif ilkedir? Bu çerçevede; insan onuru korunacak değeri; özerklik kişinin karar alanını, adalet yarar ve yüklerin dağılımını; kırılganlık ise somut korunma ihtiyacının yoğunluğunu görünür hâle getirdiğini söylemek gerekmektedir.

KIRILGANLIK KAVRAMININ ETİK VE HUKUKİ DÖNÜŞÜMÜ

Kırılganlık kavramının literatürdeki önemli açılımlardan biri, kırılganlığın sabit kişi kategorileri yerine farklı koşullarda üst üste gelebilen katmanlar şeklinde anlaşılmaya başlanmasıdır. Öte yandan Luna'nın "layers of vulnerability" yaklaşımı, kişilerin "kırılgan" ve "kırılgan olmayan" şeklinde ikili kategorilere ayrılmasına karşı çıkmakta; kırılganlığın bağlama göre ortaya çıkabilen, yoğunlaşabilen veya ortadan kalkabilen katmanlardan oluştuğunu ileri sürmektedir.

Luna'nın yaklaşımı, biyohukuk bakımından özellikle elverişlidir. Çünkü aynı kişi, eş zamanlı olarak bedensel, genetik, dijital veya ilişkisel farklı kırılganlık katmanlarına sahip olabilir. Ancak bu durum onun bütün yaşam alanlarında ve sürekli biçimde kırılgan olduğu anlamına gelmez. Hukuki değerlendirme; kişinin kim olduğundan çok, hangi kırılganlık katmanlarının, hangi somut olayda ve hangi zarar ihtimali karşısında etkinleştiğine yönelmelidir.

Biyohukukta insan onuru, özerklik, bedensel bütünlük, zarar vermeme, mahremiyet ve adalet gibi köklü ilkeler bulunurken ayrıca bir kırılganlık ilkesine ihtiyaç olup olmadığı araştırılmalıdır. Aksi takdirde kırılganlık, mevcut ilkelerin farklı bir terminolojiyle tekrarı olarak görülebilir. Avrupa bioetik ve biyohukuk literatüründe kırılganlığın ilkesel konumu bütünüyle yeni değildir.

Rendtorff, Avrupa bioetik ve biyohukuk yaklaşımında özerklik, insan onuru, bütünlük ve kırılganlığı dört temel etik ilke olarak birlikte değerlendirmiştir (Rendtorff, 2002). Bu yaklaşım, kırılganlığın özerklik eksikliğinin başka bir adı olmaktan ziyade bağımsız bir normatif koruma gerekçesi taşıyabileceğini göstermektedir. Öte yandan çalışmamızda savunduğumuz biyohukukta kırılganlık ilkesi, sayılan ilkelerin üzerinde yer alan yeni bir ilke değildir.

Kırılganlık ve İnsan Onuru

İnsan onuru, kişinin araçsallaştırılmasına ve nesneleştirilmesine karşı temel bir normatif sınır oluşturur. Biyohukukun temel değerlerinden biridir ve Oviedo Sözleşmesi'nin normatif mimarisinin merkezinde bulunmaktadır. Ancak insan onuru tek başına hangi kişinin hangi somut durumda daha yoğun koruma gerektirdiğini her zaman göstermez.

Herkes, aynı insan onuruna ve aynı temel haklara sahiptir. Bununla birlikte ağır hastalık, ekonomik bağımlılık, bilişsel durum veya teknolojik bilgi asimetrisi nedeniyle kişilerden biri aynı müdahale karşısında çok daha yüksek zarar riski taşıyabilir. İnsan onuru neden korumamız gerektiğini, kırılganlık ise korumanın ne ölçüde yoğunlaştırılması gerektiğini göstermektedir.

Kırılganlık ve Özerklik

Özerklik, kişinin kendi yaşamı ve bedeni hakkında karar verme kapasitesi ve yetkisiyle ilgilidir. Kırılganlık ise zarar görebilirlikle ilgilidir. Bu iki kavram kesişebilir ancak aynı değildir. Tam karar verme kapasitesine sahip ağır hastanın deneysel tedavi karşısında bedensel ve psikolojik kırılganlığı yüksek olabilir. Benzer biçimde karar verme desteğine ihtiyaç duyan kişinin her biyohukuki konuda aynı düzeyde zarar görebilir olduğu varsayılamaz. Bu nedenle: özerklik "kim karar vermelidir?" sorusuna; kırılganlık "karar ve müdahale hangi özel zarar ihtimallerini doğurmaktadır?" sorusuna cevap vermektedir. Kırılganlığın tanınması, bu nedenle özerkliğin reddedilmesi yerine, çoğu durumda gerçek özerkliğin koşullarının güçlendirilmesini sağlayabilir.

Kırılganlık ve Adalet

Adalet, sağlık hizmetlerinin ve biyoteknolojik kaynakların dağılımı, ayrımcılığın önlenmesi ve yararlarla yüklerin paylaşımıyla ilgilidir. Kırılganlık ise aynı dağılım kararının farklı kişiler üzerindeki etkisinin neden farklı olabileceğini görünür hâle getirir. Adalet yarar ve yüklerin dağılımını; kırılganlık bu dağılımın somut kişi üzerindeki zarar yoğunluğunu göstermektedir. Bu nedenle kırılganlık ilkesi adaletin alternatifi değil, adalet değerlendirmesini somutlaştıran tamamlayıcı bir ölçüttür.

Kırılganlığın Özgün Normatif İşlevi: Koruma Yoğunluğu

Bu ayrımlar sonucunda biyohukukta kırılganlık ilkesinin özgün işlevi daha açık biçimde ortaya çıkmaktadır. Kırılganlık; yeni bir hak üretmez; insan onurunun yerine geçmez; özerkliği ortadan kaldırmaz; adaletin alternatifi değildir.

Kırıganlığın özgün işlevi hukuki korumanın yoğunluğunu ve biçimini belirlemeye yardımcı olmaktır. Bu nedenle çalışmanın kuramsal formülü şu şekilde ifade edilebilir: İnsan onuru → neden koruyoruz? Özerklik → kimin kararına öncelik veriyoruz? Adalet → yarar ve yükleri nasıl dağıtıyoruz? Kırılganlık → ne ölçüde ve hangi araçlarla koruyoruz? Bu çerçevede kırılganlık ilkesi, biyohukukta farklılaştırılmış korumanın normatif gerekçesi olarak işlev görebilir.

KIRILGANLIK İLKESİ VE PATERNALİZM SORUNU

Kırılganlığın biyohukukta tamamlayıcı bir normatif ilke olarak kabul edilmesinin en önemli risklerinden biri, kavramın koruma gerekçesiyle paternalist müdahaleleri meşrulaştıran bir araca dönüşmesidir. Kırılgan olarak tanımlanan kişinin kendi kararlarını veremeyeceği veya kendi çıkarlarını yeterince koruyamayacağı varsayımı, hukuki korumayı kolaylıkla kişinin karar alanının daraltılmasına dönüştürebilir. Bu nedenle kırılganlık ilkesinin teorik olarak savunulabilmesi, yalnızca neyi koruduğunun değil, korumanın sınırlarının da belirlenmesini gerektirir (Mackenzie ve Ark., 2014; Rogers ve Ark., 2012).

Koruma Paradoksu ve Patojenik Kırılganlık

Kırılganlık yaklaşımının temel paradoksu, kişiyi korumak amacıyla gerçekleştirilen müdahalenin kişinin özerkliğini azaltarak yeni bir kırılganlık yaratabilmesidir. Özellikle çocuklar, yaşlılar, engelliler ve karar verme kapasitesi sınırlı bireyler bakımından bu risk belirgindir. Kişinin korunmaya ihtiyaç duyduğu varsayımından hareket edilerek onun görüşünün alınmaması, karar süreçlerinden dışlanması veya bütün karar yetkisinin üçüncü kişilere aktarılması, mevcut kırılganlığı azaltmak yerine bağımlılığı derinleştirebilir.

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Mackenzie, Rogers ve Dodds'un "patojenik kırılganlık" kavramı, bu durumu açıklamaktadır. Patojenik kırılganlık, sosyal ilişkilerin veya kırılganlığı azaltmak amacıyla oluşturulan kurum ve politikaların paradoksal biçimde yeni kırılganlıklar meydana getirmesi durumunu ifade etmektedir (Mackenzie ve Ark., 2014). Bu nedenle biyohukuk bakımından yalnızca: **"**Kişi korunuyor mu?" sorusu yanında ayrıca: "Koruma biçimi yeni bir kırılganlık yaratıyor mu?" sorusunun da sorulması gerekir. Örneğin yaşlı kişinin yalnızca yaşı nedeniyle sağlık kararlarında görüşünün ikincil kabul edilmesi, çocuğun üstün yararı gerekçesiyle görüşünün sistematik biçimde göz ardı edilmesi veya engelli kişinin destekli karar verebilmesi mümkünken bütün karar yetkisinin temsilciye bırakılması, koruyucu hukuk mekanizmalarının patojenik kırılganlık yaratabileceği durumlara örnek oluşturabilir.

Kırılganlık ve Özerklik

Kırılganlık ve özerklik arasında zorunlu bir karşıtlık bulunmamaktadır. Kişinin kırılganlığının doğru biçimde tanınması, bazı durumlarda özerkliğinin daha etkili biçimde kullanılabilmesi için gerekli koşulların oluşturulmasını sağlayabilir. İlişkisel özerklik literatürünün de gösterdiği üzere; özerklik, kişiyi bütün sosyal ilişkilerinden soyutlayan mutlak bağımsızlık anlamına gelmemekte ve bireyin karar oluşturma ve uygulama kapasitesi; toplumsal, ilişkisel ve kurumsal koşullardan etkilenmektedir (Mackenzie, 2014).

Bu nedenle kırılganlığa duyarlı hukuki koruma, kişinin yerine karar vermeyi ilk seçenek olarak benimsememelidir. Öncelikle kişinin kendi kararını verebilmesini sağlayacak koşullar güçlendirilmelidir. Daha anlaşılır bilgilendirme, karar için yeterli süre tanınması, erişilebilir iletişim araçlarının kullanılması, bağımsız danışmanlık, destekli karar verme, tercüme desteği, ikinci görüş imkânı veya ekonomik ve kurumsal baskıların azaltılması bu araçlar arasında sayılabilir.

Kırılganlık ilkesi bakımından temel normatif formül bu nedenle şöyle kurulabilir: Kırılganlık arttıkça koruma yoğunlaştırılmalı; ancak kişinin özerklik alanı zorunlu olmadıkça daraltılmamalıdır. Bu formül kırılganlık ilkesinin paternalist yorumunu sınırlayan temel içsel güvenceyi oluşturmaktadır.

Koruma ile Katılım Arasında Denge

Uluslararası araştırma etiğindeki güncel yaklaşım da kırılganlık ile katılım arasında bu dengeyi giderek daha açık biçimde benimsemektedir. CIOMS rehberi, kırılgan birey ve grupların hak ve refahının korunması için özel güvenceler öngörürken, kırılganlığın bu kişilerin araştırmalardan otomatik biçimde dışlanmasına yol açmaması gerektiğini kabul etmektedir (CIOMS, 2016, Guideline 15).

2024 Helsinki Bildirgesi de bireysel, grupsal veya topluluk düzeyindeki kırılganlığın sabit veya bağlamsal ve dinamik faktörlerden kaynaklanabileceğini kabul etmekte ve kırılganlık durumundaki kişilerin özel koruma ihtiyacı ile araştırmalara adil katılımı arasında denge kurulmasını öngörmektedir.

Özellikle dışlamanın mevcut sağlık eşitsizliklerini devam ettirebileceğinin veya ağırlaştırabileceğinin kabul edilmesi, kırılganlık yaklaşımının salt korumacı bir paradigma olmadığını göstermektedir (WMA, 2024). Kırılganlığa duyarlı hukuk, kişiyi karar alanından çıkaran hukuk değildir. Kişinin karar alanında kalabilmesi için gerekli koşulları sağlayan hukuktur.

KIRILGANLIK İLKESİNİN ULUSLARARASI NORMATİF DAYANAKLARI

Kırılganlık kavramı yalnızca etik ve hukuk teorisinin konusu değildir. Uluslararası bioetik ve biyohukuk belgelerinde de insanın kırılganlığı giderek daha görünür bir normatif değer hâline gelmiştir.

UNESCO Biyoetik ve İnsan Hakları Evrensel Bildirgesi

Kırılganlığın uluslararası bioetikteki en açık normatif ifadelerinden biri UNESCO'nun 2005 tarihli *Biyoetik ve İnsan Hakları Evrensel Bildirgesi*nin 8. maddesinde bulunmaktadır. Madde, bilimsel bilginin, tıbbi uygulamaların ve bunlarla ilişkili teknolojilerin uygulanmasında insan kırılganlığının dikkate alınmasını ve özel kırılganlığa sahip birey ve grupların korunmasını öngörmektedir (UNESCO, 2005).

Bu hüküm çalışmada önerilen teorik çerçeve bakımından özellikle önemlidir. Çünkü iki farklı düzeyi aynı anda kabul etmektedir: insan kırılganlığı ve özel kırılganlık. Birinci düzey, kırılganlığın insan varoluşunun genel bir özelliği olduğunu; ikinci düzey ise belirli kişiler veya gruplar bakımından

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kırılganlığın yoğunlaşabileceğini göstermektedir. Bu ikili yapı, çalışmada savunulan evrensel kırılganlık + yoğunlaşmış kırılganlık modeline güçlü bir normatif dayanak sağlamaktadır.

Oviedo Sözleşmesi

Avrupa Konseyi'nin İnsan Hakları ve Biyotıp Sözleşmesi kırılganlığı bağımsız bir ilke başlığı altında düzenlememekle birlikte insan onuru, kimlik, bütünlük, rıza ve karar verme kapasitesi bulunmayan kişilerin korunması gibi düzenlemeler aracılığıyla kırılganlığa duyarlı bir normatif yapı oluşturmaktadır (Council of Europe, 1997).

Özellikle biyoloji ve tıbbın uygulanmasında insanın onuru ve kimliğinin korunması ile herkesin bütünlüğüne ve diğer hak ve temel özgürlüklerine saygı gösterilmesi gereği, biyomedikal ilerlemenin insan üzerinde sınırsız müdahale yetkisi yaratamayacağını göstermektedir. Bu açıdan kırılganlık ilkesi Oviedo sisteminin alternatifi değildir. İnsan onuru, bütünlük, özerklik ve rıza korumasının somut olayda ne ölçüde yoğunlaştırılması gerektiğini değerlendirmeye yardımcı olan tamamlayıcı bir yorum ilkesi olarak düşünülebilir.

Helsinki Bildirgesi ve CIOMS Rehberi

Tıbbi araştırmalar kırılganlık kavramının en eski ve en yoğun tartışıldığı alanlardan biridir. Bunun nedeni araştırma katılımcılarının bilimsel bilgi üretimi amacıyla belirli risklere maruz bırakılması ve araştırmacı ile katılımcı arasında bilgi ve güç asimetrilerinin bulunmasıdır. CIOMS rehberi, kırılganlığı özel koruma ihtiyacını belirleyen bir unsur olarak ele almakta; ancak bu korumanın kategorik dışlamaya dönüşmemesi gerektiğini vurgulamaktadır (CIOMS, 2016, Guideline 15).

2024 Helsinki Bildirgesi ise kırılganlığın bağlamsal ve değişken olabileceğini açık biçimde kabul ederek daha dinamik bir yaklaşım benimsemektedir (WMA, 2024). Bu gelişme biyohukuk açısından önemli bir yön değişikliğini göstermektedir: statü temelli kırılganlıktan durum temelli kırılganlığa geçiş.

Genom Düzenleme ve WHO Yönetişim Yaklaşımı

Gen düzenleme teknolojilerinin gelişmesi kırılganlığın yalnızca mevcut bireyle sınırlı olmadığını göstermektedir. Özellikle kalıtsal genom düzenlemelerinin sonraki kuşakları etkileyebilme potansiyeli, klasik bireysel rıza modelinin sınırlarını ortaya çıkarmaktadır. WHO'nun 2021 tarihli insan genomu düzenlemesi belgeleri, genom düzenlemesinin güvenli ve etkili biçimde geliştirilmesi yanında etik, sosyal ve hukuki sonuçlarının da yönetişim süreçlerine dâhil edilmesini istemektedir. Küresel gözetim, araştırma kayıtları, uluslararası iş birliği ve etik denetim gibi araçların vurgulanması, teknolojik müdahalenin yalnızca mevcut kişinin bireysel tercihine indirgenemeyeceğini göstermektedir (WHO, 2021'a, 2021c).

Nuffield Council on Bioethics de insan üremesinde genom düzenlemesini gelecekte doğacak kişinin refahı ve toplumdaki ayrımcılık, dezavantaj ve bölünmelerin artmaması ölçütleri bakımından değerlendirmiştir (Nuffield Council on Bioethics, 2018). Bu yaklaşım genetik kırılganlığın zamansal ve kuşaklar arası niteliğini ortaya koymaktadır.

Nöroteknoloji ve UNESCO'nun 2025 Tavsiyesi

Nöroteknolojiler, insan beynine ilişkin verilerin elde edilmesi ve bazı durumlarda sinirsel süreçlerin etkilenmesi bakımından kırılganlığın yeni bir boyutunu ortaya çıkarmaktadır. Ienca ve Andorno, nörobilim ve nöroteknolojilerin gelişimi karşısında bilişsel özgürlük, zihinsel mahremiyet, zihinsel bütünlük ve psikolojik süreklilik gibi koruma alanlarının tartışılması gerektiğini ileri sürmüştür (Ienca & Andorno, 2017). Bu akademik tartışma 2025 yılında önemli bir uluslararası normatif aşamaya ulaşmıştır. UNESCO Genel Konferansı tarafından kabul edilen *Recommendation on the Ethics of Neurotechnology*, nöroteknolojilerin insan hakları, insan onuru ve temel özgürlüklerle uyumlu biçimde geliştirilmesi ve kullanılması için küresel etik çerçeve oluşturmuştur (UNESCO, 2025). Bu gelişme zihinsel kırılganlığın artık yalnızca teorik nörohaklar literatürünün konusu olmadığını; uluslararası bioetik yönetişimin de temel sorun alanlarından biri hâline geldiğini göstermektedir.

Sağlıkta Yapay Zekâ ve WHO

FULL TEXTS BOOK

WHO'nun sağlıkta yapay zekâya ilişkin etik ve yönetişim rehberi, teknolojinin sağlık hizmetlerinin geliştirilmesinde taşıdığı potansiyelin yanında insan özerkliği, güvenlik, şeffaflık, açıklanabilirlik, sorumluluk, kapsayıcılık ve eşitlik sorunlarını da gündeme getirmektedir (WHO, 2021b). Bu yaklaşım biyohukukta kırılganlığın dijital boyutunu görünür kılmaktadır. Çünkü hasta artık yalnızca hekim karşısında bilgi asimetrisi yaşayan kişi değildir. Aynı zamanda çalışma mantığını bilmediği algoritmik sistemler karşısında da yapısal bir bilgi ve güç asimetrisi yaşayabilir. Böylece biyohukukta klasik: hasta–hekim ilişkisine, hasta–hekim–algoritma üçgeni eklenmektedir.

KIRILGANLIĞIN FARKLI GÖRÜNÜMLERİ

Kırılganlığın biyohukukta işlevsel bir kavrama dönüştürülebilmesi için soyut "insan kırılganlığı" söyleminin ötesine geçilmesi gerekir. Bu çalışmada kırılganlık, biyohukukun güncel sorunları bakımından beş temel görünüm altında ele alınmaktadır: bedensel kırılganlık, genetik kırılganlık, zihinsel kırılganlık, dijital kırılganlık ve ilişkisel kırılganlık. Bu ayrım kapalı ve tüketici bir sınıflandırma değildir. Amaç, insan kırılganlığının biyohukukun farklı müdahale alanlarında nasıl somutlaştığını göstermek ve bu görünümler arasındaki kesişimleri ortaya koymaktır.

BEDENSEL KIRILGANLIK

Bedensel kırılganlık insanın biyolojik varoluşundan kaynaklanan en temel kırılganlık biçimidir. İnsan bedeni hastalığa, yaralanmaya, ağrıya, yaşlanmaya ve ölüme açıktır. Bu nedenle tıp ve biyoteknoloji, bir yönüyle insanın bedensel kırılganlığını azaltma çabasıdır. Ancak burada temel bir paradoks bulunmaktadır. İnsan kırılgan olduğu için tıbbi müdahaleye ihtiyaç duyar; aynı kırılganlık onu tıbbi müdahale karşısında korunmaya muhtaç hâle getirir.

Tıbbi müdahale iyileştirebilir; fakat zarar da verebilir. Cerrahi müdahale yaşam kurtarabilir; ancak bedensel bütünlüğe doğrudan müdahaledir. Organ nakli bir kişinin yaşamını kurtarırken başka bir kişinin sağlıklı bedenine müdahaleyi gerektirebilir. Bu nedenle bedensel kırılganlığın hukuki karşılığı yalnızca zarar vermeme değildir. Bedensel bütünlük, kişisel özerklik, aydınlatılmış rıza ve uygun tıbbi bakım birlikte değerlendirilmelidir (Beauchamp & Childress, 2019).

Aydınlatılmış Rızanın Sınırları

Aydınlatılmış rıza bedensel müdahalelerin temel hukuki meşruiyet araçlarından biridir. Bununla birlikte formel rızanın bulunması, kırılganlığın ortadan kalktığı anlamına gelmez. Yaşamı tehdit eden hastalığı bulunan kişinin deneysel tedaviye rıza göstermesi, hukuken geçerli bir irade açıklaması olabilir. Ancak ölüm korkusu, zaman baskısı, tedavi alternatifsizliği veya sağlık çalışanına duyulan yüksek bağımlılık karar ortamını etkileyebilir. Bu nedenle kırılganlık ilkesi rızanın yerine geçmez. Rızanın oluştuğu maddi koşulları inceler. Bu bakımdan hukuki soru yalnızca: "Rıza var mı?" değil, "Rıza hangi koşullarda oluştu?" olmalıdır.

Organ Nakli ve İlişkisel Bedensellik

Canlı vericiden organ nakli, bedensel ve ilişkisel kırılganlığın kesiştiği tipik alanlardan biridir. Vericinin karar verme kapasitesinin tam olması ve açık rızasının bulunması her zaman kararın bütün baskılardan bağımsız olduğunu göstermeyebilir.

Aile ilişkileri, sevgi, sadakat, suçluluk, ekonomik bağımlılık veya kişinin "iyi aile üyesi" olma yönündeki sosyal beklentileri, görünür bir zorlama bulunmaksızın karar üzerinde etkili olabilir. Bu nedenle canlı organ bağışında kırılganlık değerlendirmesi, rızanın yalnızca biçimsel geçerliliğine değil, ilişkisel bağlamına da yönelmelidir.

GENETİK KIRILGANLIK

Genetik kırılganlık, insanın genetik yapısının hem biyolojik kimliğinin bir parçası olması hem de gelecekteki sağlık riskleri hakkında öngörücü bilgi sağlayabilmesi nedeniyle özgün bir kırılganlık alanı oluşturmaktadır. Genetik bilgi yalnızca mevcut kişiyi ilgilendirmez. Biyolojik akrabalar hakkında da bilgi sağlayabilir ve bazı müdahalelerin sonuçları gelecek kuşaklara aktarılabilir. Bu özellikler genetik kırılganlığı klasik bireysel sağlık verisi yaklaşımından ayırmaktadır.

FULL TEXTS BOOK

Genetik Bilginin Zamansal Boyutu

Genetik bilgi, henüz ortaya çıkmamış bir hastalık ihtimalini bugünün bilgisine dönüştürebilir. Bu durum kişinin gelecekle ilişkisini değiştirebilir. Kişi henüz hasta olmadığı hâlde gelecekte belirli bir hastalığa yakalanma olasılığını öğrenebilir. Böyle bir bilgi yaşam planlarını, aile kararlarını, çalışma yaşamını ve psikolojik durumunu etkileyebilir. Bu nedenle genetik kırılganlık yalnızca bilgi mahremiyeti değildir. Aynı zamanda: geleceğe ilişkin biyolojik ihtimalin bugünkü kimliğe dönüşmesi sorunudur. Burada kişinin genetik bilgisini öğrenme hakkının yanında bilmeme hakkı da önem kazanmaktadır.

Genetik Ayrımcılık

Genetik bilginin sigorta, istihdam veya başka karar süreçlerinde kullanılması, kişinin mevcut sağlık durumundan ziyade gelecekteki hastalık ihtimali nedeniyle dezavantajlı muamele görmesine yol açabilir. Bu durumda ayrımcılık gerçekleşmiş hastalığa değil: biyolojik olasılığa dayanmaktadır. Genetik kırılganlık bu nedenle mahremiyet, eşitlik ve ayrımcılık yasağının kesişiminde yer almaktadır.

Genom Düzenleme ve Kuşaklar Arası Kırılganlık

Gen düzenleme tekniklerinin germ hattında veya kalıtsal biçimde uygulanması, kırılganlığın bireysel sınırlarını aşmaktadır. WHO'nun insan genomu düzenlemesine ilişkin yönetişim ve tavsiye belgeleri, kalıtsal genom düzenlemelerinin gelecek kuşaklar bakımından ortaya çıkarabileceği bilimsel, etik ve toplumsal sonuçlar nedeniyle güçlü denetim mekanizmalarına ihtiyaç bulunduğunu göstermektedir (WHO, 2021'a, 2021c).

Nuffield Council on Bioethics de insan üremesinde genom düzenlemesinin yalnızca ebeveynlerin üreme özgürlüğü bakımından değil, gelecekte doğacak kişinin refahı ile toplumsal ayrımcılık ve dezavantajların artmaması bakımından değerlendirilmesi gerektiğini belirtmektedir (Nuffield Council on Bioethics, 2018). Buradaki temel sorun açıktır: Müdahaleden etkilenecek gelecekteki kişi müdahaleye rıza veremez. Kalıtsal genom düzenleme, biyohukukun rıza merkezli paradigmasının sınırlarını görünür hâle getirir. Bu alanda koruma: rıza kadar, ihtiyat, temsil, insan onuru, gelecek kuşakların menfaatleri ve kuşaklar arası sorumluluk üzerinden kurulmalıdır.

ZİHİNSEL KIRILGANLIK

Nöroteknolojilerin gelişmesi insan kırılganlığının bedenden zihinsel süreçlere doğru genişleyen yeni bir görünümünü ortaya çıkarmaktadır. Beyin-bilgisayar arayüzleri, nörogörüntüleme, nörostimülasyon ve yapay zekâ destekli nöroanaliz sistemleri beynin faaliyetleri hakkında giderek daha ayrıntılı bilgi üretebilmekte ve bazı durumlarda sinirsel süreçleri etkileyebilmektedir. Ienca ve Andorno, bu gelişmeler karşısında bilişsel özgürlük, zihinsel mahremiyet, zihinsel bütünlük ve psikolojik süreklilik gibi yeni insan hakları alanlarının tartışılması gerektiğini ileri sürmektedir (Ienca & Andorno, 2017).

2025 tarihli UNESCO Nöroteknoloji Etiği Tavsiyesi de nöroteknolojilerin insan hakları, insan onuru ve temel özgürlüklerle uyumlu biçimde geliştirilmesi ve kullanılması gereğini uluslararası normatif düzeyde güçlendirmiştir (UNESCO, 2025). Bu çalışma bakımından zihinsel kırılganlığın merkezindeki koruma değeri zihinsel özerkliktir.

Zihinsel Verinin Özgün Niteliği

Beyin verileri kişinin dikkat, tepki örüntüsü, bilişsel süreçleri veya belirli zihinsel durumları hakkında bilgi sağlayabilir. Bu nedenle nöroveri sıradan kişisel veriyle tamamen aynı biçimde değerlendirilemez. Sorun yalnızca verinin başkaları tarafından görülmesi değildir. Daha önemli sorun: kişinin zihinsel iç alanının teknik sistemler tarafından giderek daha fazla hesaplanabilir hâle gelmesidir. Bu durum mahremiyet korumasının ötesinde, zihinsel özerklik ve zihinsel bütünlük tartışmasını gerektirir.

Zihnin Okunmasından Zihnin Etkilenmesine

Nöroteknolojilerin bir kısmı yalnızca zihinsel süreçleri gözlemlememekte, sinirsel faaliyet üzerinde etkide bulunabilmektedir. zihinsel kırılganlık iki yönlüdür: zihnin okunması ve zihnin etkilenmesi**.** Bu nedenle nöroteknolojik müdahalelerin hukuki değerlendirilmesinde rıza ve veri korumasının yanında müdahalenin geri döndürülebilirliği, kişilik üzerindeki etkisi, zihinsel bütünlük, zihinsel özerklik ve davranışsal manipülasyon ihtimali de dikkate alınmalıdır.

FULL TEXTS BOOK

DİJİTAL KIRILGANLIK

Biyohukukun dijitalleşmesi, insan bedeninin giderek veri üzerinden temsil edilmesine yol açmaktadır. Elektronik sağlık kayıtları, genom verileri, biyometrik veriler, giyilebilir teknolojilerden elde edilen fizyolojik veriler ve yapay zekâ sistemlerinin bu verilerden ürettiği çıkarımlar, biyolojik insan ile dijital altyapı arasındaki sınırları giderek geçirgen hâle getirmektedir. WHO, sağlıkta yapay zekânın önemli yararlar yaratabileceğini kabul ederken insan özerkliği, mahremiyet, açıklanabilirlik, sorumluluk, kapsayıcılık ve eşitlik bakımından önemli riskler taşıdığını vurgulamaktadır (WHO, 2021b).

Biyolojik Verinin Bedenden Kopması

Fiziksel müdahale genellikle belirli zaman ve mekânda gerçekleşir. Dijital veri ise kişiden ayrıldıktan sonra: saklanabilir, kopyalanabilir, başka veri kümeleriyle birleştirilebilir, sınır ötesine aktarılabilir ve yeni amaçlarla analiz edilebilir. Bu durum dijital kırılganlığın özgün özelliklerinden biridir. Beden bir yerde bulunurken bedenin verisi başka bir yerde yaşamaya devam edebilir. biyohukuki koruma artık yalnızca fiziksel bedeni değil, bedenden türetilen ve kişi hakkında biyolojik anlam taşıyan dijital temsilleri de dikkate almak zorundadır.

Çıkarımsal Kırılganlık

Dijital sağlıkta sorun yalnızca kişinin doğrudan verdiği verilerin korunması değildir. Yapay zekâ sistemleri mevcut verilerden kişinin doğrudan açıklamadığı yeni bilgiler çıkarabilir. Örneğin sağlık riski, hastalığa yatkınlık, psikolojik durum, tedaviye uyum ihtimali veya başka biyolojik özellikler algoritmik modeller tarafından tahmin edilebilir.

Böylece kişi, paylaşmadığı, hatta bazı durumlarda kendisinin dahi bilmediği bir özellik üzerinden sınıflandırılabilir. Bu durum çıkarımsal kırılganlık olarak ifade edilebilir. Çıkarımsal kırılganlık, klasik veri koruma paradigmasını zorlamaktadır. Çünkü korunması gereken şey artık yalnızca kişiden alınan veri değildir. Veriden kişi hakkında üretilen bilgidir.

Hasta–Algoritma Asimetrisi

Tıp hukukunun klasik bilgi asimetrisi hasta ile hekim arasındadır. Yapay zekâ destekli sağlık hizmetlerinde bu ilişkiye algoritmik sistem eklenmektedir. Hasta hangi verilerin kullanıldığını bilmeyebilir. Modelin nasıl çalıştığını anlayamayabilir. Kararın hangi faktörlere dayandığını göremeyebilir.

Hatta hekim de bazı karmaşık modellerin karar mantığını tam olarak açıklayamayabilir. Bu durumda ortaya çıkan kırılganlık yalnızca bilgi eksikliğinden ibaret değildir. Hesaplama kapasitesi karşısındaki yapısal asimetridir. Bu nedenle dijital kırılganlık, sağlıkta yapay zekâ bakımından şeffaflık, açıklanabilirlik, insan denetimi ve itiraz edilebilirlik gibi yeni hukuki güvenceleri gerekli kılabilir.

İLİŞKİSEL KIRILGANLIK

İnsan kırılganlığı yalnızca bedeninden veya biyolojik özelliklerinden kaynaklanmamaktadır. İnsan sosyal ve ilişkisel bir varlıktır. Bakım, aile, temsil, sevgi, ekonomik bağımlılık ve kurumsal destek ilişkileri yaşamın temel parçalarıdır. Kişinin biyohukuki kararları çoğu zaman bütünüyle bağımsız bir ortamda oluşmaz. İlişkisel kırılganlık özellikle çocuklar, yaşlılar, engelliler ve karar verme desteğine ihtiyaç duyan kişiler bakımından belirgin hâle gelmektedir.

Çocuk ve Gelişen Özerklik

Çocuğun kırılganlığı, yalnızca yaşından kaynaklanmaz. Çocuk sağlık ve biyoteknoloji alanındaki kararlarını ebeveyn, hekim, mahkeme ve diğer temsil mekanizmaları içinde verir. Bu nedenle çocuğun korunması, yalnızca onun adına doğru kararın verilmesi şeklinde anlaşılmamalıdır.

Çocuğun yaşı ve olgunluk düzeyi ölçüsünde görüşünün alınması ve gelişen özerkliğinin desteklenmesi gerekir. Aksi takdirde üstün yarar ilkesi dahi paternalist bir temsil mekanizmasına dönüşebilir. Kırılganlık yaklaşımı çocuk bakımından iki yönlü koruma gerektirir: zarardan korunma ve karar süreçlerine giderek artan ölçüde katılım.

FULL TEXTS BOOK

Yaşlılık

Yaşlılık otomatik bir kırılganlık karinesi oluşturmamalıdır. Bununla birlikte kronik hastalık, bakım bağımlılığı, ekonomik yetersizlik, bilişsel değişim veya sosyal izolasyon gibi faktörlerin üst üste gelmesi kırılganlığı yoğunlaştırabilir. Bu nedenle yaşlı kişinin hukuki durumu yalnızca kronolojik yaş üzerinden belirlenmemelidir. Kırılganlık değerlendirmesi: statü temelli değil, durum temelli olmalıdır.

Engellilik ve Destekli Karar Verme

Engellilik alanı kırılganlık yaklaşımının paternalizm riskinin en açık görüldüğü alanlardan biridir. Kişinin belirli bir konuda desteğe ihtiyaç duyması, bütün kararlarının üçüncü kişiler tarafından alınmasını gerektirmez. Kırılganlık ilkesinin amacı kişinin karar yetkisini ortadan kaldırmak değil, karar verme kapasitesinin mümkün olan en yüksek düzeyde kullanılmasını sağlamaktır. Bu nedenle kırılganlığa duyarlı biyohukuk: ikame karar verme yerine mümkün olduğu ölçüde destekli karar verme yaklaşımını öncelemelidir.

KIRILGANLIĞIN KESİŞİMSEL YAPISI

Bedensel, genetik, zihinsel, dijital ve ilişkisel kırılganlık teorik olarak ayrı başlıklarda incelenebilse de gerçek biyohukuk vakalarında çoğu zaman birlikte ortaya çıkmaktadır. Kırılganlık, katmanlıdır ve kesişimseldir. Luna'nın kırılganlık katmanları yaklaşımı da kişinin tek bir kategori nedeniyle değişmez biçimde kırılgan olarak tanımlanması yerine farklı kırılganlıkların somut koşullarda üst üste gelebileceğini göstermektedir. Örneğin ileri yaştaki bilişsel bozukluğu bulunan bir kişinin yapay zekâ destekli uzaktan sağlık sistemiyle sürekli izlenmesi durumunda: bedensel, zihinsel, dijital ve ilişkisel kırılganlık aynı anda ortaya çıkabilir.

Genetik hastalığı bulunan bir çocuğun genom verisinin yapay zekâ sistemi tarafından analiz edilmesinde ise: genetik, dijital, bedensel ve ilişkisel kırılganlık kesişebilir. Bu nedenle biyohukukta kırılganlık analizinin gerçek birimi yalnızca kırılganlık türü değildir. Asıl değerlendirilmesi gereken: kırılganlık bileşimidir. Bu düşünce farklılaştırılmış hukuki korumanın temelini oluşturabilir. Aynı teknolojiye maruz kalan iki kişinin aynı haklara sahip olması, mutlaka aynı koruma aracının yeterli olduğu anlamına gelmez. Kişinin kırılganlık bileşimi yoğunlaştıkça hukuki korumanın biçimi ve yoğunluğu da değişebilir.

TEKNOLOJİK KIRILGANLIK

Biyoteknolojik gelişmeler karşısında “teknolojik kırılganlık” kavramının ayrıca altıncı bir kategori olarak kabul edilip edilmemesi tartışılabilir. Bu çalışma bakımından teknolojik kırılganlığın bağımsız bir kırılganlık türü olarak değil, diğer kırılganlık biçimlerini etkileyen yatay bir yoğunlaştırıcı etken olarak değerlendirilmesi daha isabetlidir.

Teknoloji, bedensel müdahalenin kapsamını genişletebilir; genetik müdahaleyi kalıcı ve kuşaklar arası hâle getirebilir; zihinsel süreçlere erişimi artırabilir, biyolojik verinin sınırsız biçimde kopyalanmasını sağlayabilir, bakım ve karar ilişkilerini algoritmik sistemlere taşıyabilir. Teknoloji çoğu durumda kırılganlığın kaynağı olmaktan çok: mevcut kırılganlığı dönüştüren, ölçeklendiren veya yoğunlaştıran bir güçtür. Bu nedenle teknolojik değerlendirmede temel soru şu olmalıdır: Teknoloji mevcut kırılganlığı azaltıyor mu, yoksa yeni ve daha yoğun bir zarar görebilirlik mi yaratıyor?

KIRILGANLIĞIN YAPISAL BOYUTU VE ADALET

Kırılganlığın yalnızca bireysel özellikler üzerinden değerlendirilmesi, biyohukukun yapısal eşitsizlikleri gözden kaçırmasına neden olabilir. Aynı hastalığa sahip iki kişinin; ekonomik kaynakları, sağlık hizmetlerine erişimi, eğitim düzeyi, yaşadığı coğrafya, sigorta imkânları, dijital okuryazarlığı ve sosyal destek ağı aynı olmayabilir. Bu nedenle aynı biyolojik kırılganlığa sahip kişiler kırılganlıkla başa çıkmak bakımından aynı kapasiteye sahip değildir. Kırılganlık evrensel olsa da kişilerin dayanıklılık geliştirmesini sağlayan ekonomik, sosyal ve kurumsal kaynaklara erişimi eşit değildir. Bu nedenle devletin rolü yalnızca bireylerin hak alanlarına müdahale etmemekle sınırlı düşünülemez; kırılganlıkla başa çıkmayı mümkün kılan kurumların adil biçimde düzenlenmesi de önem taşımaktadır (Fineman, 2010). Biyohukukta bu sorun özellikle yüksek maliyetli gen tedavileri, kişiselleştirilmiş tıp, nöroteknolojik tedaviler, dijital sağlık altyapıları ve genomik danışmanlık bakımından önemlidir. Yeni

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teknolojilerin yalnızca var olması yeterli değildir. Kimlerin bu teknolojilerden yararlanabileceği de biyohukuki adalet sorunudur.

BİYOHUKUKTA KIRILGANLIK İLKESİNİN TANIMLANMASI

Kırılganlık kavramı bioetik literatüründe yeni değildir. Bununla birlikte kavram uzun süre esas olarak "kırılgan gruplar" üzerinden kullanılmıştır. Çocuklar, yaşlılar, engelliler, karar verme kapasitesi sınırlı kişiler, mahpuslar veya ekonomik açıdan dezavantajlı bireyler bu kategori içinde değerlendirilmiştir. Bu yaklaşım özellikle tıbbi araştırmalarda istismar ve zarar ihtimalinin azaltılması bakımından önemli bir koruyucu işlev üstlenmiştir. Ancak zamanla "kırılgan grup" yaklaşımının hem kavramsal hem de normatif sorunları görünür hâle gelmiştir (Hurst, 2008; Rogers ve Ark., 2012).

Güncel uluslararası araştırma etiği de kırılganlığın değişmez kişi kategorileri üzerinden tanımlanmasından giderek uzaklaşmaktadır. Dünya Tabipler Birliği'nin 2024 yılında güncellenen Helsinki Bildirgesi, bireylerin, grupların ve toplulukların sabit veya bağlamsal ve dinamik faktörler nedeniyle kırılganlık durumunda bulunabileceğini kabul etmektedir. Bildirge ayrıca kırılganlık durumundaki kişilerin araştırmalardan kategorik olarak dışlanmasının mevcut sağlık eşitsizliklerini devam ettirebileceğini veya ağırlaştırabileceğini belirterek, özel koruma ile adil katılım arasında denge kurulmasını istemektedir (WMA, 2024). Bu yaklaşım, kırılganlığın kişiye yapıştırılan kalıcı bir sıfat olmaktan çıkarılarak somut koşullara bağlı bir değerlendirme ölçütüne dönüştürülmesi bakımından önemlidir.

Fineman'ın kırılgan özne yaklaşımı, bu dönüşümün hukuk teorisindeki önemli dayanaklarından birini oluşturmaktadır. Fineman'a göre kırılganlık bazı kişileri diğerlerinden ayıran istisnai bir durum değil, insan bedeninin değişebilir, zarar görebilir ve yaşam boyunca başkalarına ve kurumlara bağımlı yapısından kaynaklanan evrensel bir insanlık durumudur. Bu yaklaşımın temel hedeflerinden biri, hukukun varsaydığı bağımsız ve kendi kendine yeterli liberal özne yerine gerçek yaşamın bedensel, ilişkisel ve kurumsal bağımlılıklarını görünür hâle getirmektir (Fineman, 2008; Fineman, 2010). Bununla birlikte kırılganlığın evrenselliği önemli bir teorik sorun yaratmaktadır. Eğer bütün insanlar kırılgansa, kırılganlık hukuken hangi durumları diğerlerinden ayırt edecektir? Evrensel kırılganlık düşüncesi, özel ve yoğunlaşmış kırılganlıkların görünmez hâle gelmesine yol açabilir mi?

Kottow'un evrensel kırılganlık ile belirli zararlara özel açıklık arasında yaptığı ayrım bu sorunun erken cevaplarından biridir. Kottow'a göre insanın varoluşsal kırılganlığı herkes için ortak olmakla birlikte, belirli kişiler hastalık, yoksunluk veya başka olumsuz koşullar nedeniyle özel zararlara daha açık hâle gelebilir. Bu durumda evrensel kırılganlık genel hak korumasını temellendirirken, özel zarar görebilirlik daha yoğun sosyal ve hukuki korumayı gerektirebilir (Kottow, 2003).

Hurst da benzer biçimde kırılganlığın yalnızca grup üyeliği üzerinden belirlenmesinin kavramın açıklayıcı gücünü azaltabileceğini ileri sürmektedir. Ona göre temel mesele, kişinin belirli bir haksızlığa maruz kalma ihtimalinin hangi koşullarda arttığının belirlenmesidir. Böylece soru "kim kırılgandır?" olmaktan çıkarak "bu kişi hangi zarar veya haksızlık karşısında, hangi nedenle ve ne ölçüde kırılgandır?" sorusuna dönüşmektedir (Hurst, 2008).

Mackenzie, Rogers ve Dodds'un geliştirdiği kırılganlık taksonomisi ise bu tartışmayı daha sistematik hâle getirmektedir. Buna göre kırılganlığın insanın bedensel ve sosyal varoluşuna içkin biçimleri bulunabileceği gibi, kişinin içinde bulunduğu ekonomik, toplumsal, politik veya kurumsal koşullardan doğan durumsal biçimleri de bulunmaktadır. Ayrıca bazı toplumsal ilişkiler veya koruma mekanizmaları bizzat yeni kırılganlıklar üretebilir; bu durum "patojenik kırılganlık" olarak ifade edilmektedir (Mackenzie ve Ark., 2014; Rogers ve AArk., 2012). Bu ayrım biyohukuk bakımından özellikle önemlidir. Bir insanın hastalanabilir olması içkin kırılganlıktır. Tedaviye ekonomik nedenlerle ulaşamaması durumsal kırılganlık yaratabilir. Koruma gerekçesiyle tedavi kararına katılmasına izin verilmemesi ise patojenik kırılganlık meydana getirebilir.

Teorik ve uygulamalı değerlendirmeler sonucunda çalışmamızda önerilen ilke şu şekilde tanımlanabilir: Biyohukukta kırılganlık ilkesi; insanın bedensel ve ilişkisel varoluşundan kaynaklanan evrensel zarar görebilirliğinin ve biyolojik, genetik, zihinsel, dijital, sosyal, ekonomik, kurumsal veya teknolojik koşullar nedeniyle yoğunlaşabilen özel kırılganlık biçimlerinin, biyomedikal ve teknolojik

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müdahalelerin meşruiyetinin, sınırlarının ve hukuki koruma yoğunluğunun belirlenmesinde dikkate alınmasını gerektiren tamamlayıcı normatif ilkedir.

Biyohukukta kırılganlık ilkesinin bu tanımında, beş temel önerme üzerine kurulmaktadır. İlk olarak, kırılganlık evrenseldir. İnsan bedensel, zamansal ve ilişkisel bir varlık olduğu için zarar görebilir. Sonra, kırılganlık farklılaşır. Bütün insanlar aynı türde ve aynı yoğunlukta kırılgan değildir. Üçüncü olarak, kırılganlık katmanlaşır. Birden fazla kırılganlık aynı kişide ve aynı olayda kesişebilir. Dördüncü önrme de kırılganlık üretilebilir. Hukuki, kurumsal veya teknolojik sistemler yeni kırılganlıklar yaratabilir. Son olarak, kırılganlık hukuki korumanın yoğunluğunu farklılaştırabilir. Bu son unsur, kırılganlık ilkesinin biyohukuktaki özgün normatif işlevini oluşturmaktadır.

BİYOHUKUKTA KIRILGANLIK TESTİ

Kırılganlık ilkesinin yalnızca soyut bir teorik öneri olarak kalmaması için hukuki değerlendirmede kullanılabilecek sistematik bir modele ihtiyaç bulunmaktadır. Bu amaçla çalışmada Biyohukukta Kırılganlık Testi önerilmektedir. Yapılacak testte öncelikle müdahale alanının belirlenmesi gerekir. İlk aşamada biyomedikal veya teknolojik müdahalenin insanın hangi alanına yöneldiği belirlenmeli ve müdahalenin; bedene, genoma, zihinsel süreçlere, biyolojik verilere veya karar ve bakım ilişkilerine mi yönelmekte olduğu tespit edilmelidir. Bu aşama, hangi temel hukuki değerlerin söz konusu olduğunu belirlemeyi sağlar. Kırılganlığın kaynağının belirlenmesi aşamasında, kırılganlığın kaynağı tespit edilmelidir. Kırılganlık: içkin mi, durumsal mı, patojenik mi, yoksa teknoloji tarafından yoğunlaştırılmış mı? Bu soruların cevabı aranır. Bu ayrım hukuki müdahalenin yönünü belirlemek bakımından önemlidir. Çünkü kırılganlığın kaynağı kişinin biyolojik durumundaysa farklı, kurum veya sistemden kaynaklanıyorsa farklı koruma araçları gerekebilir.

Kırılganlık testinin sonraki aşamasında yoğunluk ve kesişim analizi yapılarak, kırılganlığın yoğunluğu ve başka kırılganlıklarla kesişip kesişmediği değerlendirilmelidir. Birden fazla kırılganlık mevcut mu? Bu kırılganlıklar birbirini güçlendiriyor mu? Muhtemel zarar geri döndürülebilir mi? Sonuç yalnızca mevcut kişiyi mi etkiliyor? Aile üyeleri veya gelecek kuşaklar da etkileniyor mu? Sorularına cevaplar aranarak, bu aşamada kırılganlık bileşimi ortaya çıkarılmaya çalışılmalıdır. Kırılganlık testinin dördüncü aşamasında, uygun koruma aracının belirlenmesine çalışılmalıdır. Bu aşamada kırılganlığı azaltabilecek en uygun hukuki aracın ne olduğu belirlenmelidir. Bu araç, daha kapsamlı bilgilendirme, ek düşünme süresi, bağımsız danışmanlık, destekli karar verme, ikinci görüş, bağımsız temsil, etik kurul denetimi, daha güçlü veri koruması, insan gözetimi, algoritmik açıklanabilirlik veya belirli müdahalelerin sınırlandırılması olabilir. Buradaki temel nokta, kırılganlığın varlığından doğrudan yasaklama sonucuna geçilmemesidir. Koruma aracı somut kırılganlığın niteliğine uygun olmalıdır.

Kırılganlık testinin son aşamasında, paternalizm ve orantılılık denetimi yapılmalıdır. Bu son aşamada seçilen koruma aracının kişinin özerkliğini gereğinden fazla sınırlayıp sınırlamadığı değerlendirilmelidir. Koruyucu müdahale gerçekten gerekli mi? Aynı koruma daha az sınırlayıcı araçla sağlanabilir mi? Müdahalenin sağladığı koruma ile özerkliğe getirdiği sınırlama orantılı mı? Koruma mekanizması yeni bir patojenik kırılganlık yaratıyor mu? Bu sorulara cevap aranan bu son aşama, kırılganlık ilkesinin paternalist bir hukuk aracına dönüşmesini önleyen temel güvencedir. Kırılganlık testinin mantığı şu aşamalarla formüle edilip, özetlenebilir: Kırılganlığı belirle → kaynağını bul → yoğunluğunu değerlendir → uygun korumayı seç → korumanın kendisini denetle.

KIRILGANLIK İLKESİNİN BİYOHUKUKTAKİ İŞLEVLERİ

Bu çerçevede kırılganlık ilkesinin biyohukukta altı temel işlevinden söz edilebilir. İlk olarak açıklayıcı işlev görür. Genom düzenleme, nöroteknoloji, yapay zekâ destekli sağlık, organ nakli veya karar verme kapasitesi gibi birbirinden uzak görünen sorunların ortak noktasını insanın zarar görebilirliği üzerinden görünür kılar. Kırılganlık ilkesi, ikinci olarak tanımlayıcı işlev görür. Somut olayda hangi kırılganlıkların bulunduğunu belirlemeye yardımcı olur. Kırılganlık ilkesi, üçüncü olarak yorumlayıcı işlev görür. İnsan onuru, özerklik, rıza, bütünlük, mahremiyet ve adalet ilkelerinin somut olayda nasıl uygulanması gerektiğini belirlemeye katkı sağlar. Kırılganlık ilkesi, dördüncü olarak yoğunlaştırıcı işlev görür. Bazı durumlarda neden standart korumanın yeterli olmadığını ve ek hukuki güvencelere ihtiyaç bulunduğunu açıklar. Kırılganlık ilkesi, beşinci olarak önleyici işlev görür. Yeni biyoteknolojilerin henüz gerçekleşmemiş fakat öngörülebilir kırılganlıklar yaratıp yaratmayacağını değerlendirmeye

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imkân verir. Kırılganlık ilkesinin altıncı ve belki de en önemli işlevi, eleştirel işlevdir. Bu işlev, hukukun ve koruma mekanizmalarının kendisinin yeni kırılganlıklar üretip üretmediğini sorgular. Bu nedenle kırılganlık ilkesi yalnızca teknolojiye soru sormaz. Hukuka da soru sorar.

KIRILGANLIK İLKESİNİN SINIRLARI

Kırılganlık kavramının aşırı geniş kullanılması, kavramın hukuki belirleyiciliğini azaltabilir. Her insanın kırılgan olduğu kabulünden hareketle her hukuki sorun kırılganlık sorunu olarak tanımlanırsa, kavram ayırt edici gücünü kaybedebilir. Bu nedenle kırılganlık ilkesinin bazı sınırları bulunmalıdır.İlk olarak her risk kırılganlık değildir. Kırılganlık belirli bir zarar veya haksızlık ihtimalinin anlamlı biçimde artmış olmasıyla bağlantılı değerlendirilmelidir (Hurst, 2008). İkinci olarak kırılganlık kişiye yapıştırılan kalıcı bir hukuki statüye dönüşmemelidir. Kişi: "kırılgan insan" olarak değil, "belirli koşullarda belirli zararlar bakımından kırılgan insan" olarak değerlendirilmelidir.

Üçüncü olarak kırılganlık kişinin insan onurunu, hak ehliyetini veya karar verme yetkisini azaltan bir kategori değildir. Kırılganlığın hukuki sonucu: daha az hak değil, daha etkili koruma olmalıdır. Dördüncü olarak kırılganlık paternalist müdahalenin otomatik gerekçesi değildir. Beşinci olarak evrensel kırılganlık söylemi yapısal eşitsizlikleri görünmez hâle getirmemelidir. "Herkes kırılgandır." önermesi, "Herkes aynı ölçüde kırılgandır." anlamına gelmez.

GELECEĞİN BİYOHUKUKUNDA KIRILGANLIK

Kırılganlık yaklaşımının biyohukuka en önemli teorik katkılarından biri, hukukun koruduğu insan modelini yeniden düşünmeye imkân vermesidir. Klasik liberal hukuk öznesi çoğunlukla: özerk, bağımsız, rasyonel ve kendi çıkarlarını belirleyebilen kişi olarak tasavvur edilmektedir. Bu insan modeli modern hukukun özgürlük ve özerklik kazanımları bakımından son derece değerlidir. Ancak eksiktir. Çünkü gerçek insan; bedenseldir; ilişkiseldir, zamansaldır, hastalanabilir, yaşlanabilir, başkalarına ihtiyaç duyabilir, kurumsal yapılara bağımlı olabilir teknolojik sistemler karşısında bilgi ve güç asimetrisi yaşayabilir.

Kırılganlık yaklaşımı, özerk özneyi ortadan kaldırmaz. Onu gerçek insan varoluşunun koşulları içine yerleştirir. Biyohukukun insan modeli: özerk insan ile kırılgan insan arasında seçim yapmak zorunda değildir. Yeni model, özerk ve kırılgan insan olmalıdır. Bu birleşik kavram, önemli normatif sonuçlar doğurmaktadır. Hukukun görevi artık yalnızca kişinin tercihine müdahale etmemek değildir. Aynı zamanda kişinin kendi tercihini anlamlı biçimde oluşturabilmesini sağlayan: bedensel, bilgisel, ilişkisel, dijital ve kurumsal koşulları korumaktır.

Gen düzenleme, sentetik biyoloji, kişiselleştirilmiş tıp, nöroteknoloji, yapay zekâ destekli sağlık sistemleri, dijital biyobelirteçler ve sürekli biyometrik izleme gibi gelişmeler insan yaşamına ilişkin teknik müdahale kapasitesini daha da artırmaktadır. Bu gelişmeler biyohukukun klasik sorusunu değiştirmektedir. İlk soru: "Teknoloji ne yapabilir?" olabilir. Hukukun sorusu ise: "Teknolojinin yapabildiği şey hukuken yapılabilir mi?" olmalıdır. Ancak kırılganlık yaklaşımı üçüncü ve daha insan merkezli bir soru eklemektedir: "Bu teknoloji karşısında insan hangi biçimlerde kırılganlaşmaktadır?" Ardından dördüncü soru gelir: "Hukuk bu kırılganlığı azaltmak için ne yapmalıdır?" Ve son olarak hukuk kendi koruma mekanizmalarına dönerek şunu sormalıdır: "Getirdiğimiz koruma insanı gerçekten güçlendiriyor mu, yoksa onun özerkliğini azaltarak yeni bir kırılganlık mı yaratıyor?" Kırılganlık ilkesinin geleceğin biyohukukuna sağlayabileceği temel yöntemsel katkı, belki de bu sorgulama biçimi olacaktır.

SONUÇ

Biyoteknolojik ve dijital gelişmeler insan yaşamına müdahale kapasitesini tarihsel olarak görülmemiş ölçüde genişletmektedir. İnsan genomunun düzenlenmesi, zihinsel süreçlerin nöroteknolojik araçlarla analiz edilmesi veya etkilenmesi, yapay zekâ sistemlerinin sağlık kararlarında kullanılması ve biyolojik verilerin küresel dijital altyapılarda işlenmesi, biyohukukun yalnızca yeni teknolojiler için yeni kurallar üretmesini değil, koruduğu insan tasavvurunu yeniden değerlendirmesini de gerektirmektedir.

Modern biyohukukun insan onuru, kişisel özerklik, aydınlatılmış rıza, bedensel bütünlük, mahremiyet, zarar vermeme ve adalet ilkeleri korunması gereken temel normatif kazanımlardır. Kırılganlık yaklaşımı

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bu ilkelerden vazgeçilmesini gerektirmemektedir. Aksine onların dayandığı insan modelinin tamamlanmasını önermektedir. İnsan yalnızca özerk değildir. İnsan aynı zamanda kırılgandır. Kırılganlık belirli insan gruplarına özgü istisnai bir durum değildir. İnsan bedeninin hastalanabilir, yaralanabilir, değişebilir ve yaşlanabilir olması; kişinin yaşamı boyunca başkalarıyla ilişki ve bağımlılık içinde bulunması kırılganlığı insan varoluşunun ortak özelliklerinden biri hâline getirmektedir (Fineman, 2008, ss. 8–23; ten Have, 2016).

Bununla birlikte kırılganlığın evrenselliği bütün insanların aynı biçimde veya aynı yoğunlukta kırılgan olduğu anlamına gelmemektedir. Hastalık, genetik özellikler, bilişsel durum, ekonomik eşitsizlikler, bakım ilişkileri, dijital sistemler ve teknolojik müdahaleler belirli kişilerin belirli zararlar karşısındaki kırılganlığını yoğunlaştırabilir. Bu nedenle kırılganlık hem evrensel hem bağlamsal hem ortak hem farklılaşmış bir insanlık durumu olarak değerlendirilmelidir (Kottow, 2003; Hurst, 2008; Mackenzie ve Ark., 2014). Çalışmada bu kırılganlığın beş temel görünümü belirlenmiştir: bedensel kırılganlık, genetik kırılganlık, zihinsel kırılganlık, dijital kırılganlık ve ilişkisel kırılganlık. Bu kategoriler birbirinden tamamen bağımsız değildir. Gerçek biyohukuk vakalarında birden fazla kırılganlık aynı kişide ve aynı olayda kesişebilir. Bu nedenle kırılganlığın hukuki değerlendirilmesinde tek bir kırılganlık türünden ziyade kırılganlık bileşiminin belirlenmesi daha işlevsel olabilir. Teknolojik kırılganlık ise altıncı bağımsız kategori olarak değil, diğer kırılganlık biçimlerini etkileyebilen yatay bir yoğunlaştırıcı etken olarak değerlendirilmiştir. Teknoloji bedensel müdahaleyi genişletebilir, genetik değişiklikleri kuşaklar arası hâle getirebilir, zihinsel süreçlere erişimi artırabilir, biyolojik veriyi sınırsız biçimde çoğaltabilir ve bakım ilişkilerini algoritmik sistemlere taşıyabilir. Bu nedenle biyohukukun teknoloji karşısındaki temel sorularından biri, teknolojinin mevcut kırılganlığı azaltıp azaltmadığı veya yeni kırılganlıklar üretip üretmediği olmalıdır. Çalışmanın temel normatif önerisi bu teorik zeminden ortaya çıkmaktadır: Biyohukukta Kırılganlık İlkesi. Bu ilke yeni bir temel hak değildir. İnsan onurunun alternatifi değildir. Özerklikle rekabet etmez. Adaletin yerine geçmez. Kırılganlık ilkesinin özgün normatif işlevi hukuki korumanın yoğunluğunu ve biçimini belirlemeye yardımcı olmaktır. İnsan onuru neden korumamız gerektiğini; özerklik kimin kararına öncelik vermemiz gerektiğini; adalet yarar ve yükleri nasıl dağıtmamız gerektiğini; kırılganlık ise ne ölçüde ve hangi araçlarla korumamız gerektiğini gösterir. Bu ayrım, kırılganlığın neden biyohukukta bağımsız fakat tamamlayıcı bir normatif yere sahip olabileceğini açıklamaktadır.

Kırılganlık ilkesi, hukuki eşitlik anlayışını derinleştirmektedir. Eşit haklara sahip olmak her durumda aynı biçimde korunmayı gerektirmez. Bazı kişiler ve durumlar daha güçlü bilgilendirme, daha uzun karar süresi, destekli karar verme, bağımsız danışmanlık, daha sıkı veri koruması veya daha yoğun kurumsal denetim gerektirebilir. Bu farklılaştırılmış koruma, doğru sınırlar içinde uygulandığında ayrımcılık değildir. Somut kırılganlığa duyarlı eşitliktir. Ancak kırılganlık ilkesinin en önemli sınırı paternalizmdir. Kişinin kırılgan olduğunun kabul edilmesi onun kendi kararlarını verme hakkının ortadan kaldırılmasını haklı göstermez. Koruma kişinin yerine karar vermek değil, mümkün olduğu ölçüde kişinin kendi kararını anlamlı biçimde verebilmesini sağlayacak koşulları yaratmak amacı taşımalıdır. Kırılganlık arttıkça koruma yoğunlaştırılmalı; fakat kişinin özerklik alanı zorunlu olmadıkça daraltılmamalıdır. Çalışmada bu teorik yaklaşımın hukuki uygulamaya aktarılması amacıyla Biyohukukta Kırılganlık Testi önerilmiştir. Test; müdahale alanının belirlenmesi, kırılganlığın kaynağının tespiti, yoğunluk ve kesişimin değerlendirilmesi, uygun koruma aracının seçilmesi ve paternalizm ile orantılılık denetiminden oluşmaktadır. Kırılganlık ilkesi yalnızca teknolojiyi, hekimi, araştırmacıyı veya kurumu denetlememelidir. Kendi adına getirilen hukuki korumayı da denetlemelidir. Böylelikle kırılganlık ilkesi; insanı zarar karşısında korumak ve koruma adına insanın özerkliğinin gereksiz biçimde azaltılmasını önlemek olmak üzere iki yönlü bir normatif işleve kavuşmaktadır.

Kırılganlık ilkesi, özerklik paradigmasının insanın gerçek varoluş koşullarıyla tamamlanmasıdır. Geleceğin biyohukuku insanı yalnızca rasyonel, bağımsız ve kendi kendine yeterli bir hukuk öznesi olarak göremez. Fakat insanı yalnızca zayıf, bağımlı ve korunmaya muhtaç bir varlığa da indirgeyemez. Biyohukukun insanı, özerk fakat kırılgan; özgür fakat ilişkisel, teknolojiden yararlanabilen fakat teknolojik güç karşısında zarar görebilir; hak sahibi fakat kimi durumlarda haklarını kullanabilmek için desteğe ihtiyaç duyabilen bir insandır. Geleceğin biyohukukunda temel mesele yalnızca teknolojinin insan üzerinde neler yapabileceğini belirlemek olmayacaktır. Teknolojik ve biyomedikal müdahaleler karşısında insanın kırılganlığını tanırken, onun özerkliğini nasıl koruyabiliriz? Sorusu en temel sorumuz

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ve kaygımız olacaktır. Bu kapsamda odaklandığımız biyohukukta kırılganlık ilkesi, özünde bu soruya sistematik ve hukuki bir cevap geliştirme girişimidir.

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MITOCHONDRIAL BIOMARKERS AS POTENTIAL DIAGNOSTIC TOOLS IN MALE INFERTILITY

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ABSTRACT

Male infertility represents a major global reproductive health challenge, affecting approximately 15% of couples worldwide, with male-related factors accounting for nearly half of all infertility cases. Although conventional semen analysis remains the cornerstone of clinical evaluation, it frequently fails to identify the molecular abnormalities underlying impaired male fertility. Mitochondria play a pivotal role in sperm physiology by generating the ATP required for motility through oxidative phosphorylation and by regulating apoptosis, calcium homeostasis, and cellular redox balance. Increasing evidence indicates that mitochondrial dysfunction is a central pathogenic mechanism in male infertility, characterized by impaired ATP production, excessive generation of reactive oxygen species (ROS), mitochondrial DNA (mtDNA) damage, and disruption of mitochondrial membrane potential (MMP). These alterations adversely affect sperm motility, viability, DNA integrity, and fertilization capacity.

This review provides a comprehensive overview of the diagnostic potential of mitochondrial biomarkers in the evaluation of male infertility, with particular emphasis on mtDNA copy number, mitochondrial membrane potential, oxidative stress markers, and key components of the mitochondrial respiratory chain. Recent clinical and experimental studies consistently demonstrate that these biomarkers exhibit superior sensitivity and specificity compared with conventional semen parameters and may facilitate the identification of underlying mitochondrial dysfunction in cases of unexplained or idiopathic infertility. Furthermore, integrating mitochondrial biomarkers into routine diagnostic protocols may improve patient stratification, optimize treatment selection, and enhance the prediction of assisted reproductive technology (ART) outcomes.

Collectively, current evidence suggests that mitochondrial biomarkers represent promising complementary diagnostic tools for improving the molecular assessment of male infertility. Nevertheless, further large-scale prospective studies and standardized analytical methodologies are required before these biomarkers can be fully implemented in routine clinical practice.

Keywords: Male infertility; mitochondrial biomarkers; mitochondrial DNA; oxidative stress; reactive oxygen species; sperm function; diagnosis.

INTRODUCTION

Infertility is a significant global public health concern, affecting approximately 186 million individuals worldwide. According to the World Health Organization (WHO), nearly 15% of couples of reproductive age experience infertility, with male-related factors contributing to approximately 40–50% of all cases, either as the sole cause or in combination with female factors (Agarwal et al., 2015). Clinically, male infertility encompasses a heterogeneous spectrum of disorders, including oligozoospermia, azoospermia, asthenozoospermia, and teratozoospermia, each characterized by distinct impairments in semen quality and reproductive potential.

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Conventional semen analysis, performed according to WHO guidelines, remains the cornerstone of male infertility assessment. However, this approach primarily evaluates macroscopic semen parameters such as sperm concentration, motility, and morphology, while providing limited insight into the molecular and functional abnormalities that ultimately determine fertilization capacity (Krausz & Riera-Escamilla, 2018). Consequently, a substantial proportion of infertile men are classified as having idiopathic infertility despite exhibiting apparently normal semen parameters, underscoring the urgent need for more sensitive and mechanistically informative diagnostic biomarkers.

Among the cellular components essential for sperm function, mitochondria occupy a central role in maintaining male reproductive competence. Localized within the sperm midpiece, mitochondria generate approximately 70–80% of the ATP required for progressive sperm motility through oxidative phosphorylation (OXPHOS)(Amaral et al., 2013). Beyond energy production, mitochondria regulate several critical biological processes, including calcium homeostasis, reactive oxygen species (ROS) generation, redox signaling, and apoptosis. Disruption of mitochondrial function results in excessive ROS production, impaired ATP synthesis, mitochondrial DNA (mtDNA) damage, loss of mitochondrial membrane potential (MMP), and activation of apoptotic pathways, collectively compromising sperm motility, viability, acrosomal integrity, and genomic stability.

Growing evidence indicates that mitochondrial dysfunction represents one of the principal molecular mechanisms underlying male infertility. Alterations in mitochondrial bioenergetics have been associated with oxidative stress, defective spermatogenesis, reduced fertilization potential, and poor outcomes following assisted reproductive technologies (ART). Consequently, mitochondrial biomarkers have emerged as promising candidates for improving both the diagnosis and prognostic assessment of male infertility.

Among the most extensively investigated mitochondrial biomarkers are mtDNA copy number, mitochondrial membrane potential (MMP), intracellular ROS levels, oxidative DNA damage markers such as 8-hydroxy-2′-deoxyguanosine (8-OHdG), and the activity of mitochondrial respiratory chain complexes. These biomarkers provide valuable insights into sperm mitochondrial function and may complement conventional semen analysis by identifying molecular abnormalities that remain undetected using standard diagnostic approaches.

Therefore, this review aims to provide a comprehensive overview of the biological significance and clinical utility of mitochondrial biomarkers in male infertility. In particular, it summarizes current evidence regarding mtDNA copy number, mitochondrial membrane potential, oxidative stress-related biomarkers, and mitochondrial respiratory chain components, while discussing their potential integration into routine diagnostic algorithms and their future role in precision reproductive medicine.

CONCEPTUAL FRAMEWORK

1. Mitochondria and Sperm Function

Mitochondria are indispensable organelles for maintaining sperm function and male reproductive capacity. Recent advances in reproductive biology have substantially expanded our understanding of the multifaceted roles of mitochondria in sperm physiology. Located within the sperm midpiece, mitochondria are strategically organized in a helical sheath surrounding the axoneme, thereby ensuring an efficient energy supply to support flagellar movement and other energy-demanding cellular processes. Their primary function is the generation of adenosine triphosphate (ATP) through oxidative phosphorylation (OXPHOS), while simultaneously providing tricarboxylic acid (TCA) cycle intermediates required for cellular metabolism and anabolic pathways (Mai et al., 2024).

Spermatozoa produce ATP through two principal metabolic pathways: glycolysis and oxidative phosphorylation. Glycolysis predominantly occurs in the principal piece of the flagellum and sperm head, whereas OXPHOS is localized within the mitochondria-rich midpiece. Although both pathways contribute to cellular energy production, OXPHOS is considerably more efficient in ATP generation and serves as the principal energy source for progressive sperm motility. Mitochondrial ATP production is essential for several physiological processes, including sperm motility, hyperactivation, capacitation, and the acrosome reaction, all of which are prerequisites for successful fertilization (Mai et al., 2024).

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Beyond bioenergetics, mitochondria regulate numerous cellular processes that are fundamental to sperm function. These include calcium homeostasis, intracellular redox balance, reactive oxygen species (ROS) production, apoptosis, and, under specific physiological conditions, steroid hormone biosynthesis. Maintenance of an optimal mitochondrial membrane potential (MMP) is critical for preserving mitochondrial integrity and ensuring adequate ATP synthesis. Consequently, normal mitochondrial function is indispensable for maintaining sperm motility, capacitation, acrosomal integrity, and genomic stability (Vahedi Raad et al., 2024).

Accumulating evidence identifies mitochondrial dysfunction as one of the principal molecular mechanisms contributing to male infertility. A recent systematic review demonstrated a strong association between mitochondrial dysfunction and both asthenozoospermia and oligoasthenozoospermia. Structural abnormalities frequently observed in infertile men include shortening of the sperm midpiece, disruption or complete loss of the mitochondrial sheath, abnormal mitochondrial organization, and mitochondrial aggregation. Furthermore, damage to mitochondrial DNA (mtDNA), alterations in the mitochondrial transcriptome and proteome, and impairment of MMP collectively compromise mitochondrial bioenergetics, ultimately resulting in defective sperm function and reduced male fertility (Mai et al., 2024).

Oxidative stress represents another critical consequence of mitochondrial dysfunction. Approximately 30–80% of male infertility cases have been associated with excessive ROS-mediated sperm damage. Although physiological levels of ROS are required for normal sperm maturation and fertilization, excessive ROS production induces oxidative damage to lipids, proteins, and nucleic acids. Lipid peroxidation disrupts membrane fluidity, protein oxidation impairs enzymatic activity, and oxidative DNA damage compromises genomic integrity. Collectively, these alterations reduce sperm motility, impair the ability of spermatozoa to penetrate the oocyte, and negatively influence early embryonic development (Park & Pang, 2021).

Taken together, current evidence highlights mitochondria as central regulators of sperm physiology, extending far beyond their traditional role as cellular energy producers. Their integrated involvement in energy metabolism, redox homeostasis, apoptosis, calcium signaling, and maintenance of genomic integrity underscores their critical importance in male reproductive health. Consequently, mitochondrial dysfunction has emerged as a key molecular hallmark of male infertility, providing a strong biological rationale for the development of mitochondria-based biomarkers that may improve diagnostic accuracy and facilitate personalized clinical management.

2. Mitochondrial DNA (mtDNA) and Its Role in Male Infertility

Mitochondrial DNA (mtDNA) has emerged as one of the most extensively investigated molecular biomarkers of male infertility. Increasing evidence indicates that an elevated mitochondrial DNA copy number (mtDNAcn) is consistently associated with poor semen quality, reduced fertilization potential, and prolonged time to pregnancy. These findings suggest that mtDNAcn may serve as a sensitive subclinical biomarker, particularly in cases of idiopathic male infertility, where conventional diagnostic approaches often fail to identify the underlying molecular abnormalities (Sawant et al., 2026). Indeed, even in men with apparently normal semen parameters, sperm DNA damage, oxidative stress, mitochondrial dysfunction, and mtDNA heteroplasmy may impair fertility, yet these abnormalities cannot be detected through routine semen analysis alone (Wang & Swerdloff, 2014).

Evidence supporting the diagnostic significance of mtDNAcn has been reinforced by large-scale clinical studies. In a cross-sectional investigation involving 1,164 potential sperm donors, Chen et al. (2023) demonstrated a dose-dependent inverse association between mtDNA copy number and semen quality. Individuals within the highest mtDNAcn quartile exhibited significantly lower progressive and total sperm motility, sperm concentration, and total sperm count than those within the lowest quartile. These findings indicate that mtDNA copy number may represent a reliable predictor of human semen quality and mitochondrial function (Chen et al., 2023).

Beyond quantitative alterations, epigenetic modifications of mtDNA have also attracted increasing attention. In a comparative study including 30 patients with asthenozoospermia and 30 fertile controls, Geng et al. (2024) evaluated methylation levels within the mitochondrial D-loop and MT-CO1 regions

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together with mtDNA copy number using pyrosequencing and quantitative PCR. Significant alterations in both mtDNA methylation and copy number were identified in asthenozoospermic patients, suggesting that epigenetic regulation of the mitochondrial genome may contribute to the pathophysiology of male infertility (Geng et al., 2024).

Genetic variations within the mitochondrial genome have likewise been implicated in impaired male reproductive function. In particular, single-nucleotide variants (SNVs) within the mitochondrial cytochrome *b* (MT-CYB) gene have been significantly associated with male infertility. Furthermore, the 4,977-base pair mtDNA deletion, commonly referred to as the *common deletion*, has been consistently linked to mitochondrial dysfunction and impaired sperm function, highlighting the importance of mtDNA integrity in maintaining normal male fertility (Amor & Hammadeh, 2022).

The clinical relevance of mtDNA biomarkers has also been investigated in the context of assisted reproductive technologies (ART). In a comprehensive study involving 401 semen samples, Shi et al. (2022) reported that elevated mtDNA copy number and increased sperm DNA fragmentation index (DFI) were significantly associated with poor semen quality. Moreover, follow-up analyses of couples undergoing in vitro fertilization (IVF) and intracytoplasmic sperm injection (ICSI) suggested that these biomarkers may influence ART outcomes and could therefore provide additional prognostic information during fertility treatment (Shi et al., 2022). Nevertheless, the diagnostic value of mtDNA copy number remains controversial. In a prospective observational study evaluating 119 sperm samples, Tiegs et al. (2020) found that mtDNAcn was not an independent predictor of fertilization success or subsequent embryonic development following ICSI. These conflicting findings likely reflect differences in study populations, laboratory methodologies, and analytical protocols, emphasizing the need for standardized measurement techniques before mtDNA-based biomarkers can be routinely incorporated into clinical practice (Tiegs et al., 2020).

Recent investigations have further explored the combined diagnostic utility of mtDNA copy number and telomere length. In a study including 200 semen samples (150 infertile men and 50 fertile controls), Kadhim et al. (2025) compared these parameters among patients with asthenozoospermia, oligoasthenozoospermia, and oligoasthenoteratozoospermia. The authors proposed that elevated mtDNA copy number is associated with impaired mitochondrial energy production, increased oxidative stress, and activation of apoptotic pathways, all of which contribute to male infertility. These findings suggest that combining mtDNAcn with complementary molecular biomarkers may provide greater diagnostic accuracy than evaluating individual biomarkers in isolation (Kadhim et al., 2025).

Overall, current evidence supports mtDNA alterations as clinically relevant indicators of mitochondrial dysfunction and impaired male reproductive potential. However, given the multifactorial nature and biological heterogeneity of male infertility, mtDNA copy number alone is unlikely to provide sufficient diagnostic accuracy. Future diagnostic strategies should therefore focus on integrating mtDNA-based biomarkers with functional mitochondrial parameters, oxidative stress markers, and multi-omics approaches to enable a more comprehensive molecular assessment of male infertility.

3. Mitokondriyal Membran Potansiyeli (MMP)

Mitochondrial membrane potential (MMP) is widely recognized as one of the most informative functional biomarkers for assessing mitochondrial integrity and dysfunction in male infertility. As an indicator of mitochondrial bioenergetic capacity, MMP reflects the efficiency of oxidative phosphorylation and ATP production, both of which are essential for normal sperm function. Among the available analytical techniques, flow cytometric assessment using the JC-1 fluorescent probe has been demonstrated to be more reliable than the conventional Rhodamine 123 staining method. Furthermore, MMP has been shown to correlate positively with sperm motility, supporting its value as a functional indicator of sperm quality (Troiano et al., 1998). The superior analytical performance of JC-1 has therefore established it as the preferred method for evaluating mitochondrial function in both research and clinical settings.

The prognostic value of MMP has also been demonstrated in studies evaluating sperm functional capacity over time. In a clinically relevant investigation, Alamo et al. (2020) examined whether MMP measured immediately after semen liquefaction (T0) could predict subsequent changes in sperm

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motility. Mitochondrial membrane potential was assessed using JC-1 staining combined with flow cytometry, whereas total and progressive sperm motility were evaluated immediately after liquefaction (T0) and four hours after semen collection (T4). The authors demonstrated that baseline MMP was a strong independent predictor of sperm motility reserve, indicating that mitochondrial functional status at the time of semen collection may provide valuable prognostic information regarding sperm performance during laboratory processing. These findings suggest that MMP assessment may assist clinicians in optimizing sperm selection strategies for assisted reproductive technologies (ART) (Alamo et al., 2020).

More recent evidence further supports the clinical relevance of MMP in patients with unexplained forms of male infertility. Pacheco et al. (2023) compared mitochondrial membrane potential among healthy fertile men (CTRL), patients with idiopathic infertility (ID), and men with unexplained male infertility (UMI) using JC-1 staining and flow cytometric analysis. Both infertile groups exhibited a significantly lower proportion of spermatozoa with high MMP than the control group, indicating impaired mitochondrial function despite the absence of identifiable abnormalities using conventional diagnostic methods. These observations suggest that MMP assessment may improve the molecular characterization of infertile patients whose condition remains unexplained following routine clinical evaluation *(Pacheco et al., 2023)*.

Beyond its diagnostic application, MMP has also emerged as a promising biomarker for monitoring therapeutic responses. In a recent study investigating infertile men with clinical varicocele, Arya et al. (2025) evaluated sperm mitochondrial function and DNA methylation before and after varicocele treatment. A significant improvement in mitochondrial membrane potential was observed following treatment, demonstrating that restoration of mitochondrial function parallels clinical recovery. These findings indicate that MMP may serve not only as a diagnostic biomarker but also as a functional indicator of treatment efficacy and mitochondrial recovery (Arya et al., 2025),

Evidence from systematic reviews further reinforces the biological and clinical importance of MMP. Studies evaluating the relationship between mitochondrial membrane potential, sperm motility, and fertilization capacity have consistently demonstrated that sperm populations exhibiting higher MMP display superior motility characteristics and greater fertilization competence (Kasai et al., 2002). Since mitochondrial ATP production is indispensable for sperm movement and fertilization, preservation of mitochondrial membrane integrity appears to be a prerequisite for optimal reproductive function (Kasai et al., 2002).

Collectively, current evidence identifies mitochondrial membrane potential as one of the most robust functional biomarkers of sperm quality. Its strong association with sperm motility, fertilization capacity, and treatment response highlights its considerable diagnostic and prognostic value in male infertility. Nevertheless, MMP should not be interpreted as a standalone diagnostic marker. Rather, its greatest clinical utility is likely to be achieved when integrated with complementary mitochondrial biomarkers, oxidative stress indicators, and conventional semen parameters, thereby enabling a more comprehensive and accurate evaluation of male reproductive function.

4. Reactive Oxygen Species (Ros) And Oxidative Stress

Reactive oxygen species (ROS) and oxidative stress have been among the most extensively investigated mechanisms underlying male infertility. Oxidative stress arises from an imbalance between ROS generation and the antioxidant defense system, resulting in excessive oxidative damage that adversely affects both sperm production and function. Elevated levels of lipid peroxidation have been consistently associated with reduced sperm motility, impaired sperm viability, and diminished fertilization capacity (Dutta et al., 2024). (Dutta et al., 2024). Among the most extensively studied oxidative stress biomarkers are 8-hydroxy-2′-deoxyguanosine (8-OHdG), a well-established indicator of oxidative DNA damage, and F2-isoprostanes (8-isoprostanes), which reflect lipid peroxidation and oxidative membrane injury

Although physiological concentrations of ROS are essential for normal sperm maturation, capacitation, hyperactivation, and the acrosome reaction, excessive ROS production disrupts cellular homeostasis and promotes lipid peroxidation, protein oxidation, mitochondrial dysfunction, and sperm DNA fragmentation. These pathological alterations collectively impair sperm motility, morphology, and

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fertilization potential. In parallel, increased concentrations of pro-inflammatory mediators, including interleukin-6 (IL-6), interleukin-8 (IL-8), and tumor necrosis factor-α (TNF-α), are frequently detected in the seminal plasma of infertile men and have been associated with poor semen quality (Pavuluri et al., 2024). Oxidative stress and inflammation therefore interact in a bidirectional manner, establishing a self-perpetuating pathophysiological cycle that progressively compromises male reproductive function.

The clinical relevance of redox homeostasis has been further highlighted by recent systematic reviews and meta-analyses. Tan et al. (2024) evaluated the diagnostic performance of oxidation-reduction potential (ORP) as an independent biomarker of oxidative stress in male infertility. Their findings emphasized that while physiological ROS levels are indispensable for normal sperm function, excessive oxidative stress or inadequate antioxidant defenses disrupt fertilization capacity, impair sperm DNA integrity, and ultimately reduce male reproductive potential. These observations support the growing clinical interest in ORP as a comprehensive indicator of seminal oxidative status (Tan et al., 2024).

mong oxidative stress biomarkers, 8-OHdG has emerged as one of the most clinically relevant indicators of oxidative DNA damage. Because guanine is the DNA base most susceptible to oxidation, excessive ROS exposure results in the formation of the mutagenic lesion 8-OHdG, which reflects cumulative oxidative injury to the sperm genome (Takalani et al., 2023). Elevated 8-OHdG levels have consistently been associated with impaired sperm quality, increased DNA fragmentation, and reduced fertilization capacity, highlighting its potential utility as a molecular biomarker in the assessment of male infertility.

Recent advances in molecular biology have further expanded the investigation of oxidative stress beyond conventional biochemical markers. High-throughput approaches, including next-generation sequencing (NGS), differential gene expression (DEG) analyses, and epigenetic profiling, have identified numerous oxidative stress-responsive genes and regulatory pathways involved in spermatogenesis and male infertility (Dutta et al., 2024). These integrative molecular approaches provide valuable insights into the complex interactions between oxidative stress, mitochondrial dysfunction, and epigenetic regulation, thereby broadening the spectrum of potential diagnostic biomarkers.

In addition to 8-OHdG, several biochemical markers, including malondialdehyde (MDA), total antioxidant capacity (TAC), and oxidation-reduction potential (ORP), have been extensively evaluated for their diagnostic applicability. These biomarkers collectively reflect oxidative balance, antioxidant defense capacity, and inflammatory activity within the seminal microenvironment. However, despite their considerable diagnostic potential, their routine clinical implementation remains limited by the lack of standardized analytical methodologies, reference ranges, and universally accepted diagnostic thresholds (Pavuluri et al., 2024).

Overall, accumulating evidence indicates that oxidative stress is a central molecular mechanism linking mitochondrial dysfunction to impaired sperm quality and male infertility. Consequently, biomarkers reflecting oxidative DNA damage, lipid peroxidation, and redox imbalance represent valuable complementary tools for molecular diagnosis. Future diagnostic strategies are likely to benefit from integrating oxidative stress biomarkers with mitochondrial functional parameters and multi-omics approaches to improve diagnostic accuracy, patient stratification, and individualized treatment planning.

5. Respiratory Chain Complexes and Mitochondrial Bioenergetics

The role of mitochondrial respiratory chain complexes in male infertility has gained increasing attention with the rapid advancement of proteomics, genomics, metabolomics, and bioinformatics. Although sperm proteomics has substantially improved our understanding of the molecular mechanisms underlying male infertility, the mitochondrial sperm proteome remains incompletely characterized. Emerging evidence indicates that alterations in respiratory chain proteins profoundly affect mitochondrial bioenergetics, ATP production, and sperm function, highlighting their potential as novel diagnostic biomarkers (Sawaid Kaiyal et al., 2024).

Proteomics-based investigations have identified several mitochondrial proteins with considerable diagnostic potential. In a validated proteomic study exploring mitochondrial dysfunction signatures in idiopathic primary male infertility, Sawaid Kaiyal et al. (2024) identified multiple dysregulated

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mitochondrial proteins associated with impaired sperm function. Similarly, Zhong et al. (2023) developed a four-gene diagnostic panel comprising COX7A1, COX7A2, MRPS15, and AURKAIP1, which demonstrated superior diagnostic sensitivity and specificity for non-obstructive azoospermia (NOA) compared with individual biomarkers. These findings suggest that respiratory chain-associated proteins may provide greater diagnostic accuracy when incorporated into multi-marker panels rather than being evaluated individually (Zhong et al., 2023).

Experimental evidence from animal models further supports the indispensable role of mitochondrial respiratory complexes during spermatogenesis. Schumacher et al. (2024) demonstrated that genetic deletion of the mitochondrial protease PARL resulted in a marked reduction in respiratory chain Complex IV proteins, leading to complete arrest of spermatogenesis at meiotic stage I. These findings indicate that normal spermatogenesis depends not only on adequate ATP production but also on the structural integrity and functional activity of mitochondrial respiratory complexes, particularly cytochrome *c* oxidase (Complex IV) (Schumacher et al., 2024).

Integrative bioinformatics studies have likewise highlighted the importance of mitochondrial bioenergetics in male infertility. In an analysis investigating mitochondrial dysfunction-related genes in patients with non-obstructive azoospermia, Liu et al. (2026) identified PDHA2 (pyruvate dehydrogenase E1 alpha 2) as one of the most highly expressed testis-specific genes. Homozygous missense mutations in PDHA2 were associated with azoospermia, sperm immotility, and necrospermia, suggesting that impaired mitochondrial energy metabolism represents a key pathogenic mechanism underlying these reproductive disorders (Liu et al., 2026).

Metabolomic investigations provide complementary biochemical evidence supporting respiratory chain dysfunction. Targeted metabolomic analyses in patients with severe oligoasthenozoospermia revealed significantly reduced concentrations of metabolites involved in membrane integrity and mitochondrial energy metabolism (Boguenet et al., 2020). Furthermore, nicotinamide levels have been reported to correlate positively with sperm motility in men with asthenozoospermia, suggesting that cofactors involved in mitochondrial respiration may also possess diagnostic value (Zhang et al., 2024). These findings reinforce the concept that disturbances in mitochondrial metabolism are reflected not only at the genomic and proteomic levels but also through measurable metabolic alterations.

Beyond protein-coding genes, non-coding RNAs (ncRNAs) have recently emerged as important regulators of mitochondrial dynamics and spermatogenesis. Using whole-genome sequencing (WGS), Kyrgiafini et al. (2025) identified infertility-associated variants in several ncRNAs involved in the regulation of mitochondrial dynamics among men with asthenozoospermia, oligozoospermia, and teratozoospermia. Independent transcriptomic validation using RNA sequencing data derived from testicular biopsies of patients with non-obstructive azoospermia further confirmed these findings, emphasizing the complex regulatory networks linking mitochondrial function to male reproductive health (Kyrgiafini et al., 2025).

Collectively, current evidence indicates that components of the mitochondrial electron transport chain, particularly cytochrome c oxidase (Complex IV) and its associated regulatory proteins, play fundamental roles in maintaining spermatogenesis, ATP production, and sperm motility. Nevertheless, male infertility is a highly heterogeneous disorder involving multiple molecular pathways, limiting the diagnostic performance of any single biomarker. Consequently, future diagnostic strategies are likely to rely on integrated multi-omics approaches that combine genomic, transcriptomic, proteomic, metabolomic, and functional mitochondrial biomarkers into comprehensive diagnostic panels. Such strategies have the potential to improve diagnostic sensitivity, enhance patient stratification, facilitate personalized therapeutic decision-making, and provide more accurate prediction of reproductive outcomes. However, before these biomarkers can be incorporated into routine clinical practice, their clinical utility must be confirmed through large-scale multicenter studies employing standardized analytical methodologies and functional validation (Corda et al., 2024; Kovac et al., 2013; Panner Selvam & Agarwal, 2018; Stamatellos et al., 2025).

CONCLUSION AND DISCUSSION

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The literature reviewed in this study indicates that mitochondrial biomarkers provide substantial complementary diagnostic value beyond conventional semen analysis in the evaluation of male infertility. In particular, mitochondrial membrane potential (MMP), reactive oxygen species (ROS) levels, and mitochondrial DNA copy number (mtDNAcn) demonstrate strong correlations with sperm motility, morphology, and fertilization capacity. Although none of these biomarkers appears sufficient as a standalone diagnostic tool, accumulating evidence suggests that their combined assessment alongside conventional semen parameters substantially improves the molecular characterization and diagnostic accuracy of male infertility.

Evidence from systematic reviews and meta-analyses further reinforces the clinical significance of mitochondrial biomarkers. A comprehensive meta-analysis conducted by Wiweko and Utami (2017) demonstrated that ROS levels are consistently and significantly higher in infertile men than in fertile controls, with remarkable consistency across the included studies. These findings highlight oxidative stress as one of the most robust pathophysiological mechanisms underlying male infertility and further support the clinical relevance of ROS-related biomarkers (Wiweko & Utami, 2017).

The integration of mitochondrial biomarkers into routine clinical practice has the potential to transform the diagnostic and therapeutic management of male infertility. This need is particularly evident in patients presenting with apparently normal semen parameters despite persistent infertility, where conventional semen analysis frequently lacks sufficient sensitivity to identify clinically significant molecular abnormalities. In this context, mitochondrial biomarkers may facilitate: (i) risk stratification based on mitochondrial functional profiles; (ii) identification of patients who may benefit from targeted antioxidant therapy through the assessment of oxidative stress biomarkers; and (iii) optimization of assisted reproductive technology (ART) strategies in individuals exhibiting impaired mitochondrial membrane potential.

Recent studies have also established a close association between mtDNA integrity and the outcomes of in vitro fertilization (IVF) and intracytoplasmic sperm injection (ICSI). Consequently, mitochondrial assessment has emerged as an increasingly valuable component of reproductive medicine. Advanced techniques capable of evaluating mtDNA quality in both spermatozoa and the fertilized oocyte have shown considerable promise for predicting embryo quality, implantation success, and reproductive outcomes (Luo et al., 2013).

Despite their considerable diagnostic potential, several challenges continue to hinder the routine clinical implementation of mitochondrial biomarkers. The lack of standardized protocols for sample collection, laboratory methodologies, analytical procedures, and reference ranges substantially limits the reproducibility and comparability of published findings. Furthermore, many currently available techniques require relatively large semen volumes, specialized instrumentation, and highly trained personnel, thereby restricting their widespread application in routine clinical laboratories.

Future research should prioritize several key areas to facilitate clinical translation. First, large multicenter studies are required to establish standardized reference intervals and analytical protocols. Second, the diagnostic performance of integrated multi-biomarker panels should be evaluated to determine whether combinations of mitochondrial biomarkers outperform individual markers. Third, artificial intelligence and machine learning algorithms should be incorporated into biomarker integration models to improve patient stratification, individualized risk prediction, and treatment selection. Finally, well-designed prospective clinical trials are needed to determine whether therapeutic strategies guided by mitochondrial biomarker profiles can improve IVF and ICSI outcomes and ultimately enhance reproductive success.

RESULTS

This review demonstrates that mitochondrial biomarkers provide meaningful complementary information beyond conventional semen analysis for the evaluation of male infertility. Biomarker panels incorporating mitochondrial membrane potential (MMP), reactive oxygen species (ROS), mitochondrial DNA copy number (mtDNAcn), and mitochondrial respiratory chain activity show considerable promise for improving diagnostic accuracy when interpreted alongside traditional semen parameters.

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Nevertheless, the widespread clinical implementation of these biomarkers remains constrained by the lack of methodological standardization, universally accepted reference values, and technical accessibility. Addressing these limitations will be essential for translating current research findings into routine clinical practice.

Looking forward, integrated diagnostic approaches combining mitochondrial functional biomarkers with genomic, proteomic, metabolomic, and oxidative stress profiling are expected to play an increasingly important role in precision reproductive medicine. Large-scale prospective multicenter studies incorporating standardized analytical methodologies and functional validation are urgently needed to establish the clinical utility of these biomarkers and to develop evidence-based diagnostic protocols capable of improving treatment selection and assisted reproductive outcomes.

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SEMAPHORIN SIGNALING IN MALE REPRODUCTIVE BIOLOGY: EMERGING ROLES IN FERTILITY

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ABSTRACT

Semaphorins represent a large family of cell-surface and secreted proteins that were initially identified as key mediators of axonal growth cone guidance in the central and peripheral nervous systems. However, over the past two decades, accumulating evidence has revealed their essential roles as critical regulators of immune system function. Among these molecules, "immune semaphorins," particularly Sema3A, Sema4D (CD100), and Sema7A (CD108), regulate diverse immunological processes, including T-cell activation, antigen-presenting cell maturation, macrophage polarization, and leukocyte migration through plexin and neuropilin receptor-mediated signaling pathways. The testis is considered an immune-privileged organ, partially protected from immune surveillance by the blood–testis barrier and specialized immunosuppressive cellular populations. Disruption of this immune homeostasis has been associated with chronic inflammation, oxidative stress, and impaired spermatogenesis. In this review, we summarize the immunoregulatory functions of immune semaphorins and discuss their potential implications in the context of the testicular immune microenvironment, macrophage-mediated inflammatory responses, and oxidative stress-related mechanisms underlying male infertility. Particular emphasis is placed on the potential immunomodulatory role of Sema3A as an emerging regulator of male reproductive function. This review aims to establish a conceptual framework for understanding the potential relationship between semaphorin signaling and male fertility, an area that remains largely unexplored and warrants further investigation.

Keywords: Semaphorins; Sema3A; Immune regulation; Testicular immune privilege; Male infertility; Inflammation; Oxidative stress; Macrophage polarization

INTRODUCTION

Male infertility is estimated to be associated with infectious and inflammatory etiologies in approximately 13–14% of cases (Babcock et al., 2026). The testis has evolved as an "immune-privileged" organ to protect autoantigenic germ cells that emerge during spermatogenesis from immune-mediated destruction. However, this immune privilege is not absolute and represents a tightly regulated yet vulnerable equilibrium that can be disrupted by systemic or local inflammatory stimuli. Over the past two decades, semaphorin family proteins, initially identified as axonal guidance molecules in the nervous system, have emerged as important regulators of immune responses, functioning as "immune semaphorins" that modulate T cell–antigen-presenting cell interactions, macrophage activity, and the magnitude of inflammatory responses (A. Kumanogoh & H. Kikutani, 2003a; Messina & Giacobini, 2013). This review aims to discuss the potential interplay between the semaphorin–plexin/neuropilin signaling axis and male fertility by integrating current immunological and andrological evidence, with particular emphasis on the regulation of the testicular immune microenvironment, macrophage-mediated inflammation, and oxidative stress-related mechanisms.

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CONCEPTUAL FRAMEWORK

1. Testicular Immune Privilege And Semaphorins

Testicular immune privilege is maintained through a complex network of overlapping mechanisms rather than a single regulatory process. These mechanisms include the blood–testis barrier formed by tight junctions between Sertoli cells, a highly immunosuppressive intratesticular cytokine and hormonal milieu (particularly transforming growth factor-beta 1 [TGF-β1] and testosterone), and the distinctive low-reactivity phenotypes of resident testicular macrophages and dendritic cells (Babcock et al., 2026). The blood–testis barrier represents one of the most specialized biological barriers, consisting of an integrated network of tight junctions, ectoplasmic specializations, desmosomes, and gap junctions. It divides the seminiferous epithelium into basal and adluminal compartments and provides structural and immunological protection for developing germ cells (Mruk & Cheng, 2015). While restricting systemic immune exposure to neoantigens expressed by meiotic and post-meiotic germ cells, this barrier is not static; rather, it undergoes dynamic remodeling to permit the controlled migration of germ cells across the seminiferous epithelium during spermatogenesis.

Sertoli cells represent central regulators of testicular immune privilege. Through the secretion of TGF-β1 and various immunosuppressive mediators, Sertoli cells suppress lymphocyte proliferation and contribute to the prolonged survival of even allogeneic tissue grafts within the testicular microenvironment (Babcock et al., 2026). In this context, semaphorin–plexin signaling, initially characterized in the nervous system as a regulator of growth cone collapse and cellular migration through actin–myosin cytoskeletal remodeling (Robert P. Kruger et al., 2005), may represent a conserved mechanism involved in cellular reorganization and barrier regulation within the testicular microenvironment. Supporting this concept, semaphorins regulate immune cell trafficking through similar cytoskeletal mechanisms, including the regulation of dendritic cell migration into lymphatic vessels via myosin II-dependent processes.

The concept of “immune semaphorins” emerged following the demonstration that semaphorin family members participate in reciprocal interactions between T cells and antigen-presenting cells, including dendritic cells, B cells, and macrophages (Atsushi Kumanogoh & Hitoshi Kikutani, 2003). SEMA4D (CD100) is constitutively expressed on resting T cells and, following cellular activation, promotes B-cell and dendritic cell maturation through interaction with its receptor CD72. Similarly, SEMA3A mediates signaling through neuropilin-1 (NRP-1) and plexin-A family receptors in both neuronal and immune cell populations (Atsushi Kumanogoh & Hitoshi Kikutani, 2003; Suzuki et al., 2008).

Whether these semaphorin–receptor signaling systems are locally expressed and functionally involved in maintaining the immune-privileged status of the testis remains largely unexplored. Therefore, elucidating the potential contribution of semaphorin signaling to the regulation of the testicular immune microenvironment may provide a novel conceptual framework for understanding the molecular mechanisms linking immune dysregulation, inflammation, and male reproductive dysfunction.

2. Macrophages and Semaphorin-Mediated Immune Regulation

Testicular macrophages represent a major leukocyte population within the testicular microenvironment, accounting for approximately 20–25% of intratesticular immune cells, and play essential roles in maintaining testicular immune privilege. These cells exhibit a characteristic alternatively activated/M2-like polarization profile, characterized by low production of pro-inflammatory cytokines, including TNF-α and IL-1β, together with enhanced secretion of immunoregulatory mediators such as IL-10 (Da Silva & Barton, 2016). The regulatory effects of semaphorins on macrophage biology have been extensively characterized within the immune system. SEMA4D has been reported to promote angiogenic and migratory signaling pathways in tumor-associated macrophages, whereas SEMA7A can attenuate inflammatory responses by inducing IL-10 production from macrophages in epithelial-associated tissues (Czopik et al., 2006; Suzuki et al., 2007). In particular, Sema7A secreted by intestinal epithelial cells has been shown to direct intestinal macrophages toward an IL-10-producing phenotype through αvβ1 integrin-mediated signaling, thereby reducing the severity of experimental colitis.

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Another well-characterized function of SEMA7A in immune regulation involves the activation of T cell-mediated inflammatory responses through interaction with α1β1 integrin (Suzuki et al., 2007). However, SEMA7A may exert either protective or pathogenic effects depending on the inflammatory context, as demonstrated in models of acute peritonitis and systemic sepsis (Czopik et al., 2006). This dual functional profile suggests that, within highly immunosuppressive tissues such as the testis, the biological outcome of semaphorin signaling, whether promoting or restraining inflammation, may be largely determined by the local cellular environment, including Sertoli cell-derived signals, androgen availability, and the phenotypic state of resident macrophages.

The effects of SEMA3A on macrophage biology are similarly complex. SEMA3A regulates monocyte/macrophage migration, cytoskeletal remodeling, and phagocytic activity through the neuropilin-1 (NRP1)/plexin-A1 receptor complex and may induce either pro-inflammatory or anti-inflammatory responses depending on macrophage activation status (Chaudhuri, 2014; Shelly et al., 2011). Recent reviews examining the involvement of the semaphorin–plexin axis in innate immune responses and inflammatory disorders, including acute inflammation and sepsis, emphasize that these molecules can modulate neutrophil and macrophage functions and influence the extent of tissue injury (Kanth et al., 2021). Collectively, these findings suggest that the potential responsiveness of testicular macrophages to semaphorin signaling represents an important and previously underexplored research direction, particularly in inflammatory conditions of the testis, including orchitis and inflammation-associated male reproductive dysfunction.

3. Cytokines, Inflammation, and Male Infertility

The detrimental impact of systemic or local inflammation on male reproductive function has been demonstrated in numerous animal and human studies. A seminal study showed that bacterial lipopolysaccharide (LPS) administration disrupts multiple aspects of testicular function in rats, including steroidogenesis, blood–testis barrier integrity, and spermatogenesis (O'Bryan et al., 2000). Such systemic inflammatory challenges activate resident testicular macrophages, resulting in increased local production of pro-inflammatory cytokines, including tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6). These inflammatory mediators contribute to impaired Leydig cell steroidogenic activity through suppression of steroidogenic enzyme expression and may directly induce damage to the germinal epithelium (Hedger, 2011).

The deleterious effects of inflammatory mediators on sperm function are largely mediated by excessive production of reactive oxygen species (ROS). Pro-inflammatory cytokines, such as TNF-α and IL-6, have been shown to enhance ROS generation in human spermatozoa, leading to lipid peroxidation, disruption of membrane integrity, and subsequent impairment of sperm motility (Tremellen, 2008). These findings provide a mechanistic basis for the recognition of leukocytospermia as an adverse prognostic indicator of semen quality, as activated leukocytes serve as both sources of inflammatory cytokines and major contributors to ROS production within the seminal environment.

Comprehensive analyses of the immunophysiology of inflammation in the testis and epididymis have highlighted that recognition of pathogen-associated signals through Toll-like receptors (TLRs) can rapidly shift the testicular immune privilege toward a pro-inflammatory state, potentially resulting in reversible or irreversible impairments in spermatogenesis (Hedger, 2011). Within this framework, the ability of immune semaphorins, particularly SEMA7A and SEMA3A, to regulate macrophage polarization and cytokine profiles may represent an additional layer of immune regulation influencing the magnitude and outcome of testicular inflammation. However, the direct contribution of semaphorin signaling to inflammation-associated male reproductive dysfunction remains largely unexplored and requires further experimental investigation.

4. Semaphorins, Oxidative Stress, and Sperm Damage

The primary cellular mechanism underlying semaphorin signaling involves the regulation of cytoskeletal dynamics through the cytoplasmic GTPase-activating protein (GAP) domains of plexin receptors, which modulate the activity of Rho family small GTPases, including RhoA, Rac1, and Rnd1 (R. P. Kruger et al., 2005). This signaling cascade contributes to the regulation of essential cellular

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processes, including cell morphology, migration, and adhesion (Oinuma et al., 2010; Pasterkamp & Giger, 2009).

Oxidative stress represents a major pathological condition characterized by an imbalance between reactive oxygen species (ROS) production and antioxidant defense mechanisms, ultimately leading to cellular damage. The contribution of oxidative stress to male infertility is well established, as excessive ROS accumulation can induce sperm DNA fragmentation, lipid peroxidation, mitochondrial dysfunction, and impaired sperm motility (Agarwal et al., 2003; Aitken & Baker, 2006; Tremellen, 2008).

Although direct evidence linking semaphorin signaling to oxidative stress remains limited, potential mechanistic associations can be proposed based on the established roles of semaphorins in regulating cytoskeletal remodeling, cellular stress responses, and inflammatory signaling pathways (Kar et al., 2020; Maione et al., 2009). For example, SEMA3A has been reported to modulate ROS production in endothelial cells and contribute to vascular inflammatory responses (Acevedo et al., 2008). Similarly, SEMA4D signaling in immune cells has been suggested to be associated with oxidative responses during cellular activation. Within the testicular microenvironment, semaphorin-mediated regulation of macrophage polarization and cytokine production may indirectly influence local oxidative stress levels (A. Kumanogoh & H. Kikutani, 2003b).

Importantly, pro-inflammatory M1-like macrophages are known to promote ROS generation, whereas alternatively activated M2-like macrophages exhibit antioxidant and tissue-repair-associated properties. Therefore, the potential ability of semaphorins to regulate macrophage polarization toward pro-inflammatory or immunoregulatory phenotypes may represent a previously unexplored mechanism influencing oxidative stress severity and subsequent sperm damage in the testis (Orecchioni et al., 2019).

Taken together, the potential involvement of semaphorin signaling in testicular oxidative stress and sperm dysfunction represents an emerging research area. Future studies should investigate whether semaphorin pathways directly interact with antioxidant defense systems, ROS-generating enzymes, or mitochondrial regulatory mechanisms to clarify their contribution to male reproductive health and infertility.

CONCLUSIONS AND FUTURE PERSPECTIVES

Beyond their well-established functions in nervous system development, semaphorins have emerged as multifunctional signaling molecules with critical roles in diverse physiological processes, including immune regulation and reproductive biology. This review has evaluated the potential relationship between immune semaphorins and male fertility within the context of the testicular immune microenvironment, macrophage-mediated inflammation, and oxidative stress based on current evidence. The potential involvement of semaphorin signaling in maintaining testicular immune privilege and regulating inflammatory responses has been highlighted. In particular, immune semaphorins such as Sema3A, Sema4D, and Sema7A may influence testicular homeostasis by modulating key immunological processes, including T-cell activation, macrophage polarization, and leukocyte trafficking.

Given the increasing recognition of inflammation and oxidative stress as important contributors to the pathophysiology of male infertility, elucidating the role of semaphorin signaling pathways in these processes represents an important area of investigation. Future studies should clarify the direct effects of semaphorins on testicular cell populations, including Sertoli cells, Leydig cells, and germ cells, as well as their potential roles in maintaining blood–testis barrier integrity and regulating oxidative stress-associated molecular pathways. Furthermore, the association between genetic variations in semaphorin-related genes or alterations in semaphorin expression profiles and human infertility should be investigated through well-designed prospective clinical studies.

Such investigations may establish semaphorins as potential diagnostic biomarkers or therapeutic targets for male infertility and contribute to the development of novel strategies for improving reproductive health outcomes.

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İŞ HAYATININ RASYONELLEŞTİRİLMESİ: ELTON MAYO'DAN DİJİTAL DAYANIKLILIK ÇAĞINA ALGORİTMİK KÜLTÜR DÖNÜŞÜMÜ

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ÖZET

Bu çalışma, sanayi devriminden günümüze iş hayatının rasyonelleştirilme sürecini çalışan kimliği ve kurum iletişimi ekseninde ele almaktadır. Frederick Taylor'ın işçiyi mekanik bir üretim aracı olarak konumlandıran katı rasyonelliğinden, Elton Mayo'nun çalışma ortamındaki sosyal etkileşimi ve çalışanın özne olarak tanınma ihtiyacını öne çıkaran yaklaşımına uzanan bu çizgi, bugün yapay zeka destekli algoritmik yönetim sistemleriyle yeni bir aşamaya girmiştir. Microsoft Teams gibi kurumsal mesajlaşma, görüntülü toplantı ve dosya paylaşım platformları ile Salesforce gibi müşteri ilişkileri yönetimi (CRM) ve performans takip sistemleri, çalışanın iletişim pratiklerini ve gündelik etkileşimlerini, insan eylemlerinin dijital izler üzerinden ölçülebilir veri setlerine dönüştürülmesi olarak tanımlanan (Mayer-Schönberger & Cukier, 2013; van Dijck, 2014) sistematik bir "verileşme" *(datafication)* sürecine dahil etmektedir. Bunun bir çıktısı olarak insani bağlar giderek ölçülebilir ve denetlenebilir algoritmik çıktılara dönüşmektedir. Platform kapitalizmi ve algoritmik yönetim literatürü genellikle makro-yapısal düzeyde tartışılmaktadır.

Bu çalışma ise "beyaz yakalı çalışanın yıllar içinde biriktirdiği mesleki tecrübe ve sezgisel uzmanlık, kurumsal arayüzler tarafından nasıl mülksüzleştirilmektedir?" diyerek özgül bir soruna eğilmektedir. Bu soruyu yanıtlamak amacıyla, Türkiye'deki kurumsal lojistik, operasyon ve müşteri hizmetleri sektörlerinde çalışan 10 beyaz yakalı profesyonelle derinlemesine görüşmeler yapılmış, elde edilen veriler Eleştirel Söylem Analizi (ESA) ve Yorumlayıcı Fenomenolojik Analiz (YFA) yöntemleriyle incelenmiştir. Bulgular, kurumsal söylemde bir yetkinlik olarak sunulan "dijital dayanıklılık" kavramının, algoritmik rasyonelleşmenin yarattığı yabancılaşmayı ve dijital tükenmişliği görünmez kılan ideolojik bir işlev gördüğünü ortaya koymaktadır.

Anahtar Kelimeler: Algoritmik Kültür, Rasyonelleşme, Verileşme *(Datafication)*, Dijital Dayanıklılık, Eleştirel Söylem Analizi.

ABSTRACT

This study examines the rationalization process of work life from the Industrial Revolution to the present day, focusing on employee identity and corporate communication. Moving from the rigid rationality of Frederick Taylor's scientific management—which positioned the worker as a mechanical tool—to Elton Mayo's approach, which emphasized social interaction and the recognition of the employee as a subject, this lineage has entered a new phase with AI-supported algorithmic management systems. Contemporary corporate platforms such as Microsoft Teams and Salesforce systematically incorporate informal workplace practices and daily interactions into a process of "datafication." As a result, human connections are increasingly transformed into measurable and controllable algorithmic outputs. While platform capitalism and algorithmic management literature are often discussed at a macro-structural level, this study addresses a specific question: How do corporate interfaces reshape the professional expertise and intuitive knowledge of white-collar workers within the framework of algorithmic governance? To answer this, in-depth interviews were conducted with 10 white-collar professionals working in the logistics, operations, and customer service sectors in Turkey. The data were analyzed using Critical Discourse Analysis (CDA) and Interpretative Phenomenological Analysis (IPA). The findings reveal that the concept of "digital resilience," presented as a competence in corporate discourse,

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serves as an ideological strategy that renders the alienation and digital burnout caused by algorithmic rationalization invisible.

Keywords: Algorithmic Culture, Rationalization, Datafication, Digital Resilience, Critical Discourse Analysis.

Giriş

Endüstrileşme döneminin klasik yönetim anlayışından kopan çalışma pratikleri, günümüzde algoritmik yönetim sistemleri ve veri odaklı denetim mekanizmaları üzerinden yeni bir dönüşüme ulaşmıştır. Bu çalışma, söz konusu değişimin günümüzdeki en belirgin yansıması olan "dijital dayanıklılık" söyleminin, yapısal sömürüyü bireysel bir uyum sorununa nasıl indirgediğini ele almaktadır.

Kurumsal söylemde bir yetkinlik olarak sunulan "dijital dayanıklılık", Shoshana Zuboff'un (2021) gözetim kapitalizmi çerçevesinde vurguladığı üzere, demokratik düzenin sürdürülebilirliği ile gözetim toplumunun mekanizmaları arasındaki temel çelişkiyi örtbas etmektedir. Literatürde sıkça tartışıldığı gibi, "demokrasinin varlığı ile gözetim toplumunun aynı anda ikame edilmesi" imkansız bir çelişkidir. Bu bağlamda "dijital dayanıklılık" söylemi, çalışanı söz konusu gözetim mekanizmalarına gönüllü bir aktör olarak eklemleyerek, bu çelişkiyi bireysel bir uyum sorununa indirgemektedir (Fisher, 2011; Joseph, 2013).

Günümüz algoritmik kültüründe bu rasyonelleştirme süreci, yapay zeka ve veri analitiği aracılığıyla yeni bir aşamaya taşınmıştır. Microsoft Teams gibi kurumsal mesajlaşma, görüntülü toplantı ve dosya paylaşım platformları ile Salesforce gibi müşteri ilişkileri yönetimi (CRM) ve performans takip sistemleri, çalışanın iletişim pratiklerini ve gündelik etkileşimlerini sistematik bir "verileşme" (datafication) sürecine dahil etmektedir. Gönderilen her mesaj, katılınan her toplantının süresi veya tamamlanan görev sayısı, sistem tarafından kayıt altına alınan ölçülebilir bir veri noktasına dönüşmektedir (Fuchs, 2016). Michael Burawoy'un (1979) endüstriyel üretimde işçinin sisteme nasıl eklemlendiğini açıklayan "rızanın imali" tezi, bugün bu tür platformlar üzerinden izlenen performans metrikleri ve esneklik söylemleri aracılığıyla yeniden üretilmektedir; çalışanlar "dayanıklı" kalarak kendi sömürü süreçlerinin özneleri haline gelmektedir. Bu noktada kurumsal söylemde bir yetkinlik olarak sunulan "dijital dayanıklılık" (digital resilience) kavramı, Shoshana Zuboff'un (2021) gözetim kapitalizmi çerçevesinde vurguladığı üzere, demokratik düzenin sürdürülebilirliği ile gözetim toplumunun mekanizmaları birbirini dışlayan bir yapıdadır. Literatürde sıkça tartışıldığı gibi, "demokrasinin varlığı ile gözetim toplumunun aynı anda ikame edilmesi" imkansız bir çelişkidir. Bu bağlamda "dijital dayanıklılık" söylemi, çalışanı söz konusu gözetim mekanizmalarına gönüllü bir aktör olarak eklemleyerek, bu çelişkiyi bireysel bir uyum sorununa indirgemektedir.

Taina Bucher'ın (2018) algoritmik görünürlük yaklaşımı, bu kurumsal arayüzlerin sadece iş süreçlerini koordine eden teknik araçlar olmadığını, aynı zamanda çalışanın yıllar içinde biriktirdiği örtük bilgiyi (tacit knowledge) işleyen ve mülksüzleştiren yapısal mekanizmalar olduğunu göstermektedir. Nick Srnicek'in (2019) "platform kapitalizmi" kavramsallaştırmasını da içeren bu eleştirel yazına karşın, egemen yönetim ve organizasyon literatürü algoritmik yönetimi genellikle teknik bir zorunluluk, "dijital dayanıklılık" söylemini ise kriz anlarında geliştirilen olumlu bir yetkinlik olarak okuma eğilimindedir. Oysa dayanıklılık kavramı, sistemsel bir kapasiteyi tanımlamaktan çok, sorumluluğu bireye kaydıran bir yönetişim tekniği olarak da okunabilir (Joseph, 2013). Türkiye'deki yazında da kurumsal iletişimin dijitalleşmesi ve bunun yarattığı yabancılaşma son dönemde tartışılmaya başlanmış olsa da (Özdemir, 2014; Çelik & Öz, 2022; Yılmaz, 2021), bu çalışmaların büyük ölçüde makro-yapısal düzeyde kaldığı gözlemlenmektedir. Çalışanın mikro düzeydeki öznel deneyimini ve mesleki tecrübesinin nasıl dönüştüğünü inceleyen ampirik çalışmaların sınırlı olduğu görülmektedir.

Literatürdeki bu boşluk, çalışmanın temel sorunsalını oluşturmaktadır. Mayo ile başlayan "insanı merkeze alma" yaklaşımı, günümüz dijital ekosisteminde algoritmik yönetim aracılığıyla nasıl yeni ve daha incelikli bir tahakküm biçimine dönüşmüştür? Egemen literatür "dijital dayanıklılık" olgusunu nötr ve işlevsel bir esneklik başarısı olarak ele alma eğilimindeyken, bu çalışma söz konusu söylemin arkasındaki hegemonik boyutu deşifre etmeyi amaçlamaktadır. Nitekim Mayo'nun fabrikada keşfettiği

ilgi ve aidiyet ihtiyacı, bugün dijital platformlar tarafından bireyi sistemde tutmak için araçsallaştırılmakta; çalışanın sosyal ve iletişimsel ihtiyaçları özgür birer tercih olmaktan çıkarılarak algoritmik verimlilik adına birer veri girdisine dönüştürülmektedir (Netchitailova, 2020). Mark Fisher'ın "kapitalist gerçekçilik" çerçevesinde tartıştığı "stresin özelleştirilmesi" kavramı bu noktada açıklayıcı bir zemin sunmaktadır: dijitalleşmenin yapısal koşullarından kaynaklanan tükenmişlik ve uyum sorunları, "dijital dayanıklılık" söylemi aracılığıyla bireyin kendi psikolojik becerisiyle çözmesi gereken kişisel bir mesele olarak yeniden çerçevelenmektedir. Bu çerçeveleme, sorumluluğu kurumsal yapıdan bireye kaydırarak hem yabancılaşmayı görünmez kılmakta hem de eleştirel sorgulamayı geciktirmektedir.

Bu doğrultuda çalışmanın amacı, işyeri iletişiminin ve tecrübe aktarımının geçirdiği dönüşümü, klasik yönetim teorileri (Taylorizm ve İnsan İlişkileri Yaklaşımı) ile güncel algoritmik sistemler bağlamında karşılaştırmalı olarak incelemektir. Çalışma, kurumsal söylemde olumlanan "dijital dayanıklılık" kavramının, algoritmik denetim altındaki beyaz yakalı çalışanların yabancılaşma ve dijital tükenmişlik süreçlerini nasıl rasyonalize ettiğini eleştirel ve ampirik bir düzlemde ortaya koymayı hedeflemektedir.

Çalışmanın önemi, yapay zeka ve veriyi genellikle "teknolojik donanım" çerçevesinde ele alan ana akım yaklaşımın aksine, dijitalleşmeyi iletişimsel ve kültürel bir rasyonelleşme süreci olarak incelemesinden kaynaklanmaktadır. Veriyi "yeni dünyanın petrolü" olarak fetişleştiren söylemlere karşılık bu araştırma, çalışanın nasıl "verileşmiş bir özneye" dönüştüğünü saptaması bakımından alana özgün bir katkı sunmayı amaçlamaktadır. Bu çerçevede çalışma, iletişim sosyolojisi ve dijital emek alanlarını kesiştirerek; örgüt içi iletişimin artık yalnızca bilgi aktarımına hizmet eden teknik bir süreç değil, aynı zamanda öznelliğin ve mesleki kimliğin yeniden inşa edildiği bir iktidar alanı olduğunu göstermeyi hedeflemektedir. Ayrıca çalışma, uluslararası literatürdeki teorik tartışmaları Türkiye'deki kurumsal lojistik, operasyon ve müşteri hizmetleri sektörlerinin özgül ampirik dinamikleriyle harmanlayarak, bu alanlardaki yerel yazın boşluğunu doldurmayı hedeflemektedir.

Bu amaç çerçevesinde çalışma üç temel soruya yanıt aramaktadır:

Lojistik, operasyon ve müşteri hizmetleri sektörlerindeki kurumsal söylem, "dijital dayanıklılık" kavramını algoritmik rasyonelleşmeyi ve dijital tükenmişliği rasyonalize etmek için nasıl inşa etmektedir?

Beyaz yakalı çalışanlar, kurumsal platformlar (Teams, Salesforce vb.) aracılığıyla gerçekleşen "verileşme" süreçlerini ve bu süreçlerin yarattığı yabancılaşmayı nasıl deneyimlemektedir?

Çalışanlar, algoritmik kültürün getirdiği görünürlük rejimlerine ve tasarlanmış boyun eğme mekanizmalarına karşı ne tür uyumlanma veya mikro-direniş pratikleri geliştirmektedir?

Bu sorulara yanıt aramak amacıyla çalışma, karma bir nitel araştırma deseni üzerine kurgulanmıştır. Kurumsal vizyon belgeleri ve platform arayüzleri Fairclough'un (2019) Eleştirel Söylem Analizi (ESA) yöntemiyle incelenmiş ve bu söylem altında şekillenen çalışan öznelliği ve yabancılaşma deneyimi ise Smith, Flowers ve Larkin'in geliştirdiği Yorumlayıcı Fenomenolojik Analiz (YFA) yöntemiyle çözümlenmiştir. Katılımcılar, nitel örnekleme yöntemlerinden “ölçüt örnekleme” (*criterion sampling*) stratejisiyle belirlenmiştir (Creswell, 2015). Araştırmaya dahil edilme ölçütleri arasında lojistik, operasyon veya müşteri hizmetleri sektörlerinde beyaz yakalı statüsünde çalışmak ve en az iki yıldır Microsoft Teams, Salesforce veya benzeri algoritmik performans platformlarını aktif olarak kullanmak yer almaktadır. Bu ölçütler çerçevesinde, Türkiye'deki ilgili sektörlerde çalışan 10 beyaz yakalı profesyonelle derinlemesine görüşmeler gerçekleştirilmiştir; katılımcı sayısının sınırlı tutulması, YFA'nın ideografik (birey merkezli) odağına uygun olarak her bir öznenin deneyimini derinlemesine analiz edebilmek amacıyla yapılmış metodolojik bir tercihtir. Veri toplama sürecinde kurumsal dokümanlar ile görüşme verileri birlikte kullanılarak metodolojik çeşitlendirme (triangulation) sağlanmış ve bu sayede hem kurumsal söylemin makro düzeydeki ideolojik inşası hem de bu söylemin çalışan deneyiminde yarattığı mikro düzeydeki kırılmalar aynı çalışma içinde görünür kılınmıştır.

Çalışmanın ilerleyen bölümlerinde önce Taylorizm'den Mayo'nun İnsan İlişkileri Yaklaşımı'na, oradan da algoritmik yönetim ve gözetim kapitalizmi tartışmalarına uzanan kuramsal çerçeve detaylandırılacak; ardından araştırmanın yöntemi ve örneklemine ilişkin ayrıntılar sunulacaktır. Bulgular bölümünde

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katılımcı ifadelerinden hareketle aidiyetin buharlaşması, tecrübenin mekanizasyonu ve iş güvencesi kaygısı temaları tartışılacak; sonuç bölümünde ise bu bulguların alana sunduğu kuramsal ve ampirik katkı değerlendirilecektir.

Bu bağlamda çalışma, kurumsal bir eleştiriden ziyade, yapısal ve teknolojik etkileşimin sosyolojik bir okumasını amaçlamakta; lojistik sektörünün dinamiklerini, dijital dönüşümün beyaz yakalı emek üzerindeki yapısal etkilerini görünür kılmak için bir "gözlem alanı" olarak kullanmaktadır.

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THE ENERGY POTENTIAL OF THE CASPIAN SEA AS AN ALTERNATIVE ENERGY SOURCE

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ABSTRACT

The Caspian Sea, the largest inland body of water in the world, holds considerable scientific, ecological, and economic significance owing to its unique nature and biological wealth. In recent years, rapid industrialization, population growth, and resource extraction have disturbed the ecological equilibrium of the Caspian basin, manifesting as water pollution, biodiversity loss, and ecosystem degradation. At the same time, rising global energy consumption and the negative environmental impact of non-renewable resources call for new, sustainable solutions. This paper examines the natural characteristics and ecological status of the Caspian Sea and evaluates its potential as a source of alternative energy, with particular attention to wind, solar, hybrid, and biotechnological opportunities along its coast. The study draws on the current experience of the littoral states — Azerbaijan, Kazakhstan, Turkmenistan, and Uzbekistan — in developing renewable energy capacity and positions the Caspian region as an emerging supplier of green energy, including green hydrogen, to European markets. The findings indicate that favorable wind speeds, high solar radiation, and the presence of native microalgae species such as Spirulina create strong prospects for diversifying the region's energy base while reducing dependence on fossil fuels and supporting international climate commitments.

Keywords: Caspian Sea, alternative energy, renewable energy, wind energy, hybrid energy systems, Spirulina, Azerbaijan.

INTRODUCTION

The Caspian Sea has always been a subject of study and of great significance from a scientific, ecological, and economic point of view because of its unique nature, biological wealth, and strategic relevance.

During recent years, rapid industrialization and population growth, as well as resource extraction, have contributed to changes in the ecological equilibrium within the basin of the Caspian Sea. In particular, such problems as water pollution, biodiversity decrease, and destruction of the ecosystem were noted. On the other hand, the increase in global energy consumption together with the negative effects of the use of non-renewable resources makes it necessary to find new solutions for sustainable energy generation.

Taking into consideration this situation, the application of alternative energy sources becomes particularly relevant. The Caspian Sea area may become attractive for the development of wind, solar, and hybrid energy systems owing to the presence of favorable climatic conditions, such as regular winds and a high level of solar radiation. The adoption of renewable energy sources may be considered a way of reducing greenhouse gas emissions, enhancing energy security, and promoting sustainable economic development. Therefore, studying the energy sources of the Caspian Sea and evaluating the possibilities of alternative energy sources is a scientifically relevant and topical task.

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The Caspian Sea is a detached inland water body with no immediate connection to the world ocean, and this isolation exerts a considerable impact on its properties. The sea should be considered not as a single entity but rather as three major areas — the Northern, Middle, and Southern Caspian — each having different depths, salinity levels, and other environmental features. The Northern Caspian is shallow and strongly affected by freshwater inflow, especially from the Volga River, while the Southern Caspian is characterized by high depth and a constant hydrochemical composition.

The Caspian Sea is also characterized by considerable biodiversity, including about 850 species of animals and over 500 species of plants, some of which are endemic. The wetlands of the basin serve as a habitat for over 400 species of birds, and the sea is traditionally known for its sturgeon species, which produce the most valuable caviar in the world. However, overfishing, habitat destruction, pollution, invasive species such as Mnemiopsis leidyi, and climate change continue to threaten this biodiversity, highlighting the need for effective environmental protection alongside the search for sustainable energy alternatives.

RESEARCH AND FINDINGS

Use of Alternative Energy Sources in the World

Alternative energy is energy generated from sources and technologies that do not deplete natural resources and cause minimal harm to the environment. Renewable energy is extracted from natural sources that regenerate themselves within a relatively short period, such as biomass, solar, wind, and hydro energy, while green energy refers specifically to renewable energy with minimal environmental impact.

Forecasts indicate that global energy consumption and CO2 emissions will double by 2030 and triple by 2050. As of 2018, renewable energy sources accounted for 25.1% of global electricity generation (35.3% including nuclear power), with hydropower contributing 15.8%, wind energy 4.8%, solar energy 2.2%, and bioenergy 2.0%. Some 66 states, including all EU members, 29 US states, and 9 Canadian provinces, have introduced policy programs for alternative energy development, and 44 countries have established renewable energy standards.

National experience varies considerably: in Germany, renewable sources produced more electricity than coal and nuclear power combined for the first time in 2019 (47.3% versus 43.4%); in Canada, hydroelectric, wind, solar, and biomass sources together with geothermal and marine energy accounted for more than 70% of electricity generation in 2018; and in Kazakhstan, renewable energy sources, though still limited to 1.3% of total generation, increased fivefold over five years, supported by favorable geographic conditions and the 2017 EXPO exhibition dedicated to future energy technologies.

Renewable Energy Prospects in Azerbaijan

The energy sector is strategically important for Azerbaijan's economic development and its position in the regional energy market. The development of renewables is among the main goals of the country's energy policy, formalized through Presidential Decree No. 1209 of 2019 on accelerating reforms in the energy sector and the 2021 Law on the Use of Renewable Energy in the Production of Electricity. Azerbaijan's renewable energy resources include an onshore potential of 135 GW and an offshore potential of 157 GW, with an economic potential of about 27 GW, comprising 3,000 MW of wind energy, 23,000 MW of solar energy, 380 MW of biomass energy, and 520 MW of hydroenergy from mountain rivers.

As of the study period, Azerbaijan's renewable energy power plants had an installed capacity of 1,829.6 MW, including 65 hydropower stations, five wind power stations, nine solar power plants, one biomass power plant, and three hybrid power plants, together generating about 18.8% of total electricity. Major projects under development include the Garadagh Solar Energy Project (230 MW, with Masdar of the UAE), the Khizi-Absheron Wind Energy Project (240 MW, with ACWA Power

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of Saudi Arabia), the Shafag Solar Energy Project (240 MW, with bp), the Masdar mega-initiative in Bilasuvar and Neftchala, the Gobustan Solar Energy Facility, and the Ufug and Shams Solar Power Plants developed as part of the Green Energy Zone established in the liberated territories. Azerbaijan has also piloted a floating solar plant at Boyukshor Lake and has published a National Strategic Review for Hydrogen, highlighting the profitability of green hydrogen production for both export and domestic use.

Azerbaijan has voluntarily committed to reducing emissions by 40% by 2050 and to raising the share of renewable energy investment to 30% of its total energy portfolio by 2030. At COP29, held in Baku, the country supported the Global Pledge on Renewable Energy and Energy Efficiency as well as the Global Energy Storage and Grids Pledge, the Green Energy Zones and Corridors Pledge, and the Hydrogen Declaration.

Advantages of Utilizing the Energy Potential of the Caspian Sea

Since 2022, the European Union has shown increasing interest in the prospects for green energy development in the Caspian Sea, focusing especially on green hydrogen alongside solar and wind energy. Kazakhstan, Azerbaijan, and neighboring Uzbekistan have made explicit commitments to become important renewable energy suppliers to the EU: Uzbekistan aims to add 20 GW of wind and solar capacity, Kazakhstan aims to add 5 GW by 2030, and Azerbaijan intends to generate 5 GW of energy from wind and solar power by the same year. Successful implementation of green hydrogen exports will depend on effective logistics, including the Trans-Caspian International Transport Route, which allows delivery of products without transiting Russia.

Tidal motions in the Caspian Sea are forced vibrations arising within the water mass itself, since the sea is isolated from the World Ocean and receives no external tidal influence. Semidiurnal and diurnal tidal peaks are observed in the Middle and Southern Caspian, while no such peaks arise in the Northern Caspian, where wind and river discharge are the dominant factors affecting water level. The greatest tidal amplitude, associated with a 100-year recurrence model, is 21 centimeters in the southeastern part of the sea near Aladga. Wind-induced surges are far more significant than tidal fluctuations: maximum positive surges of 4.5 m above mean sea level have been recorded near Kaspiysky, while negative surges of up to □3 m occur in the eastern part of the Northern Caspian, extending flooded zones up to 50 km in width.

The evaluation of wind energy resources shows significant opportunities along the Caspian coast. Average annual wind speeds near the western coast, particularly around the Absheron Peninsula, fall between 7 and 9 m/s, an optimal range for wind turbine operation. The steady nature of offshore winds and reduced turbulence increase the feasibility of offshore wind farms, where turbines convert wind kinetic energy into electricity that is transferred via underwater cables to offshore substations, then exported to shore for distribution. Wind power generation follows the standard relation $P = (1/2)\cdot\square\cdot A\cdot v^3$, where □ is air density, A is the swept area of the turbine blades, and v is wind velocity.

Hybrid Renewable Energy Systems (HRES), which combine multiple renewable sources such as solar photovoltaics and wind turbines, offer a practical solution to the limitations of individual technologies: photovoltaic panels generate little power at night or in overcast conditions, while wind turbines are inefficient at very low or very high wind speeds. Combining the two technologies compensates for their seasonal variation, since wind turbines typically generate more power in winter and photovoltaics more in summer. In the Caspian Sea, offshore oil and gas platforms currently rely on fossil fuels delivered by ship, a practice vulnerable to weather disruption and associated with environmental risk; hybrid solar-wind systems installed on these platforms could reduce fossil fuel consumption and environmental impact.

Beyond physical energy sources, the Caspian Sea also offers biotechnological potential. The microalga Spirulina platensis, valued in the food and pharmaceutical industries for its high protein, vitamin, and antioxidant content, has been shown to replace fish meal protein in the diet of species.

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such as Nile tilapia, guppy fish, rainbow trout, catfish, and rohu without adversely affecting growth performance, while also improving immune response parameters. Because the cost of producing and transporting commercial Spirulina is high, isolating native Spirulina-like cyanobacteria from the Caspian Sea — such as the native strain identified as Spirulina laxissima with 99.9% genetic similarity in molecular analysis — may reduce production costs for the livestock, poultry, and aquaculture industries. Optimization of growth conditions such as light, temperature, and pH using Response Surface Methodology has been shown to positively influence biomass yield under laboratory conditions.

CONCLUSION

The Caspian Sea is an important ecological and geographical ecosystem that plays a significant role in both environmental and economic terms, yet it continues to face rising pressure from industrial activity, oil and gas production, agricultural pollutants, invasive species, and climate change, all of which have contributed to biodiversity loss, including declines in sturgeon and Caspian seal populations.

At the same time, the Caspian Sea region shows great potential for developing wind, solar, and hybrid energy technologies owing to its favorable climatic conditions and geographic features. The use of wind energy in combination with other renewable sources along the coastal area can reduce dependence on fossil fuels, strengthen energy security, and support global decarbonization initiatives, while Hybrid Renewable Energy Systems offer a technologically sound approach to resolving the intermittency of individual renewable sources.

Finally, biotechnological investigations of native microalgae such as Spirulina laxissima demonstrate additional potential for wastewater treatment, aquaculture, and bio-resource production, suggesting that a comprehensive strategy for the Caspian Sea should combine renewable energy development with ecosystem protection and biotechnological innovation. Achieving this balance will require sustained international cooperation among the littoral states, appropriate legislative frameworks, and continued investment in green finance and infrastructure.

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IMPROVING DYNAMIC BALANCE IN YOUTH FOOTBALL THROUGH AN 18-WEEK CORE TRAINING PROGRAM

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ABSTRACT

In modern football, postural control and dynamic balance are critical elements for optimizing athletic performance and preventing non-contact lower-limb injuries in young players.

This study aimed to evaluate the impact of a structured 18-week core training program on dynamic stability, lumbopelvic muscular endurance, and explosive-reactive performance parameters.

Twenty male youth football players (aged 15–17 years) participated in this experimental study. The 18-week intervention (3 sessions/week) followed a progressive three-phase model: activation, construction, and functional integration. Pre- and post-intervention evaluations included dynamic balance via the Star Excursion Balance Test (SEBT) and BOSU balance assessment, trunk isometric endurance (Plank, Sørensen, Trunk Flexor/Lateral Endurance tests), and jump kinematic performance via the OptoJump system (Squat Jump, Countermovement Jump, Reactive Strength Index - RSI).

Post-test assessments demonstrated significant improvements across all SEBT directions (+6.2 cm to +7.5 cm mean increase). Core muscular endurance improved uniformly: Frontal Plank by +24.76% ($p<0.05$), Sørensen Test by +28.78% ($p<0.05$), and Lateral Plank by +30.8%. OptoJump evaluation revealed increased jump height in Squat Jump (2.5–3.5 cm) and CMJ (3–4 cm), accompanied by a reduction in ground contact time (15–25 ms) and an RSI increase of 10–18%.

An 18 week progressive core training program significantly enhances dynamic stability, increases core stiffness, and optimizes energy transfer during the stretch-shortening cycle (SSC). Integrating this protocol into youth football conditioning and rehabilitation is strongly recommended for injury prevention and performance enhancement.

Keywords: Dynamic balance, Core training, Youth football, SEBT, OptoJump, Injury prevention.

INTRODUCTION

Football is characterized by continuous, high-intensity intermittent movements, requiring players to repeatedly execute explosive actions such as sprinting, dribbling, tackling, and shooting. These physical demands place significant stress on the musculoskeletal system, particularly on the lower extremities. The most prevalent injuries in football include:

- **Anterior Cruciate Ligament (ACL) Tears:** Typically caused by sudden deceleration, plant-and-cut maneuvers, and rapid changes of direction.
- **Hamstring Strain Injuries:** Primarily resulting from high-speed running, maximal sprinting, and mechanical overload during the late swing phase.
- **Ankle Sprains:** Frequently occurring during physical tackles, direct contact, or single-leg landings from jumps.

The high prevalence of these injuries highlights the critical importance of preventive strategies, which primarily focus on enhancing balance and postural stability. Dynamic balance and core stability training constitute essential components of these regimens, offering significant benefits in both injury prevention and rehabilitation protocols [1].

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As football continues its global expansion and commercialization, the age at which athletes join professional teams is steadily decreasing. Consequently, the development of high-level motor capabilities prior to entering elite competition has become imperative. Physical proficiency and motor control have thus emerged as indispensable attributes for both preventive measures and rehabilitative pathways. Furthermore, as a high-impact sport with injuries resulting from both contact and non-contact mechanisms, football presents a substantial risk of musculoskeletal trauma. Indeed, the injury risk for professional players has been shown to be up to 1,000 times higher than that of the general population [3].

Eccentric training, the assessment of eccentric-concentric strength ratios, plyometrics, proprioceptive training, and particularly balance optimization have become fundamental components in the rehabilitation of lower-limb injuries in football players, as these structures experience the highest functional loads and injury rates in the sport [2]. Consequently, core strengthening plays a pivotal role in modern injury prevention programs, such as the "FIFA 11+" protocol.

Although the analytical biomechanics of trunk musculature and isolated exercises are well documented, current research and athletic practice have shifted toward a holistic, movement-based functional approach. This methodology targets sport-specific movement patterns by fostering optimal interaction between muscular and articular components. Such biomechanical efficiency is essential given the match demands: during high-level competition, a player performs a sprint approximately every 90 seconds, with each bout lasting an average of 2 to 4 seconds [9], underscoring the short and explosive nature of match sprinting [8].

Although the biomechanics of the trunk region and the analysis of isolated exercises are well documented, research interest has shifted toward a holistic functional framework. Movement-specific training is replacing the conditioning of isolated muscle groups to achieve system balance, where muscular and articular components interact harmoniously to perform complex motor tasks. Consequently, the traditional concept of "abdominal musculature" has been superseded by the comprehensive paradigm of Core Stability.

Anatomically, core stability encompasses the lumbopelvic-hip complex and functions to maintain spinal equilibrium within physiological limits, thereby reducing undesirable displacement and preserving structural integrity [6]. From a functional perspective, the core operates as an essential kinetic chain, facilitating the optimal transfer of force and energy between the lower and upper extremities [7].

This experimental study investigates the impact of an 18-week integrated core training mesocycle (3 sessions per week) among youth football players aged 15–17 years. The intervention applied a progressive loading and mechanical instability design, with standard pre- and post-intervention measurements. The study aims to evaluate the effectiveness of core training in enhancing dynamic balance, postural stability, and lumbopelvic muscular endurance as critical components for injury prevention and rehabilitation in youth football.

Dynamic balance is defined as the ability to maintain postural stability during movement and represents a critical motor capacity in football. This necessity stems from the inherently unpredictable nature of the sport, which is characterized by explosive accelerations, rapid changes of direction, and frequent physical contact. The findings and recommendations presented in this study contribute to the scientific body of knowledge in sports physiotherapy, providing a valuable evidence-based resource for practitioners working with athletes across all competitive levels.

Core Concept in Rehabilitation

The concept of the Core has received substantial attention in both scientific literature and mainstream media over the past several decades [1]. However, a universally accepted definition remains elusive, as the concept assumes varying interpretations based on author perspective and contextual application.

Historically, the core was conceptualized as a "cylindrical box" bounded by the abdominal musculature anteriorly, the paraspinal and gluteal muscles posteriorly, the diaphragm superiorly, and the pelvic floor along with the coxofemoral joint inferiorly. Subsequent frameworks expanded this concept, defining it as the "lumbopelvic-hip complex", which encompasses the lumbar spine, pelvis, hip joints, and all

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associated musculature responsible for producing or restricting movement across these segments [4]. As noted in the literature, the definition of core stability is intrinsically tied to its domain of application, exhibiting distinct operational focus across biomechanical laboratories, clinical rehabilitation settings, and athletic training environments [5].

Considering these aspects, the authors proposed the following operational definition: core stability is the capacity of the osteoarticular and muscular structures, coordinated by the motor control system, to maintain or restore a intended trunk position or trajectory when subjected to internal or external forces.

The core structure comprises both passive and active elements:

- Passive structures include the thoracolumbar spine and the pelvis;
- Active structures consist of the surrounding trunk musculature.

These muscles are responsible for maintaining segmental stability of the spine and pelvis, while facilitating the generation and transfer of forces between the trunk and extremities during athletic performance. Consequently, beyond its stabilizing function, the core exerts a dynamic and motor control function, fundamentally because the trunk serves as the anatomical link between the upper and lower extremities.

Core stability plays a vital role in movement functionality and athletic performance. Strengthening these muscles influences the central nervous system by enhancing feed-forward mechanisms that prepare the trunk and pelvis to act as a solid foundation. This neuromuscular optimization improves overall movement efficiency, enhances dynamic control, and contributes significantly to injury prevention during sports activities [11].

METODOLOGY

This study was conducted in collaboration with an active youth football academy in Albania, focusing on players aged 15–17 years (U-17). This age category was selected as it represents a critical window of physical and neuromuscular development, during which the incidence of sport-specific injuries increases substantially, underscoring the need for targeted preventive and rehabilitative interventions. Integrating core stability training and developing static and dynamic balance during this developmental stage facilitates not only functional recovery, but also the optimization of athletic performance.

This paper details the statistical methodology employed for data analysis and interpretation to ensure scientific rigor and validity. The analytical framework focuses on comparative evaluations between the experimental and control groups. The primary objective of this study is to evaluate the impact of a structured core training intervention on enhancing dynamic stability in youth football players, thereby advancing evidence-based conditioning and rehabilitation strategies in high-demand neuromuscular sports such as football.

This study employed a controlled experimental pre-test/post-test design. The intervention spanned an 18-week period with a frequency of three training sessions per week, a duration deemed sufficient to induce neuromuscular adaptations, structural changes, and functional performance enhancements. The study cohort comprised 20 elite male youth football players (aged 15–17 years) actively engaged in structured athletic training.

To evaluate the efficacy of the core training intervention, all participants underwent a comprehensive battery of functional and biomechanical assessments at two specific time points: baseline (pre-test) and following the 18-week intervention (*post-test*). Baseline assessments were conducted to establish initial performance levels and ensure baseline homogeneity between the experimental and control groups. Post-intervention testing followed identical standardized procedures and environmental conditions, enabling an objective evaluation of changes in dynamic stability and neuromuscular control.

In this study, a comprehensive battery of standardized functional and biomechanical assessments was implemented to evaluate dynamic stability, muscular endurance, and neuromuscular control:

1. Star Excursion Balance Test (SEBT) Dynamic balance and postural control were evaluated using the Star Excursion Balance Test (SEBT). This test assesses the participant's capability to maintain

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single-leg postural stability while maximally reaching with the contralateral limb in specific directions. During testing, participants maintained a single-leg stance at the center of the grid and executed controlled reaches with the free extremity without compromising balance or lifting the stance foot. The testing protocol incorporated three primary reach directions: anterior, anteromedial, and anterolateral, performed on both the dominant and non-dominant limbs. The maximum reach distance for each direction was recorded, and the composite mean score across the three reach directions was calculated for both extremities.



Figure 1. Star Excursion Balance Test (SEBT)

2. BOSU balance assessment was utilized to evaluate neuromuscular control and postural adaptability under conditions of mechanical instability. This functional assessment measures the athlete's capacity to maintain trunk and lower-limb stability while dynamically responding to postural perturbations, thereby simulating the unstable, sport-specific demands encountered during high-level match play**.**



Figure 2 . BOSU balance assessment

3. Sorensen test was utilized to evaluate the isometric endurance capacity of the trunk extensor musculature, specifically targeting the lumbar and paraspinal muscle groups. Widely recognized as a gold-standard assessment in sports rehabilitation and exercise science, this test provides a validated metric of posterior core muscle function and postural stability. In the present study, the Sørensen test was administered to quantify the participants' capacity to maintain dynamic trunk alignment during sustained isometric contraction, as well as to detect neuromuscular adaptations in muscular endurance prior to and following the 18-week core training program

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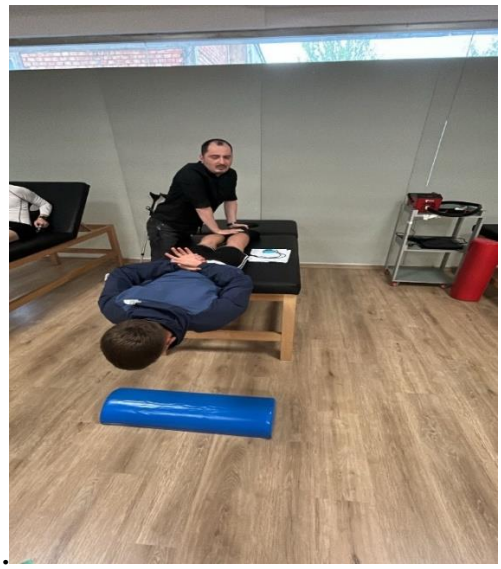


Figure 3. Sorensen Test

4. Trunk Flexor Endurance Test was administered to quantify the muscular endurance of the anterior trunk flexors and assess the capacity of the local stabilizing musculature to sustain postural control during prolonged isometric contractions. This assessment serves as a fundamental component of the dynamic core stability evaluation battery, as the endurance capacity of the anterior core complex is intrinsically linked to lumbopelvic stability, athletic performance optimization, and the mitigation of musculoskeletal injury risk..



Figure 4. Trunk Flexor Endurance Test

5. The Side Bridge Test was utilized to quantify the isometric endurance of the lateral trunk stabilizers (primarily the Quadratus Lumborum and oblique complex). Participants assumed a side-plank position, supporting their body weight on the ipsilateral forearm with the torso elevated and aligned in a straight line from head to ankles. Timing commenced immediately upon establishing the standardized biomechanical position. The test was terminated when the participant failed to maintain the neutral alignment of the trunk (pelvic sag) or could no longer sustain the supporting position. Measurements were performed bilaterally for both the left and right sides.

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6. The Front Plank Test was administered to evaluate global core muscle endurance and capture functional stability adaptations prior to and following the 18-week training intervention. Participants maintained a prone forearm plank stance supported by the forearms and toes, with the elbows positioned directly beneath the shoulder joints. The body was maintained in a rigid straight line from head to ankles, engaging the abdominal and gluteal musculature to avoid compensatory lumbar lordosis. Holding time was recorded in seconds until muscle failure or until the participant could no longer maintain correct postural alignment.



Figure 5. Plank Test

7. OptoJump system was utilized to quantify neuromuscular performance, explosive power, and biomechanical vertical jump parameters prior to and following the 18-week core training intervention. This assessment aimed to evaluate the impact of core stability enhancements on dynamic neuromuscular control and reactive capacity in youth football players.

The testing battery encompassed the following standardized jumping protocols:

- Squat Jump (SJ): Evaluated concentric explosive power in the absence of the stretch-shortening cycle (SSC);
- Countermovement Jump (CMJ): Assessed explosive power utilizing elastic energy storage and myotatic reflex potentiation;
- Single-Leg Countermovement Jump (SL-CMJ): Measured unilateral force production and identified inter-limb functional asymmetries;
- Drop Jump (DJ): Evaluated muscular reactivity and lower-limb mechanical stiffness.

The specific biomechanical variables recorded by the OptoJump system included:

- Jump height (cm);
- Flight time (ms);
- Ground contact time (ms);
- Explosive power output (W/kg);
- Reactive Strength Index (RSI = jump height / ground contact time).

Following baseline testing (*pre-test*), the experimental group completed a structured, progressive core training intervention spanning 18 weeks, with a frequency of three 60-minute sessions per week (totaling 54 sessions). All training sessions were directly supervised and monitored by a sports physiotherapist and movement specialist to ensure exercise fidelity and correct biomechanical execution.

The intervention protocol was systematized into three distinct 6-week progressive phases:

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- **Phase I – Activation and Motor Control (Weeks 1–6):** Focused on isolated isometric recruitment of the deep lumbopelvic stabilizers, postural control, and diaphragmatic breathing patterns. Core exercises included the Bird-Dog, Dead-Bug, and abdominal bracing protocols.
- **Phase II – Dynamic Stability and Resistance Development (Weeks 7–12):** Introduced progressive external resistance (medicine balls, Therabands) and mechanical instability via compliant surfaces (BOSU balance trainer, instability pads, elastic mats). Emphasis was placed on single-leg dynamic stability, intermuscular coordination, and lumbopelvic control during sport-specific movement patterns.
- **Phase III – Functional Sport-Specific Integration and Plyometrics (Weeks 13–18):** Advanced to multi-planar, sport-specific functional movement patterns, incorporating rapid accelerations/decelerations, cutting maneuvers, ball-handling drills, dynamic Mountain Climbers, and lower-body plyometrics. Exercise intensity and neuromuscular complexity were maximized to promote high-level neuromuscular adaptations and biomechanical transference to football performance.

The exercise selection within the 18-week intervention adhered to principles of progressive biomechanical overload and motor control refinement, encompassing the following key modalities:

- **Prone Forearm Plank**
- **Side plank**
- **Bird-dog exercise**
- **Single-leg balance exercises**
- **Core-Stabilized Squats**
- **Dynamic Lunges**
- **Dead bug exercise**
- **Glute bridge**
- **Unstable Surface Training**
- **Dynamic Mountain climbers**
- **Rotational core exercises**
- **Elastic Resistance Band Protocols**

RESULTS

To evaluate the efficacy of the 18-week core training intervention on dynamic stability and trunk control, baseline (Pre-test) values were compared with post-intervention (*Post-test*) outcomes across all study participants.

The Star Excursion Balance Test (SEBT) was implemented to determine functional movement adaptations following the core stability program, providing quantitative metrics on postural control and single-leg dynamic stability. The detailed reach distances across the three evaluated vectors (anterior, anteromedial, and anterolateral) for both the dominant and non-dominant extremities are summarized in Table 1 below.

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Code	Dominant Leg			Non dominant Leg		
	Anterior	Postero lateral	Posteromedial	Anterior	Postero Lateral	Posteromedial
01	62	93	80.3	64	88.6	99.3
02	61.6	82.6	82.3	69.3	93	84
03	68.3	91.3	87	72.3	93.3	85.6
04	75	79.6	73.6	68.6	92.6	93.3
05	58.6	97.3	90.3	63	85.6	95
06	62.6	95	78.6	68.3	94.6	103
07	61.3	85	93.6	64	90.3	96.6
08	63.3	80	89.3	67.3	94.6	89.6
09	57.6	84.3	87	64	89.3	93.6
10	68.3	105	104.6	82	109.6	115.6
11	76.3	104	123.6	76	115.3	121.6
12	70	104	90	76	112.3	103
13	54	98	97.6	57	108.3	101
14	61.6	87.6	93.6	69	101.6	85
15	59.3	87	85	62.6	86.6	87.3
16	68.3	104.3	98	65	94	99.3
17	68.3	105.3	97.6	64	93	85.6
18	57.6	84.3	87	64	89.3	93.3
19	68.3	91.3	87	72.3	93.3	85.6
20	75	79.6	73.6	68.6	92.6	85.6

Table 1. Star Excursion Balance Test (cm) [Pre-Test]

A detailed individual analysis across all 20 study participants revealed the following key observations:

- **Anterior Reach Vector (range 60–70 cm):** Participants designated as Code 04 and Code 20 demonstrated peak reach distances (75 cm), reflecting superior quadriceps recruitment control and single-leg knee joint stability.
- **Posteromedial Reach Vector (range 80–120 cm):** The maximum value was observed in Code 11 (123.6 cm), indicating superior dynamic balance and postural control during multi-planar excursion.
- **Posterolateral Reach Vector (range 80–115 cm):** Participants exhibiting reach distances exceeding 100 cm (Codes 10, 11, 12, and 13) displayed significantly higher dynamic stability relative to the rest of the cohort.

In the SEBT literature, an inter-limb reach distance difference exceeding 4 cm between the dominant and non-dominant extremities is clinically established as a substantial risk factor for lower-extremity musculoskeletal injuries. Notably, (Code 10) demonstrated a prominent 14 cm asymmetry in the anterior reach direction (68.3 cm vs. 82.3 cm). Despite adequate force production capacity, this athlete exhibits a severe unilateral dynamic control deficit. Due to its high sensitivity in detecting subtle balance deficits and side-to-side functional asymmetries, the SEBT represents an indispensable metric for tracking neuromuscular adaptations in youth football players.

Post-intervention data were recorded using identical units of measurement and standardized testing protocols as baseline (pre-test) evaluations, thereby ensuring objective comparability and data integrity across both assessment time points.

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Code	Dominant Leg			Nondominant Leg		
	Anterior	Postero lateral	Posteromedial	Anterior	Postero Lateral	Posteromedial
01	68	99.2	88.5	71.2	95.1	100.6
02	66.1	88.8	89.4	74	99.2	91.3
03	74.2	98	95.5	78.3	100.2	91.7
04	80.3	86.5	80.4	75	97.6	98.2
05	64.5	103	97.2	69.3	92	101.5
06	68.8	102.2	86.5	74.5	101	109.3
07	67.6	92.8	100.6	71	97.2	103.4
08	69.3	86.8	95.8	73.1	101.3	96.2
09	63.9	90.9	93.5	70.4	95.7	100
10	75.4	112.2	111.4	88	117.6	123.4
11	83.6	111	130.5	82.7	122.8	128.6
12	76.8	111.4	97.3	82.5	119.6	110.3
13	60.5	105.6	104.8	64	115.2	108.7
14	67.5	94.5	100.6	75.8	108.4	91.8
15	65.1	93.5	91.8	69	93.4	94.5
16	74.6	112	105.4	71.3	101.2	106.7
17	74.8	113.3	104.5	70.8	100.2	92.7
18	63.8	90.8	93.7	70.2	95.6	99.8
19	74.5	98.2	94.5	78.2	100	93.6
20	80	86.8	80.1	74.8	99.6	92.6

Table 2. Star Excursion Balance Test (cm) [Post-Test

Across all three evaluated excursion vectors (anterior, posteromedial, and posterolateral), mean reach distances in centimeters demonstrated substantial increases compared to baseline (pre-test) values. The most pronounced improvements were observed in the posterior reach directions (posteromedial and posterolateral), which impose greater demands on lumbopelvic control during single-leg stance. Participants designated as (Code 10 and Code 11) exhibited the highest dynamic stability scores, exceeding 110% of normalized reach distance relative to lower-limb length bilaterally. However, in the anterior reach vector, 11 out of 20 participants (55%) maintained an inter-limb asymmetry exceeding the clinically established 4 cm risk threshold. These metrics indicate that despite absolute gains in reach distance, monitoring residual functional asymmetries remains a critical component of injury prevention frameworks.

Overall, the SEBT outcomes demonstrated significant enhancements in dynamic postural stability following the core training intervention. All movement vectors exhibited consistent performance gains across both the dominant and non-dominant extremities. The proportional progression observed between limbs indicates that the intervention consolidated postural control and core stability without inducing secondary functional asymmetries.

Following dynamic balance testing, participants completed a comprehensive assessment battery evaluating trunk muscular endurance and static/unstable postural control. This battery comprised the Prone Plank, Side Plank (Bilateral), Sørensen Trunk Extensor Test, Trunk Flexor Endurance Test, and BOSU Balance Test (Bilateral). The resulting empirical data are summarized in Table 2 below.

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Code	Plank	Right Side Plank	Left Side Plank	Sorensen	Trunk Endurance	Left Bozu	Right Bozu
01	123	90	90	138	168	10	26
02	155	32	35	60	60	2	1.7
03	270	60	60	141	240	5	11
04	120	45	43	67	106	19	13
05	93	61	63	144	93	57	75
06	60	55	46	62	135	23	26
07	93	54	46	63	180	17	22
08	240	60	60	93	250	32	16
09	90	102	102	90	120	10	25
10	70	50	40	75	60	15	10
11	240	70	61	60	130	60	55
12	250	92	94	62	120	21	18
13	270	90	99	75	120	59	54
14	127	91	90	120	200	22.9	20
15	120	60	60	130	154	12	5
16	128	90	73	110	134	55	54
17	120	55	57	90	120	18	25
18	125	90	90	80	95	10	16
19	90	65	55	60	75	15	20
20	120	90	80	85	130	12	14

Table 3. Trunk Endurance Test (s) [Pre-Test]

The functional assessment battery revealed inter-individual variability across parameters of core stability, isometric muscular endurance, and dynamic balance. Select participants displayed superior isometric endurance capacity and neuromuscular control, whereas others exhibited distinct functional deficits during postural stability testing.

Elevated endurance times in the Prone Plank, Sørensen, and Trunk Flexor Endurance assessments reflect an enhanced capacity of both local and global lumbopelvic stabilizing musculature. Concurrently, performance metrics from the BOSU Balance Test capture the degree of dynamic postural control and balance adaptability on an unstable surface.

Notably, participants presenting with diminished core endurance capacity (Code 02 and Code 10) aligned with those exhibiting pronounced inter-limb reach asymmetries on the SEBT and lower reactive power output during vertical jump protocols. These empirical observations substantiate the hypothesis that core endurance deficits serve as a fundamental catalyst for dynamic lower-extremity instability.

Table 2 details the individual and summary outcomes for all 20 participants across the functional core endurance and postural balance battery. Evaluated parameters include the Prone Plank, Side Plank (Right/Left), Sørensen Trunk Extensor Test, Trunk Flexor Endurance Test, and BOSU Balance Test (Left/Right). All variables are reported in seconds (s), denoting the maximum isometric hold time sustained prior to technique degradation or fatigue.

In the Prone Plank test, maximum holding times reached 340 seconds (Code 13) and 330 seconds (Code 03), whereas the lowest recorded score was 82 seconds (Code 06). Holding times demonstrated a significant increase across the cohort, reflecting enhanced isometric endurance of the anterior abdominal wall.

The post-intervention values for the bilateral Side Plank assessment exhibited strong symmetry (93.2 seconds for the right side vs. 89.1 seconds for the left side), indicating balanced lateral core stability (Quadratus Lumborum and oblique complex) following the 18-week intervention.

The Sorensen test, assessing the isometric capacity of the spinal extensor musculature, yielded holding times ranging from 75 seconds (Code 02) to 182 seconds (Code 05). The observed endurance gains in the paraspinal and lumbar extensor chain represent a crucial adaptation for enhancing posterior lumbopelvic stability and mitigating low back injury risk.

Finally, in the Trunk Flexor Endurance Test, overall performance times ranged from 78 seconds (Code 02) to 315 seconds (Code 08), confirming positive, variable, yet statistically substantial functional adaptations across the study sample.

Code	Plank	Right Side Plank	Lefy Side Plank	Sorensen	Trunk Endurance	Left Bozu	Right Bozu
01	158	117	116	178	209	15	6
02	190	43	45	75	78	6	3
03	330	77	77	181	295	7	13
04	155	62	58	88	136	68	87
05	123	79	81	182	123	36	34
06	82	71	61	82	165	26	30
07	121	72	63	84	220	39	22
08	305	79	80	118	315	21	29
09	116	132	128	117	150	20	19
10	93	66	54	98	80	71	66
11	303	92	80	82	165	34	28
12	318	117	121	82	152	28	24
13	340	116	127	98	150	67	60
14	163	117	116	156	245	29	28
15	155	83	76	165	188	18	10
16	167	117	96	142	165	66	64
17	155	73	74	118	150	27	31
18	164	118	115	105	120	19	22
19	114	85	72	78	95	25	27
20	159	118	103	109	165	18	24

Table 4. Trunk Endurance Test (s)[Post-Test]

These empirical findings indicate that the designated participants possess a high functional capacity for sustaining lumbopelvic stability during prolonged isometric loading.

Regarding the dynamic postural evaluation via the *BOSU Balance Test*, bilateral metrics demonstrated close proximity between sides (30.6 seconds for the left extremity vs. 28.2 seconds for the right extremity). This marginal inter-limb variance confirms the absence of pronounced motor asymmetries or lateralized neuromuscular control deficits.

Furthermore, performance durations on the unstable surface were systematically shorter relative to assessments conducted on stable ground. This reduced holding time is attributable to the heightened proprioceptive demands, increased biomechanical complexity, and continuous postural micro-adjustments required to preserve dynamic equilibrium under conditions of mechanical perturbation.

During the unstable surface balance assessment (BOSU Balance Test), performance times for the left extremity ranged from 6 seconds (Code 02) to 71 seconds (Code 10), whereas the right extremity ranged from 3 seconds (Code 02) to 87 seconds (Code 04). Maintaining dynamic equilibrium on the compliant surface demonstrated a statistically significant improvement for the left side, characterized by a substantial increase in hold duration. On the right side, despite an absolute increase in performance time, the adaptation did not reach statistical significance ($p > 0.05$). These empirical observations suggest that proprioceptive adaptations and fine neuromuscular control require extended training exposure compared to rapid gains in isometric muscular endurance.

Individual profile analysis revealed that specific participants (Codes 03, 08, 11, 12, 13, and 14) consistently displayed superior performance across the entire battery, reflecting advanced static strength, neuromuscular control, and lumbopelvic stability. Conversely, participants such as (Code 02) and partially (Code 06) presented diminished values across most parameters, indicating a more constrained baseline functional capacity.

Furthermore, the data indicate that core muscular endurance does not directly correlate with dynamic balance capacity, suggesting that postural control is concurrently mediated by sensorimotor integration,

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proprioceptive feedback, and intermuscular coordination. This finding substantiates the paradigm that lumbopelvic core stability and postural equilibrium, although functionally interdependent, represent distinct neurophysiological domains of motor performance.

Overall, the trunk endurance assessment battery demonstrated a statistically significant enhancement in isometric holding capacity following the 18-week intervention. The uniform progression observed across all muscle complexes (flexors, extensors, and lateral obliques) confirms that the intervention consolidated global core capacity in a balanced manner. Preserving bilateral symmetry during the Side Plank and BOSU assessments confirms the effective mitigation of functional trunk asymmetries.

The final diagnostic protocol implemented in this assessment battery comprised the optoelectronic evaluation via the OptoJump system, which quantified the biomechanical and neuromuscular parameters of vertical jump performance for each participant. The resulting empirical metrics are summarized in Table 5 below.

Code	SJ (cm)	CMJ (cm)	Flight Time (ms)	Contact Time (ms)	RSI	Power (W/Kg)
01	31.8	37.2	565	206	2.74	38.2
02	32.7	38.1	572	202	2.83	39
03	32.4	37.8	570	205	2.78	38.7
04	33.1	38.5	578	200	2.89	39.4
05	32.5	38	565	205	2.76	38.1
06	33.4	39.1	580	198	2.93	39.8
07	34.2	39.6	585	198	2.95	37.9
08	30.9	35.8	548	214	2.56	36.8
09	34.5	40.2	590	192	3.07	41.2
10	33.2	38.8	578	199	2.9	39.6
11	31.6	37	560	208	2.69	37.9
12	32.6	38.2	580	198	2.93	39.9
13	30.7	36.1	548	215	2.55	36.9
14	33.5	39	580	199	2.91	39.8
15	34.8	40.5	594	190	3.13	41.5
16	26.6	29.9	498	255	1.95	30.2
17	28.7	33.5	528	225	2.35	34.8
18	31.2	36.5	555	210	2.64	37.5
19	29.5	34.7	540	218	2.48	35.9
20	31.6	36.9	560	208	2.69	37.9

Table 5 . Optojump Test [Pre-Test]

The biomechanical evaluation of vertical jump performance revealed the following key neuromuscular characteristics within the study cohort:

- **Stretch-Shortening Cycle (SSC) Utilization:** Mean jump height during the Countermovement Jump (CMJ: 37.34 ± 2.44 cm) was substantially higher than that observed in the Squat Jump (SJ: 32.07 ± 2.05 cm). This 16.4% enhancement reflects efficient utilization of the stretch-shortening cycle (SSC) and superior elastic energy potentiation within the muscle-tendon unit.
- **Lower-Bound Performance Profiling:** Participant *Code 16* recorded the lowest performance metrics across the cohort (SJ: 26.6 cm, CMJ: 29.9 cm, RSI: 1.95) alongside the longest ground contact time (255 ms), indicating a severe deficit in reactive strength and lower-limb mechanical stiffness.
- **High-Level Neuromuscular Capacity:** Conversely, participants designated as Code 09) and (Code 15) demonstrated superior reactive neuromuscular power, attaining Reactive Strength Index (RSI) values of 3.07 and 3.13, respectively, coupled with relative mechanical power outputs exceeding 40 W/kg.

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Following the completion of the 18-week core training intervention, all participants underwent post-intervention re-evaluations (post-test) adhering strictly to identical assessment protocols. The resulting post-intervention metrics are detailed in Table 6 below.

Code	SJ (cm)	CMJ (cm)	Flight Time (ms)	Contact Time (ms)	RSI	Power (W/Kg)
01	34.8	40.6	590	192	3.07	41.4
02	35.6	41.4	596	188	3.17	42.2
03	35.2	41.1	595	190	3.13	41.8
04	36.1	42.2	602	185	3.25	42.8
05	35.5	41.3	595	189	3.15	41.9
06	36.5	42.5	606	183	3.31	43.3
07	37.3	43.1	609	182	3.34	43.6
08	33.8	39.2	578	198	2.93	40.2
09	37.6	43.8	613	180	3.41	44.6
10	36.3	42.2	604	184	3.27	43.1
11	34.6	40.3	588	193	3.05	41.2
12	35.9	41.8	602	184	3.27	42.9
13	33.7	39.4	579	197	2.94	40.4
14	36.5	42.4	605	184	3.29	43.2
15	38.0	44.3	618	178	3.47	45.1
16	30.4	34.6	545	220	2.48	36.7
17	32.5	37.8	570	202	2.82	39.1
18	34.2	39.8	588	193	3.06	41.1
19	32.5	38.4	575	200	2.88	39.8
20	34.6	40.4	590	191	3.09	41.5

Table 6. Optojump Test [Post-Test]

Comparative evaluation between baseline (*pre-test*) and post-intervention (*post-test*) metrics demonstrated statistically and functionally meaningful enhancements across all vertical jump biomechanical parameters:

- **Squat Jump (SJ):** Mean increase of 2.5–3.5 cm;
- **Countermovement Jump (CMJ):** Mean increase of 3.0–4.0 cm;
- **Flight Time:** Mean increase of 20–30 ms;
- **Ground Contact Time:** Mean reduction of 15–25 ms;
- **Reactive Strength Index (RSI):** Mean increase of 10–18%;
- **Relative Power Output:** Mean increase of 2.0–4.0 W/kg.

These empirical metrics reflect substantial improvements in explosive neuromuscular capacity across the study cohort. Across all individual profiles, CMJ performance remained systematically superior to SJ, confirming efficient stretch-shortening cycle (SSC) utilization, enhanced muscle-tendon elastic storage, and superior intermuscular coordination.

Individual performance profiling identified participants (Code 07, Code 09, and Code 15) as top-tier performers across all biomechanical variables, exhibiting maximal jump heights, prolonged flight times, reduced ground contact durations, elevated RSI values, and superior relative power outputs. Conversely, participant (Code 16) consistently recorded lower-bound values across SJ, CMJ, RSI, and power output, coupled with extended ground contact time, indicating constrained rapid force development capacity and reduced passive tissue elasticity utilization.

Overall, the core training intervention proved highly effective in augmenting both isolated concentric explosive force (SJ) and dynamic reactive-elastic capacity (CMJ). These findings substantiate that

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lumbopelvic core consolidation enhances kinetic chain energy transfer efficiency during high-velocity dynamic actions.

DISCUSSION

The findings of this 18-week intervention confirm the primary research hypothesis, demonstrating that a structured, progressive core training program yields statistically significant improvements in dynamic stability, trunk muscular endurance, and explosive-reactive performance metrics among youth football players aged 15–17 years.

The post-intervention performance gains observed across all vectors of the Star Excursion Balance Test (SEBT) indicate enhanced lumbopelvic control during single-leg dynamic actions. These outcomes align with the authors [6], who emphasized that optimal core stability allows for more efficient center-of-gravity regulation. Nevertheless, the persistence of an inter-limb asymmetry exceeding the clinically established 4 cm threshold in the anterior reach vector among 55% of participants at post-test highlights the imperative for individualized secondary interventions, as such functional side-to-side side imbalances represent documented risk factors for lower-extremity injuries, specifically anterior cruciate ligament (ACL) sprains.

The substantial increases in isometric hold durations (Prone Plank +24.76%, Side Plank +30.8%, and Sørensen Test +28.78%) reflect positive neuromuscular adaptations within both local and global core stabilizing complexes. The endurance gains in the Sørensen protocol are particularly crucial for mitigating lumbar spine mechanical strain during high-velocity athletic tasks. These empirical observations substantiate the biomechanical frameworks proposed by the authors [4,5], which posit that trunk endurance provides the requisite kinetic platform for efficient torque and force transfer between the lower and upper extremities during multi-planar athletic actions.

Postural equilibrium outcomes on the compliant BOSU trainer yielded a statistically significant improvement for the left extremity, whereas gains on the right side did not attain statistical significance. This lateral discrepancy suggests that sensorimotor and proprioceptive adaptation pathways require extended training exposures to consolidate relative to rapid isometric endurance adaptations. As noted by the authors [1], postural control on unstable surfaces is governed not solely by muscular force generation, but by complex central nervous system sensorimotor integration and reflex mechanisms.

Finally, the positive adaptations captured by the OptoJump system characterized by increased vertical jump height, shortened ground contact times, and elevated Reactive Strength Index (RSI) scores demonstrate that core stability directly optimizes stretch-shortening cycle (SSC) dynamics. A consolidated lumbopelvic complex provides high mechanical trunk stiffness, preventing kinetic energy dissipation during the amortization phase and facilitating superior reactive power output during explosive actions.

CONCLUSIONS

The implementation of an 18-week structured, progressive core training program (delivered at 3 sessions per week) significantly enhances dynamic stability, postural control, and trunk muscular endurance in youth football players.

Strengthening the lumbopelvic musculature and optimizing core rigidity directly transfer to superior explosive and reactive performance, as evidenced by enhanced vertical jump height (Squat Jump and Countermovement Jump), alongside reduced ground contact time and elevated Reactive Strength Index (RSI) scores.

The training intervention demonstrated high efficacy in establishing bilateral symmetry across lateral and posterior trunk endurance chains, providing a crucial mechanical foundation for mitigating non-contact musculoskeletal injury risks (such as anterior cruciate ligament - ACL ruptures and soft-tissue strains).

Postural adaptations on unstable compliant surfaces (BOSU) necessitate specialized focus and prolonged training exposures, confirming that neuro-proprioceptive control develops at a distinct kinetic rate compared to rapid gains in isometric muscular endurance.

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Core stability frameworks should be systematically incorporated into periodic training microcycles and injury prevention/rehabilitation protocols within youth football development, aiming to maximize athletic performance potential while preserving athlete musculoskeletal health.

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THE ROLE OF DEMOGRAPHIC VARIABLES IN THE EFFECT OF SUSTAINABLE HRM PRACTICES ON WORK ENGAGEMENT

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ABSTRACT

In this study, the moderating role of six demographic variables (age, gender, education level, tenure, marital status, and position) in the relationship between sustainable human resource management (HRM) practices and employees' levels of work engagement is empirically tested. Sustainable HRM practices are defined as a set of practices that aim to preserve and develop an organization's long-term human capital, prioritizing employee well-being, development, and engagement. Work engagement, as conceptualized by Schaufeli et al. (2002), is based on the dimensions of vigor, dedication, and absorption. The Job Demands–Job Resources model proposed by Demerouti et al. (2001) forms the theoretical framework of this study. Data were collected from 651 employees of companies listed on the Borsa Istanbul (BIST) that publish sustainability reports, and the hypotheses were tested using hierarchical regression analysis. The findings reveal that sustainable HRM practices have a strong and significant effect on work engagement ($\beta = .605$, $p < .001$). However, this effect did not differ significantly across any of the six demographic characteristics examined; equivalence tests showed that the standardized coefficient magnitudes of the six interaction terms—representing variations in the effect of sustainable HRM across demographic groups—all remained below 0.10. At least in this sample, the contribution of sustainable HRM practices to job engagement does not appear to be limited to specific groups but seems to hold true across a wide range of demographic groups. This suggests that organizations may prioritize implementing these practices consistently across the entire workforce rather than tailoring them to specific demographic groups.

Keywords: Sustainable HRM, sustainable HRM practices, Work Engagement, Job Demands–Resources Model

1. INTRODUCTION

In today's business world, where boundaries are dissolving, competition is intensifying, and sustainability has become one of the most important organisational goals, firms are undergoing a fundamental transformation in both the nature and content of their human resource policies. Whereas practices grounded in traditional human resource management are short-term, cost-oriented, and efficiency-driven, sustainable human resource management focuses on long-term, value-creating practices that place employee well-being at the forefront. This shift rests on the notion of sustainability articulated in the Brundtland Report of the World Commission on Environment and Development

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(WCED, 1987), which frames sustainability as a holistic approach that addresses not only the economic but also the social and environmental dimensions of business systems.

Beyond the field of human resource management, the concept of work engagement—which has attracted growing interest in the employee-psychology and organisational-behaviour literature—refers to the intense enthusiasm, dedication, and deep focus that employees feel toward their work (Schaufeli et al., 2002). Employees with high levels of work engagement gain a more meaningful work experience for themselves while also contributing more to the organisation. For this reason, work engagement has become an important element and a strategic objective for firms seeking sustainable performance (Christian et al., 2011).

Because both concepts encompass employee well-being and a long-term horizon, the relationship between sustainable HRM practices and work engagement is expected to be strong. However, whether this relationship differs according to employees' age, gender, education level, tenure, and marital status—in other words, according to their demographic characteristics—and whether demographic variables play a role in this relationship remain insufficiently examined in the literature.

Given that the job expectations, career priorities, and psychological needs of employees with different demographic characteristics may diverge markedly, the effect of sustainable HRM practices on these groups is unlikely to be homogeneous (Robinson et al., 2004; James et al., 2011). This draws attention to how important demographic differences may be when firms formulate and develop their HRM policies.

Within this framework, the main aim of this study is to empirically test the role of demographic variables in the relationship between sustainable HRM practices and work engagement using data obtained from employees of firms operating on BIST, thereby offering a fresh perspective for future research. The study comprises a theoretical framework, an empirical study built on the hypotheses derived from it, and concluding and discussion sections.

2. CONCEPTUAL FRAMEWORK

2.1. Sustainable Human Resource Management (HRM) Practices

The concept of sustainable development drew the attention of countries worldwide through the report titled "Our Common Future" published by the United Nations World Commission on Environment and Development (Brundtland Report, 1987). Defined in the report as "meeting the needs of the present without compromising the ability of future generations to meet their own needs," the concept became both the definition and the guiding principle of sustainability. The genuine application of sustainability within the field of human resource management became possible through Ehnert's (2009) pioneering work.

Ehnert (2009) defines sustainable HRM practices as a set of practices that enable organisations to meet their present and future human resource needs in a balanced manner while also protecting employees' physical, mental, and social well-being. This definition moves beyond the short-term efficiency emphasised in strategic HRM and foregrounds the creation of long-term value (Kramar, 2014). Mariappanadar (2003) explains sustainable HRM strategies as an approach that seeks to minimise the potential negative effects on employees, their families, and society while enhancing the firm's profitability.

Unlike other researchers, Järlström et al. (2018) examined the content of sustainable HRM in relation to the firm's stakeholders, offering a holistic approach. This holistic understanding encompasses concrete HRM practices such as career-development opportunities, fair pay policies, participatory decision-making, work–life balance, diversity management, and psychological safety. De Prins et al. (2014), within the framework of their "Respect–Openness–Continuity" model, define sustainable HRM as practices that enhance employees' intrinsic motivation, increase their involvement in work-related processes, and enable them to establish a long-term, trust-based relationship with the organisation.

As emphasised in Ehnert et al. (2014), sustainable HRM comprises an HRM system that overlaps with corporate social responsibility practices and supports organisational sustainability. Voegtlin and

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Greenwood's (2016) work reinforce this link with empirical evidence, showing that CSR-oriented HRM practices have a determining effect on employees' attitudes and behaviours.

2.2. Work Engagement

The concept of work engagement was first addressed systematically by Kahn (1990). Kahn explained work engagement in terms of the extent to which employees express themselves physically, cognitively, and emotionally in their work, and argued that the conditions of psychological meaningfulness, psychological safety, and psychological availability are the fundamental factors that determine such engagement. Kahn's contribution to the literature attracted increasing attention in subsequent years and inspired many researchers seeking to identify the psychological factors that affect working life and to measure their effects.

Schaufeli et al. (2002) addressed work engagement through three dimensions: vigour, dedication, and absorption. Vigour corresponds to the high level of energy and mental resilience felt during work; dedication to the meaning, enthusiasm, and pride that work holds for the employee; and absorption to being fully immersed in one's work and to the sense that time passes quickly. These three dimensions are measured through the Utrecht Work Engagement Scale developed by the researchers; the short form of the scale (UWES-9) has become a widely used measurement tool whose validity has been confirmed across different cultural contexts (Schaufeli et al., 2006).

The Job Demands–Resources model developed by Demerouti et al. (2001) is one of the theoretical frameworks used to explain the organisational effects of work engagement. According to the model, job demands are associated with burnout, whereas job resources (autonomy, support, feedback, development opportunities, etc.) strengthen employees' motivational processes and help increase their level of work engagement. Schaufeli and Bakker (2004) investigated the model with larger samples and demonstrated that job resources reduce burnout and increase work engagement.

Macey and Schneider (2008) broadened the conceptual framework of work engagement by treating it not only as a psychological state but also as a behavioural one. Saks's (2006) research demonstrated that perceived organisational support, leader support, and rewards have a determining effect on the level of work engagement.

2.3. The Relationship Between Sustainable HRM Practices and Work Engagement

The relationship between sustainable HRM practices and work engagement can be grounded in several theories. According to the core proposition of the job demands–resources model addressed in this study, the job resources offered to employees nurture work engagement (Demerouti et al., 2001). Through their dimensions—investment in employee development, participatory management, fair pay and reward policies, and work–life balance support—sustainable HRM practices constitute job resources in the direct sense. Consequently, the comprehensive implementation of sustainable HRM practices is expected to increase employees' levels of work engagement.

According to Hackman and Oldham's (1976) job characteristics model, job features such as task significance, task identity, and autonomy increase an employee's motivation and job satisfaction. Sustainable HRM practices can indirectly enhance work engagement by strengthening these job characteristics through job enrichment, delegation of authority, and career-development opportunities.

The psychological meaningfulness proposed by May et al. (2004) can also be considered in this context. By involving employees in organisational decision-making processes, providing development opportunities, and ensuring long-term job security, sustainable HRM increases the sense of psychological meaningfulness. This increase can be directly associated with work engagement.

When examined through the lens of Deci and Ryan's (1985) self-determination theory, sustainable HRM practices are expected to satisfy the basic psychological needs of autonomy, competence, and relatedness. Satisfying these needs increases the employee's intrinsic motivation and, consequently, work engagement. Voegtlin and Greenwood's (2016) work also supports this theory.

According to the JD-R model, the effect of a job resource on work engagement depends on the extent to which that resource meets the employee's individual need (Bakker and Demerouti, 2007). In this

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respect, although sustainable HRM practices carry the quality of job resources, these resources may not influence the motivation of all employees to an equal degree. Which job resource is more important for which employee may vary according to that employee's demographic characteristics. For example, needs that change with career stage bring different resources to the fore for different age groups, while work–life balance expectations that differ by gender may alter the effect of particular practices on employee motivation. Therefore, the resource–engagement chain that constitutes the core proposition of the JD-R model is theoretically expected to differ according to demographic characteristics.

2.4. Demographic Variables and Work Engagement

The relationship between demographic variables and work engagement has attracted growing research interest in recent years. The divergence of career expectations, sources of job satisfaction, and psychological needs across employees of different age groups suggests that demographic variables may have both a direct effect on work engagement and a moderating role in the sustainable HRM–work engagement relationship.

With respect to age, James et al.'s (2011) study in the retail sector shows that the work engagement of employees in different age groups diverges markedly. In that study, career-development opportunities and learning opportunities for younger employees, job autonomy for middle-aged employees, and organisational recognition and a sense of meaning for senior employees emerge as important, priority factors shaping work engagement. The fact that sustainable HRM practices include lifelong-learning and career-management dimensions suggests that their effect may differ across employees in different age groups. Because both the expectations and needs of different age groups differ, employees' engagement levels may vary with age.

Regarding gender differences, Richman et al.'s (2008) study revealed that the contribution of flexible working arrangements and work–life-balance-supporting policies to employee engagement is more pronounced among female employees. The work–life-balance and diversity dimensions of sustainable HRM may generate motivational effects of differing magnitude for female and male employees. Moreover, according to role-conflict theory (Greenhaus & Beutell, 1985), because female employees experience the pressure of work–life balance more intensely, this dimension of sustainable HRM may produce a stronger engagement effect among them.

Marital status can shape the perception of work–life balance through employees' non-work responsibilities and life-role burdens. According to Greenhaus and Beutell's (1985) role-conflict theory, married individuals may experience conflict between work and family roles more intensely, which may make the work–life-balance practices offered by sustainable HRM more decisive for them. Kossek and Ozeki (1998), meanwhile, showed that the effect of family obligations on job satisfaction and work dedication differs by marital status. In this framework, the effect of sustainable HRM practices on work engagement is expected to differ significantly by marital status.

When evaluated in terms of education level, highly educated employees are known to hold more advanced career expectations and demands for autonomy. Because highly educated employees carry expectations of autonomy and career development (Saks, 2006), sustainable HRM's provision of these resources may generate a more pronounced increase in their engagement. Saks's (2006) findings offer theoretical clues that the effect of perceived organisational support and fairness on work engagement may be shaped together with education level.

Tenure indicates how deep an employee's relationship with the organisation is; because senior employees adapt more fully to organisational norms and culture, they may internalise sustainable HRM practices more strongly. Because senior employees form a deeper psychological contract with the employer, they may perceive sustainable HRM practices as more meaningful (Rousseau, 1995). This perception may increase employees' level of work engagement.

An employee's position within the firm (manager/employee) may, within the JD-R framework, directly affect control over job resources and decision-making autonomy. Because individuals in managerial positions may participate in the design and implementation of sustainable HRM practices, they may embrace these practices more than those in employee positions (Saks, 2006). Furthermore, according to

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the taking-charge approach proposed by Morrison and Phelps (1999), as one's position in the firm rises, employees tend to participate more actively in organisational processes; this may lead them to internalise practices more fully and positively affect their level of work engagement. Because managers are closer to the process of designing and implementing sustainable HRM practices, they may internalise these practices more strongly.

Drawing on the theory and prior studies above, the following hypotheses were developed to determine the effect between sustainable HRM practices and work engagement:

H_1: Sustainable HRM practices have a significant and positive effect on work engagement.

H_2: Employees' gender moderates the effect of sustainable HRM practices on work engagement.

H_3: Employees' age moderates the effect of sustainable HRM practices on work engagement.

H_4: Employees' education level moderates the effect of sustainable HRM practices on work engagement.

H_5: Employees' tenure moderates the effect of sustainable HRM practices on work engagement.

H_6: Employees' marital status moderates the effect of sustainable HRM practices on work engagement.

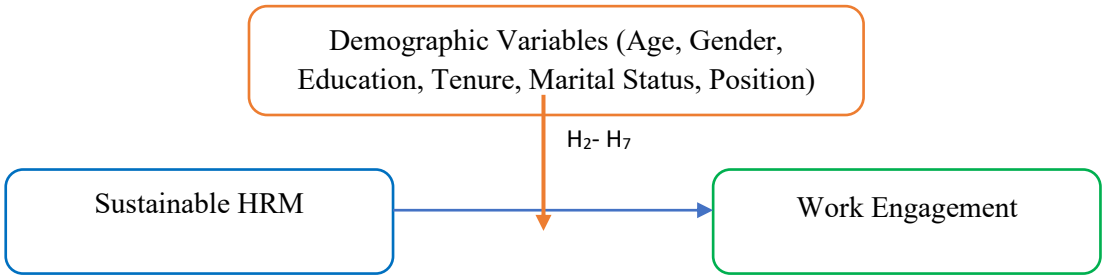
H_7: Employees' position within the firm moderates the effect of sustainable HRM practices on work engagement.

3. METHODOLOGY

Drawing on the information explained in the theoretical framework, this study was shaped around the questions "Do sustainable HRM practices significantly predict employees' level of work engagement?" and "Does the effect of sustainable HRM practices on work engagement differ significantly according to employees' demographic characteristics such as gender, age, education level, and tenure?", and hypotheses were developed accordingly. The research model was constructed on the basis of these questions and hypotheses.

3.1. Research Model

In the conceptual model developed on the basis of the job demands–resources model (Demerouti et al., 2001) and the sustainable HRM literature, sustainable HRM practices are positioned as the independent variable, work engagement as the dependent variable, and demographic characteristics as moderating variables. The model constructed in line with these variables is shown in Figure 1.



Note: Demographic variables were used in the analyses both as control variables and as moderators.

Figure 1. Research Model

3.2. Sample

The population of this study consists of firms traded on BIST that have published a sustainability report. In June 2025, when the study was conducted, 88 firms met these criteria and constituted the sampling frame. Participants were drawn from these firms using a simple random sampling approach, and an online questionnaire was administered to them. Of the 723 employees who were invited to participate, 651 provided valid and complete responses, yielding a completion rate of approximately 90%. The

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adequacy of the sample size was evaluated against the criteria recommended for regression analysis and found to be sufficient.

3.3. Data Collection Instruments

3.3.1. Sustainable HRM Practices Scale

In the first part of the questionnaire, a 25-item scale compiled from expressions used in various studies in the literature and adapted into Turkish was used to measure sustainable HRM practices (Sükan, 2026). The content validity of the scale was established through the opinions of three experts. Confirmatory factor analysis (CFA) was conducted to test construct validity. The CFA results showed that the five-factor structure of the scale was consistent with the data ($\chi^2/df = 1.064$; CFI = .99; NFI = .99; GFI = .97; IFI = .99; RMSEA = .010). Factor loadings ranged from .662 to .847, and all items loaded adequately onto their respective factors. The internal consistency coefficient of the scale was high ($\alpha = .933$).

3.3.2. Work Engagement Scale

To determine levels of work engagement, the Turkish adaptation by Özkalp and Meydan (2015) of the scale developed by Schaufeli et al. (2002) was used. The Cronbach's alpha coefficient of the scale was at a reliable level ($\alpha = .875$).

3.4. Data Analysis

The data were analysed using the SPSS 25.0 statistical program. To determine whether parametric tests could be applied, the assumptions of normality and homogeneity were first tested. Normality was assessed using multiple criteria. The Kolmogorov–Smirnov test was statistically significant for both variables (Work engagement: $D(651) = .163$, $p < .001$; Sustainable HRM practices: $D(651) = .142$, $p < .001$). However, it is well known that in large samples ($N > 200$) these tests flag even practically negligible deviations as significant (Field, 2024). For this reason, skewness and kurtosis coefficients were also evaluated; the obtained values remained within ±1.5 (Tabachnick and Fidell, 2013). Considered together, these findings led to the conclusion that the distribution could be regarded as sufficiently normal for parametric tests. The homogeneity of variances was tested with Levene's test, and the assumption of equal variance across groups was found to be met.

Because the data on the independent and dependent variables were measured simultaneously from the self-reports of the same participants, common method variance was tested with Harman's single-factor test. When all items were forced onto a single factor, this factor explained 35.01% of the total variance. The fact that this proportion is clearly below the 50% threshold indicates that common method variance does not pose a serious threat to the findings (Podsakoff et al., 2003).

Pearson correlation analysis was used to examine the relationships among the variables. Linear regression analysis was conducted to test the direct effect of sustainable HRM practices on work engagement. The multicollinearity assumption was tested by examining VIF and tolerance values. The VIF values ranged from 1.007 to 4.892 (all < 5) and the tolerance values ranged from .204 to .993. These findings indicate that multicollinearity does not pose a serious problem for the models (Field, 2024).

Hierarchical regression analysis was used to test the moderating role of the demographic variables (gender, age, education level, and tenure) in the relationship between sustainable HRM and work engagement. Before proceeding to the moderation analysis, sustainable HRM and the demographic variables were transformed using mean centring to minimise the potential multicollinearity arising from interaction terms (Aiken and West, 1991). The hierarchical regression analysis was built in three steps. In the first step, the demographic variables (age, gender, tenure, and education level) were entered into the model as control variables. In the second step, the main predictor—sustainable HRM practices—was added. In the third step, the interaction term (product score) between sustainable HRM and the relevant demographic variable was entered into the model separately for each moderator. At each step, the change in R^2 (ΔR^2) and the change in F (ΔF) were examined to evaluate the statistical significance of the moderation effect.

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4. FINDINGS

4.1. Demographic Findings

When the data obtained from 651 employees are examined, the sample displays a demographically rather heterogeneous structure. In terms of gender distribution, female participants (51.61%) constitute a slight majority over male participants (48.39%), and this balance enhances the sample's representativeness. The age profile is concentrated mainly in the middle and older age groups; the 45–54 age range constitutes the largest group (34.72%), while participants aged 55 and over account for more than one-fifth of the sample (21.35%). In terms of education, bachelor's-degree holders represent the leading group (35.48%), followed by those with postgraduate education (22.43%) and associate-degree holders (28.11%). With respect to marital status, the proportion of married individuals (57.60%) is markedly higher than that of single individuals (42.40%). In terms of professional experience, individuals with 7–9 years of tenure constitute roughly half of the sample (42.55%). By organisational position, the great majority of participants hold employee status (67.59%), while managers account for 32.41%. Finally, the sectoral distribution shows that the study was conducted across a broad range of sectors, led by technology (9.37%), banking (8.91%), insurance (8.76%), information and communication (8.14%), and chemistry–pharmaceuticals–petroleum (8.14%). This demographic diversity indicates that the sample has strong representative quality with respect to the generalisability of the findings to different contexts. The demographic findings are presented in Table 1.

Table 1. Demographic Findings

Variable	Category	f	%
Gender	Female	336	51.61
	Male	315	48.39
Age	18–24	74	11.37
	25–34	116	17.82
	35–44	96	14.75
	45–54	226	34.72
	55 and over	139	21.35
Education	High school	91	13.98
	Associate degree	183	28.11
	Bachelor's degree	231	35.48
	Postgraduate	146	22.43
Marital status	Married	375	57.60
	Single	276	42.40
Tenure	Less than 1 year	87	13.36
	1–3 years	133	20.43
	4–6 years	83	12.75
	7–9 years	277	42.55
	10 years and over	71	10.91
Position	Employee	440	67.59
	Manager	211	32.41
Sector	Banking	58	8.91
	Information & communication	53	8.14

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Variable	Category	f	%
	Education/health/sports & entertainment services	37	5.68
	Electricity/water/natural gas	28	4.30
	Holdings & investment companies	37	5.68
	Manufacturing	28	4.30
	Construction & public works	40	6.14
	Chemicals, pharmaceuticals, petroleum, rubber & plastics	53	8.14
	Financial institutions	29	4.45
	Professional, scientific & technical activities	51	7.83
	Insurance	57	8.76
	Non-metallic minerals (stone & earth-based)	27	4.15
	Technology	61	9.37
	Wholesale & retail trade	40	6.14
	Transportation & storage	52	7.99

4.2. Analysis and Findings on the Relationship Among the Variables

The results of the correlation analysis conducted to determine the relationships among the variables and their sub-dimensions are presented in Table 2. As shown, sustainable HRM practices are positively and significantly correlated with work engagement ($r = .605$, $p < .01$), and all sub-dimensions are significantly intercorrelated.

Table 2. Correlations Among Sustainable HRM Practices, Work Engagement, and Their Sub-Dimensions

Variable	1	2	3	4	5	6	7	8	9	10
1. Sust. recruitment	1									
2. Sust. training & development	.521**	1								
3. Sust. pay & reward	.545**	.387**	1							
4. Sust. occupational health & safety	.542**	.333**	.399**	1						
5. Sust. participation & work conditions	.540**	.378**	.445**	.345**	1					
6. Sustainable HRM practices (total)	.837**	.670**	.816**	.642**	.729**	1				
7. Vigor	.499**	.313**	.355**	.401**	.374**	.512**	1			
8. Dedication	.488**	.365**	.353**	.333**	.355**	.514**	.583**	1		
9. Absorption	.471**	.314**	.313**	.362**	.353**	.476**	.535**	.469**	1	
10. Work engagement (total)	.587**	.400**	.411**	.465**	.435**	.605**	.852**	.833**	**.800****	1

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*Note: N = 651. **All correlations are significant at p < .01. Variables 1–5 are the sub-dimensions of sustainable HRM practices; variable 6 is the composite; variables 7–9 are the engagement dimensions; variable 10 is the composite work-engagement score.*

The three engagement dimensions loaded highly on the overall construct (r = .800–.852 with the composite) and were themselves substantially intercorrelated (r = .469–.583). On this basis—and in line with common practice in the UWES literature (Schaufeli et al., 2006) —work engagement was analysed as a single composite score in the hypothesis tests.

Convergent and discriminant validity were then assessed using composite reliability (CR) and average variance extracted (AVE), computed from the standardised factor loadings of the measurement solution. As Table 3 shows, CR exceeded the .70 criterion for all eight factors (.825–.903) and AVE exceeded the .50 criterion for all eight (.513–.664), supporting convergent validity. For discriminant validity, the square root of each factor's AVE (.716–.815) was larger than that factor's correlations with the remaining factors (maximum r = .583; Table 2), satisfying the Fornell–Larcker criterion.

Table 3. Composite Reliability, Average Variance Extracted, and Discriminant Validity

Factor	CR	AVE	√AVE
Sustainable recruitment	.840	.513	.716
Sustainable training & development	.868	.622	.789
Sustainable pay & reward	.903	.538	.733
Sustainable occupational health & safety	.855	.664	.815
Sustainable participation & work conditions	.879	.592	.770
Vigor	.825	.611	.781
Dedication	.851	.656	.810
Absorption	.841	.637	.798

Note. CR = composite reliability; AVE = average variance extracted. Loadings are taken from the reported factor solution (five-factor sustainable HRM and three-factor work engagement structures, both confirmed by CFA: $\chi^2/df = 1.064$ and 3.918, respectively). Discriminant validity holds where √AVE exceeds the factor's correlations with the other factors in Table 2.

4.3. Findings on the Hypotheses

The regression analyses conducted to test the study's hypotheses and their findings are presented below.

4.3.1. Test and Findings on the Effect of Sustainable HRM Practices on Work Engagement

Linear regression analysis was conducted to investigate the effect of sustainable HRM practices on work engagement. The regression results are presented in Table 4.

Table 4. Analysis of the Effect of Sustainable HRM Practices on Work Engagement

Predictor	**B**	**SE**	**β**	**t**	**p**
Constant	1.180	.102	—	11.524	.000
Sustainable HRM practices	.675	.035	.605	19.341	.000

Note: Dependent variable: Work engagement. R = .605; R^2 = .366; Adjusted R^2 = .365; F(1, 649) = 374.093, p < .001.

As shown in Table 4, the regression coefficients and their corresponding t-values indicate that sustainable HRM practices explain 36.6% of the variance in work engagement. Using Cohen's (1988) effect-size criteria, the effect size calculated with the formula $f^2 = R^2/(1 - R^2)$ was f^2 = .578. This value exceeds Cohen's (1988) criterion for a large effect ($f^2 > .35$) and shows that the effect of sustainable HRM practices on work engagement is also practically strong. The overall statistical significance of the

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model was tested and confirmed, F = 374.093 (p < .001). This finding shows that the observed variation in work engagement is significantly predicted by sustainable HRM practices.

4.3.2. The Role of Demographic Characteristics in the Effect of Sustainable HRM Practices on Work Engagement

The regression analyses conducted to examine the role and effect of demographic characteristics in the relationship between sustainable HRM practices and work engagement are presented together in Table 5.

Table 5. Moderating Effects of Demographic Characteristics on the Sustainable HRM–Work Engagement Relationship

Predictor (β)	Model 1	Model 2	Model 3
Control variables			
Age	-.013	-.004	
Gender	.017	.010	
Tenure	-.041	-.010	
Education level	.020	.013	
Main Predictor			
Sustainable HRM practices		.605***	
Interaction terms			
Sustainable HRM × Age			-.013
Sustainable HRM × Gender			.012
Sustainable HRM × Tenure			-.033
Sustainable HRM × Education			-.022
Sustainable HRM × Marital status			-.024
Sustainable HRM × Position			-.004
R^2	.003	.367	.367
ΔR^2	—	.364	.000
F	.559	74.845	—

*Note: Dependent variable: Work engagement; N = 651. Model 1: control variables. Model 2: control variables plus sustainable HRM practices. Model 3: each moderator was tested separately (Sustainable HRM × Age, × Gender, × Tenure, × Education, × Marital status, × Position); the Model 3 column summarises the interaction-term coefficients from six separate analyses. ***p < .001.*

In the first step, age, gender, tenure, and education level were entered into the model. The model as a whole was non-significant (F = .559, p > .05) and explained only 3% of the variance in work engagement

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(R^2 = .003). No demographic variable emerged as a significant predictor. This finding indicates that demographic characteristics alone do not determine work engagement.

In the second step, the main predictor—sustainable HRM practices—was added to the model. With this addition, the explained variance rose from 3% to 36.7% (ΔR^2 = .364) and the model became highly significant (F = 74.845, p < .001). Sustainable HRM practices emerged as a strong and significant predictor of work engagement (β = .605, p < .001). None of the control variables made a significant contribution in this model either. Consequently, H_1 is supported.

In the third step, whether the effect of sustainable HRM practices on work engagement differed according to demographic variables was tested. The six interaction terms were tested separately. According to the results, none of the interaction terms was statistically significant: Sustainable HRM × Age (β = −.013, p = .678); Sustainable HRM × Gender (β = .012, p = .706); Sustainable HRM × Tenure (β = −.033, p = .290); Sustainable HRM × Education (β = −.022, p = .478); Sustainable HRM × Marital status (β = −.024, p = .449); Sustainable HRM × Position (β = −.004, p = .897). The change in R^2 was extremely small across all analyses (ΔR^2 = .000). These findings show that H_2, H_3, H_4, H_5, H_6, and H_7 are not supported.

Since a single meaningless interaction does not, on its own, prove the absence of moderation, equivalence tests (two one-tailed tests; TOST) were applied to the six interaction terms. A threshold of |β| = 0.10 was adopted as the negligible s value for a standardized moderation coefficient. The results are presented in Table 6.

Table 6. Equivalence Tests (TOST) for the Six Interaction Terms

Interaction term	β	SE	90% CI (β)	TOST p
Sustainable HRM × Age	−.013	.031	[−.064, .038]	.003
Sustainable HRM × Gender	.012	.032	[−.040, .064]	.003
Sustainable HRM × Tenure	−.033	.031	[−.084, .018]	.016
Sustainable HRM × Education	−.022	.031	[−.073, .029]	.006
Sustainable HRM × Marital status	−.024	.032	[−.076, .028]	.008
Sustainable HRM × Position	−.004	.031	[−.055, .047]	.001

Note: N = 651. TOST = two one-sided tests against the equivalence bounds ±0.10 (standardised). β is the standardised interaction coefficient; the 90% CI corresponds to the α = .05 TOST decision. A TOST p < .05 indicates that the effect is statistically equivalent to a negligible value.

As shown in Table 6, the 90% confidence interval for each interaction remained within the range of ±0.10, and all six equivalence tests were significant (p ≤ .016). This indicates that the effects are very small, meaning that the contribution of sustainable HRM practices to job commitment operates similarly across demographic groups.

The findings of the hierarchical regression analysis reveal that sustainable HRM practices have a strong and significant effect on job engagement (β = .605, p < .001). However, this effect was not significantly moderated by any of the six demographic characteristics examined (age, gender, education level, tenure, marital status, and position).

5. CONCLUSION AND DISCUSSION

In this study, the moderating role of demographic variables in the relationship between sustainable HRM practices and work engagement was framed theoretically on the basis of the JD-R model and tested empirically, and a related conceptual model and hypotheses were developed. Grounded in the job demands–resources model, this study shows that sustainable HRM practices can play a determining role in increasing employees' passion for and commitment to their work, while also examining whether this effect differs according to demographic characteristics.

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This research offers several original contributions to the literature. First, it is one of the few studies to empirically test the relationship between sustainable HRM and work engagement in the Turkish context. Second, by systematically testing demographic characteristics as moderators, it directly responds to and addresses the observation by Thom et al. (2025) that moderating variables have not been sufficiently investigated in the sustainable HRM field. Third, by providing findings on the consistency and inclusiveness of sustainable HRM across employees with different demographic characteristics, it strengthens the theoretical foundation of the sustainable human resource management approach.

The absence of any significant moderation warrants careful interpretation. Because the theoretical arguments developed above lead one to expect demographic differences, the uniform null result is itself noteworthy and admits several explanations. First, the sustainable HRM measure captures broad, organisation-wide practices; such distal, aggregate resources may act as a common baseline that benefits all employees similarly, whereas moderation by career stage or gender may surface only for specific, proximal practices (e.g., particular flexibility arrangements)—a reading consistent with the distinction between basic and specific job resources within the JD-R framework. Second, the demographic moderators were modelled as categorical or ordinal variables, which reduces the statistical power to detect interactions and may mask genuine but modest moderation. Third, common-method variance and a possible ceiling effect in the engagement scores may attenuate the interaction terms. Finally, because a non-significant interaction is not by itself evidence of equivalence, equivalence tests (TOST) were conducted (Table 5); these indicated that all six interactions are statistically equivalent to a negligible effect ($|\beta| < 0.10$), which strengthens—though, given the chosen bound, does not prove beyond every threshold—the interpretation that the effect is not meaningfully moderated. Accordingly, the present results indicate no demographic moderation of at least small size in this sample, while very small effects cannot be excluded.

With this caveat in mind, the findings still carry a useful practical message. Because the engagement benefits of sustainable HRM practices did not vary detectably across the demographic groups sampled, organisations may reasonably treat these practices as a broadly effective foundation and prioritise increasing their quality and scope over designing separate variants for different demographic segments. This tentative pattern is broadly compatible with the universality and inclusiveness principles often associated with sustainable HRM, although—given the limitations above—it should be regarded as a working conclusion to be confirmed rather than as established invariance.

When the findings of this study are compared with prior studies in the literature, the results partly overlap with some studies and diverge from others.

James et al. (2011) examined work engagement in an age-diverse workforce and showed that the weight of certain predictors changes according to career stage, revealing partial differences across age groups. In this respect, the present findings do not fully overlap with theirs. However, the fact that core predictors such as managerial support and job clarity were significant across all age groups is partly consistent with the present finding that sustainable HRM operates independently of demographic characteristics.

Richman et al. (2008) showed that job flexibility and work–life-balance policies significantly predict work engagement. In their study, gender and tenure were used as control variables, and whether these demographic characteristics played a determining role in the relationship was not directly stated. Although the absence of a direct test of demographic characteristics complicates a full comparison, the overall framework can be said to be consistent with the present findings. Saks (2006) showed that perceived organisational support, job characteristics, and procedural justice predict work engagement. Demographic variables were not tested as moderators but were used only for control purposes. This framework, in which structural and organisational factors are more decisive than demographic characteristics, generally overlaps with the present findings. Nevertheless, owing to its small sample and different focus, it diverges from the present study.

Dumont et al.'s (2017) research in the context of green HRM presents a mixed picture with respect to the present findings. That study found that age and tenure did not play a determining role in employee behaviours, which overlaps with the present findings. However, education level was found to influence pro-environmental workplace behaviours through green HRM practices, a result that diverges from the

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present study. This inconsistency may stem from the different dependent variables of the two studies. Gyensare et al. (2024), who included gender, age, education, and tenure as control variables, found that these demographic characteristics had no determining effect on the relationship between green HRM and employee well-being. This finding is consistent with the present study, in which the moderating role of demographic variables was non-significant.

Zacher and Kooij (2021) showed that flexibility practices increase work engagement among younger employees while contributing to job performance among older employees. Because of these age-differentiated effects, this study does not overlap with the present findings. However, this divergence may stem from that study's focus on a specific HRM practice (flexibility practices) and its use of a different sample structure. Finally, Wu et al. (2025) argued that an intergenerationally inclusive climate increases job satisfaction and retention across age groups and that sustainable HRM practices play an important role in this process. This framework, which anticipates age-differentiated effects, does not fully align with the present findings. Nonetheless, because Wu et al.'s (2025) study is a conceptual review that addresses intergenerational dynamics from a broad perspective, a direct comparison between the two studies is difficult.

This study has several limitations; some of these are directly related to the finding that moderation was not significant. First, the cross-sectional design makes it difficult to establish a causal relationship among the variables; longitudinal studies could examine this relationship in greater detail. Second, limiting the sample to companies operating on the BIST that publish sustainability reports restricts the generalizability of the findings to companies that do not engage in sustainability reporting or to companies of different sizes. Third, demographic moderators were treated at the categorical or ordinal level; measuring these variables by dividing them into a small number of groups reduces the power to detect interactions (moderation). Therefore, the fact that moderation was found to be insignificant across all variables may be partly due to this situation. Fourth, common method variance was assessed using only Harman's one-factor test; this is a relatively weak diagnostic, and approaches such as marker variables or common latent factors would provide stronger control. Finally, the study used data based solely on employee self-reports; objective data sources, such as manager evaluations, were excluded.

Future research could address this topic from several different perspectives. For example, the long-term effects of sustainable HRM practices on job engagement could first be examined using a longitudinal research method. In addition, it could be investigated whether variables such as psychological safety and perceptions of organizational justice play a mediating or moderating role in the relationship between sustainable HRM and job engagement. Retesting demographic variables across different sectors and cultural contexts will significantly contribute to the generalizability of the findings.

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AN EXAMINATION OF WORKPLACE MOBBING IN LIGHT OF COURT OF CASSATION RULINGS: AN ANALYSIS FROM THE PERSPECTIVE OF EMPLOYEE RIGHTS AND EMPLOYER RESPONSIBILITIES

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ABSTRACT

Workplace mobbing refers to an employee being subjected, in a systematic and persistent manner, to psychological pressure, exclusion, humiliation or intimidating conduct by supervisors, co-workers or subordinates. In addition to producing adverse outcomes for employees' psychological and physical health, mobbing may reduce job satisfaction, organizational commitment and job performance, while increasing absenteeism, turnover and legal disputes. The aim of this study is to examine Court of Cassation rulings concerning workplace mobbing claims within the framework of employee rights and employer responsibilities, and thereby to identify the core criteria taken into account in the legal assessment of mobbing.

The study employs document analysis, one of the qualitative research methods. Accordingly, selected Court of Cassation rulings were examined covering such matters as psychological harassment at work, changes of duty station, assignment to work incompatible with the employee's professional qualifications, arduous working conditions, trade-union activity, and practices following pregnancy and maternity leave. In these rulings, employees' claims, employers' defences, witness statements, working conditions, the manner in which the employment contract was terminated, and the courts' legal reasoning were evaluated together.

The rulings examined show that not every adverse or unfair employer practice is, on its own, accepted as mobbing. For conduct to be characterized as mobbing, elements such as persistence, systematicity, an intimidating purpose, and harm to the employee's personality rights and professional standing must be assessed jointly. That said, frequent changes to an employee's duty station, assignment to work unrelated to their expertise and incompatible with their professional reputation, or the exertion of pressure aimed at forcing resignation may be treated by the Court of Cassation as indicators of mobbing. Furthermore, employer practices contrary to the duties of equal treatment, protection of the employee, and provision of a healthy and safe working environment are seen to give rise to legal consequences such as justified termination, severance pay and reinstatement.

In conclusion, employers must exercise their managerial prerogative in a manner consistent with the rule of good faith, the principle of proportionality, and employees' personality rights. Preventing mobbing requires establishing transparent complaint mechanisms within organizations, raising managers' awareness, and regularly monitoring employment relations.

Keywords: Mobbing, psychological harassment, Court of Cassation rulings, employee rights, employer liability, labour law

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1. INTRODUCTION

Working life is an important domain in which individuals not only meet their economic needs but also form social relationships, develop their professional identities and sustain their psychological well-being. Negative behaviours arising in this domain can substantially affect employees' job performance, their attitudes towards the organization, and their physical and mental health. One of the significant problems encountered in the workplace is systematic psychological harassment aimed at intimidating, excluding or driving out a particular employee.

The concept of mobbing denotes conduct in which one or more persons in working life engage, over a prolonged period and in a systematic manner, in hostile and unethical behaviour directed at a specific employee. The concept gained currency in the field of work psychology particularly through the studies of Heinz Leymann. Mobbing may manifest as obstructing the employee's communication, excluding them from social relationships, damaging their professional reputation, assigning them tasks incompatible with their competencies, and exposing them to behaviour that adversely affects their physical or psychological health (Leymann, 1996; Tınaz, 2006).

In the Turkish literature, various terms such as "psychological harassment," "psychological violence," "workplace intimidation," "emotional abuse" and "workplace bullying" are used as equivalents of the concept of mobbing. This diversity indicates that mobbing is not merely an interpersonal conflict, but rather a multidimensional phenomenon with psychological, organizational and legal dimensions (Yıldız & Kılkış, 2010). Nevertheless, not every disagreement, criticism or one-off negative behaviour occurring in the workplace can be classified as mobbing. For conduct to be characterized as mobbing, it must continue for a certain period, be repeated systematically, and pursue the aim of intimidating, discrediting or removing the targeted person from employment.

The consequences of mobbing for employees emerge in economic, social, psychological and physical dimensions. Employees exposed to mobbing may experience anxiety, depression, loss of self-confidence, sleep disorders, difficulty concentrating, headaches and back pain, digestive system problems, and post-traumatic stress disorder. Damage to the employee's social relationships, loss of professional identity and resignation are also among the probable consequences of mobbing (Tınaz, 2006). From an organizational standpoint, mobbing may reduce employee motivation and performance, increase turnover and sick leave, impair the organizational climate, and raise legal costs.

The legal dimension of mobbing is significant in terms of protecting the employee's personality rights and delimiting the boundaries of the employer's managerial prerogative and duty of care. In exercising the managerial prerogative, the employer is obliged to protect employees' personality values, professional reputation and human dignity. Continual changes to an employee's duty station, assignment to work incompatible with their professional qualifications, exclusion by co-workers, exposure to unjust disciplinary measures, or pressure to resign may, depending on the circumstances of the case, constitute a breach of the employer's duty of care.

In assessing mobbing claims, Court of Cassation rulings consider jointly the persistence, systematicity and purpose of the conduct, its effects on the employee, witness statements and other concrete evidence. Indeed, the Court of Cassation treated the frequent relocation of an employee and their assignment to a post incompatible with their professional career as mobbing, once it was established that these practices had been carried out in order to force the employee to resign. Conversely, where systematic psychological harassment cannot be demonstrated by sufficient and credible evidence, the mobbing claim is not upheld. Accordingly, in the practice of the Court of Cassation, not every unlawful employer act is regarded as mobbing; the conduct is required to be assessed as a whole.

The aim of this study is to examine the phenomenon of workplace mobbing through selected Court of Cassation rulings and to evaluate it in terms of employee rights and employer responsibilities. Within this scope, the study addresses the conceptual framework of mobbing, its effects on employees and organizations, the assessment criteria taken into account by the Court of Cassation, and the legal consequences that mobbing may entail. In this way, it aims to delineate the boundaries between the employer's managerial prerogative and the protection of the employee's personality rights within the framework of Court of Cassation case law.

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2. CONCEPTUAL FRAMEWORK

2.1. The Concept of Mobbing

Mobbing refers to systematic and persistent hostile behaviour carried out by one or more persons in the work environment against a particular employee. Such behaviour may result in the employee being psychologically intimidated, excluded from social relationships, having their professional reputation damaged, or being driven out of the workplace. According to Leymann (1996), mobbing consists of behaviour amounting to harassment directed at a person, collective targeting, and psychological terror in the workplace. Systematic examination of the concept in the context of working life began in the 1980s.

In the Turkish literature, terms such as "psychological harassment," "workplace intimidation," "psychological violence," "emotional abuse" and "workplace bullying" are used as equivalents of the concept of mobbing. This conceptual diversity shows that mobbing is not an ordinary disagreement between employees, but a multifaceted problem of working life with psychological, social, organizational and legal dimensions (Yıldız & Kılkış, 2010).

Not every conflict, criticism, change of duty or one-off negative behaviour occurring in the workplace is accepted as mobbing. For conduct to be assessed as mobbing, it must be directed at a particular employee, be repeated over time, form a systematic pattern, and pursue an intimidating purpose. The conduct in question is also expected to cause harm to the employee's personality rights, professional reputation, psychological health or standing in the workplace (Savaş Kutsal, 2016).

For this reason, in determining mobbing, incidents must be evaluated not individually and in isolation, but as part of an overall process. An employer act that may be regarded as unlawful or unjust on its own does not always constitute mobbing. However, where adverse acts carried out on different dates display a systematic coherence aimed at intimidating, discrediting or forcing the resignation of a particular employee, mobbing may be said to exist (Savaş Kutsal, 2016).

2.2. Parties Involved in the Mobbing Process

Three principal parties are involved in the mobbing process: the perpetrators, the victims, and the bystanders who witness the mobbing behaviour. Perpetrators are those who engage in behaviour such as exclusion, humiliation, discrediting, threats or excessive supervision against the employee they target. The victim is the employee directly exposed to this systematic conduct, while bystanders are the employees who witness such conduct but participate in the process directly or indirectly (Tınaz, 2006).

The perpetrator of mobbing need not be a manager or the employer. Mobbing may arise as conduct by superiors towards subordinates, between employees at the same level, or by subordinates towards their managers. Accordingly, depending on the parties' positions in the organizational hierarchy, mobbing is classified as top-down vertical mobbing, horizontal mobbing, and bottom-up vertical mobbing (Yıldız & Kılkış, 2010).

A superior's systematic use of authority as an instrument of pressure against a subordinate is regarded as top-down mobbing. The exclusion or discrediting of a co-worker by employees of similar status falls within horizontal mobbing. Where subordinates systematically withhold information from a manager, fail to implement instructions, or act collectively to undermine the manager's authority, this is described as bottom-up mobbing (Tınaz, 2006).

2.3. Indicators of Mobbing Behaviour

Mobbing may take the form of overt conduct such as direct insult, threat or humiliation, but it may also be carried out through more covert and indirect practices. Leaving the employee out of important work-related developments, not inviting them to meetings, conversations stopping when they enter the work area, rumours being spread about them, and being assigned tasks outside their area of expertise are among the indicators of mobbing (Tınaz, 2006; Yıldız & Kılkış, 2010).

Monitoring an employee's arrival and departure times, telephone calls and rest breaks in unusually detailed fashion, differently from other employees, may likewise be regarded as psychological

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harassment. Similarly, constant criticism of the employee, rejection of their suggestions without justification, failure to respond to their verbal or written requests, exclusion from social activities, and mockery of their appearance are counted among the behavioural indicators of the mobbing process (Tınaz, 2006).

Nevertheless, the presence of such behaviour on its own does not mean that mobbing has definitively occurred. In determining whether conduct constitutes mobbing, persistence, systematicity, targeting, intimidating purpose and the effects of the conduct on the employee must be considered together. Court of Cassation rulings likewise examine whether the employer's practices rest on an objective and business-related ground, whether the conduct is directed at a particular person, and whether it forms a pattern of psychological harassment as a whole (Savaş Kutsal, 2016).

2.4. Consequences of Mobbing for Employees

Mobbing may produce significant consequences for employees' psychological and physical health. Victims of mobbing may exhibit depression, anxiety, fear, panic attacks, loss of self-confidence, difficulty concentrating, sleep disturbance and symptoms of post-traumatic stress (Leymann, 1996; Tınaz, 2006).

The physical effects of mobbing include headaches and back pain, high blood pressure, palpitations, sweating, trembling, gastric and intestinal complaints, skin problems and respiratory difficulties. It is noted that prolonged psychological pressure can weaken the employee's immune system and render them more vulnerable to a range of physical health problems (Tınaz, 2006).

The consequences of mobbing are not limited to psychological and physical health problems. Deterioration in the victim's relationships with co-workers and family, withdrawal from their social circle, loss of professional identity, and being compelled to leave their job are also among the social and economic consequences of mobbing (Yıldız & Kılkış, 2010).

The victim of mobbing may be obliged to incur economic expenditure for the treatment of health problems and may be deprived of a regular income if they lose their job. Mobbing may therefore affect not only the employee's current working conditions but also their long-term professional life and economic security (Tınaz, 2006).

2.5. Organizational Consequences of Mobbing

Mobbing produces serious consequences not only for the victimized employee but also for the organization. The spread of mobbing behaviour in the workplace may reduce trust among employees, increase conflict, impair the organizational climate and weaken the organizational culture (Tınaz, 2006).

In an environment where employees do not feel safe, motivation, organizational commitment, creativity and job performance may decline. Employees who are not directly exposed to mobbing but who witness such conduct may also suffer damage to their trust in the organization and its management. This demonstrates that mobbing cannot be regarded merely as an individual problem between the victim and the perpetrator (Yıldız & Kılkış, 2010).

The economic consequences of mobbing for organizations include increased sick leave, the departure of qualified employees, higher turnover, and additional costs for recruiting and training new employees. Declining overall performance and work quality, compensation payments, litigation expenses and early retirement costs are likewise among the organizational consequences of mobbing (Tınaz, 2006).

2.6. The Societal and International Dimension of Mobbing

The effects of mobbing are not confined to the boundaries of the workplace; they also extend to the societal and economic level. The physical and psychological health problems arising from mobbing may increase health and insurance expenditure. Unemployment, early retirement, loss of tax revenue and rising demand for social assistance programmes are also among the consequences of mobbing for the national economy (Tınaz, 2006).

The withdrawal from working life of individuals whose professional competence and motivation to work have been damaged by mobbing may lead to reduced societal productivity. Moreover, the deterioration

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of victims' family and social relationships shows that mobbing constitutes a societal problem beyond an individual workplace issue (Yıldız & Kılkış, 2010).

The Violence and Harassment Convention No. 190, adopted by the International Labour Organization in 2019, is the first international convention to recognize everyone's right to a world of work free from violence and harassment. The Convention provides an international framework for preventing unacceptable behaviour and practices in the world of work that result in, or are likely to result in, physical, psychological, sexual or economic harm (International Labour Organization [ILO], 2019).

2.7. The Legal Dimension of Mobbing and Employer Liability

In the legal assessment of mobbing, the employer's obligations to protect the employee, safeguard their personality rights, treat employees equally and provide a safe working environment are of central importance. The employer's managerial prerogative is not unlimited and must be exercised in accordance with the principles of good faith, proportionality and equality. Using the managerial prerogative in order to humiliate an employee, damage their professional reputation or force them to leave their job may give rise to unlawful outcomes (Savaş Kutsal, 2016; Yıldız & Kılkış, 2010).

Depending on the circumstances of the case, an employee subjected to mobbing may have the right to terminate the employment contract for just cause and to claim severance pay, non-pecuniary damages and unpaid employment receivables. Where conduct constituting mobbing also amounts to a criminal offence, criminal liability may additionally arise for the person engaging in it (Savaş Kutsal, 2016).

In assessing mobbing claims, Court of Cassation rulings consider together changes of duty station, assignments contrary to professional qualifications, unjust disciplinary measures, working conditions, witness statements and the persistence of the conduct. In particular, frequent changes to an employee's duty station and assignment to work incompatible with their professional career may be assessed as mobbing where it is established that these acts were carried out in order to force the employee to resign (Savaş Kutsal, 2016).

The continual relocation of an employee working as a computer operator and, ultimately, their assignment to the operating theatre door — a post unrelated to their professional career — was assessed as psychological harassment intended to bring about the employee's resignation. Conversely, in disputes where systematicity and an intimidating purpose could not be established by sufficient evidence, the mobbing claim was not upheld.

3. METHODOLOGY

This study adopts document analysis within a qualitative research design, and the data obtained were evaluated through content analysis. No data were collected from any participant group; instead, Court of Cassation rulings concerning the phenomenon of workplace mobbing were examined systematically. Within this scope, the analysis addressed how mobbing is defined and assessed in the rulings, which forms of evidence are taken into account, how the employer's responsibilities are treated, and the legal consequences the rulings entail for employee rights.

3.1. Research Method

In this study, **a qualitative research method** was adopted in order to examine how the phenomenon of workplace mobbing is addressed in Court of Cassation rulings within the framework of employee rights and employer responsibilities. The research design was determined to be **document analysis**, which permits the systematic examination of existing written and legal documents.

Document analysis involves examining, according to specified criteria, written materials containing information about the phenomenon or events under investigation. Accordingly, the data source of the study consists of Court of Cassation rulings related to psychological harassment at work, mobbing, termination of the employment contract, reinstatement, severance pay and non-pecuniary damages.

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3.2. Population and Sample

The population of the study comprises Court of Cassation rulings issued in relation to workplace mobbing claims in Türkiye. The sample consists of Court of Cassation rulings identified through criterion sampling, one of the purposive sampling methods.

The following criteria were applied in including rulings in the study:

- The ruling contains a direct claim of mobbing or psychological harassment;
- The ruling was issued within the scope of an employee–employer relationship;
- It contains sufficient explanation of the claims of the plaintiff and the defendant;
- It contains reasoned assessment by the court or the Court of Cassation;
- It relates to at least one of the following: employee rights, the employer's duty of care, termination, reinstatement or compensation.

The rulings examined in the study involve claims by employees in different sectors concerning matters such as mobbing, arduous working conditions, change of duty, trade-union activity, assignment following pregnancy and maternity leave, overtime work, and occupational health and safety. The sample of the study consists of 6 Court of Cassation rulings meeting the specified criteria.

3.3. Data Collection

The research data were obtained by examining Court of Cassation rulings and related legal documents. The rulings were classified in terms of decision number, relevant civil chamber, subject matter of the case, plaintiff's claims, defendant's defences, the first-instance court's decision, the Court of Cassation's assessment, and the final outcome.

Table 1. Field of examination and Content of Court of Cassation

Field of examination	Content
Case identification details	Chamber, case and decision number, date
Mobbing claim	Alleged conduct
Direction of mobbing	Vertical, horizontal or mixed
Evidence	Witness, written document, medical report, notarized notice, etc.
Employer's defence	Business decision, performance, discipline, change of duty, etc.
Court's assessment	Acceptance or rejection of mobbing
Legal outcome	Reinstatement, severance pay, dismissal of claim, reversal, etc.
Employer liability	Duty of care, equal treatment, occupational health and safety obligation

4.DATA ANALYSIS

The Court of Cassation rulings examined within the scope of the research were subjected to content analysis in line with nine predetermined themes. The plaintiffs' claims, employers' defences, witness statements, courts' reasoning and the outcomes of the judgments contained in the rulings were evaluated together. The analysis yielded the following findings.

4.1. Conduct Alleged to Constitute Mobbing

In the rulings examined, mobbing claims are seen to arise not from a single act but from the combination of different practices relating to working conditions and the employee's position in the workplace. The principal forms of conduct alleged to constitute mobbing are: continual or frequent changes to the employee's duty station; assignment to work unrelated to their post and professional competence; exposure to a workload beyond their capacity; employment under conditions unsuitable in terms of occupational health and safety; exposure to insult and physical violence; subjection to wage and pay-

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rise practices different from those applied to other employees; pressure on account of trade-union activity; the intensification of working conditions following pregnancy and maternity leave; assignment to a workplace far from the employee's residence; obstruction of the use of nursing leave; and being steered towards resignation.

In the ruling of the 7th Civil Chamber of the Court of Cassation dated 26.04.2016, no. 2016/9309, it was established that the plaintiff, who worked as a computer operator, had their duty station changed at frequent intervals and was ultimately assigned to the operating theatre door, a post unrelated to their profession. Since witness statements also supported the finding that the changes of duty had been made in order to steer the employee towards resignation, these practices were assessed as mobbing. The rejection of the plaintiff's claim for severance pay was accordingly held to be a ground for reversal.

In the other ruling, concerning an employee working as a driver, the plaintiff argued that he had been forced to operate a forklift despite not holding an operator's certificate, that his working conditions had been made more arduous, that his overtime wages had not been paid, and that different practices had been applied among employees. The Court of Cassation concluded that the evidence in the case file was insufficient to prove the mobbing claim. Nevertheless, practices such as having an uncertified worker operate a forklift and the non-payment of certain employment receivables were accepted as constituting just cause for termination on the employee's part. As the chamber, case and decision numbers of this ruling were not given in the uploaded presentation, the decision number could not be added to the text.

4.2. The Persistence and Systematicity of Mobbing

The rulings examined show that, in its assessment of mobbing, the Court of Cassation does not consider it sufficient for conduct merely to be unjust, adverse or distressing from the employee's point of view. For conduct to be accepted as mobbing, it must continue for a certain period, be repeated, and display a systematic coherence aimed at intimidating the employee, devaluing them, forcing their resignation, or removing them from working life.

In the ruling of the 7th Civil Chamber of the Court of Cassation dated 26.04.2016, no. 2016/9309, it was established that the plaintiff, who worked as a computer operator, had their duty station changed frequently and was ultimately assigned to the operating theatre door, a post unrelated to their duties and professional career. Witness statements likewise supported the finding that these changes of duty had been made in order to bring about the plaintiff's resignation. Rather than treating the acts as independent individual measures, the Court of Cassation assessed all of the practices directed at the plaintiff together and concluded that the employee had been subjected to psychological harassment. In this respect, the ruling shows that repeated changes of duty and assignments damaging the employee's professional standing may constitute mobbing where they are carried out in pursuit of a particular purpose.

By contrast, not every measure relating to a change of duty or a disciplinary penalty is assessed as mobbing on its own. In the ruling of the 22nd Civil Chamber of the Court of Cassation, no. 2018/15175, the case examined concerned a person working as an electrician and occupational safety representative in an electrical maintenance unit who was assigned to the warehouse on account of a medical report stating "unfit for heavy and hazardous work" and who was given a two-day wage deduction penalty in connection with the leave procedure. The penalty imposed was assessed as not being procedurally improper, and the employee's claims were dismissed. This ruling shows that a change of duty based objectively on a medical report, or a disciplinary penalty applied lawfully, does not constitute mobbing in the absence of persistence, systematicity and an intimidating purpose.

In sum, in determining the existence of mobbing, the Court of Cassation takes into account the frequency of the conduct, its duration, the connections between individual acts, the employer's purpose and the cumulative effect of the practices on the employee, rather than a single incident.

4.3. Evidence Used in Proving Mobbing

In the rulings, witness statements appear to be the form of evidence most frequently relied upon in assessing mobbing claims. In addition, employment contracts, documents relating to changes of duty, notarized notices, medical reports, job advertisements, wage records and documents showing working

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hours are also taken into account. The principal forms of evidence used in the rulings examined are as follows:

Table 2. Type of evidence and Manner of use in the rulings

Type of evidence	Manner of use in the rulings
Witness statements	Providing information about insults, arduous working conditions, changes of duty and the employer's purpose
Medical reports	Determining whether the employee is fit to work in heavy and hazardous jobs
Notarized notice	Establishing the grounds on which the employee terminated the employment contract
Employment contract	Assessing the scope of the employer's authority to change the employee's duty and workplace
Job advertisements	Examining the accuracy of the employer's defence that no vacant position was available
Wage and working-time records	Determining overtime, travel allowance and other employment receivables
Expert report	Calculating overtime pay and other monetary receivables
Assignment measures	Assessing the frequency and nature of changes of duty and the purpose for which they were made

4.4. Protection of the Employee's Personality and Employment Rights

The rulings examined show that not only employees' wage and compensation rights are protected, but also their professional dignity, physical and psychological integrity, and right to work under conditions consistent with human dignity.

Assigning an employee to work unrelated to their profession and inconsistent with their career was assessed as a practice damaging their professional identity and personality rights. Likewise, insult, physical violence, excessive workload and failure to take the necessary occupational health and safety measures are among the forms of conduct that violate the employee's personality and employment rights.

In the case forming the subject of the **ruling of the 7th Civil Chamber of the Court of Cassation dated 09.11.2015, no. 2015/21881**, the plaintiff argued that he worked in hot-dip galvanizing, that he was constantly subjected to insults and physical violence by the foreman at the workplace, that he had contracted occupational asthma because the necessary occupational health and safety measures had not been taken, and that following a work accident he had been sent to hospital only the next day. He further stated that he had worked overtime at the workplace and that part of his wage had been paid in cash.

The court accepted that the employee had terminated the employment contract for just cause and had become entitled to severance pay, and partially upheld the claim. In its review, the Court of Cassation ordered reversal not in respect of the just-cause termination and severance pay, but on the ground that annual leave periods had not been excluded from the overtime calculation. Accordingly, while this ruling underscores the importance of the employee's physical integrity and right to work under healthy conditions, it should be noted that the ground for reversal related essentially to the calculation of overtime pay.

4.5. The Employer's Duties of Equal Treatment and Care

In the rulings examined, the employer's duty to protect and look after the employee is addressed within the framework of the obligations to provide safe and healthy working conditions, to refrain from arbitrary differentiation among employees, and to exercise managerial authority in accordance with the rule of good faith.

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In the ruling concerning the plaintiff who worked as a driver, the employee argued that he had received a lower pay rise than the rate applied to other employees, that travel allowances were differentiated among employees, that his working conditions had been made more arduous, and that he had been made to work under conditions inadequate in terms of occupational health and safety. The employer, for its part, argued that wage increases were determined according to variables such as promotion, seniority and performance, that it was not obliged to grant the same rate of increase to all employees, and that the plaintiff had not been made to operate construction machinery.

The Court of Cassation stated that the mobbing claim had not been sufficiently proven on the case file. Nevertheless, witness statements confirmed that the plaintiff had been forced to operate a forklift despite not holding an operator's certificate. Statements were also recorded to the effect that working conditions were arduous, that employees were burdened with work beyond their capacity, that the ventilation system was inadequate, and that employees were affected by chemical substances. Assessing these matters together with the unpaid employment receivables, the employee's termination of the employment contract was found to be justified and he was accepted as entitled to severance pay. However, it was stated that the claim for notice pay had to be dismissed, since it was the employee who had terminated the employment contract.

The ruling demonstrates that the employer's managerial prerogative is not unlimited. The employer must not have employees perform hazardous work for which they lack professional competence; must take measures to protect employees' health and safety; and must base its practices concerning wages and working conditions on objective criteria. Accordingly, exposing employees to chemical substances, having them work in an environment with inadequate ventilation, or forcing them to operate machinery without the requisite certification and competence are matters directly related to the employer's duty of care.

4.6. Changes of Duty and Workplace

Changes of duty and workplace constitute one of the prominent themes in the Court of Cassation rulings examined. Nevertheless, the Court of Cassation does not accept every change of duty or workplace effected by the employer as mobbing. In assessing whether a change constitutes mobbing, consideration is given to whether the change rests on an objective and business-related ground, whether the employment contract grants the employer authority to change duties, the compatibility of the new post with the employee's professional competence, the persistence of the change, and whether it is aimed at steering the employee towards resignation. The employee's family and personal circumstances, and the consistency between the employer's defences and its actual practices, are also of importance.

In the ruling of the 7th Civil Chamber of the Court of Cassation dated 26.04.2016, no. 2016/9309, it was established that the plaintiff, who worked as a computer operator, had their duty station changed frequently and was ultimately assigned to the operating theatre door, a post unrelated to their duties and professional career. Witness statements likewise supported the finding that these changes had been made in order to bring about the plaintiff's resignation. Assessing the practices directed at the plaintiff as a whole, the Court of Cassation concluded that the changes of duty in question constituted mobbing.

In the ruling of the 9th Civil Chamber of the Court of Cassation, no. 2015/9129, the situation examined concerned an employee whom the employer sought to assign to another branch following pregnancy and maternity leave. Although the employment contract contained a provision allowing the employer to assign the employee to different branches and units, it was assessed that the change of duty station did not rest on a valid ground in the specific circumstances of the case. Consideration was given to the fact that the new duty station was far from the employee's residence and made it difficult for her to use her nursing leave. Moreover, notwithstanding the employer's defence that no other position was available, the publication of job advertisements for the same position at different branches two days after the termination of the employment contract revealed the contradiction between the employer's defence and its actual practice. The termination was therefore found invalid and the employee's reinstatement was ordered.

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4.7. Termination of the Employment Contract and Reinstatement

In the rulings examined, mobbing claims are mostly connected with the ending of the employment contract. While some employees themselves terminated the employment contract on account of mobbing and arduous working conditions, the contracts of some employees were terminated by the employer.

As regards termination by the employee, where mobbing or other unlawful employer practices are proven, the employee may acquire the right to terminate for just cause. In the computer operator case, mobbing was clearly accepted and the rejection of the employee's claim for severance pay was held to be a ground for reversal.

In the case of the employee working as a driver, although mobbing could not be proven, the termination by the employee was accepted as justified on account of being made to operate a forklift without certification, unpaid employment receivables and the working conditions. However, since it was the employee who terminated the employment contract, it was stated that notice pay could not be awarded.

In the case concerning the pregnant employee, the termination effected by the employer was found invalid and the employee's reinstatement was ordered. It was decided that, should the employee apply within the statutory period but not be taken back to work, compensation in the amount of four months' wages would be paid, and that wages and other entitlements accruing until the judgment became final, for a maximum of four months, would be granted.

4.8. Outcomes Concerning Severance, Notice and Non-Pecuniary Damages

The outcomes of the rulings examined vary according to whether the mobbing claim is upheld, whether the employer's unlawful practices are proven, and which party brought the employment contract to an end.

Where it is accepted that the employee terminated the employment contract with just cause on account of mobbing, arduous working conditions or other unlawful employer practices, the employee is seen to become entitled to severance pay. In the ruling of the 7th Civil Chamber of the Court of Cassation dated 26.04.2016, no. 2016/9309, the frequent relocation of the plaintiff, who worked as a computer operator, and their assignment to work unrelated to their professional career were assessed as mobbing. The rejection of the plaintiff's claim for severance pay was accordingly held to be a ground for reversal.

Similarly, in the ruling of the 7th Civil Chamber of the Court of Cassation dated 09.11.2015, no. 2015/21881, the termination by the employee, who terminated the employment contract on account of arduous and unhealthy working conditions, insults and allegations of physical violence, was accepted as justified and the employee was held entitled to severance pay. That said, the Court of Cassation's ground for reversal arose not from severance pay but from the failure to exclude annual leave periods from the overtime calculation.

It is accepted that an employee who terminates the employment contract themselves, even for just cause, cannot become entitled to notice pay. In the ruling concerning the employee working as a driver, although the mobbing claim could not be sufficiently proven, the termination was found justified because the plaintiff had been forced to operate a forklift without an operator's certificate and certain employment receivables had gone unpaid. However, since the party ending the employment contract was the employee, it was stated that the claim for notice pay had to be dismissed. The uploaded document does not contain the chamber, date or decision number of this ruling.

In the ruling of the 9th Civil Chamber of the Court of Cassation, no. 2015/9129, the termination effected after an employee refused to accept assignment to a branch far from her residence following pregnancy and maternity leave was found invalid, and the employee's reinstatement was ordered. It was decided that, should the employee apply for work within the statutory period but not be taken back by the employer, compensation in the amount of four months' wages for failure to reinstate would be paid. It was further ordered that wages and other entitlements accrued until the judgment became final, for a maximum of four months, be paid to the employee.

The document examined states that a victim of mobbing may claim non-pecuniary damages where the requisite conditions are met. However, the summaries of the rulings within the sample do not include a

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decision in which non-pecuniary damages were directly awarded and in which the amount of compensation and the grounds for its acceptance were explained in detail. For this reason, it is not possible to make a definitive assessment, on the basis of the rulings examined, regarding the amount, method of calculation or conditions of acceptance of non-pecuniary damages.

In general, the rulings show that proof of mobbing or of the employer's unlawful practices may produce outcomes in the employee's favour with respect to severance pay and reinstatement; whereas, with respect to notice pay, the determinative factor is which party terminated the contract.

4.9. Grounds for Upholding or Rejecting a Mobbing Claim

The factors that led the Court of Cassation to uphold or reject mobbing claims across the rulings examined are summarised comparatively in Table 3.

Table 3. Factors Effective in Upholding and Rejecting Mobbing Claims in Court of Cassation Rulings

Factors effective in upholding a mobbing claim	Factors effective in rejecting a mobbing claim
Repetition and persistence of the conduct	The existence of a single or temporary measure
A purpose of intimidating, devaluing or steering the employee towards resignation	The measure resting on an objective and business-related ground
Changes of duty being incompatible with the employee's profession and career	The change of duty being consistent with a medical report or the employment contract
Witness statements supporting the employee's claims	The claims not being supported by concrete and credible evidence
Contradiction between the employer's defence and the documents on file	The employer's measure being procedurally and legally compliant
The employee being targeted in a specific and systematic manner	Adverse working conditions not being directed at a particular employee
Several adverse practices occurring together and in connection with one another	The managerial prerogative being exercised reasonably, proportionately and objectively

4.10. General Assessment

The rulings examined show that, in its assessment of mobbing, the Court of Cassation focuses on the totality, persistence, systematicity and purpose of the conduct rather than on a single act. A change of duty, a wage differential, a disciplinary penalty or arduous working conditions are not in every case accepted as mobbing on their own. However, where such practices are repeated with the aim of intimidating the employee, devaluing them, forcing their resignation or removing them from working life, a conclusion of mobbing may be reached.

Although witness statements constitute important evidence in the rulings, written documents and the chronological development of events are also determinative. In particular, a contradiction between the business grounds asserted by the employer and its actual practices leads to an assessment in the employee's favour. In sum, while the Court of Cassation accepts the employer's managerial prerogative, it holds that this prerogative must be limited by the employee's personality rights, professional reputation, health, family obligations and right to work under conditions consistent with human dignity.

5. CONCLUSION AND DISCUSSION

This study addressed the phenomenon of workplace mobbing within the framework of employee rights and employer responsibilities, evaluating selected Court of Cassation rulings by means of document analysis and content analysis. The rulings examined show that not every adverse, unjust or distressing behaviour occurring in the workplace can be characterized as mobbing on its own. In assessing mobbing claims, the Court of Cassation considers together whether the conduct is directed at a particular employee, whether it displays persistence and systematicity, whether it involves a purpose of

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intimidation or removal from employment, and whether it produces adverse consequences for the employee's personality rights and professional standing.

The research findings reveal that mobbing mostly consists not of a single act but of mutually reinforcing practices repeated over time. Frequent changes to an employee's duty station, assignment to work incompatible with their professional qualifications, exposure to arduous and unhealthy working conditions, subjection to practices different from those applied to other employees, pressure on account of trade-union activity, and being steered towards resignation are among the principal forms of conduct grounding mobbing claims in the rulings examined. However, whether such practices can be accepted as mobbing depends on the conduct forming a systematic pattern and on an intimidating purpose being discernible from the specific circumstances of the case.

Among the rulings examined in the study, the continual relocation of a person working as a computer operator and their assignment to a post unrelated to their professional career is particularly notable. In the ruling of the 7th Civil Chamber of the Court of Cassation dated 26.04.2016, no. 2016/9309, these practices were assessed as mobbing once witness statements likewise supported the finding that the changes of duty were aimed at securing the employee's resignation. This ruling shows that a change of duty is considered not in isolation but together with the frequency and nature of the changes and the purpose behind them. By contrast, the fact that a change of duty grounded on a medical report and arising from an objective necessity, and a disciplinary penalty imposed in accordance with proper procedure, were not accepted as mobbing demonstrates that the employer's lawful managerial acts are distinguished from practices amounting to psychological harassment.

The findings show that witness statements occupy an important place in proving mobbing. Alongside witness accounts, however, medical reports, notarized notices, employment contracts, assignment documents, job advertisements, wage records, documents showing working hours and expert reports are also influential in the courts' assessments. In particular, a contradiction between the employer's defence and the documents on file or its actual practices may lead to an assessment in the employee's favour. The ruling concerning the employee whom the employer sought to assign to another branch following pregnancy and maternity leave — in which a job advertisement for the same position was published shortly after the termination despite the employer's defence that no vacancy existed — exemplifies this situation.

Another important finding of the study is that the rejection of a mobbing claim does not mean that the employer's other unlawful practices go without consequence. In the case of the employee working as a driver, although mobbing could not be sufficiently proven, being made to operate a forklift without an operator's certificate, arduous working conditions and unpaid employment receivables were assessed as just cause for termination on the employee's part. This finding shows that mobbing and grounds for just-cause termination may be subject to different legal assessments. In other words, the fact that conduct does not carry the elements of persistence and systematicity required for mobbing does not eliminate the employer's breach of its obligations regarding occupational health and safety, payment of wages, or the duty of care towards the employee.

The rulings examined also make clear that the employer's managerial prerogative is not unlimited. The employer may change duties and workplaces for the purposes of carrying out the work, may take decisions concerning the working arrangements, and may exercise disciplinary authority under certain conditions. However, these powers must be exercised in accordance with the rule of good faith, the duty of equal treatment, the principle of proportionality and the employee's personality rights. Using the managerial prerogative in order to humiliate an employee, damage their professional reputation, hinder their exercise of statutory rights or steer them towards leaving their job may give rise to unlawful outcomes.

The rulings show that not only employees' wage and compensation rights are protected, but also their physical and psychological integrity, professional dignity and right to work under conditions consistent with human dignity. Practices such as insult, physical violence, excessive workload, inadequate ventilation, exposure to chemical substances, and being made to perform hazardous work without the requisite professional competence are directly related to the employer's obligation to protect the

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employee and provide a safe working environment. For this reason, the legal assessment of mobbing should not be confined to claims of psychological pressure; working conditions and the employer's duty of protection should also be addressed holistically.

Mobbing and other unlawful employer practices were found to produce different consequences with respect to the ending of the employment contract. An employee who terminates the employment contract with just cause on account of mobbing or arduous working conditions may become entitled to severance pay. By contrast, an employee who terminates the contract themselves is seen to be unable to acquire entitlement to notice pay, even where the termination is justified. Where a termination effected by the employer is found invalid, reinstatement, wages for the period of idleness and compensation for failure to reinstate may arise. These outcomes show that, in mobbing disputes, which party ended the contract and on what ground is a fundamental element in determining the legal consequences.

The findings of the study demonstrate the importance of the chronological sequence and overall coherence of events in assessing mobbing claims. Practices that, taken individually, might appear to be ordinary managerial acts may acquire the character of mobbing when they are repeated against a particular employee and converge around a common intimidating purpose. It is therefore important that courts consider changes of duty, disciplinary measures, wage practices, working conditions and the termination process not independently of one another, but with regard to the totality of events and their cumulative effect on the employee.

In practical terms, employers should not regard mobbing merely as a conflict occurring between individual employees. The employer must monitor the conduct of managers and employees, investigate psychological harassment claims effectively, and establish mechanisms ensuring the protection of the victim. It is recommended that organizations establish accessible and reliable complaint channels, that complaints be examined confidentially and impartially, that managers be trained on mobbing and the limits of the managerial prerogative, and that changes of duty and disciplinary measures be carried out in written, reasoned form based on objective criteria.

It is also important that employees not be placed at a disadvantage on grounds such as pregnancy, maternity leave, nursing leave, trade-union activity and health status. Employer measures relating to such situations should be planned so as not to prevent employees from actually exercising their statutory rights, and should rest on objective grounds that do not create an impression of discrimination among employees. Since inconsistency between the employer's defence and its actual practices may be assessed against the employer in legal disputes, human resources and management processes must be transparent and capable of being documented.

The principal limitation of the study is that it is confined to six selected Court of Cassation rulings and to the information contained in the accessible summaries of those rulings. The fact that some rulings do not set out case and decision numbers, the full witness accounts, or other documents in the case file in detail limits the comparison of the rulings. Moreover, since the rulings examined include no detailed example in which non-pecuniary damages were directly awarded, a comprehensive assessment of the conditions of acceptance and the amount of such damages could not be made.

Future studies would benefit from using a larger sample of Court of Cassation rulings to compare mobbing decisions by year, sector, type of employer, direction of mobbing and case outcome. In addition, examining non-pecuniary damages, discrimination compensation, trade-union compensation and reinstatement decisions separately, and evaluating the weight of witness statements, medical reports and digital evidence in proving mobbing, could contribute to the literature.

In conclusion, Court of Cassation rulings establish that, in determining mobbing, conduct must be assessed holistically within the framework of persistence, systematicity, targeting and intimidating purpose. While the employer's managerial prerogative is recognized, this prerogative must be limited by the employee's personality rights, professional reputation, health, family obligations and right to work under conditions consistent with human dignity. Preventing mobbing depends not only on the application of legal sanctions, but also on the development of preventive human resources policies, the strengthening of internal oversight, and the creation of a safe organizational culture.

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DENTAL INNOVATION ADOPTION AS A CATALYST FOR ALBANIAN DENTAL TOURISM GROWTH

Technology Investment, Patient Expectations, and the Competitive Positioning of Albanian Dentistry in the European Market

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ABSTRACT

A patient from Zurich books a dental appointment in Tirana. She has researched three clinics online, watched video walkthroughs of their equipment, reviewed before-and-after galleries on Instagram, and exchanged digital scans with a prosthodontist she has never met in person. By the time she boards the flight, she knows more about the clinic she is visiting than she knows about her GP at home. She is not unusual — she is representative of a dental tourism patient in 2026. And what she is looking for — digital workflows, CBCT imaging, same-day restorations, guided implant surgery — is exactly what the majority of Albanian dental practices cannot currently offer. This paper examines the relationship between dental technology adoption and dental tourism growth in Albania, arguing that innovation is not merely a clinical upgrade — it is the primary commercial differentiator in a market where cost advantage alone is no longer sufficient to attract and retain international patients. Drawing on survey data from 420 Albanian dental practitioners, analysis of 22,000+ international patient records from 18 Albanian dental tourism clinics (2021–2024), and comparative data from competing dental tourism destinations, we quantify the innovation gap, model its commercial consequences, and propose a technology-led growth framework for Albanian dental tourism.

Keywords: dental tourism; Albania; dental innovation; CAD/CAM; CBCT; digital dentistry; dental tourism competitiveness; technology adoption; diaspora dentistry; Western Balkans; patient decision-making; teledentistry

1. Introduction

Albania's dental tourism sector has grown faster than almost anyone predicted. In 2015, it barely registered as a category. By 2023, an estimated 18,000–22,000 international patients — predominantly diaspora Albanians from Italy, Germany, Switzerland, and the UK, alongside a growing cohort of non-Albanian cost-seekers from Western Europe — were travelling to Albania specifically for dental treatment. The revenues generated by that traffic, concentrated in a small number of Tirana-based premium clinics, represent the most significant private-sector investment in dental technology the Albanian market has seen. Those clinics have CBCT scanners. They have CAD/CAM units. They offer same-day crowns, guided implant surgery, and digital treatment planning with files sent across Europe before the patient has booked a flight.

The problem is what happens outside that small cluster. Of Albania's approximately 2,100 registered dental clinics, **fewer than 60 are meaningfully equipped** to serve international dental tourism patients by the standards those patients bring from their home countries. The other 2,040+ are not failing — they serve Albanian patients perfectly adequately by Albanian market standards. But dental tourism is not an Albanian market. It is a European market, and in that market, the technology gap between Albanian dentistry and its competitors — Hungary, Croatia, Turkey, Poland — is closing from the wrong direction. Those countries are getting better. Albania is not getting worse, but it is not getting better fast enough to hold its competitive position on anything other than price. And price, alone, is a position that erodes.

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"Albania's dental tourism success was built on price. Its future depends on whether price plus technology can outcompete price alone in every competing market."

2. Albanian Dental Tourism: Market Position and Growth Trajectory

2.1 Market Size and Patient Profile

Albania entered the dental tourism market later than Croatia, Hungary, or Turkey but has grown at a rate that none of those markets matched in their comparable early phase. The diaspora channel — more than 1.4 million ethnic Albanians living across Western Europe — provides a patient base with pre-existing linguistic trust, family networks in destination cities, and both the income to afford travel and the price sensitivity to make the cost differential compelling.

Year	Estimated International Patients	Revenue (€M, est.)	Primary Origin Markets	YoY Growth
2018	6,200–8,000	€8–11M	Italy (41%), Germany (28%), Switzerland (14%), UK (9%), Other (8%)	—
2019	9,500–12,000	€13–17M	Italy (38%), Germany (31%), Switzerland (13%), UK (11%), Other (7%)	~52%
2020	3,800–5,000	€5–7M	Italy (44%), Germany (29%), Switzerland (12%), UK (8%), Other (7%)	−58% (COVID)
2021	10,500–13,500	€14–19M	Italy (37%), Germany (30%), Switzerland (15%), UK (11%), Other (7%)	~175% rebound
2022	15,000–18,500	€21–27M	Italy (35%), Germany (32%), Switzerland (14%), UK (12%), Other (7%)	~38%
2023	18,000–22,000	€26–33M	Italy (33%), Germany (33%), Switzerland (13%), UK (13%), Other (8%)	~21%
2024 (est.)	21,000–26,000	€30–40M	Italy (31%), Germany (34%), Switzerland (13%), UK (14%), Other (8%)	~17%

Table 1. Albanian dental tourism market size, revenue, and patient origin estimates (2018–2024). Sources: Albanian Ministry of Tourism (2023); Author survey of 18 dental tourism clinics (2024); Diaspora Health Network (2023).

> **Albanian dental tourism revenues estimated at €26–33M in 2023, up from €8–11M in 2018 — a ~200% increase in five years. Germany overtook Italy as the top origin market in 2023 for the first time. Non-Albanian Western European patients now represent ~8% of visitors and growing.**

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2.2 Why Patients Choose Albania — and Why They Might Not Next Time

Cost is the primary driver of initial dental tourism decisions to Albania. A full-arch implant rehabilitation that costs €28,000–€35,000 in Germany costs €8,000–€14,000 in Tirana. A ceramic crown that costs €800–€1,200 in Switzerland costs €180–€350 in Albania. These differentials are large enough to justify the cost and disruption of international travel, and they are the reason Albania grew as fast as it did. But a survey of 1,240 dental tourism patients conducted across 18 Albanian clinics in 2024 reveals a more complicated picture when patients are asked about their ***next*** treatment decision:

Factor	% Rating as 'Very Important' for First Visit	% Rating as 'Very Important' for Return/Repeat Decision	Gap (Δ)
Cost / price advantage	91%	58%	−33pp
Digital treatment planning / remote pre-consultation	34%	79%	+45pp
CBCT / advanced imaging available	28%	74%	+46pp
Same-day or fast-turnaround restorations	41%	81%	+40pp
Digital records transferable to home-country dentist	29%	77%	+48pp
English / German language communication	62%	71%	+9pp
Online reviews and verified patient testimonials	73%	68%	−5pp
Guided implant surgery (precision planning)	21%	69%	+48pp
Clinic accreditation / international certification	31%	64%	+33pp
Teledentistry / pre-visit consultation	26%	72%	+46pp

Table 2. Factors driving initial versus return dental tourism decisions: survey of 1,240 international patients across 18 Albanian dental tourism clinics (2024). Source: Author survey (2024).

The pattern is consistent and commercially significant: cost drives the first visit, but technology drives the return. A patient who experiences digital impressioning, receives a digital treatment record she can share with her dentist in Hamburg, and gets a same-day ceramic crown without two separate trips — that patient comes back. A patient who pays a low price but goes through an analogue workflow that feels ten years behind what she experiences at home — she tells her friends it was fine, but she researches Croatia for the next procedure.

3. The Technology Gap: What Dental Tourism Patients Expect vs. What Albania Offers

3.1 Technology Adoption Across the Albanian Dental Market

Dental tourism patients arrive in Albania having already been treated at clinics in Germany, Switzerland, Italy, or the UK. Their baseline expectation is set by those home-country experiences. When a patient in Munich has had an intraoral scan instead of an alginate impression for the last five years, an alginate impression in Tirana does not feel like a cost-saving — it feels like a downgrade. The technology gap between what Albanian dental tourism clinics offer and what patients experience at home is the single most important competitive risk the Albanian dental tourism sector faces.

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Technology	Albanian Tourism Clinics (Top 60)	Albanian General Market (~2,040)	Hungary (benchmark)	Croatia (benchmark)	Turkey (benchmark)	Patient Expectation Score*
CBCT / 3D imaging	78%	2.1%	94%	88%	91%	8.7/10
CAD/CAM chairside milling	51%	0.5%	87%	79%	83%	8.2/10
Digital intraoral scanning	84%	7.3%	96%	91%	88%	9.1/10
Guided implant surgery	63%	1.8%	89%	82%	86%	8.6/10
Teledentistry / pre-visit consultation	79%	0.9%	91%	84%	78%	9.3/10
Digital treatment records (transferable)	71%	1.2%	93%	88%	81%	9.2/10
Laser-assisted soft tissue procedures	44%	3.2%	71%	64%	69%	7.1/10
AI-assisted radiograph analysis	18%	<1%	41%	33%	38%	6.4/10
3D-printed surgical guides / prosthetics	39%	<1%	74%	61%	68%	7.8/10
Same-day ceramic restorations	49%	0.5%	83%	76%	79%	8.9/10

*Table 3. Technology adoption rates: Albanian dental tourism clinics vs. general market vs. competing destinations (2024). *Patient Expectation Score = mean importance rating (1–10) from patient survey (n=1,240). Sources: Author survey (2024); EFP (2023); ITI (2023); Hungarian Dental Association (2023).*

Albanian dental tourism clinics outperform the general Albanian market dramatically: 78% CBCT adoption vs 2.1% general market. 84% digital scanning vs 7.3%. But against Hungary (96% digital scanning, 94% CBCT) and Croatia (91%, 88%), Albanian tourism clinics are still trailing on every key technology metric.

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3.2 The Commercial Cost of the Technology Gap

Technology gaps have a price. In the dental tourism market, that price is measurable in patient leakage — tourists who visit once and choose a competitor for the next procedure — and in the ceiling it places on average treatment value (ATV). A clinic that cannot offer guided implant surgery loses the €8,000–€12,000 full-arch implant case to Budapest or Zagreb. A clinic without same-day CAD/CAM loses the patient who cannot afford a second trip for the crown fitting. Based on analysis of treatment records from 18 Albanian tourism clinics (2021–2024), clinics in the **top technology quartile** generated **2.3× the average treatment value** of clinics in the bottom quartile — €1,840 vs €790 per patient visit — and achieved a repeat visit rate of 61% vs 22%.

Technology Quartile (Albanian Tourism Clinics)	Avg. Treatment Value (€/visit)	Repeat Visit Rate (%)	Most Common Procedure Mix	Revenue per Patient Over 3 Years (est.)
Top quartile (Q1) — high adoption	€1,840	61%	Full-arch implants; complex prosthodontics; guided surgery; same-day ceramics	€4,200–€6,800
Second quartile (Q2)	€1,290	44%	Implants (basic); veneers; multi-unit fixed prosthodontics	€2,600–€4,100
Third quartile (Q3)	€970	31%	Crowns; bridges; basic implants; composite veneers	€1,600–€2,800
Bottom quartile (Q4) — low adoption	€790	22%	Basic crowns; extractions; simple fillings; scaling	€980–€1,600

Table 4. Commercial performance by technology adoption quartile: 18 Albanian dental tourism clinics (2021–2024). Sources: Author analysis of clinic records (n=22,400 patient visits); Author survey (2024).

"The clinic with a CBCT scanner and a CAD/CAM unit earns €1,840 per patient visit. The clinic without earns €790. The technology gap is not a clinical question — it is a revenue question."

4. Dental Tourism as an Innovation Adoption Engine

4.1 How Tourism Demand Changes the Investment Calculus

The payback period for advanced dental technology is dramatically shorter in a dental tourism context than in a domestic Albanian market context. A CBCT unit costing €90,000 that generates €200 per scan in the domestic market needs 450 scans to recoup the purchase price — at two scans per working day, that is roughly 225 working days, or nearly a full year of dedicated use. In a dental tourism clinic where the CBCT scan is bundled into a €2,800 implant treatment package and the clinic treats 8 international implant patients per week, the same equipment generates €22,400 per week in package revenue — transforming the payback calculation entirely.

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Technology	Purchase Cost (€)	Revenue per Use (Domestic Market)	Revenue per Use (Tourism Patient, bundled)	Payback Period — Domestic	Payback Period — Tourism Clinic	ROI multiplier
CBCT unit	€80,000–€120,000	€80–€200/scan	Bundled in €2,500–€4,500 implant package	4–8 years	14–22 months	3–5×
CAD/CAM chairside system	€85,000–€110,000	€150–€280/crown	€380–€600/crown (tourism premium)	6–10 years	18–28 months	3–4×
Digital intraoral scanner	€10,000–€22,000	€30–€60/scan	Bundled — €150–€280 value add	2–4 years	5–9 months	4–6×
Guided implant surgery system	€8,000–€18,000	€200–€350/guide	€600–€1,200/surgical guide	2–5 years	6–14 months	3–5×
Teledentistry platform	€500–€2,000/year	€0 (domestic rare)	€80–€200/consultation; patient conversion value €2,000–€8,000	N/A	<3 months	10–20×
Laser (diode/Er:YAG)	€15,000–€38,000	€50–€120/procedure	€200–€450/procedure (tourism premium)	4–8 years	12–24 months	2–4×

Table 5. Technology investment payback comparison: domestic Albanian market vs. dental tourism context (2024). Sources: Author survey (2024); manufacturer data; clinic financial records (n=18).

4.2 The Diaspora Channel as an Innovation Multiplier

The Albanian diaspora plays a role in dental tourism that goes beyond being a patient source. Diaspora patients arrive in Albania having lived in functioning European dental markets — they have had digital impressions, digital records, online consultations, and laser-assisted procedures. They bring those expectations with them and communicate them clearly to the clinics they visit. Many diaspora patients specifically choose clinics **because** of the technology — not despite pricing constraints, but because they are willing to pay a premium for the technology experience at a price still below what they would pay at home. This creates a direct market demand signal for Albanian dental innovation adoption that the domestic market — with its ~60% out-of-pocket dependence and price sensitivity — cannot generate.

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Diaspora Segment	Origin Country	Avg. Annual Spend (€/patient)	Technology Expectation Level	Key Technology Drivers	Willingness to Pay Premium for Technology
Albanian-Italian diaspora	Italy	€1,200–€2,800	High	Digital records; intraoral scanning; CBCT	Up to 40% above base Albanian price
Albanian-German diaspora	Germany	€1,800–€3,800	Very High	Full digital workflow; CAD/CAM; guided surgery; teledentistry	Up to 60% above base Albanian price
Albanian-Swiss diaspora	Switzerland	€2,200–€4,500	Very High	Same-day restorations; precision implantology; digital planning	Up to 70% above base Albanian price
Albanian-UK diaspora	UK	€1,600–€3,200	High	NHS-comparable minimum; digital records; CBCT	Up to 50% above base Albanian price
Non-Albanian Western European patients	Germany, Austria, Netherlands	€2,400–€5,200	Very High	Full digital workflow; international certification; English communication	Up to 80% above base Albanian price

Table 6. Diaspora and international patient segments: spending patterns, technology expectations, and price premium willingness (2024). Sources: Author survey of 1,240 patients (2024); Diaspora Health Network (2023).

5. The Competitive Landscape: Albania vs. European Dental Tourism Destinations

Albania does not compete for dental tourists in a vacuum. Every international patient who considers Tirana also considers Budapest, Zagreb, Istanbul, Kraków, and — for implant work — Bucharest. The competitive dynamics of this market have shifted significantly since 2019: price gaps between destinations have narrowed as Albanian costs have risen modestly and Hungarian costs have fallen relatively; technology levels in Hungary and Croatia have accelerated; and patient information channels — Instagram, Google Reviews, dental tourism aggregator platforms — have made cross-destination comparison far easier than it was five years ago.

Destination	Full-Arch Implant (All-on-4) Price Range	CBCT Adoption Rate	Digital Scanning Rate	Same-Day Crown Available	Teledentistry	English Proficiency	Competitive Position
Hungary	€7,500–€12,000	94%	96%	87% of clinics	91%	Very High	Market leader — technology + price
Croatia	€8,500–€14,000	88%	91%	79%	84%	High	Strong — EU member trust premium
Turkey (Istanbul)	€5,500–€9,000	91%	88%	83%	78%	Moderate-High	Price leader; volume model
Poland	€7,000–€11,500	81%	87%	71%	76%	High	Growing; strong EU brand
Albania (top clinics)	€8,000–€14,000	78%	84%	49%	79%	Moderate	Price + service; technology gap vs Hungary
Albania (general market)	€4,500–€9,000	2.1%	7.3%	<1%	0.9%	Low	Price only; not competitive for informed tourists
Romania	€6,500–€10,500	76%	82%	68%	71%	Moderate	Emerging; EU member; growing reputation
Serbia	€6,000–€10,000	61%	71%	54%	62%	Moderate	Growing; price competitive; technology improving

Table 7. Competitive positioning of major European dental tourism destinations (2024). Sources: European Dental Tourism Association (2023); Author survey (2024); ITI (2023); Dental Departures platform data (2024).

> **Hungary leads on technology AND price: 94% CBCT adoption, 96% digital scanning, same-day crown available at 87% of clinics — at prices comparable to Albania's top clinics. Albania's top clinics compete. Albania's general market does not. The gap between the two is the most urgent problem in Albanian dental tourism strategy.**

The most significant competitive threat is not Turkey (which competes on volume and radical price leadership in a different patient segment) but Hungary, which has spent a decade systematically building exactly the technology-and-price combination that Albania needs to match. Hungarian dental tourism is EU-regulated, technology-intensive, and priced within 10–20% of Albanian premium clinic rates. A patient who can choose between Budapest at €9,500 with 96% digital scanning adoption and Tirana at €10,000 with 84% digital scanning adoption among tourism clinics — and who doesn't have the diaspora connection to give Tirana an automatic advantage — is not an automatic Albanian tourism patient. That patient is a decision, and the decision requires Albania to offer something beyond price.

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6. A Technology-Led Growth Framework for Albanian Dental Tourism

6.1 The Three-Tier Clinic Model

Not every Albanian dental clinic needs to be equipped for international dental tourism — and attempting system-wide technology adoption would be both economically unrealistic and strategically unnecessary. A more effective model is a three-tier structure that matches technology investment to patient segment and commercial ambition, with clear pathways between tiers.

Tier	Target	Technology Minimum	Patient Segments	Investment Range	Revenue Potential
Tier 1 — International Premium	Full dental tourism service	CBCT; CAD/CAM or lab network; digital scanning; guided implant system; teledentistry; EHR transferable records; English/German staff	Non-Albanian Western Europeans; high-spending diaspora; complex cases	€150,000–€350,000 (equipment)	€800K–€2.5M/year from tourism alone
Tier 2 — Diaspora Standard	Diaspora and returning-migrant patients	Digital scanning; CBCT (own or shared); EHR; teledentistry; basic CAD/CAM or lab partnership	Diaspora patients; Albanian expats; domestic premium	€40,000–€120,000	€250K–€700K/year combined
Tier 3 — Domestic + Referral	Albanian domestic patients + referral to Tier 1/2	Digital X-ray; EHR; referral protocols to Tier 1/2 for tourism cases	Albanian domestic patients; basic dental needs	€8,000–€25,000	€60K–€180K/year

Table 8. Three-tier dental clinic model for Albanian dental tourism: technology requirements, patient segments, and revenue potential. Source: Author framework (2024) based on clinic benchmarking data.

6.2 The Innovation Investment Roadmap

Phase	Timeline	Priority Investments	Target Outcome	Funding Mechanism
Phase 1 — Foundation	2025–2026	Teledentistry platform (all Tier 1/2 clinics); digital intraoral scanner; EHR with international transfer capability	Pre-visit digital consultation standard; digital records interoperability; patient confidence in workflow	Practice revenue; equipment leasing; dental tourism association co-investment
Phase 2 — Differentiation	2026–2027	CBCT unit (own or regional shared); CAD/CAM or lab partnership for same-day ceramics; guided implant surgery system	Same-day restorations available; guided implant surgery standard in top clinics; close gap with Croatia	EIB professional loan scheme; EU pre-accession grants; dental tourism revenue reinvestment
Phase 3 — Leadership	2027–2029	AI-assisted diagnostics; 3D printing (surgical guides + prosthetics); laser-assisted surgery suite; full digital workflow integration	Albanian top clinics technologically competitive with Hungary and Croatia; Albania positioned as Western Balkans dental tourism leader	Accumulated tourism revenues; government innovation fund; foreign direct investment

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Table 9. Technology investment roadmap for Albanian dental tourism competitiveness (2025–2029). Source: Author framework (2024).

6.3 The Enabling Conditions

Technology investment without supporting conditions delivers partial results. Three enabling conditions are essential for the technology-led growth model to function at scale:

Enabling Condition	Current Status	Required Action	Responsible Actor	Priority
Teledentistry legal framework	No specific legal framework for cross-border dental consultation	Establish legal status of teledentistry consultations; patient data protection provisions for international records	Ministry of Health; Ministry of Justice	Immediate
Equipment financing instruments	No dental-specific investment loan product in Albanian banking market	Develop dental innovation loan scheme: 3–5% APR, 5–7 year term, collateralised against equipment	Ministry of Finance; Bank of Albania; commercial banks	2025–2026
International accreditation pathway	No Albanian dental clinic holds recognised international accreditation (ISO, JCI, or equivalent)	Establish Albanian Dental Tourism Accreditation Standard — mapped to ISO 9001 and JCI criteria	Order of Dentists of Albania; Ministry of Health; Albanian Dental Tourism Association	2025–2027
Digital workflow standards	No national standard for EHR format, interoperability, or international transfer	Adopt EU-compatible digital health record format; mandate for all Tier 1/2 clinics	Ministry of Health; MoISP	2025–2026
Tourism marketing integration	Dental tourism not formally integrated into Albanian national tourism strategy	Include dental tourism as a defined sector in National Tourism Strategy 2026–2030; allocate co-marketing budget	Ministry of Tourism; Albanian Dental Tourism Association	2025

Table 10. Enabling conditions for technology-led dental tourism growth: status, required actions, and priorities. Source: Author analysis (2024).

7. Projected Impact: Technology Adoption Scenarios

To estimate the commercial impact of accelerated technology adoption on Albanian dental tourism revenues, three scenarios were modelled against the 2023 baseline of approximately €29M in dental tourism revenue across 18,000–22,000 international patients. Scenario assumptions are based on observed relationships between technology adoption levels and average treatment values in existing clinic data, combined with conservative dental tourism patient growth projections.

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Scenario	Technology Assumption	Projected Patients (2029)	Projected Avg. Treatment Value (€)	Projected Total Revenue (€M)	vs. 2023 Baseline
Baseline — No change	General market stays at current adoption; top 60 clinics hold position	20,000–24,000	€1,450	€29–35M	0%
Scenario A — Tier 1/2 Technology Upgrade	Top 60 clinics reach Hungarian adoption levels by 2028; 40 additional clinics reach Tier 2 standard	27,000–34,000	€1,920	€52–65M	~80–90%
Scenario B — Sector-Wide Acceleration	200+ clinics reach Tier 2+ by 2029; teledentistry universal among tourism clinics; accreditation scheme launched	35,000–45,000	€2,280	€80–103M	~175–250%
Scenario C — Regional Leadership	Albania matches Hungary technology levels across 300+ clinics; national accreditation; formal EU alignment	45,000–60,000	€2,650	€119–159M	~310–450%

Table 11. Dental tourism revenue projections by technology adoption scenario, Albania 2029. Sources: Author modelling based on clinic financial records, patient survey data, and market growth assumptions.

> **Scenario A — upgrading the top 100 clinics to Croatian/Hungarian technology levels — would generate €52–65M in dental tourism revenue by 2029, nearly doubling the 2023 baseline. Scenario B — 200+ clinics at Tier 2+ standard — would generate €80–103M. The investment required: €40–120K per clinic at Tier 2. The return: measurable within 18–28 months in a tourism context.**

8. Discussion

The central argument of this paper is simple: Albania's dental tourism sector was built on price, and price alone will not sustain it. The cost differential between Albania and Western European dental markets remains significant — it will not disappear in the medium term. But cost differentials are a floor, not a ceiling. They determine whether a patient considers a destination. Technology determines whether they return.

The data from 22,000+ patient visits across 18 Albanian clinics makes this concrete: patients at high-technology clinics return at **61%**, generate **€1,840 per visit**, and refer an average of 2.3 additional patients within 18 months. Patients at low-technology clinics return at 22%, generate €790 per visit, and refer 0.8 additional patients. The revenue gap between these two groups over a three-year patient lifetime is not marginal — it is the difference between a sustainable dental tourism business model and a volume-

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dependent one that will be undercut by Turkey the moment Turkish operators identify the Albanian diaspora as a target segment.

The other argument this paper makes — that dental tourism can **fund** broader Albanian dental innovation adoption — deserves emphasis. The 18,000–22,000 international patients who visited Albanian clinics in 2023 generated revenues that, if reinvested in technology, could upgrade 150–200 clinics to Tier 2 standard within three years. The tourism sector is not just a revenue opportunity — it is a financing mechanism for the modernisation of Albanian dentistry as a whole. Every crown milled for a German patient in Tirana is also a demonstration to Albanian patients, Albanian dentists, and Albanian policymakers of what the sector is capable of producing.

9. Conclusion

The patient from Zurich who opened this paper has booked her appointment. She chose the clinic with the CBCT scanner, the CAD/CAM unit, and the dentist who sent her a digital treatment plan two weeks before she landed. She paid €2,400 for a procedure that would have cost her €6,800 in Zurich. She is coming back next year. She has already recommended the clinic to three people in her building.

That is what dental tourism looks like when the technology is right. Albania has the cost advantage, the geographic position, the diaspora network, and — in a small number of Tirana clinics — the clinical talent to become one of Europe's leading dental tourism destinations. What it does not yet have is the technology infrastructure across enough of the market to capture the full commercial potential of the patient flows that cost advantage generates. Closing that gap requires investment, and investment requires financing instruments that don't currently exist, a regulatory framework that rewards technology adoption, and a national strategy that treats dental tourism as a sector worth building — not a side effect of low prices, but a deliberate product of clinical excellence at a compelling price point. The market is there. The patients are there. The dentists are there. The question is whether the conditions will be built around them fast enough to matter.

"Albania has the price. Albania has the talent. Albania has the diaspora. What Albania needs now is the technology — and the policy infrastructure to make investing in it rational."

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THE EMERGENCE AND DEVELOPMENT OF BIOETHICAL THEORY IN THE PHILOSOPHICAL SCHOOLS OF THE EAST AND WEST

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ABSTRACT

The biological revolution of the last decades has set a new serious problem for a person, addressed to his consciousness and conscience. The progress of science gives mankind great hopes, but also creates many social problems, including on issues of evolutionary theories and problems of environmental conservation. It is known that the traditional methodological tool used to understand the scientific-socio-political-spiritual nature of bioethics in modern times is to conduct an excursion into the history of the creation and development of the subject.

The influence of various scientific factors and philosophical categories on the formation of bioethics over the centuries cannot be ignored. In particular, some stages are of particular importance; for example, we witness through the evolutionary process starting from Hippocrates' Oath until the Nuremberg Trials after World War II, how the bioethics turned to a subject of public thought.

Long before the emergence of religious views, there were special rules for the members of the tribe to protect themselves, to meet the material and spiritual needs of their lives, and to establish family and domestic relations. Later, over the centuries, the moral and ethical norms of the next periods of human history were formed on these grounds, reached the present day, and became ethical knowledge and teachings. For this reason, the development and importance of ethical knowledge in the system of sciences has been extensively studied in classical and modern philosophical literature.

Keywords: bioethics, classical philosophy, ethical systems, globalization, secularism.

INTRODUCTION

Among the main objectives of the study is provision of the information on the evolution of ethical views in philosophy and public thought from ancient times up to modernity, the place and relations of ethics in the unified scientific system, the moral values that great thinkers want to see in people and society, the reasons for the formation of bioethics on ethical foundations, and the essence of this new scientific-practical synthesis. The importance of the concept of bioethics for modern society, the importance of the ideology of kindness and compassion for everyone, the need to observe bioethical principles and norms in experimental biology and astonishing fundamental research in the biomedicine were highlighted firstly as moral norms in philosophy and ethics.

1. PHILOSOPHICAL and METHODOLOGICAL APPROACH to BIOETICHICS

The reason for the first moral thoughts was socio-moral contradictions between society (tribe, people, segments of society, police, city) and the individual. Morality lived at the level of practical activity of the ancient Greeks [Boqomolov, 1985]. For example, moral, dignified behavior was also considered as intelligent behavior. At the same time, the germs of moral consciousness began to emerge, the origin of human became more and more important, and the pursuit of fame and the good of the good became vital goals.

For centuries, the spiritual and moral aspects of Eastern culture have found their own special approach and analysis in the thoughts and actions of sages, thinkers, philosophers and scientists, great masters of poetry and prose. In the ethical teachings of the East, the morality of good and evil becomes a kind of

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evaluative-normative category of consciousness. In the history of ethics and philosophy, as well as in the history of art, the explanations of good and evil have been ambiguous, given from different points of view (materialist, idealist, religious, naturalist, hedonic, eudemonic, utilitarian etc.), have been changed from century to century, from people to people, from society to society, and in some cases those interpretations were full of contradictions. [Urbanayeva,1988].

2. MANUPULATIONS OF CONSCIOUSNESS and CRITICAL POSITION of ISLAM IN RELATION TO SECULARISM

We face today reaffirms the appeal to the Divine source: bioethical disturbances - demographic explosion, declining production - hunger and energy crisis, energy exploration - environmental disasters, devaluation of moral values - will lead to the collapse of the family. In the age of modern globalization, moral and spiritual issues are among the most pressing issues facing society. The world is changing rapidly, and against the background of the degradation of national and moral values, serious moral violations are becoming the norm. Europe, which allowed same-sex marriage and adoption, has now begun to legalize other abominations, such as incest and pedophilia. The legalization of such inhumane acts and the criminal prosecution of those who fight against this abnormality are the result of years of serious work. There is no doubt that these processes are synchronous and controlled by certain forces. But before we talk about who needs them, we need to pay attention to how the processes are carried out.

CONCLUSION

Bioethics and its experimental problems cover and concern all humanity today. The rules of human life must be supported both legally and socially, as well as religiously and morally. Although the attitude of world religions to bioethics is not always the same, the main principle of religious ethics is the establishment of a moral context. Like all existing religions based on its basic sources and divine values, Islam seeks to preserve the importance of moral principles, the system of national and spiritual values in today's world, and calls on the scientific community, political and social structures to pay attention to spiritual issues.

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KIZILCAHAMAM (ANKARA) İLÇESİNDE ARAZİ KULLANIMI ÇATIŞMA ALANLARININ LUCIS MODELİ İLE BELİRLENMESİ

DETERMINATION OF LAND USE CONFLICT AREAS IN KIZILCAHAMAM (ANKARA) DISTRICT USING THE LUCIS MODEL

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ÖZET

Bu çalışmanın amacı, Ankara ilinin kuzeyinde yer alan Kızılcahamam ilçesinde tarım, koruma ve yerleşme amaçlı arazi kullanım taleplerinin aynı mekânda oluşturduğu çatışma alanlarını Coğrafi Bilgi Sistemleri (CBS) tabanlı LUCIS (Land Use Conflict Identification Strategy/Arazi Kullanımı Çatışma Tanımlama Stratejisi) modeli ile belirlemektir. Kızılcahamam; geniş orman alanları, Soğuksu Millî Parkı, su kaynakları, termal turizm olanakları, kırsal üretim faaliyetleri ve Ankara metropolüne ulaşılabilirliği nedeniyle koruma, tarım ve gelişme taleplerinin birlikte etkili olduğu hassas bir çalışma alanıdır. Araştırmada tez kapsamında üretilen jeomorfoloji, yükselti, eğim, bakı, hidroloji, toprak, arazi yetenek sınıfları, mevcut arazi kullanımı/arazi örtüsü, nüfus, ulaşım ve korunan alan katmanları kullanılmış; veriler ortak bir CBS ortamında standardize edilerek tarım, koruma ve yerleşme için uygunluk analizleri gerçekleştirilmiştir. Uygunluk yüzeylerinin düşük, orta ve yüksek sınıflar halinde yeniden sınıflandırılması ve çakıştırılması sonucunda kullanım öncelikleri ile ikili ve üçlü uyuşmazlık alanları belirlenmiştir. Modelde değerlendirilen 159.732,7 ha alanın %52,0'sinde belirgin bir uyuşmazlık bulunmazken %46,2'sinde farklı kullanım taleplerinin çatıştığı görülmüştür; kalan %1,8'lik bölüm mevcut korunan alanlar, mevcut yerleşim alanları ve su kütleleri nedeniyle maskelenmiştir. En geniş ikili çatışma, 30.178,4 ha ve %18,9 pay ile ziraat-yerleşme arasında ortaya çıkmıştır. Koruma-yerleşme çatışmaları %10,4, ziraat-koruma çatışmaları %2,9, üç kullanımın birlikte yüksek düzeyde çatıştığı alanlar ise %14,0 oranındadır. Mekânsal dağılış, özellikle ilçe merkezi, ana ulaşım koridorları, düşük eğimli vadi tabanları ve orman-tarım-yerleşme geçiş zonlarının planlama bakımından kritik olduğunu göstermektedir. Sonuçlar, LUCIS modelinin Kızılcahamam'da sürdürülebilir arazi kullanım kararlarının geliştirilmesi, tarımsal üretim alanlarının korunması ve yerleşme baskısının uygun sahalara yönlendirilmesi için işlevsel bir karar destek aracı olduğunu ortaya koymaktadır.

Anahtar Kelimeler: LUCIS modeli, arazi kullanım çatışması, CBS, arazi uygunluğu, sürdürülebilir planlama, Kızılcahamam.

ABSTRACT

This study aims to identify land-use conflict areas created by competing agricultural, conservation and settlement demands in Kızılcahamam district, located in the northern part of Ankara Province, through the GIS-based LUCIS (Land Use Conflict Identification Strategy) model. Kızılcahamam is a sensitive case area where conservation, agricultural and development pressures interact due to its extensive forest cover, Soğuksu National Park, water resources, thermal-tourism opportunities, rural production activities and accessibility to the Ankara metropolitan area. The study uses spatial layers produced within the master's thesis, including geomorphology, elevation, slope, aspect, hydrology, soils, land capability classes, current land use/land cover, population, transportation and protected areas. These data were standardized in a common GIS environment and suitability analyses were carried out

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separately for agriculture, conservation and settlement. The resulting suitability surfaces were reclassified into low, medium and high suitability levels and overlaid to identify land-use priorities as well as binary and triple conflict areas. Of the 159,732.7 ha area evaluated in the model, 52.0% presents no distinct conflict, while 46.2% is characterized by competing land-use demands; the remaining 1.8% was masked because it consists of existing protected areas, existing settlements and water bodies. The largest binary conflict is between agriculture and settlement, covering 30,178.4 ha (18.9%). Conservation-settlement conflicts account for 10.4%, agriculture-conservation conflicts for 2.9%, and high-level triple conflicts involving all three land-use categories for 14.0%. The spatial pattern indicates that the district center, major transport corridors, low-slope valley floors and forest-agriculture-settlement transition zones constitute the most critical areas for planning. The results demonstrate that the LUCIS model provides a practical decision-support framework for sustainable land-use planning in Kızılcahamam, particularly for protecting productive agricultural land, maintaining ecological integrity and directing settlement pressure toward more suitable locations.

Keywords: LUCIS model, land-use conflict, GIS, land suitability, sustainable planning, Kızılcahamam.

1. Giriş

Arazi kullanımı, doğal çevrenin insan ihtiyaçları doğrultusunda değerlendirilme biçimini göstermesi nedeniyle coğrafi mekândaki insan-doğa etkileşiminin en görünür sonuçlarından biridir. Nüfus artışı, kentleşme, ulaşılabilirliğin artması ve ekonomik faaliyetlerin çeşitlenmesi; tarım, koruma ve yerleşme gibi farklı kullanım taleplerinin aynı alanlarda karşı karşıya gelmesine yol açmaktadır. Arazi sınırlı bir kaynak olduğundan, bu taleplerin plansız biçimde genişlemesi yalnızca arazi örtüsünün değişmesine değil, verimli toprakların kaybına, ekolojik bütünlüğün bozulmasına ve planlama maliyetlerinin artmasına da neden olmaktadır. Bu nedenle arazi kullanımının mevcut yapısını ortaya koymanın yanında, farklı kullanımların gelecekte hangi sahalarda rekabet edeceğini belirlemek sürdürülebilir planlama açısından temel bir gerekliliktir.

Ankara ili ölçeğinde yapılan çalışmalar kentleşme ile tarımsal ve doğal alanlar arasındaki bu ilişkiyi açık biçimde göstermektedir. Bayar ve Karabacak (2017), 2000-2012 döneminde yerleşim alanlarının Ankara'da en fazla büyüyen arazi örtüsü sınıfı olduğunu, tarım ve otlak alanlarının ise azalma eğilimi gösterdiğini belirlemiştir. Aynı alan için beşerî etki indeksi kullanan Bayar ve Karabacak (2020), 2006-2018 dönemindeki arazi örtüsü değişiminin yaklaşık %64'ünün beşerî etkinin orta, yüksek ve çok yüksek olduğu alanlarda gerçekleştiğini ortaya koymuştur. Bu sonuçlar, arazi kullanım değişiminin yalnızca fiziki uygunluklarla değil, erişilebilirlik, nüfus yoğunluğu ve yerleşim baskısıyla birlikte değerlendirilmesi gerektiğini göstermektedir.

Bu gereksinime yanıt veren yaklaşımlardan biri, Carr ve Zwick (2007) tarafından geliştirilen LUCIS modelidir. Model, tarım, koruma ve yerleşme/gelişme amaçları için uygunlukları ayrı ayrı değerlendirir; daha sonra bu uygunluk yüzeylerini çakıştırarak birden fazla kullanımın aynı mekânda yüksek veya benzer uygunluk gösterdiği çatışma alanlarını belirler. LUCIS'in temel üstünlüğü, yalnızca "hangi alan uygundur?" sorusuna yanıt vermekle kalmayıp "aynı alan için birden fazla kullanım uygun olduğunda hangi çatışmalar ortaya çıkmaktadır?" sorusunu da mekânsal olarak görünür hâle getirmesidir.

Türkiye'deki LUCIS uygulamaları farklı coğrafi ortamlarda modelin güçlü bir karar destek aracı olabildiğini göstermektedir. Gölbaşı ilçesinde arazi örtüsü sınıflarının yaklaşık %66'sında çatışma saptanmış ve özellikle ilçenin kuzeyinde yerleşim alanlarının genişleme eğilimi vurgulanmıştır (Karabacak ve Bayar, 2021). Efeler ilçesinde toplam alanın %48,84'ünün çatışma alanı içinde kaldığı, yüksek çatışmalı sahalarda tarımsal alanların belirgin biçimde öne çıktığı belirlenmiştir (Keloğlu ve Bayar, 2022). Serik ilçesinde LUCIS ve çok kriterli karar verme teknikleriyle yapılan tarımsal uygunluk analizleri, alanın %47'sinin tarıma çok uygun, %88'inin ise çok veya orta derecede uygun olduğunu; mevcut tarım alanlarının yaklaşık %3'ünün kentsel kullanımlar tarafından işgal edildiğini göstermiştir (Okudan ve Bayar, 2022). Menteşe ilçesinde ise arazi örtüsü sınıflarının %78'inde çatışma belirlenmiş ve sürdürülebilir planlama için tarım, koruma ve yerleşim alanlarına yönelik mekânsal öncelikler geliştirilmiştir (Uzun ve Bayar, 2024).

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Bu araştırma, söz konusu yaklaşımı Ankara'nın kuzeyindeki Kızılcahamam ilçesine uygulamaktadır. İlçenin geniş orman örtüsü, korunan alanları, su kaynakları, termal turizm ve rekreasyon potansiyeli ile tarım-hayvancılık faaliyetlerini aynı coğrafi sistem içinde barındırması, arazi kullanım çatışmalarını bölgesel coğrafya açısından anlamlı hâle getirmektedir. Çalışmanın temel amacı, tarım, koruma ve yerleşme için uygunlukların birlikte değerlendirilmesiyle Kızılcahamam'daki arazi kullanım önceliklerini ve uyuşmazlık alanlarını belirlemek; elde edilen sonuçları sürdürülebilir mekânsal planlama açısından yorumlamaktır.

1.1. Araştırmanın Amacı ve Soruları

Çalışma üç temel soruya odaklanmaktadır: Kızılcahamam'da tarım, koruma ve yerleşme kullanımları açısından uygun alanlar nerelerde yoğunlaşmaktadır; bu üç kullanımın uygunluk yüzeyleri çakıştırıldığında hangi ikili ve çoklu çatışma türleri ortaya çıkmaktadır; belirlenen çatışmaların mekânsal dağılışı yerleşim baskısı, tarımsal potansiyel ve koruma öncelikleri bakımından nasıl yorumlanabilir? Bu sorular, tez kapsamında üretilen ayrıntılı mekânsal veri setlerinin kongre bildirisi ölçeğinde yeniden sentezlenmesiyle yanıtlanmıştır.

Bu yönüyle çalışma, yalnızca bir uygunluk haritalaması değil, karar vericilerin çatışma alanlarını erken aşamada tanımlayabilmesini sağlayan bir mekânsal önceliklendirme çerçevesi sunmaktadır. Tarım alanlarının yapılaşma karşısında korunması, koruma alanlarının ekolojik bütünlüğünün sürdürülmesi ve yerleşme gelişiminin doğal eşikler doğrultusunda yönlendirilmesi araştırmanın planlama bakımından temel hedeflerini oluşturmaktadır.

2. Çalışma Alanının Yeri ve Genel Özellikleri

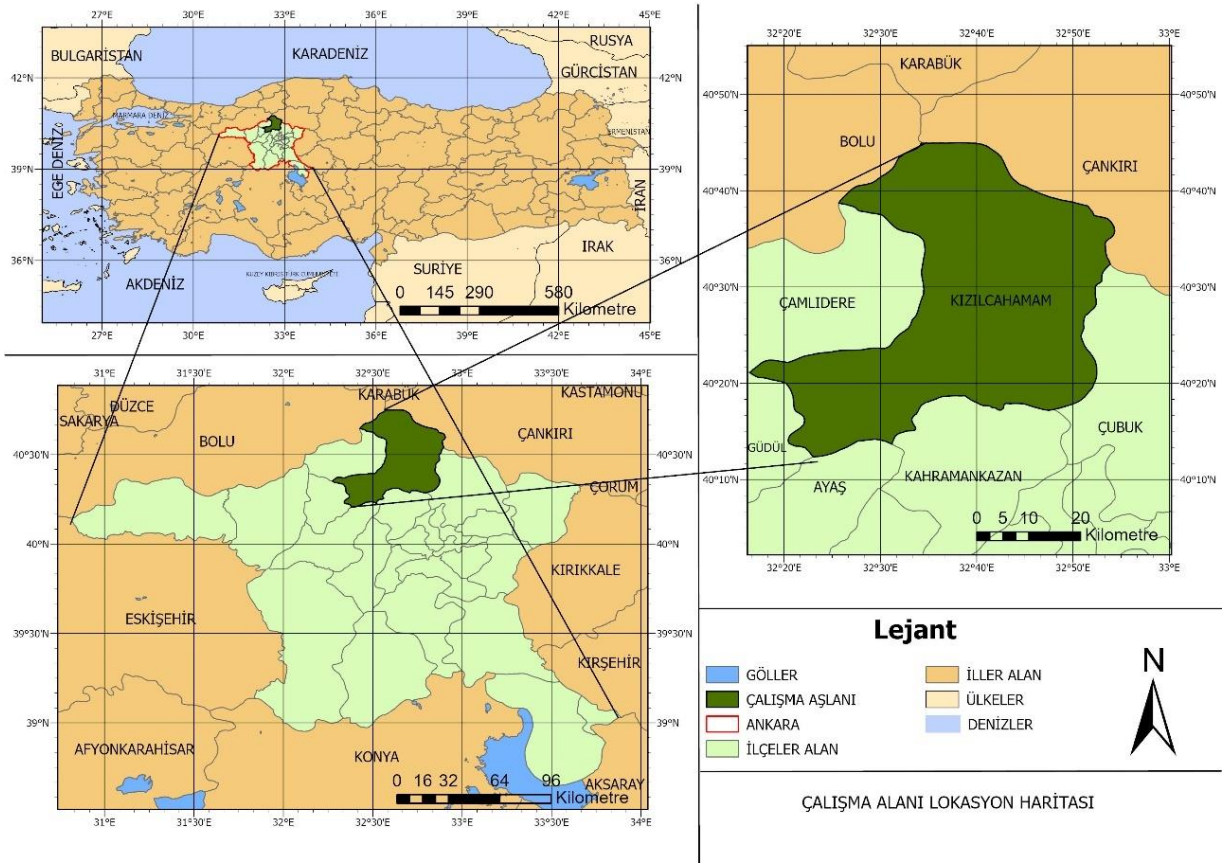
Kızılcahamam, Ankara ilinin kuzey kesiminde yer almakta; batıda Çamlıdere ve Güdül, güneyde Ayaş ve Kahramankazan, güneydoğuda Çubuk, doğuda Çankırı'nın Orta ilçesi, kuzeyde ise Bolu ve Karabük yönündeki dağlık alanlarla çevrelenmektedir. İlçe, Ankara metropolüne kara yolu bağlantısı, kuzey-güney doğrultulu vadi sistemleri ve geçiş konumu nedeniyle hem bölgesel ulaşım hem de rekreasyon bakımından önem taşımaktadır (Şekil 1).

Fiziki coğrafya bakımından Kızılcahamam belirgin bir yükselti ve engebe çeşitliliğine sahiptir. Vadi tabanları ve alçak düzlükler yerleşme ile tarımsal faaliyetler için daha elverişli koşullar sunarken, yükseltinin ve eğimin arttığı kesimler orman ve yarı doğal örtünün devamlılık gösterdiği alanlardır. Bu topografik ayrışma, arazi kullanımının dağılışını doğrudan etkilediği gibi farklı kullanım taleplerini düşük eğimli koridorlarda yoğunlaştırarak çatışma olasılığını da artırmaktadır.

Kızılcahamam'ın doğal kaynakları, Soğuksu Millî Parkı başta olmak üzere koruma statüsü taşıyan alanlar, orman ekosistemleri ve su kaynakları ile temsil edilmektedir. Buna karşılık ilçe merkezi ve ana ulaşım aksları çevresinde yerleşme, turizm ve rekreasyon talepleri daha belirgindir. Tarım ve hayvancılık faaliyetleri ise özellikle eğimin azaldığı vadi tabanları, plato yüzeyleri ve kırsal yerleşmeler çevresinde sürdürülmektedir. Dolayısıyla çalışma alanı, koruma-kullanma dengesinin mekânsal olarak sınanabildiği bir örnek niteliğindedir.

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Şekil 1. Kızılcahamam ilçesinin lokasyonu



Kaynak: Yıldırımoğlu (2026).

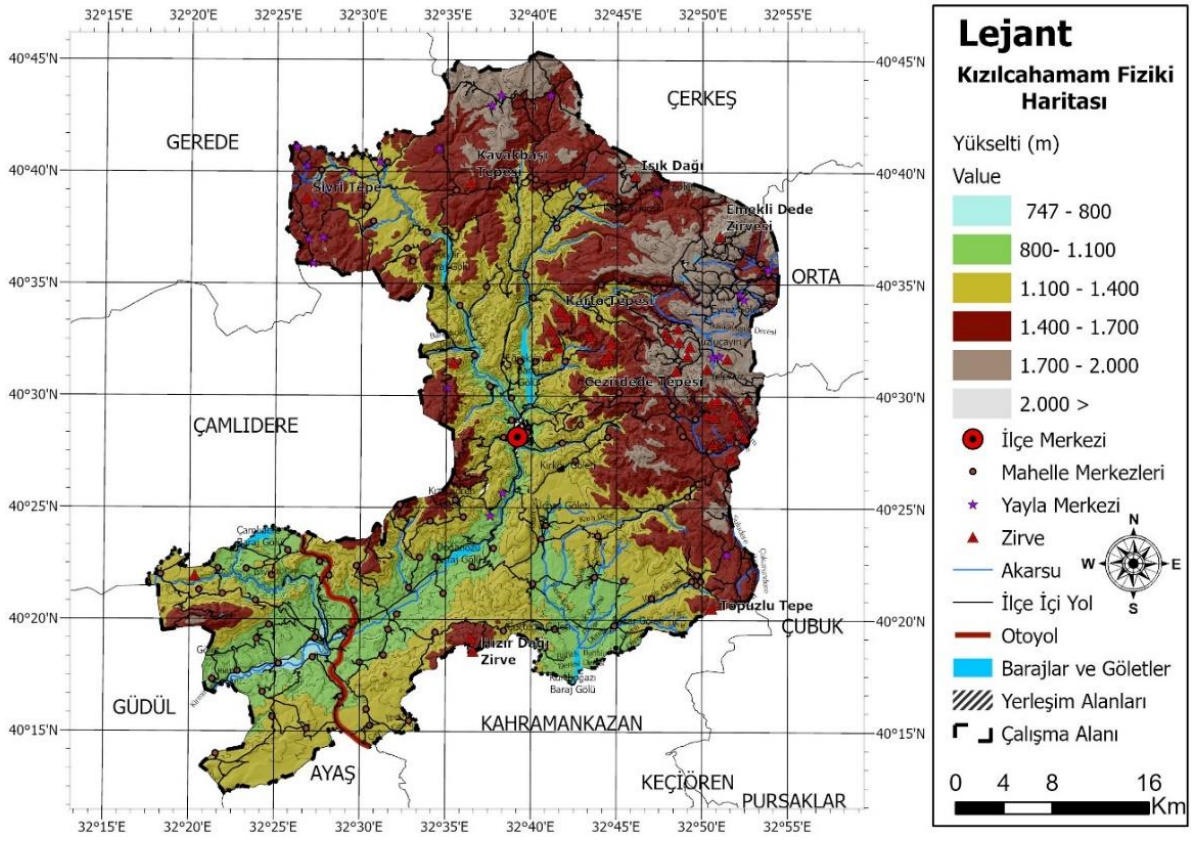
İlçenin kuzey ve doğu kesimlerinde yükselti ve eğimin artması, orman ve yarı doğal alanların sürekliliğini desteklerken; vadi tabanları ve güneybatıya uzanan daha düşük eğimli yüzeyler tarım, ulaşım ve yerleşme bakımından daha yoğun kullanılmaktadır. Bu mekânsal ayrım, LUCIS modelindeki uygunluk yüzeylerinin temel fiziki arka planını oluşturmaktadır.

Hidrolojik sistem ile orman örtüsü, Kızılcahamam'ın koruma değerini artıran başlıca doğal unsurlardır. Buna karşılık ilçe merkezinin Ankara'ya bağlantısı, termal turizm ve rekreasyon fonksiyonları yerleşme ve gelişme talebini güçlendirmektedir. Koruma değeri yüksek alanların gelişme baskısı taşıyan koridorlarla yakın temas etmesi, çatışmaların yalnızca tarım-yerleşme ekseninde değil koruma-yerleşme ekseninde de ele alınmasını gerekli kılmaktadır.

Bu özellikler bir arada değerlendirildiğinde Kızılcahamam, tarımsal üretim, ekolojik koruma ve yerleşme/gelişme işlevlerinin topografik olarak sınırlı koridorlarda birbirine yaklaştığı bir çalışma alanıdır. Fiziki harita, söz konusu koridorların yükselti ve drenaj sistemiyle ilişkisini açık biçimde göstermektedir (Şekil 2).

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Şekil 2. Kızılcahamam fiziki haritası



Kaynak: Yıldırımoğlu (2026).

3. Veri ve Yöntem

Araştırmanın temel veri kaynağını, Kızılcahamam ilçesi için hazırlanan yüksek lisans tezinde üretilen ve düzenlenen mekânsal katmanlar oluşturmaktadır. Analizde jeomorfoloji, yükselti, eğim, bakı, hidroloji, toprak özellikleri, arazi yetenek sınıfları, mevcut arazi kullanımı/arazi örtüsü, ulaşım, yerleşim, nüfus dağılışı ve korunan alan verileri kullanılmıştır. Mevcut arazi örtüsünün değerlendirilmesinde CORINE 2018 sınıfları, çalışma sahasının ayrıntılı fiziki ve beşerî özellikleriyle birlikte ele alınmıştır. Farklı kaynaklardan temin edilen veriler CBS ortamında ortak koordinat sistemine aktarılmış, analiz ölçeğine uygun biçimde rasterlaştırılmış ve karşılaştırılabilir hâle getirilmiştir.

LUCIS modeli, tarım, koruma ve yerleşme olmak üzere üç temel kullanım kategorisinin uygunluğunu ayrı hiyerarşik yapılar içinde değerlendirmektedir (Carr ve Zwick, 2007). Bu çalışmada her kategori için doğal ve beşerî ölçütler, tezde tanımlanan amaç ve alt amaçlar doğrultusunda puanlanmış ve standardize edilmiştir. Tarımsal uygunlukta başta eğim, arazi yetenek sınıfları, toprak özellikleri, suya ve pazara erişim ile mevcut tarımsal kullanım; koruma uygunluğunda doğal ve yarı doğal örtü, su kaynakları, orman ve korunan alanlar; yerleşme uygunluğunda ise topoğrafik elverişlilik, ulaşılabilirlik, mevcut yerleşimlere yakınlık ve gelişme baskısını temsil eden beşerî değişkenler dikkate alınmıştır.

Her bir ana kullanım için elde edilen uygunluk yüzeyleri düşük, orta ve yüksek sınıflara yeniden sınıflandırılmıştır. Sonraki aşamada tarım, koruma ve yerleşme sınıfları kodlanarak üst üste çakıştırılmış; tek bir kullanımın belirgin öncelik taşıdığı sahalar ile iki veya üç kullanımın birlikte rekabet ettiği uyuşmazlık alanları ayrılmıştır. Bu yaklaşım, Gölbaşı ve Efeler uygulamalarında olduğu gibi uygunlukların yalnızca ayrı ayrı değerlendirilmesini değil, piksel düzeyinde bir arada okunmasını sağlamaktadır (Karabacak ve Bayar, 2021; Keloğlu ve Bayar, 2022).

Model çıktılarında bazı alanlar analizden maskelenmiştir. Mevcut korunan alanlar, mevcut yerleşim alanları ve su kütleleri toplam 2.823,4 ha alan kaplamakta ve araştırma alanının %1,8'ine karşılık gelmektedir. Geri kalan alanlarda kategorilerin uygunluk kodları üzerinden öncelik ve uyuşmazlıklar

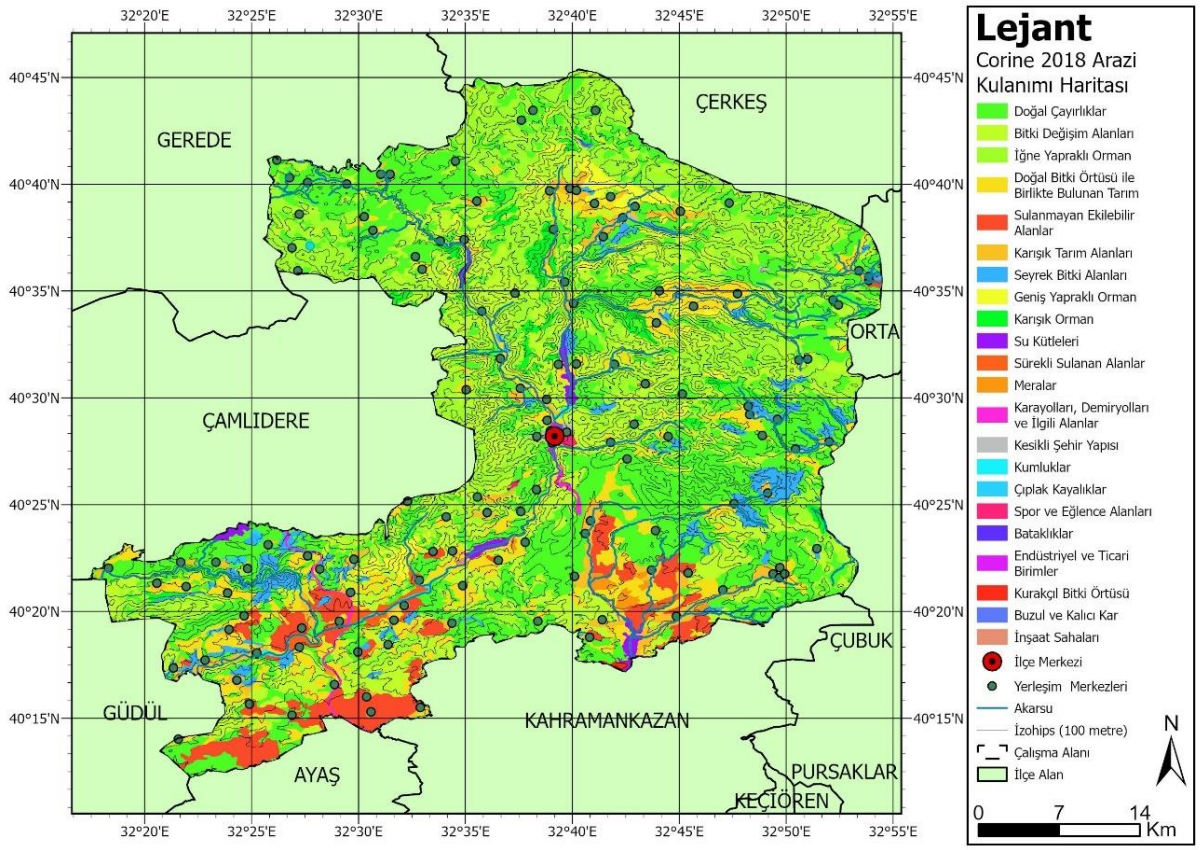
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belirlenmiştir. Son aşamada LUCIS çıktıları, mevcut CORINE arazi kullanım deseni ve fiziki coğrafya haritaları ile birlikte yorumlanarak planlama önerileri geliştirilmiştir.

Tablo 1. LUCIS modelinde kullanılan temel veri grupları ve değerlendirme yönleri

Ana kullanım	Başlıca veri/ölçüt grupları	Değerlendirme amacı
Tarım	Eğim, toprak, arazi yetenek sınıfları, suya/pazara erişim, mevcut tarım	Üretim açısından fiziksel ve ekonomik uygunluk
Koruma	Orman ve yarı doğal alanlar, su kaynakları, korunan alanlar, ekolojik hassasiyet	Ekolojik bütünlük ve doğal kaynakların korunması
Yerleşme	Eğim, ulaşım, mevcut yerleşim, erişilebilirlik, gelişme baskısı	Yerleşme ve gelişme için mekânsal uygunluk

Şekil 3. Kızılcahamam CORINE 2018 arazi kullanım/arazi örtüsü haritası



Kaynak: Yıldırımoğlu (2026).

4. Bulgular

4.1. Mevcut Arazi Kullanımı ve Mekânsal Baskılar

CORINE 2018 arazi örtüsü haritası, Kızılcahamam'ın kuzey ve yüksek kesimlerinde orman ve yarı doğal alanların geniş yer tuttuğunu; tarımsal kullanımların ve yerleşme birimlerinin ise daha çok vadi sistemleri, ulaşım hatları ve eğimin görece düşük olduğu alanlarda yoğunlaştığını göstermektedir (Şekil

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3). İlçe merkezi, kuzey-güney doğrultulu ana ulaşım bağlantısı ve yakın çevresindeki düşük eğimli yüzeyler, farklı arazi kullanım taleplerinin aynı anda güçlendiği başlıca çekim sahalarıdır.

Bu dağılış, Ankara geneli için belirlenen kentleşme-arazi örtüsü ilişkileriyle uyumludur. Bayar ve Karabacak (2017), yerleşim alanlarının büyümesinin tarım ve otlak alanlarındaki azalmayla birlikte gerçekleştiğini; Bayar ve Karabacak (2020) ise arazi örtüsü değişimlerinin önemli bölümünün beşerî etkinin yoğun olduğu alanlarda toplandığını ortaya koymuştur. Kızılcahamam'da da erişilebilirliğin arttığı ve yerleşim/turizm taleplerinin yoğunlaştığı koridorlar, tarım ve doğal alanlar üzerindeki baskının yükseldiği geçiş zonlarını oluşturmaktadır.

Özellikle düşük eğimli alanların hem tarımsal üretim hem de yapılaşma açısından elverişli olması, tarım-yerleşme çatışmasının yapısal nedenini oluşturmaktadır. Benzer bir durum Efeler'de de belirlenmiş ve kentsel yayılmanın verimli tarım alanları üzerinde gelişme eğiliminde olduğu gösterilmiştir (Keloğlu ve Bayar, 2022). Serik örneğinde tarıma çok ve orta derecede uygun alanların geniş paya sahip olması, tarımsal potansiyelin plan kararlarında ayrı bir öncelik olarak ele alınması gerektiğini göstermektedir (Okudan ve Bayar, 2022). Kızılcahamam'da ise tarımsal potansiyel daha parçalı bir dağılım gösterdiğinden, korunması gereken düşük eğimli ve üretken sahaların önceden belirlenmesi daha da önem kazanmaktadır.

4.2. Tarım, Koruma ve Yerleşme Uygunluklarının Genel Görünümü

Daraltılmış uygunluk sınıfları, her bir ana kullanımın en yüksek uygunluk gösterdiği alanları öne çıkarmaktadır. Yerleşme açısından yüksek uygunluk gösteren alanlar 21.829,8 ha ile araştırma alanının %13,7'sini; koruma açısından yüksek uygunluk gösteren alanlar 36.215,0 ha ile %22,7'sini; tarım açısından yüksek uygunluk gösteren alanlar ise 25.580,3 ha ile %16,0'sını oluşturmaktadır. Bu değerler tek başına bir nihai kullanım kararı anlamına gelmemektedir; çünkü aynı piksel birden fazla kullanım için orta veya yüksek uygunluk gösterebilmektedir. LUCIS modelinin temel işlevi tam da bu örtüşmeleri saptamaktır.

Yerleşme uygunluğunda orta sınıfın %56,3 gibi geniş bir paya ulaşması, ilçede yapılaşma açısından tek bir çekirdek alan yerine geniş bir geçiş kuşağının bulunduğunu göstermektedir. Koruma uygunluğunda orta (%40,4) ve yüksek (%22,7) sınıfların toplamı geniş bir alan kaplamakta; bu durum ormanlar, su kaynakları ve doğal eşiklerin planlamada güçlü bir koruma bileşeni oluşturduğunu göstermektedir. Tarımsal uygunlukta ise orta sınıf %45,2, yüksek sınıf %16,0 düzeyindedir. Tarım açısından sınırlı sayıdaki yüksek uygunluk alanının yerleşme talebiyle çakışması, korunması gereken üretim sahalarının önemini artırmaktadır.

Tablo 2. Daraltılmış uygunluk analizlerinde yüksek uygunluk gösteren alanlar

Ana kullanım	Yüksek uygun alan (ha)	Araştırma alanındaki payı (%)
Yerleşme	21.829,8	13,7
Koruma	36.215,0	22,7
Tarım/Ziraat	25.580,3	16,0

4.3. Arazi Kullanım Öncelikleri ve Uyuşmazlık Alanları

Uygunluk haritalarının çakıştırılması sonucunda modelde değerlendirilen 159.732,7 ha alanın %52,0'sinde kullanım önceliği belirgin olup uyuşmazlık görülmemektedir. Bu grup içerisinde koruma öncelikli alanlar 45.462,6 ha (%28,5), ziraat öncelikli alanlar 24.545,9 ha (%15,4) ve yerleşme öncelikli alanlar 13.082,6 ha (%8,2) büyüklüğündedir. Araştırma alanının %46,2'sinde ise iki veya üç kullanım türü aynı mekânda rekabet etmektedir. Bu değer, Kızılcahamam'da arazi kullanım kararlarının yaklaşık yarıya yakın bir alanda tek bir sektörün uygunluğuna bakılarak verilemeyeceğini göstermektedir.

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İkili uyuşmazlıklar içinde en geniş alan ziraat-yerleşme çatışmasına aittir. Bu sınıf 30.178,4 ha ile araştırma alanının %18,9'unu kaplamaktadır. Koruma-yerleşme uyuşmazlığı 16.642,6 ha (%10,4), ziraat-koruma uyuşmazlığı ise 4.616,8 ha (%2,9) düzeyindedir. Tarım, koruma ve yerleşme uygunluklarının birlikte yüksek olduğu üçlü çatışma alanları 22.380,5 ha ile %14,0 oranındadır. Üçlü çatışmalar, tek bir kullanımın tercih edilmesinin diğer iki işlev üzerinde doğrudan maliyet yaratabileceği en hassas planlama sahalarıdır.

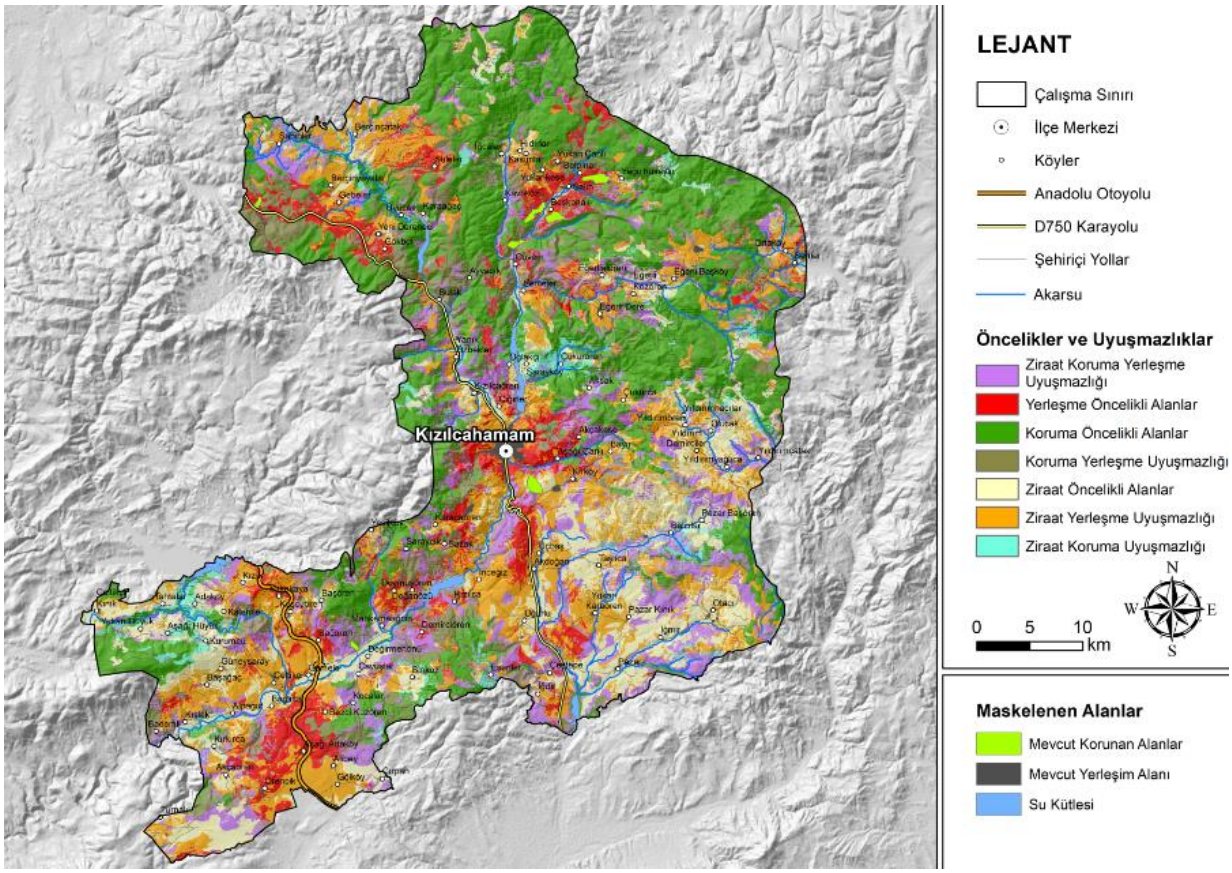
Kızılcahamam'da toplam uyuşmazlık oranı, Gölbaşı'nda belirlenen yaklaşık %66 ve Menteşe'deki %78 düzeyinden daha düşük, Efeler'deki %48,84 oranına ise oldukça yakındır (Karabacak ve Bayar, 2021; Keloğlu ve Bayar, 2022; Uzun ve Bayar, 2024). Ancak oranların doğrudan sıralanması yerine her çalışma alanının fiziki, sosyo-ekonomik ve veri yapısının farklı olduğu dikkate alınmalıdır. Kızılcahamam açısından belirleyici sonuç, çatışmanın özellikle tarım-yerleşme ekseninde yoğunlaşması ve koruma değerlerinin de geniş alanlarda planlama sürecine dâhil edilmesinin zorunlu olmasıdır.

Tablo 3. Kızılcahamam LUCIS modelinde arazi kullanım öncelikleri ve uyuşmazlıkların alansal dağılımı

Arazi kullanım önceliği / uyuşmazlık türü	Alan (ha)	Pay (%)
Ziraat öncelikli	24.545,9	15,4
Koruma öncelikli	45.462,6	28,5
Yerleşme öncelikli	13.082,6	8,2
Uyuşmazlık: Ziraat-Koruma	4.616,8	2,9
Uyuşmazlık: Ziraat-Yerleşme	30.178,4	18,9
Uyuşmazlık: Koruma-Yerleşme	16.642,6	10,4
Yüksek düzey uyuşmazlık: Ziraat-Koruma-Yerleşme	22.380,5	14,0
Maskelenen alanlar	2.823,4	1,8
Toplam	159.732,7	100,0

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Şekil 4. Kızılcahamam arazi kullanım önceliği ve uyuşmazlık alanları



Kaynak: Yıldırımoğlu (2026).

4.4. Uyuşmazlık Yoğunluk Düzeyleri

Çatışma kodları yoğunluk düzeylerine göre toplulaştırıldığında araştırma alanının 51.437,8 ha (%32,2) bölümünde orta düzey, 22.380,5 ha (%14,0) bölümünde ise yüksek düzey uyuşmazlık bulunduğu görülmektedir. Orta düzey uyuşmazlıklar ziraat-koruma, ziraat-yerleşme ve koruma-yerleşme ikili çatışmalarının toplamını; yüksek düzey uyuşmazlık ise tarım, koruma ve yerleşmenin birlikte rekabet ettiği üçlü sınıfı temsil etmektedir. Uyuşmazlık görülmeyen kategori öncelikleri 83.091,0 ha (%52,0), maskelenen alanlar ise 2.823,4 ha (%1,8) düzeyindedir.

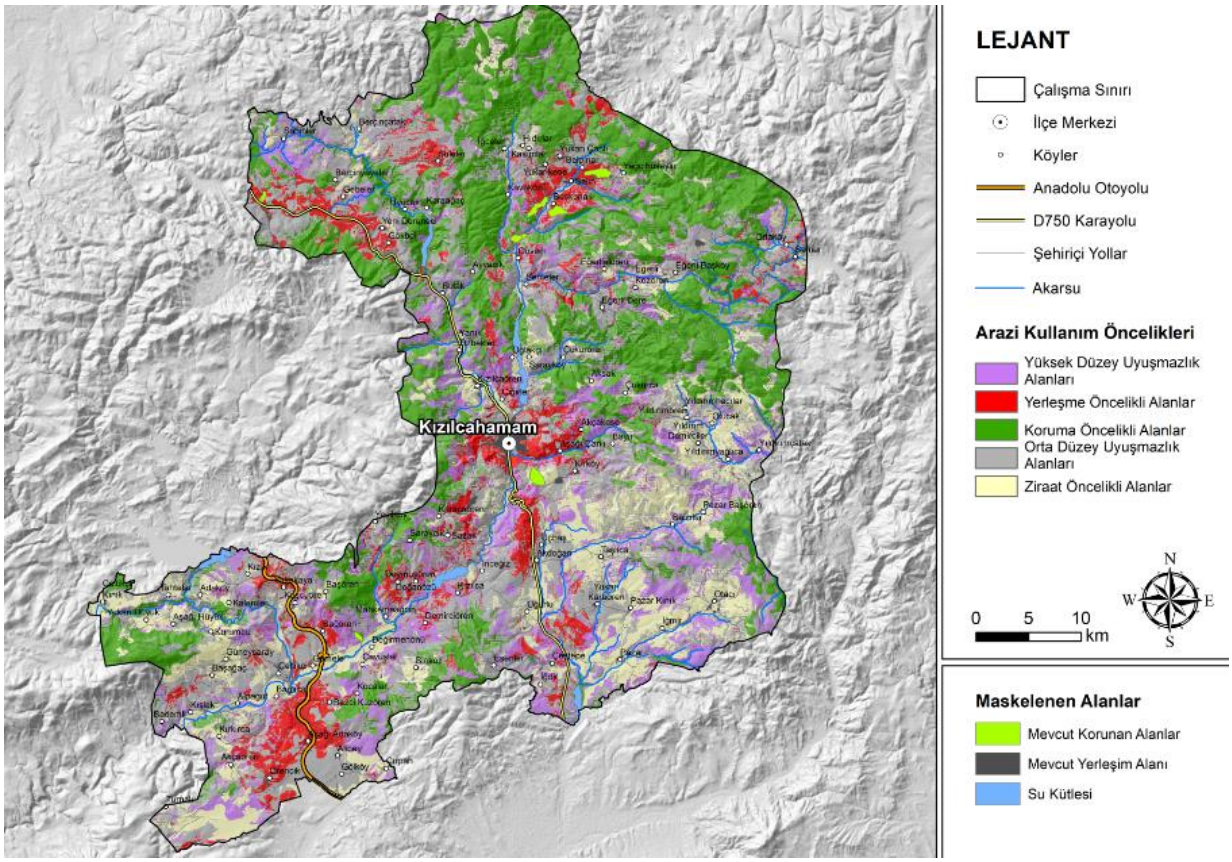
Orta düzey çatışmaların geniş bir paya sahip olması, Kızılcahamam'da birçok sahada tek bir kullanımın mutlak üstünlük taşımadığını göstermektedir. Yüksek düzey çatışmalar ise üç temel kullanımın da planlama açısından güçlü gerekçelere sahip olduğu alanları işaret etmektedir. Bu nedenle yüksek uyuşmazlık zonları ayrıntılı arazi incelemesi, plan kararlarının karşılaştırılması ve koruma-tarım-gelişme hedeflerinin birlikte değerlendirilmesi gereken öncelikli sahalar olarak ele alınmalıdır.

Tablo 4. Kızılcahamam'da uyuşmazlık yoğunluk düzeyleri

Uyuşmazlık düzeyi	Alan (ha)	Pay (%)
Uyuşmazlık görülmeyen alanlar	83.091,0	52,0
Orta düzey uyuşmazlık	51.437,8	32,2
Yüksek düzey uyuşmazlık	22.380,5	14,0
Maskelenen alanlar	2.823,4	1,8
Toplam	159.732,7	100,0

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Şekil 5. Kızılcahamam arazi kullanım öncelikleri ile orta ve yüksek düzey uyuşmazlık alanları



Kaynak: Yıldırımoğlu (2026).

4.5. Çatışmaların Mekânsal Dağılışı ve Planlama Açısından Yorumlanması

Şekil 4 ve Şekil 5, uyuşmazlıkların ilçe genelinde homojen dağılmadığını göstermektedir. İlçe merkezi ve yakın çevresi, ulaşım koridorları, vadi tabanları ve düşük eğimli geçiş zonları ziraat-yerleşme ve yerleşme-koruma çatışmalarının belirginleştiği sahalardır. Buna karşılık yükselti ve eğimin arttığı, orman örtüsünün devamlılık gösterdiği kesimlerde koruma önceliği daha güçlüdür. Tarım öncelikli alanlar ise daha çok topografyanın elverişli olduğu, ulaşılabilir ve üretim açısından avantajlı sahalarda parçalı kümeler hâlinde ortaya çıkmaktadır.

Tarım-yerleşme çatışmasının yüksek payı, Kızılcahamam'da kontrollü büyüme ilkesini öne çıkarmaktadır. Yerleşme gelişiminin yalnızca yapılaşma maliyeti veya ulaşılabilirlik üzerinden değerlendirilmesi, aynı düşük eğimli alanlarda bulunan verimli tarım topraklarının kaybını hızlandırabilir. Bu nedenle tarımsal yüksek uygunluk alanlarında yapılaşmayı sınırlandıran plan kararları geliştirilmeli; yeni yerleşme talepleri tarım ve koruma değeri daha düşük, fakat jeolojik ve topoğrafik açıdan uygun alternatif sahalara yönlendirilmelidir.

Koruma-yerleşme çatışmaları, özellikle doğal alanların ve koruma statüsü bulunan sahaların yakın çevresinde tampon zon yaklaşımını gerekli kılmaktadır. Kızılcahamam'ın termal turizm ve rekreasyon potansiyeli ekonomik bir fırsat oluşturmakla birlikte, turizm ve ikincil konut yatırımlarının orman bütünlüğü, su kaynakları ve millî park çevresindeki ekolojik geçişler üzerinde baskı oluşturmaması gerekir. Bu nedenle koruma-kullanma dengesinin yalnızca yasal sınırların korunmasıyla değil, sınırların çevresindeki işlevsel ekolojik alanların da planlamaya dâhil edilmesiyle kurulması gerekmektedir.

Üçlü çatışma alanları ise planlama bakımından en hassas sınıfı oluşturmaktadır. Bu sahalarda koruma, tarımsal üretim ve yerleşme uygunluğu birlikte yüksek olduğundan, tek ölçütlü kararlar yerine çok kriterli değerlendirme yapılmalıdır. LUCIS modeli bu alanları önceden görünür hâle getirerek karar vericilere, yatırım veya imar kararlarından önce alternatif kullanım senaryolarını karşılaştırma olanağı

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sunmaktadır. Modelin düzenli aralıklarla güncel arazi örtüsü, nüfus, ulaşım ve plan verileriyle yenilenmesi; çatışma alanlarının zaman içindeki yönünü izlemeyi mümkün kılacaktır.

5. Tartışma

Kızılcahamam sonuçları, Ankara'da arazi örtüsü değişimi ve beşerî etki konusunda yapılan çalışmalarla birlikte değerlendirildiğinde, ulaşılabilirliğin ve yerleşim baskısının arazi dönüşümünde belirgin bir rol oynadığı görülmektedir. Ankara genelinde yerleşim büyümesinin tarım ve otlak alanları aleyhine gelişmesi (Bayar ve Karabacak, 2017) ile beşerî etkinin orta ve üzeri olduğu alanlarda arazi örtüsü değişiminin yoğunlaşması (Bayar ve Karabacak, 2020), Kızılcahamam'da ana ulaşım aksları ve ilçe merkezi çevresinde saptanan çatışmaların bölgesel bir örüntünün parçası olduğunu düşündürmektedir.

Gölbaşı, Efeler, Serik ve Menteşe örnekleri LUCIS yaklaşımının farklı coğrafi koşullarda aynı temel problemi, yani sınırlı arazi üzerindeki rekabeti farklı biçimlerde ortaya çıkardığını göstermektedir. Gölbaşı'nda Ankara metropolitan alanının etkisi yerleşme baskısını güçlendirmiş; Efeler'de verimli Büyük Menderes ovası tarım ve kentsel gelişme arasındaki çatışmanın merkezine yerleşmiş; Serik'te tarımsal uygunluk son derece geniş alanlarda yüksek çıkmış; Menteşe'de ise koruma işlevleri ve engebeli topoğrafya arazi kullanım önceliklerini güçlü biçimde şekillendirmiştir (Karabacak ve Bayar, 2021; Keloğlu ve Bayar, 2022; Okudan ve Bayar, 2022; Uzun ve Bayar, 2024). Kızılcahamam bu örneklerden, yüksek orman varlığı ve koruma değerleri ile birlikte Ankara'ya bağlı rekreasyon ve gelişme taleplerini aynı anda taşıması bakımından ayrılmaktadır.

Bu farklılık, model sonuçlarının mekanik bir uygunluk sıralaması olarak değil, yerel coğrafi bağlama göre yorumlanması gerektiğini ortaya koymaktadır. LUCIS çıktısı kararın kendisi değildir; kararın hangi alanlarda daha dikkatli, çok ölçütlü ve paydaşlar arası değerlendirme gerektirdiğini gösteren bir karar destek katmanıdır. Bu nedenle model sonuçlarının arazi gözlemleri, güncel plan kararları, mülkiyet yapısı, tarımsal üretim verileri ve ekolojik hassasiyet çalışmalarıyla birlikte değerlendirilmesi gerekmektedir.

Araştırmanın bir diğer önemli sonucu, çatışma oranının yalnızca büyüklüğü değil, çatışma türlerinin içeriğidir. Kızılcahamam'da ziraat-yerleşme uyuşmazlığının %18,9 ile en geniş ikili sınıf olması, sürdürülebilir arazi kullanımında tarım alanlarını koruyacak eşiklerin öncelikli olduğunu göstermektedir. Bunun yanında üçlü çatışmanın %14 gibi yüksek bir paya sahip olması, bazı alanların aynı anda tarımsal üretim, ekolojik koruma ve yerleşme açısından cazip olduğunu ve planlama maliyetinin bu sahalarda daha yüksek olacağını göstermektedir.

6. Sonuç ve Öneriler

Bu çalışmada Kızılcahamam ilçesindeki tarım, koruma ve yerleşme amaçlı arazi kullanım uygunlukları LUCIS modeli çerçevesinde bir arada değerlendirilmiş ve arazi kullanım öncelikleri ile uyuşmazlık alanları belirlenmiştir. Modelde değerlendirilen 159.732,7 ha alanın %46,2'sinde kullanım çatışması bulunması, ilçede mekânsal planlama kararlarının önemli bir bölümünde birden fazla kullanım talebinin birlikte ele alınması gerektiğini göstermektedir. Uyuşmazlık görülmeyen alanların payı %52,0, maskelenen alanların payı ise %1,8'dir.

Çatışma türleri içinde en geniş alan, %18,9 ile ziraat ve yerleşme arasındaki uyuşmazlığa aittir. Bu sonuç, düşük eğimli ve erişilebilir arazilerin hem tarımsal üretim hem de yapılaşma için elverişli olmasının doğrudan bir sonucudur. Koruma-yerleşme uyuşmazlığı %10,4, ziraat-koruma uyuşmazlığı %2,9 düzeyindedir. Tarım, koruma ve yerleşmenin birlikte çatıştığı yüksek düzey uyuşmazlık alanları ise %14,0 oranındadır. Bu alanların plan kararlarında öncelikli inceleme ve müdahale zonları olarak değerlendirilmesi gerekmektedir.

Planlama açısından üç temel yönelim önerilmektedir. Birincisi, yüksek tarımsal uygunluğa sahip ve yerleşme baskısıyla çakışan alanlarda tarım önceliğini koruyacak yasal ve mekânsal eşikler oluşturulmalıdır. İkincisi, koruma alanları ve orman bütünlüğü çevresindeki turizm, rekreasyon ve yapılaşma talepleri tampon zonlar ve taşıma kapasitesi yaklaşımıyla değerlendirilmelidir. Üçüncüsü, yerleşme gelişimi tarım ve koruma değeri daha düşük ancak topoğrafik ve altyapısal açıdan uygun sahalara yönlendirilmelidir.

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Sonuç olarak LUCIS modeli, Kızılcahamam'da arazi kullanım taleplerini tek tek incelemek yerine aynı karar yüzeyi üzerinde karşılaştırarak çatışmaların yerini ve büyüklüğünü görünür hâle getirmiştir. Modelin güncel CORINE/uydu verileri, nüfus ve ulaşım değişimleri, plan revizyonları ve arazi gözlemleriyle belirli aralıklarla yenilenmesi, geri dönüşü güç arazi dönüşümleri gerçekleşmeden önce önleyici planlama kararları alınmasına katkı sağlayacaktır. Bu yönüyle çalışma, Kızılcahamam'ın yanı sıra benzer koruma-tarım-yerleşme baskılarını birlikte yaşayan ilçeler için de uygulanabilir bir mekânsal karar destek yaklaşımı sunmaktadır.

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TEAR INFLAMMATORY BIOMARKERS IN DRY EYE DISEASE

KURU GÖZ HASTALIĞINDA GÖZYAŞI İNFLAMATUAR BİYOBELİRTEÇLERİ

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ABSTRACT

Dry eye disease (DED) is a multifactorial ocular surface disorder characterized by tear film instability, hyperosmolarity, ocular surface damage, inflammation, and neurosensory abnormalities. Current diagnosis is based on the combined evaluation of symptoms and findings related to the tear film and ocular surface. However, the frequent discordance between symptoms and signs makes it difficult to determine the biological activity and phenotype of the disease using clinical tests alone. Tear fluid is an attractive biomarker matrix because it can be obtained minimally invasively and may directly reflect immune activation, epithelial stress, and the protective secretory capacity of the ocular surface.

Among the inflammatory biomarker candidates most frequently reported in dry eye disease are MMP-9, IL-1β, IL-6, IL-8/CXCL8, TNF-α, IFN-γ, S100A8/A9, complement C3, and soluble ICAM-1. In contrast, decreased levels of lactoferrin, lysozyme, lipocalin-1, lacritin, PRR4, CST4, and secretoglobins indicate that the disease is associated not only with an increased inflammatory burden but also with a loss of the protective and homeostatic capacity of the tear film. The levels of certain biomarkers, including IL-4, IL-10, IL-12, IL-17, and CXCL10, may vary according to disease phenotype, sampling method, and analytical technique; therefore, these molecules should not be evaluated in isolation.

In clinical practice, biomarkers should complement rather than replace standard examination. Multi-marker panels may be useful for distinguishing inflammatory activity from secretory dysfunction, classifying patients, selecting and monitoring anti-inflammatory treatment, and identifying subclinical risk before ocular surgery. This paper proposes the combined evaluation of inflammatory activity and the protective capacity of the tear film in dry eye disease. Although this approach has not yet been clinically validated, it may provide a more comprehensive assessment than tests based on a single biomarker. Future studies should standardize tear collection and storage methods, develop point-of-care tests capable of measuring multiple biomarkers simultaneously, and validate these tests in different dry eye phenotypes.

Keywords: Dry eye disease, tear fluid, inflammatory biomarker, MMP-9, cytokine

ÖZET

Kuru göz hastalığı (KGH), gözyaşı filmi instabilitesi, hiperozmolarite, oküler yüzey hasarı, inflamasyon ve nörosensoriyel bozuklukların birlikte görüldüğü çok faktörlü bir oküler yüzey hastalığıdır. Güncel tanı, semptomların gözyaşı filmi ve oküler yüzeye ait bulgularla birlikte değerlendirilmesine dayanır. Bununla birlikte semptom-bulgu uyumsuzluğunun sık görülmesi, yalnızca klinik testlerle hastalığın biyolojik aktivitesini ve fenotipini belirlemeyi güçleştirmektedir. Gözyaşı; minimal invaziv olarak elde edilebilmesi ve oküler yüzeydeki immün aktivasyon, epitel stresi ile koruyucu sekretuvar kapasiteyi doğrudan yansıtabilmesi nedeniyle dikkat çekici bir biyobelirteç matriksidir.

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Kuru göz hastalığında çalışmalarda en sık bildirilen inflamatuar biyobelirteç adayları arasında MMP-9, IL-1β, IL-6, IL-8/CXCL8, TNF-α, IFN-γ, S100A8/A9, kompleman C3 ve çözünür ICAM-1 öne çıkmaktadır. Buna karşılık laktoferrin, lizozim, lipokalin-1, lakritin, PRR4, CST4 ve sekretoglobin düzeylerindeki azalma, hastalığın yalnızca artmış inflamatuar yükle değil, gözyaşının koruyucu ve dengeleyici kapasitesindeki kayıpla da ilişkili olduğunu göstermektedir. IL-4, IL-10, IL-12, IL-17 ve CXCL10 gibi bazı belirteçlerin düzeyleri ise hastalık fenotipi, örnekleme yöntemi ve kullanılan analiz tekniğine göre farklılık gösterebildiğinden bu moleküllerin tek başına değerlendirilmesi uygun değildir.

Klinik uygulamada biyobelirteçler standart muayenenin yerine geçmemeli, onu tamamlamalıdır. Çoklu paneller; inflamatuar aktivite ile sekretuvar yetersizliği ayırmada, hasta sınıflandırmasında, antiinflamatuar tedavi seçim ve izleminde ve oküler cerrahi öncesi subklinik riskin belirlenmesinde yararlı olabilir. Bu bildiride, kuru göz hastalığının değerlendirilmesinde inflamasyon düzeyi ile gözyaşının koruyucu kapasitesinin birlikte ele alınması önerilmektedir. Henüz klinik olarak doğrulanmamış olan bu yaklaşım, tek bir biyobelirtece dayanan testlere göre hastalığın daha bütüncül değerlendirilmesini sağlayabilir. Gelecekte gözyaşı örneklerinin standart yöntemlerle alınması ve saklanması, birden fazla biyobelirteci aynı anda ölçebilen hasta başı testlerin geliştirilmesi ve bu testlerin farklı kuru göz tiplerinde doğrulanması gerekmektedir.

Anahtar Kelimeler: Kuru göz hastalığı, gözyaşı, inflamatuar biyobelirteç, MMP-9, sitokin

GİRİŞ

Kuru göz hastalığı, günlük yaşamı, görsel performansı ve yaşam kalitesini etkileyen kronik bir oküler yüzey bozukluğudur. Güncel tanımlamada temel sorun gözyaşı filmi homeostazının kaybıdır. Gözyaşı filmi instabilitesi, hiperozmolarite, oküler yüzey inflamasyonu ve hasarı ile bazı hastalarda nörosensoriyel anormallikler bu kaybın bileşenleri olarak kabul edilmektedir (Craig et al., 2017; Bron et al., 2017; Wolffsohn et al., 2025). Hastalığın aköz yetmezlik, evaporatif mekanizmalar, meibomian bez disfonksiyonu, otoimmün süreçler, cerrahi veya tedaviye bağlı nedenler ve nöropatik ağrı gibi farklı fenotipleri bulunur. Bu durum, aynı semptom düzeyine sahip iki hastada farklı biyolojik mekanizmaların etkin olabileceği anlamına gelir (D'Souza et al., 2022; Kumar et al., 2023; Ahmed et al., 2026).

Klinik tanı; oküler semptomlar ile gözyaşı kırılma zamanı, osmolarite, oküler yüzey boyanması ve kapak-meibomian bez değerlendirmesi gibi objektif testlerin birleştirilmesine dayanır. Ancak semptom ve bulguların her zaman paralel olmaması önemli bir sorundur. Şiddetli oküler rahatsızlığı olup sınırlı oküler boyanması bulunan hastalar kadar, belirgin yüzey hasarı olmasına rağmen semptomu olmayan hastalar da vardır. Bu uyumsuzluk, inflamatuar aktivitenin doğrudan ölçülmesine yönelik ilgiyi artırmıştır. Gözyaşı biyobelirteçleri, hastalığın yalnızca varlığını değil, baskın mekanizmasını ve aktivite düzeyini belirleme potansiyeline sahiptir (D'Souza et al., 2022; Kumar et al., 2023).

Gözyaşı çalışmalarında, kuru göz hastalığını tek başına gösteren belirli bir protein saptanmamıştır. Bunun yerine inflamasyon, epitel hasarı, immun hücrelerin hareketi, protein yıkımı ve koruyucu moleküllerdeki azalmayı birlikte yansıtan bir biyobelirteç profili ortaya çıkmaktadır. Ahmed ve arkadaşlarının 50 klinik proteomik çalışmayı değerlendirdiği derlemede, kuru göz hastalığında 123 proteinin arttığı, 35 proteinin ise azaldığı bildirilmiştir. Bunlar arasında en az iki farklı çalışmada aynı yönde değişen 40 artmış ve 12 azalmış protein, daha güçlü biyobelirteç adayları olarak belirlenmiştir. Kumar ve arkadaşlarının, son on yılda yayımlanan 102 çalışmayı incelediği derlemede gözyaşındaki 95 çözünebilir faktörü değerlendirmiştir. MMP-9, IL-6, TNF-α, IL-1β, IL-17A, sICAM-1 ve IL-10'un farklı kuru göz hastalığı türlerinde sık incelendiği bildirilmiştir. (Kumar et al., 2023; Ahmed et al., 2026).

Bu derlemenin amacı, gözyaşındaki inflamatuar biyobelirteçleri yalnızca artan veya azalan moleküller olarak sıralamak değil; bu belirteçlerin hastalık gelişimindeki rollerini, tanıdaki sınırlılıklarını ve tedavi seçimindeki olası katkılarını değerlendirmektir. Ayrıca inflamasyon düzeyi ile gözyaşının koruyucu protein kapasitesini birlikte ele alan iki yönlü bir yaklaşım önerilmektedir. Böylece kuru göz hastalığı yalnızca inflamasyonun varlığına göre değil, inflamatuar yük ile oküler yüzeyin savunma kapasitesi arasındaki dengeye göre değerlendirilmektedir.

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ARAŞTIRMA VE BULGULAR

1. Kuru Göz Hastalığının Patofizyolojisi ve İnflamasyon

KGH patofizyolojisinin merkezinde lakrimal fonksiyonel ünitenin bozulması yer alır. Kornea ve konjonktiva epiteli, lakrimal bez, meibomian bezleri, göz kapakları, duyusal ve otonom sinirler ile immün sistem normalde gözyaşı filminin miktarını ve bileşimini birlikte düzenler. Aköz üretimin azalması veya buharlaşmanın artması, gözyaşı filminde hiperozmolariteye ve mekanik strese yol açar. Hiperozmolar çevre, epitel hücrelerinde stres yanıtlarını ve proinflamatuar sinyal yollarını etkinleştirir; sitokin, kemokin ve matriks metalloproteinazlarının salınması yüzey bariyerini bozar. Bariyer bozukluğu gözyaşı filminin daha da instabil hale gelmesine neden olarak kısır bir döngü oluşturur (Bron et al., 2017; Kumar et al., 2023).

Doğal immün yanıtın ilk bileşenleri korneal ve konjonktival epitel hücreleri, antijen sunan hücreler, makrofajlar, nötrofiller ve doğal öldürücü hücrelerdir. Epitel kaynaklı tehlike sinyalleri ve sitokinler antijen sunan hücrelerin olgunlaşmasını kolaylaştırır. Ardından Th1 ve Th17 yanıtlarının belirginleşmesi, IFN-γ ve IL-17 aracılı immün aktiviteyi artırır. IFN-γ goblet hücre kaybı, epitel aktivasyonu ve skuamöz metaplaziyle; IL-17 ise bariyer bozukluğu ve MMP üretimiyle ilişkilidir. IL-1β, IL-6 ve TNF-α, immun hücreleri aktive eder ve epitel hücrelerindeki inflamatuar yanıtı güçlendirir. Bu nedenle gözyaşındaki sitokin düzeyleri, kuru göz hastalığında inflamasyonu sürdüren mekanizmalar hakkında bilgi verebilir (de Paiva et al., 2022; Ahmed et al., 2026).

İnflamasyon KGH'nin tüm hastalarda aynı yoğunlukta ve aynı yolla ilerleyen tek bir bileşeni değildir. Aköz eksikliği ve Sjögren ilişkili KGH'de lakrimal bez ve adaptif immün yanıt daha belirgin olabilirken, meibomian bez disfonksiyonuna bağlı evaporatif KGH'de kapak kenarı inflamasyonu, lipid bozukluğu ve lokal epitel stresi ön plandadır. Bu nedenle aynı sitokinin düzeyi, farklı kuru göz tiplerinde farklı olabilir (Wu et al., 2020; Kumar et al., 2023; Ahmed et al., 2026).

2. Gözyaşının Biyobelirteç Matrisi Olarak Özellikleri

Gözyaşı; proteinler, lipidler, müsinler, elektrolitler, metabolitler ve hücre dışı veziküller içeren dinamik bir biyolojik sıvıdır. Lakrimal bez, konjonktival goblet hücreleri, meibomian bezleri, oküler yüzey epiteli ve plazma kökenli bileşenlerin tümü gözyaşı proteomuna katkıda bulunur. Bu yakın anatomik ilişki, gözyaşını oküler yüzeydeki inflamasyonu değerlendirmek için serumdan daha önemli bir örnek haline getirir. Örneklemenin görece kolay olması ve tekrar ölçümlere elverişli olması, seri ölçüm ve tedavi izlemi açısından avantaj sağlar. (Wei et al., 2013; Benitez-Del-Castillo et al., 2021; Ahmed et al., 2026).

Bununla birlikte gözyaşı küçük hacimli, hızla değişen ve örnekleme biçiminden kolayca etkilenen bir sıvıdır. Schirmer şeritleri daha yüksek toplam protein miktarı sağlar; ancak mekanik temas, refleks gözyaşı oluşumu ve epitel hücresi kaynaklı proteinlerin örneğe karışması proteomik profili değiştirebilir. Kapiller tüple alınan örnekler bazal gözyaşını daha iyi yansıtır; ancak örnek hacminin az olması bazı biyobelirteçlerin saptanmasını zorlaştırabilir. Örnekleme süresi ve saati, damla uygulaması, kontakt lens kullanımı, kapak manipülasyonu ve çevresel nem de sonuçları etkileyebilir. Tekrarlayan dondurma-çözme işlemi protein kaybına veya hücresel bileşen salınımına yol açabilir (Nättinen et al., 2020; Gijs et al., 2023; Tham et al., 2023).

İmmünoanalizler belirli biyobelirteçleri duyarlı ve özgül biçimde ölçebilir; ancak yalnızca önceden seçilen sınırlı sayıdaki molekülü değerlendirir. Kütle spektrometrisi çok sayıda proteini aynı anda inceleyebilir, fakat gözyaşında çok düşük düzeylerde bulunan sitokinleri her zaman saptayamayabilir. (Dionne et al., 2016; Ahmed et al., 2026). Bir biyobelirtecin klinikte kullanılabilmesi için farklı laboratuvarlarda benzer sonuç vermesi, örnek alma ve saklama koşullarından mümkün olduğunca az etkilenmesi ve klinik karar vermeye yardımcı olacak bir eşik değere sahip olması gerekir (Gijs et al., 2023; Ahmed et al., 2026). Günümüzde kuru göz hastalığında bu özelliklerin tümünü karşılayan kapsamlı bir biyobelirteç paneli bulunmamaktadır. Ticari MMP-9 hasta başı testleri, klinik kullanıma en fazla yaklaşan örnekler arasındadır (Messmer et al., 2016; Lee et al., 2021; Kumar et al., 2023).

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3. Gözyaşındaki Başlıca İnflamatuar Biyobelirteçler

3.1. Proinflamatuar Sitokinler

IL-1β, IL-6 ve TNF-α, KGH'de gözyaşında artan en sık bildirilen sitokinlerdir. IL-1β, epitel hücrelerinde inflamatuar sinyali ve apoptozu destekler, ağrı duyarlılığını artırabilir ve MMP üretimini uyarabilir. IL-6 akut faz yanıtı, T hücre farklılaşması ve epitel bariyer bozukluğunda rol oynar; çeşitli çalışmalarda hastalık şiddetiyle ilişkilendirilmiştir. TNF-α ise hücre adezyonu, lökosit göçü ve doku hasarını güçlendiren bir mediyatördür (Bron et al., 2017; Massingale et al., 2009; Roda et al., 2020; de Paiva et al., 2022). Kumar ve arkadaşlarının derlemesinde IL-6'nın incelendiği 51, TNF-α'nın incelendiği 42 ve IL-1β'nın incelendiği 38 çalışmanın çoğunda artış bildirilmiştir. Ancak bazı çalışmalarda azalma veya değişiklik olmaması yöntem ve kuru göz tipi etkisini göstermektedir (Kumar et al., 2023).

IFN-γ ve IL-17A adaptif immün yanıtı gösteren önemli belirteçlerdir. IFN-γ, Th1 yanıtının göstergesi olup özellikle otoimmün ve ağır KGH'de goblet hücre kaybı, epitelde majör histokompatibilite kompleks ekspresyonu ve yüzey keratinizasyonuyla ilişkilidir. IL-17A, Th17 uyarısıyla oluşan bir sitokin olup epitel bariyerini bozabilir ve proteaz üretimini artırabilir. IL-2, IL-4, IL-9, IL-12 ve IL-13 düzeylerinde de değişiklikler bildirilmiştir; ancak sonuçlar çalışmalar arasında farklılık göstermektedir. Özellikle IL-4 ve IL-12 gibi sitokinlerin alerji, otoimmünite, hastalık evresi veya tedavi durumuna göre değişmesi, tek başına tanısal test olarak kullanılmalarını sınırlar (Kumar et al., 2023; Ahmed et al., 2026).

IL-10 ve IL-1 reseptör antagonisti (IL-1RA), inflamasyonu sınırlamaya yardımcı olan düzenleyici moleküllerdir. IL-10 düzeyi bazı çalışmalarda artmış, bazı çalışmalarda ise azalmış veya değişmemiştir. IL-1RA ise çoğu çalışmada yüksek bulunmuş ve bu artış, IL-1 aracılı inflamasyonu azaltmaya yönelik koruyucu bir yanıt olarak yorumlanmıştır. Bu nedenle IL-10 ve IL-1RA, tek başına değil, proinflamatuar sitokinlerle birlikte değerlendirilmelidir (Kumar et al., 2023; Ahmed et al., 2026).

3.2. Kemokinler ve Lökosit Göçü

Kemokinler, inflamatuar hücrelerin oküler yüzeye göç etmesinde temel rol oynar. IL-8/CXCL8, nötrofil kemotaksisini sağlayan ve KGH çalışmalarında en çok artış gösteren kemokinlerdendir. CCL2/MCP-1 monosit göçünü, CCL3/MIP-1α ve CCL4 ise çeşitli lökosit alt gruplarının dokuya göçünü destekler. Bu moleküllerin artışı, gözyaşındaki inflamatuar mediyatörlerin yalnızca epitel stresini değil, aktif hücresel infiltrasyonu da yansıtabileceğini düşündürür. Özellikle IL-8'in yüksekliği, epitel hasarı ve aktif yüzey inflamasyonunun bir bileşeni olarak değerlendirilebilir (Kumar et al., 2023; Ahmed et al., 2026).

CXCL10/IP-10 ve CCL5/RANTES düzeyleri, bazı çalışmalarda artmış, bazı çalışmalarda ise azalmış bulunmuştur. Bu farklılıklar; kuru gözün tipi, hasta özellikleri, örnekleme yöntemi ve kullanılan ölçüm tekniğiyle ilişkili olabilir. Bu nedenle bu kemokinler tek başına değil, klinik bulgular ve diğer inflamatuar belirteçlerle birlikte değerlendirilmelidir (Kumar et al., 2023; Ahmed et al., 2026).

3.3. MMP-9 ve Proteolitik Doku Hasarı

Matriks metalloproteinaz-9 (MMP-9), KGH'de klinik kullanıma en çok yaklaşmış inflamatuar biyobelirteçtir. Hiperozmolar stres ve proinflamatuar sitokinler tarafından uyarılan MMP-9, epitel sıkı bağlantı proteinlerini ve ekstrasellüler matriks bileşenlerini parçalayarak bariyer geçirgenliğini artırır. Böylece inflamasyon ile yüzey hasarı arasında bir köprü oluşturur. Kumar ve arkadaşlarının değerlendirdiği 42 çalışmanın büyük bölümünde MMP-9 artmış; Ahmed ve arkadaşlarının proteomik değerlendirmesinde de farklı çalışmalarda benzer biçimde yüksek bulunan temel proteinler arasındadır (Kumar et al., 2023; Ahmed et al., 2026).

Ticari hasta başı MMP-9 testleri, gözyaşındaki MMP-9'un belirli bir eşik değerin üzerinde olup olmadığını kalitatif veya yarı kantitatif olarak gösterebilir. Bu yaklaşım hızlı ve uygulanabilir olsa da; gözyaşı hacmi, aktif blefarit veya alerji, yakın zamanda cerrahi ve diğer oküler yüzey hastalıklar sonucu etkileyebilir. Pozitiflik oküler yüzey inflamasyonunu destekler, ancak KGH'ye özgü değildir; negatiflik de inflamasyonu kesin olarak dışlamaz. Bu nedenle MMP-9, tanıyı tek başına koyan bir testten çok,

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inflamatuar yükü doğrulayan yardımcı bir belirteç olarak kullanılmalıdır (Messmer et al., 2016; Lee et al., 2021).

MMP-9'un hastalığın seyri ve kuru göz tiplerinin belirlenmesindeki rolü araştırılmaktadır. MMP-9 pozitifliğinin zamanla gözyaşı üretiminde azalma, meibomian bez bozukluğu ve Sjögren ile ilişkili kuru gözle bağlantılı olabileceği bildirilmiştir. Trombospondin-1/MMP-9 oranı ise koruyucu ve yıkıcı süreçleri birlikte değerlendirmeyi amaçlayan bir göstergedir. Ancak bu oranın klinikte kullanılabilecek eşik değerleri ve farklı hasta gruplarındaki güvenilirliği henüz yeterince belirlenmemiştir (Masli ve Akpek, 2022).

3.4. Adezyon Molekülleri ve Akut Faz Proteinleri

Çözünür interselüler adezyon molekülü-1 (sICAM-1), lökositlerin oküler yüzey hücrelerine tutunmasında görev alan ICAM-1'in gözyaşında ölçülebilen çözünür formudur. Kuru göz hastalarında gözyaşı sICAM-1 düzeylerinin çoğu çalışmada arttığı bildirilmiştir. Bu artış, oküler yüzeydeki immün hücre hareketliliğini ve inflamatuar aktiviteyi yansıtabilir. ICAM-1 yolunun lifitegrast gibi ilaçlarla hedeflenebilmesi, sICAM-1'in tedavi yanıtının değerlendirilmesinde de yararlı olabileceğini düşündürmektedir (Pflugfelder et al., 2017; Kumar et al., 2023).

S100A8 ve S100A9, nötrofil ve monositlerden kaynaklanan ve inflamasyonu artırabilen proteinlerdir. Kuru göz hastalarında gözyaşında artmaları, bu proteinleri olası biyobelirteç adayları hâline getirmektedir. Kompleman C3, orosomukoid-1, transferrin, albümin ve annexin A1 düzeylerindeki artış da bağışıklık yanıtı ve akut faz tepkisini yansıtabilir. Ancak bu proteinlerin bir kısmı plazma kaynaklı olduğundan, örnekleme sırasında oluşan epitel hasarı sonuçları etkileyebilir. Bu nedenle tek başlarına değil, diğer sitokinler ve klinik bulgularla birlikte değerlendirilmelidir (Ahmed et al., 2026).

3.5. Koruyucu Proteinlerde Azalma

Çalışmalarda KGH'de çoğunlukla artan inflamatuar belirteçler incelenir. Ancak gözyaşındaki koruyucu proteinlerin azalması da önemli bir bulgudur. Laktoferrin, lizozim, lipokalin-1, lakritin, prolin açısından zengin proteinler, sekretoglobinler ve sistatinler; göz yüzeyinin korunmasına, kayganlığın sağlanmasına ve protein yıkımının dengelenmesine katkıda bulunur. Ahmed ve arkadaşlarının derlemesinde laktoferrin, lizozim, lipokalin-1, lakritin, PRR1, PRR4, PIP, CST4 ve SCGB1D1 düzeylerinin farklı çalışmalarda azaldığı bildirilmiştir (Ahmed et al., 2026).

Laktoferrin düzeyinin azalması, lakrimal bez işlevinin bozulduğunu ve aköz yetersiz kuru göz tipini düşündürebilir. Lipokalin-1 azalması, gözyaşındaki yağların taşınmasını bozarak gözyaşı filmi kararsızlığına katkıda bulunabilir. Lakritin, gözyaşı salgısını ve epitel hücrelerinin korunmasını desteklediği için azalması kuru göz açısından önemli bir bulgudur. CST4 azalması ise protein yıkımını sınırlayan koruyucu sistemin zayıfladığını gösterebilir (Ahmed et al., 2026).

Bu nedenle yüksek MMP-9 ile düşük CST4 veya laktoferrin düzeylerinin birlikte bulunması, inflamasyonun artmasına ek olarak gözyaşının koruyucu kapasitesinin de azaldığını düşündürebilir. Koruyucu gözyaşı proteinlerinin ölçülmesi, aktif inflamasyonu düşük ancak lakrimal bez veya goblet hücre işlevi azalmış hastaların belirlenmesine yardımcı olabilir. Örneğin sitokin düzeyleri düşükken laktoferrin ve lakritin belirgin azalmışsa, temel sorun gözyaşı salgısındaki yetersizlik olabilir ve yalnızca antiinflamatuar tedavi yeterli olmayabilir. Buna karşılık inflamatuar belirteçlerin yüksek, koruyucu proteinlerin ise korunmuş olması hastalığın aktif bir dönemini düşündürebilir. Ancak bu yaklaşımlar henüz klinik olarak doğrulanmamıştır.

4. Tanı, Tiplendirme ve Hastalık Şiddetindeki Önemi

Gözyaşı biyobelirteçleri, klinik muayeneyi tamamlayarak oküler yüzeydeki inflamasyonun değerlendirilmesine yardımcı olabilir. Semptomlar ile klinik bulguların uyumlu olmadığı hastalarda MMP-9, IL-6, IL-1β veya sICAM-1 düzeylerinin yüksek olması inflamatuar aktiviteyi destekleyebilir. Belirgin semptomlara rağmen inflamatuar belirteçlerin düşük olduğu hastalarda nörosensoriyel nedenler, çevresel etkenler ve diğer oküler yüzey hastalıkları göz önünde bulundurulmalıdır. Biyobelirteçler tek başına tanı koydurmamalı, klinik muayeneyle birlikte değerlendirilmelidir (D'Souza et al., 2022; Kumar et al., 2023; Ahmed et al., 2026).

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Kuru göz tipini belirlemede tek bir biyobelirteç yerine, birden fazla belirtecin birlikte değerlendirilmesi daha yararlıdır. Aköz yetersizliği ve Sjögren ile ilişkili kuru gözde laktoferrin, lakritin ve sekretoglobinler azalabilirken; IFN-γ, IL-17A ve immünoglobulinlerle ilişkili proteinlerde değişiklik görülebilir. Meibomian bez disfonksiyonunda ise IL-8, MMP-9 ve epitel stres belirteçleri artarken lipid taşıyan proteinler azalabilir. Cerrahi veya tedavi sonrasında gelişen kuru gözde geçici inflamasyon ve sinir sistemiyle ilişkili değişiklikler birlikte görülebilir. Ancak çalışmaların hasta grupları ve tanı ölçütleri farklı olduğundan, bu biyobelirteç profillerinin klinikte kullanılmadan önce başka çalışmalarda doğrulanması gerekir (Wu et al., 2020; Kuo et al., 2019; Ahmed et al., 2026).

Bazı gözyaşı biyobelirteçleri hastalık şiddetiyle ilişkili bulunmuştur; ancak sonuçlar çalışmalar arasında farklılık göstermektedir. IL-6, IL-8, IFN-γ ve MMP-9 düzeylerinin daha ağır kuru göz hastalarında artabileceği, laktoferrin ve lipokalin-1 düzeylerinin ise azalabileceği bildirilmiştir. Bununla birlikte gözyaşı miktarı ve örnekleme yöntemi, ölçülen biyobelirteç düzeylerini etkileyebilir. Bu nedenle sonuçlar değerlendirilirken örnek hacmi, toplam protein miktarı ve kullanılan analiz yöntemi dikkate alınmalıdır (Kumar et al., 2023; Gijs et al., 2023; Ahmed et al., 2026).

Katarakt veya refraktif cerrahi planlanan hastalarda inflamatuar belirteçlerin ölçülmesi, ameliyat sonrası kuru göz gelişme riskini değerlendirmeye yardımcı olabilir. Özellikle semptomsuz ancak oküler yüzey bozukluğu veya meibomian bez disfonksiyonu bulunan hastalarda yararlı olabilir. Şikâyetleri fazla, klinik bulguları ise hafif olan hastalarda inflamatuar ve nörosensoriyel faktörler birlikte değerlendirilmelidir. Ancak biyobelirteç sonuçlarına göre cerrahiyi ertelemek veya tedavi başlamak için henüz belirlenmiş eşik değerler bulunmamaktadır (Kumar et al., 2023).

5. Tedavi Seçimi ve Yanıt İzlemindeki Önemi

KGH tedavisinde suni gözyaşı, kapak bakımı, meibomian bezine yönelik uygulamalar ve gerektiğinde antiinflamatuar ilaçlar kullanılabilir. Bazı çalışmalarda fluorometolon, siklosporin, punktum oklüzyonu ve meibomian bez tedavileri sonrasında IL-6 gibi inflamatuar sitokinlerde veya MMP-9 düzeylerinde azalma bildirilmiştir. Bu bulgular, gözyaşı biyobelirteçlerinin tedavi yanıtının izlenmesine yardımcı olabileceğini düşündürmektedir. Ancak biyobelirteç sonuçlarına göre doğrudan tedavi seçimi henüz doğrulanmamıştır ve sonuçlar klinik muayeneyle birlikte değerlendirilmelidir (Nättinen et al., 2018; Tong et al., 2016; Moon et al., 2021; Mullick et al., 2021). Ölçümlerin karşılaştırılabilir olması için örnekleme yöntemi, örnekleme zamanı, son göz damlasından sonra geçen süre ve saklama koşulları mümkün olduğunca aynı tutulmalıdır (Wei et al., 2013; Nättinen et al., 2020; Gijs et al., 2023; Boychev et al., 2025).

Bir biyobelirtecin tedavi sonrasında azalması, başlangıç düzeyinin tedaviye yanıtı önceden gösterebildiği anlamına gelmez. Bunun gösterilebilmesi için başlangıç biyobelirteç düzeylerinin değerlendirildiği ve farklı tedavilerin karşılaştırıldığı kontrollü çalışmalara ihtiyaç vardır. Mevcut kuru göz çalışmalarında gözyaşı biyobelirteçleri daha çok tedavi sonrasındaki değişimi izlemek amacıyla kullanılmıştır. Ancak yalnızca biyobelirteç sonucuna göre belirli bir ilacın seçilmesini sağlayan doğrulanmış bir test henüz bulunmamaktadır (Nättinen et al., 2018; Tong et al., 2016; Moon et al., 2021; Mullick et al., 2021; Ballman, 2015).

6. Özgün Bir Yaklaşım

Kuru gözde biyobelirteçler genellikle tek tek değerlendirilir ve çoğunlukla inflamatuar belirteçlere odaklanılır. Ancak hastalıkta hem inflamasyonun artması hem de gözyaşının koruyucu proteinlerinin azalması önemlidir. Bu nedenle iki yönlü bir değerlendirme yapılabilir. İlk bölümde MMP-9, IL-1β, IL-6, IL-8/CXCL8, TNF-α, IFN-γ, S100A8/A9 ve sICAM-1 gibi inflamatuar belirteçler; ikinci bölümde ise laktoferrin, lizozim, lipokalin-1, lakritin, PRR4, CST4 ve sekretoglobinler gibi koruyucu proteinler değerlendirilebilir.

İnflamatuar belirteçlerin yüksek, koruyucu proteinlerin normal olması aktif inflamasyonu düşündürebilir. Her iki grupta da bozulma olması daha ileri hastalığa işaret edebilir. İnflamasyon düşükken koruyucu proteinlerin azalması ise gözyaşı salgısındaki yetersizliği düşündürebilir. Her iki

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grup normal olduğu hâlde semptomlar belirginse başka nedenler araştırılmalıdır. Ancak bu sınıflandırma henüz klinik olarak doğrulanmamıştır.

Bu yaklaşımın amacı yalnızca inflamasyonu değil, gözyaşının koruyucu kapasitesini de değerlendirmektir. Örneğin aynı MMP-9 düzeyi, laktoferrin ve CST4 normal veya düşük olduğunda farklı anlam taşıyabilir. Böylece tedavinin hem inflamasyonu azaltıp azaltmadığı hem de gözyaşı dengesini düzeltip düzeltmediği birlikte değerlendirilebilir.

7. Klinik Uygulamaya Geçişte Sınırlılıklar

En önemli sorun, çalışmalarda farklı yöntemlerin kullanılmasıdır. Schirmer şeridi ve kapiller tüple alınan gözyaşı örnekleri farklı sonuçlar verebilir. Anestezi kullanımı, refleks gözyaşı, örnekleme süresi ve göz yüzeyinde oluşan tahribat de ölçümleri etkileyebilir. Saklama sıcaklığı, santrifüj işlemi, kullanılan tampon ve dondurma-çözme sayısı da çalışmalar arasında aynı değildir. Sonuçların farklı birimlerle bildirilmesi, çalışmaların karşılaştırılmasını daha da zorlaştırır. Tear Research Network verileri de gözyaşı toplama, saklama ve analiz yöntemlerinin dünya genelinde standart olmadığını göstermektedir (Gijs et al., 2023; Boychev et al., 2025).

İkinci önemli sorun, çalışmalardaki hasta gruplarının birbirinden farklı olmasıdır. Kuru göz çalışmaları; aköz yetersizliği, evaporatif kuru göz, Sjögren hastalığı, kontakt lens kullanımı ve cerrahi sonrası kuru göz gibi farklı hasta gruplarını içerebilir. Yaş, cinsiyet, sistemik hastalıklar, kullanılan tedaviler ve çevresel koşullar da biyobelirteç düzeylerini etkileyebilir. Bu nedenle bazı belirteçler farklı çalışmalarda artmış, azalmış veya değişmemiş bulunmuştur. Gelecek çalışmalarda kuru göz tipi, tanı ölçütleri ve eşlik eden hastalıklar ayrıntılı olarak belirtilmelidir (Kumar et al., 2023; Ahmed et al., 2026).

Üçüncü önemli sorun, bir biyobelirtecin gruplar arasında anlamlı farklı bulunmasının tek başına klinik olarak yararlı olduğunu göstermemesidir. Bir testin klinikte kullanılabilmesi için hastaları doğru ayırması, tekrarlanan ölçümlerde benzer sonuç vermesi ve tedavi kararlarına katkı sağlaması gerekir (Bossuyt et al., 2012; FDA-NIH Biomarker Working Group, 2016).

8. Gelecek Yaklaşımlar

Gelecekte kuru göz araştırmaları için standart bir gözyaşı paneli oluşturulmalıdır. Bu panelde MMP-9, IL-1β, IL-6, IL-8, TNF-α, IFN-γ ve sICAM-1 gibi inflamatuar belirteçler bulunabilir. Ayrıca laktoferrin, lipokalin-1, lakritin ve CST4 gibi koruyucu proteinler de ölçülebilir. Böylece hem inflamasyon hem de gözyaşının koruyucu kapasitesi birlikte değerlendirilebilir.

Sonuçların karşılaştırılabilmesi için gözyaşı örnekleri aynı yöntemle alınmalı, aynı koşullarda saklanmalı ve standart ölçüm yöntemleri kullanılmalıdır. Ölçülen düzeyler değerlendirilirken gözyaşı hacmi ve toplam protein miktarı da dikkate alınmalıdır. Ayrıca panelin farklı yaş, etnik köken ve kuru göz tiplerindeki normal değerleri belirlenmelidir.

Yeni teknolojiler çok az miktarda gözyaşından birden fazla biyobelirteci aynı anda sayısal olarak ölçebilir. Lu ve arkadaşlarının geliştirdiği hızlı MMP-9 biyosensörü, hasta başı testlerin yalnızca pozitif veya negatif sonuç vermek yerine sayısal sonuçlar sunabileceğini göstermektedir (Lu et al., 2022). Klinik kullanıma uygun bir cihazın hassas, kolay uygulanabilir ve hızlı olması gerekir. Ayrıca refleks gözyaşından mümkün olduğunca az etkilenmeli ve kalite kontrolü yapılabilmelidir.

Biyobelirteçlerin hastalığın seyri ve tedavi yanıtındaki rolünü anlamak için aynı hastaların zaman içinde izlendiği çalışmalar gereklidir. Hastalığın alevlenmesi öncesinde, sırasında ve sonrasında gözyaşı örnekleri alınabilir. Bu sonuçlar klinik bulgular, görüntüleme ve çevresel etkenlerle birlikte değerlendirilmelidir. Böylece bir biyobelirtecin hastalığın nedeni mi, sonucu mu yoksa yalnızca eşlik eden bir bulgu mu olduğu daha iyi anlaşılabilir. Cerrahi öncesi ve sonrası takip edilen hastalar, belirti vermeyen inflamasyonun önemini araştırmak için uygun olabilir.

SONUÇ

Gözyaşındaki inflamasyon belirteçleri, kuru göz hastalığının farklı biyolojik özelliklerini anlamaya yardımcı olur.

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MMP-9, IL-1β, IL-6, IL-8, TNF-α, IFN-γ, S100A8/A9, kompleman C3 ve sICAM-1 inflamatuar aktiviteyi gösterebilecek başlıca belirteçlerdir. Laktoferrin, lizozim, lipokalin-1, lakritin, PRR4, CST4 ve sekretoglobinlerin azalması ise gözyaşının koruyucu kapasitesinin zayıfladığını düşündürür. IL-4, IL-10, IL-12, IL-17 ve CXCL10 gibi belirteçlerin sonuçları değişken olduğundan, bu moleküller kuru göz tipi ve kullanılan ölçüm yöntemiyle birlikte değerlendirilmelidir.

Günümüzde gözyaşı biyobelirteçleri tek başına tanı koymak için yeterli değildir. Ancak semptomlar ile klinik bulgular arasındaki uyumsuzluğu açıklamaya, inflamasyonu değerlendirmeye, kuru göz tipini belirlemeye ve tedavi yanıtını izlemeye yardımcı olabilir. Yalnızca MMP-9'u ölçmek yerine, inflamatuar belirteçlerle koruyucu proteinleri birlikte değerlendiren paneller daha yararlı olabilir. Bunun için örnekleme ve ölçüm yöntemlerinin standartlaştırılması, panellerin farklı hasta gruplarında doğrulanması ve klinik kararlara gerçekten katkı sağladığının gösterilmesi gerekir.

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TEAR INFLAMMATORY BIOMARKERS IN KERATOCONUS

KERATOKONUSTA GÖZYAŞI İNFLAMATUAR BİYOBELİRTEÇLERİ

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ABSTRACT

Keratoconus is a corneal ectasia characterized by progressive stromal thinning and irregular corneal protrusion. It is generally bilateral and asymmetric. Because classic signs of inflammation, such as cellular infiltration and neovascularization, are usually absent, keratoconus was considered a non-inflammatory disease for many years. Current studies indicate that keratoconus is a multifactorial disorder involving genetic susceptibility, oxidative stress, epithelial damage, structural changes in the corneal tissue, atopy, and frequent eye rubbing. Low-grade chronic inflammation may also accompany this process. Tear fluid may provide information about molecular activity that cannot be detected by corneal topography by reflecting biological changes in the cornea in a minimally invasive manner.

IL-1β, IL-6, TNF-α, MMP-9, and HMGB1 are among the main biomarker candidates associated with inflammation and corneal tissue degradation. Decreased levels of SOD3, cystatins, albumin, and other protective proteins may indicate weakened antioxidant and antiprotease defenses. A recent study reported that IL-1β, TNF-α, and MMP-9 levels increased with advancing disease stage. In another study, several inflammatory biomarkers were elevated in patients with clinically stable keratoconus, but these elevations were not associated with disease stage. This suggests that inflammatory activity may persist independently of structural progression in the cornea. Proteomic studies have also identified new biomarker candidates, including CHI3L2, PLOD1, secretoglobins and cystatins. However, these biomarkers remain at the research stage because of small sample sizes and methodological differences.

Tear biomarkers should not replace corneal topography, pachymetry, or biomicroscopic examination. Instead, they should provide additional information to these methods. The combined measurement of biomarkers reflecting inflammation and tissue degradation, together with proteins related to antioxidant defense and tissue repair, may help identify high-risk patients, monitor patients after corneal cross-linking, and guide the management of ocular allergy. Evaluating structural progression and molecular activity separately may help identify patients who have persistent inflammation despite stable corneal findings. However, this approach has not yet been validated and should be assessed in long-term follow-up studies. Future priorities include the standardization of tear sampling methods, follow-up of high-risk young patients and their family members, development of point-of-care tests, and integration of biomarkers into artificial intelligence–based risk models.

Keywords: Keratoconus, tear fluid, inflammatory biomarker, MMP-9, cytokine, proteomics

ÖZET

Keratokonus; ilerleyici korneal stromal incelme ve düzensiz kornea protrüzyonu ile seyreden, genellikle bilateral ve asimetrik bir kornea ektazisidir. Hücresel infiltrasyon ve neovaskülarizasyon gibi klasik inflamasyon bulgularının çoğunlukla bulunmaması nedeniyle uzun yıllar inflamatuar olmayan bir hastalık olarak kabul edilmiştir. Güncel çalışmalar, keratokonusun genetik yatkınlık, oksidatif stres,

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epitel hasarı, kornea dokusundaki yapısal değişiklikler, atopi ve sık göz ovuşturmanın birlikte rol oynadığı çok faktörlü bir hastalık olduğunu göstermektedir. Bu sürece düşük düzeyli kronik inflamasyon da eşlik edebilir. Gözyaşı, korneadaki biyolojik değişiklikleri minimal invaziv biçimde yansıtarak topografi ile belirlenemeyen moleküler aktivite hakkında bilgi sağlayabilir.

IL-1β, IL-6, TNF-α, MMP-9 ve HMGB1; inflamasyon ve kornea dokusundaki yıkımla ilişkili başlıca biyobelirteç adaylarıdır. SOD3, sistatinler, albümin ve diğer koruyucu proteinlerin azalması ise antioksidan ve antiproteaz savunmanın zayıfladığını düşündürmektedir. Güncel bir çalışmada IL-1β, TNF-α ve MMP-9 düzeylerinin hastalık evresi ilerledikçe arttığı bildirilmiştir. Başka bir çalışmada ise klinik olarak stabil keratokonus hastalarında birçok inflamatuar belirteç yüksek bulunmuş, ancak bu artışın hastalık evresiyle ilişkili olmadığı gösterilmiştir. Bu durum, inflamatuar aktivitenin korneadaki yapısal ilerlemeden bağımsız olarak devam edebileceğini düşündürmektedir. Proteomik çalışmalarda CHI3L2, PLOD1, sekretoglobinler ve sistatinler gibi yeni biyobelirteç adayları da belirlenmiştir. Ancak örnek sayılarının az olması ve yöntemsel farklılıklar nedeniyle bu belirteçler henüz araştırma aşamasındadır.

Gözyaşı biyobelirteçleri, kornea topografisi, pakimetri ve biyomikroskopik incelemelerin yerine geçmemelidir. Bu yöntemlere ek bilgi sağlamalıdır. İnflamasyon ve doku yıkımını gösteren belirteçlerle antioksidan savunma ve doku onarımını gösteren proteinlerin birlikte ölçülmesi; riskli hastaların belirlenmesine, korneal çapraz bağlama sonrası izleme ve alerji tedavisinin planlanmasına yardımcı olabilir. Yapısal ilerleme ile moleküler aktivitenin ayrı ayrı değerlendirilmesi, kornea bulguları stabil olduğu hâlde inflamasyonu devam eden hastaların belirlenmesini sağlayabilir. Ancak bu yaklaşım henüz doğrulanmamıştır ve uzun süreli takip çalışmalarında değerlendirilmelidir. Gelecekte gözyaşı örnekleme yöntemlerinin standartlaştırılması, yüksek riskli genç hastaların ve aile bireylerinin izlenmesi, hasta başı testlerin geliştirilmesi ve biyobelirteçlerin yapay zekâ destekli risk modellerine eklenmesi önem taşımaktadır.

Anahtar Kelimeler: Keratokonus, gözyaşı, inflamatuar biyobelirteç, MMP-9, sitokin, proteomik

GİRİŞ

Keratokonus, korneanın santral veya parasantral bölümünde ilerleyici incelme ve dikleşme ile karakterize, düzensiz astigmatizma ve görme seviyesinde azalmaya yol açan bir kornea ektazisidir. Hastalık çoğunlukla ergenlik döneminde başlar, genç erişkinlikte ilerler ve iki göz arasında belirgin asimetri gösterebilir. Görme rehabilitasyonu gözlük, sert gaz geçirgen veya skleral kontakt lensler, kornea içi halka segmentleri ve ileri olgularda keratoplastiyle sağlanabilse de hastalığın ilerlemesini durdurduğu kanıtlanmış temel yaklaşım korneal kollajen çapraz bağlamadır. Bu nedenle erken tanı ve ilerleme riskinin doğru belirlenmesi, geri dönüşümsüz görme kaybının önlenmesinde kritik öneme sahiptir (Gomes et al., 2015; Lombardo et al., 2025).

Keratokonus uzun süre yalnızca biyomekanik bir bozukluk olarak değerlendirilmiştir. Korneada belirgin lökosit infiltrasyonu, neovaskülarizasyon veya ön kamara reaksiyonu bulunmaması bu görüşü desteklemiştir. Ancak çalışmalar gözyaşı, kornea epiteli ve stromada inflamasyon, doku yıkımı, hücre ölümü ve oksidatif stresle ilişkili moleküllerin değiştiğini göstermiştir. Bu nedenle keratokonus klasik bir inflamatuar keratit olarak kabul edilmese de genetik yatkınlık ve mekanik stresle ilişkili, düşük düzeyli kronik bir inflamasyonun hastalığa eşlik edebileceği düşünülmektedir. (Galvis et al., 2015; Wisse et al., 2015; Lombardo et al., 2025).

Keratokonusun takibinde kornea eğriliği, arka yüzey yüksekliği, en ince kornea kalınlığı, refraksiyon ve görme keskinliğindeki değişiklikler değerlendirilir. Ancak bu yapısal değişiklikler ortaya çıktığında korneadaki zayıflama ilerlemiş olabilir. Ayrıca klinik olarak stabil görünen bazı hastalarda gözyaşı sitokinlerinin yüksek kaldığı bildirilmiştir. Bu nedenle topografik olarak stabil olmak, hastalığın biyolojik olarak tamamen sessiz olduğu anlamına gelmeyebilir (Gil et al., 2025). Görüntüleme yöntemleri ile gözyaşı biyobelirteçlerinin birlikte değerlendirilmesi, riskin daha erken belirlenmesine yardımcı olabilir.

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Bu çalışmanın amacı; keratokonus patofizyolojisinde inflamasyonun yerini, gözyaşındaki başlıca sitokin, proteaz, oksidatif stres ve proteomik belirteçleri, bunların tanı ve hastalık izlemi açısından olası değerini ve gelecekteki tedavi yaklaşımlarına katkısını değerlendirmektir. Ayrıca topografik ilerleme ile moleküler aktivitenin aynı yönde seyretmek zorunda olmadığı varsayımına dayanan bir yaklaşım önerilmektedir.

ARAŞTIRMA VE BULGULAR

1. Keratokonusun Patofizyolojisi

Korneanın saydam ve düzenli yapısını koruması, tüm kornea tabakalarının uyumlu çalışmasına bağlıdır. Keratokonusta epitel kalınlığı düzensizleşir. Bowman tabakasında çatlaklar oluşur ve stromal kollajen liflerinin düzeni bozulur. Kollajen, lumikan, dekorin ve keratan sülfat gibi yapı proteinlerindeki değişiklikler korneanın dayanıklılığını azaltır. Kollajen yıkımının artması ve yeni doku oluşumunun yetersiz kalması da korneanın incelmesine katkıda bulunur (de Almeida Borges et al., 2026; Nautiyal et al., 2026).

Keratokonus, genetik yatkınlık ile çevresel etkenlerin birlikte rol oynadığı karmaşık bir hastalıktır. Ailelerde ve tek yumurta ikizlerinde daha sık görülmesi genetiğin rolünü destekler. Ancak hastalığın aynı ailede farklı şiddette seyretmesi, çevresel ve epigenetik faktörlerin de etkili olduğunu gösterir. LOX, ZNF469, COL5A1, FOXO1 ve FLG gibi genlerin korneanın yapısı, oksidatif stres yanıtı ve epitel bariyeriyle ilişkili olduğu bildirilmiştir. Özellikle FLG genindeki bazı değişikliklerin atopi ve daha ağır keratokonusla ilişkili olması, epitel bariyer bozukluğu ile inflamasyon arasında bağlantı olabileceğini düşündürmektedir (Lombardo et al., 2025; Nautiyal et al., 2026).

Keratokonusta kornea hücrelerinde artmış apoptoz, mitokondri işlev bozukluğu ve oksidatif stres bildirilmiştir. Antioksidan savunmanın yetersiz kalması, proteinlere ve kollajene zarar vererek korneanın dayanıklılığını azaltabilir. Ayrıca epitel iyileşmesinin bozulması, korneanın tekrarlayan küçük travmaları onarma kapasitesini sınırlayabilir (Navel et al., 2021; Monteiro de Barros & Chakravarti, 2022).

Bu bulgular, keratokonusun yalnızca korneanın şekil bozukluğu olmadığını göstermektedir. Hastalıkta epitel ve stromadaki değişikliklere oksidatif stres ve düşük düzeyli inflamasyon eşlik edebilir. Ancak inflamasyon tek başına keratokonus gelişimini açıklamaz. Göz ovuşturan veya alerjisi olan herkeste keratokonus gelişmemesi; genetik yatkınlık, korneanın biyomekanik zayıflığı ve çevresel etkenlerin birlikte rol oynadığını düşündürmektedir (Lombardo et al., 2025; Gil et al., 2025).

2. İnflamasyon-Mekanik Stres Döngüsü

Atopi, alerjik konjonktivit, astım ve egzama keratokonusla sık birlikte görülen durumlardır. Bu hastalıklarda oküler kaşıntı göz ovuşturmayı artırır; göz ovuşturma ise epitelde mekanik hasar, lokal ısı artışı, keratosit apoptozu ve inflamatuar mediyatör salınımına neden olabilir. Böylece oküler yüzey inflamasyon kaşıntıya, kaşıntı göz ovuşturmaya yol açarak kısır bir döngü oluşturur (Balasubramanian et al., 2013; Lombardo et al., 2025).

Tekrarlayan göz ovuşturma, korneada mekanik hasara neden olur ve IL-6, TNF-α ve MMP-9 gibi inflamasyon ve doku yıkımıyla ilişkili belirteçleri artırabilir. Bu durum kornea dokusunun zayıflamasına ve keratokonusun ilerlemesine katkıda bulunur. Keratokonus gençlerde daha hızlı ilerleyebildiği için özellikle ergenlerde alerjinin kontrol edilmesi ve göz ovuşturmanın önlenmesi önemlidir (Balasubramanian et al., 2013; Lombardo et al., 2025; Gil et al., 2025).

3. Gözyaşının Biyobelirteç Matrisi Olarak Özellikleri

Gözyaşı; sitokinler, proteinler, enzimler, lipidler ve metabolitler gibi birçok molekül içerir. Kornea epiteliyle doğrudan temas ettiği için korneadaki biyolojik değişiklikler hakkında bilgi verebilir. Ayrıca non-invaziv, örneklemesi ve tekrarlanabilirliği kolaydır. Bu nedenle gözyaşı biyobelirteçleri, keratokonusta hastalık aktivitesini ve zaman içindeki değişimi izlemeye yardımcı olabilir (Lombardo et al., 2025; Gil et al., 2025; Nautiyal et al., 2026).

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Gözyaşı örneğinin alınma yöntemi, ölçüm sonuçlarını etkileyebilir. Schirmer şeridiyle örnek almak kolaydır ve yeterli miktarda gözyaşı sağlar. Ancak şeridin göze temas etmesi refleks gözyaşını artırabilir ve protein düzeylerini değiştirebilir. Kapiller tüple alınan örnekler bazal gözyaşını daha iyi yansıtır; fakat örnek hacmi az olduğu için düşük düzeydeki sitokinlerin ölçülmesi zor olabilir. Ayrıca örnekleme saati, göz damlasının son kullanım zamanı, kontakt lens kullanımı, alerjinin aktif olup olmaması ve örnekleme öncesinde yapılan topografi veya floresein uygulaması göz önüne alınarak değerlendirilmelidir (Gil et al., 2025; de Almeida Borges et al., 2026).

ELISA, önceden belirlenen bir biyobelirtecin miktarını ölçmek için kullanılır. Boncuk tabanlı çoklu immünoanalizler ise az miktarda gözyaşı örneğinden birçok sitokini aynı anda ölçebilir. Kütle spektrometrisine dayalı proteomik yöntemler, önceden belirteç seçmeden çok sayıda proteini inceleyerek yeni biyobelirteç adaylarının bulunmasını sağlar. Ancak çok düşük düzeyde bulunan sitokinler bu yöntemle saptanamayabilir. Bu nedenle proteomik çalışmalarda bulunan yeni adaylar, klinik kullanımdan önce hedefe yönelik testlerle ve farklı hasta gruplarında doğrulanmalıdır (Gil et al., 2025; Pallamreddy et al., 2026; de Almeida Borges et al., 2026).

4. Başlıca İnflamatuar ve İlişkili Biyobelirteçler

4.1. Proinflamatuar ve Düzenleyici Sitokinler

IL-1β, IL-6 ve TNF-α, keratokonusta sık araştırılan inflamatuar sitokinlerdir. IL-1β inflamasyonu ve MMP üretimini artırabilir. IL-6 inflamasyon ve doku yenilenmesinde rol oynar. TNF-α ise hücre ölümünü ve doku yıkımını artırabilir. Bu üç sitokinin birlikte artması, keratokonusta inflamasyon ve doku yıkımının birlikte devam ettiğini düşündürebilir (Lema & Durán, 2005; Shetty et al., 2017; Lombardo et al., 2025).

Pallamreddy ve arkadaşları, 18 keratokonus hastası ile 25 sağlıklı bireyi karşılaştırmış ve IL-1β, IL-4, IL-6, IL-10, MMP-9 ve TNF-α düzeylerini keratokonus grubunda daha yüksek bulmuştur. Hastalık şiddetiyle en güçlü ilişki IL-1β'de görülürken, TNF-α ve MMP-9 da şiddetle anlamlı ilişki göstermiştir. IL-6 ve IL-10 için daha orta düzeyde ilişki saptanmış, IL-4 ise hastalık şiddetiyle anlamlı ilişki göstermemiştir. Özellikle IL-1β, IL-6 ve MMP-9 düzeyleri orta ve ağır keratokonusta hafif hastalığa göre daha yüksek bulunmuştur. Bu sonuçlar, bu belirteçlerin hastalık şiddetini değerlendirmede yararlı olabileceğini düşündürmektedir. Ancak çalışma az sayıda hastayı içermekte ve hastaları yalnızca tek bir zamanda değerlendirmektedir. Bu nedenle bu biyobelirteçlerin ileride hastalığın ilerleyip ilerlemeyeceğini öngördüğü söylenemez (Pallamreddy et al., 2026).

IFN-γ, IL-17A ve IL-12p70, bağışıklık yanıtında rol alan sitokinlerdir. IL-4 ve IL-10 ise daha çok düzenleyici ve Th2 tipi bağışıklık yanıtıyla ilişkilidir. Keratokonusta bu sitokinlerin bir kısmının birlikte arttığı gösterilmiştir. Özellikle stabil keratokonus hastalarında hem proinflamatuar hem de düzenleyici sitokinlerin yüksek bulunması, bağışıklık sistemindeki aktivitenin devam ettiğini düşündürmektedir. Bu nedenle sitokinler tek tek değil, oluşturdukları genel profil ve hastanın klinik özellikleriyle birlikte değerlendirilmelidir (Gil et al., 2025; Lombardo et al., 2025; Pallamreddy et al., 2026).

4.2. MMP-9 ve Matriks Yıkımı

MMP-9, keratokonusta inflamasyon ve kornea dokusunun yıkımıyla ilişkili önemli bir belirteçtir. IL-1β, IL-6 ve TNF-α gibi sitokinler MMP-9 üretimini artırabilir. Artan MMP-9, korneanın yapısal proteinlerinin parçalanmasına ve dokunun zayıflamasına katkıda bulunabilir. Ayrıca göz ovuşturma sonrasında proteaz aktivitesinin artması, mekanik stresin bu süreci artırabileceğini düşündürmektedir (Balasubramanian et al., 2012, 2013).

Proteazların etkisi yalnızca MMP-9 düzeyine bağlı değildir. Sistatinler ve serpinler gibi proteinler, doku yıkımını sınırlayan koruyucu mekanizmalardır. Keratokonusta CST2, CST3 ve CST5 gibi sistatinlerin azalması, bu koruyucu etkinin zayıflayabileceğini düşündürmektedir. Bu nedenle yüksek MMP-9 ile düşük proteaz inhibitörü düzeylerinin birlikte bulunması, kornea dokusunda daha fazla yıkım riski olduğunu gösterebilir (de Almeida Borges et al., 2026).

Hasta başı MMP-9 testleri, oküler yüzeyde inflamasyon olup olmadığını hızlı şekilde gösterebilir. Ancak MMP-9 artışı keratokonusa özgü değildir; kuru göz, alerjik konjonktivit, kontakt lens kullanımı

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veya cerrahi sonrasında da görülebilir. Bu nedenle MMP-9 tek başına keratokonus tanısı veya çapraz bağlama kararı için kullanılmamalı; diğer biyobelirteçler, kornea topografisi ve göz ovuşturma öyküsüyle birlikte değerlendirilmelidir (Nautiyal et al., 2026).

4.3. HMGB1, Oksidatif Stres ve Antioksidan Savunma

Yüksek hareketlilik grubu kutu 1 proteini (HMGB1), normalde hücre çekirdeğinde bulunan bir proteindir. Hücre hasarı sırasında hücre dışına salındığında inflamasyonu uyarabilir. Keratokonusta gözyaşı HMGB1 düzeyinin artması, kornea hücrelerinde hasar ve inflamasyon olduğunu düşündürebilir. MMP-9 ve HMGB1'in yüksek, SOD3'ün düşük olması ise inflamasyon, doku yıkımı ve antioksidan savunmanın zayıflamasının birlikte görülebileceğini gösterir (Roszkowska et al., 2025; Lombardo et al., 2025).

SOD3, zararlı oksijen radikallerini temizleyen önemli bir antioksidan enzimdir. Keratokonusta oksidatif stresin arttığı ve antioksidan savunmanın azaldığı bildirilmiştir. Bu durum hücre hasarını, apoptozu ve kornea dokusunun bozulmasını artırabilir. Ayrıca IL-1 ailesi SOD üretimini azaltarak inflamasyon ile oksidatif stres arasındaki ilişkiyi güçlendirebilir (Navel et al., 2021; Roszkowska et al., 2025; Lombardo et al., 2025).

Albumin, laktoferrin, transferrin ve lakritin, göz yüzeyinin korunmasına ve oksidatif strese karşı savunmaya katkıda bulunan proteinlerdir. Keratokonusta bu proteinlerin düzeylerinde azalma veya değişiklikler bildirilmiştir. Bu durum, korneanın oksidatif strese karşı savunmasının zayıflayabileceğini düşündürmektedir. İnflamatuar belirteçlerin bu koruyucu proteinlerle birlikte değerlendirilmesi, hastalığın biyolojik durumunu daha iyi anlamaya yardımcı olabilir (de Almeida Borges et al., 2026; Nautiyal et al., 2026).

4.4. Proteomik Çalışmalar

Proteomik çalışmalar, keratokonusta inflamasyonun yanı sıra oksidatif stres ve hücre dışı matriks düzenlenmesinin de bozulduğunu göstermektedir. de Almeida Borges ve arkadaşları, keratokonus**ta** gözyaşında çok sayıda proteinde değişiklik saptamış; özellikle CHI3L2 ve PLOD1 gibi inflamasyon ve doku yeniden yapılanmasıyla ilişkili proteinleri yeni biyobelirteç adayları olarak bildirmiştir. Ayrıca sistatinler ve sekretoglobinler gibi koruyucu proteinlerde de değişiklikler görülmüştür. Ancak sonuçlar çoklu karşılaştırma düzeltmesinden sonra anlamlılığını korumadığından, bu proteinler henüz doğrulanmış biyobelirteçler değil, araştırma aşamasındaki adaylardır (de Almeida Borges et al., 2026).

5. Tanı, Hastalık Şiddeti, İlerleme ve İzlemdeki Önemi

Keratokonusun tanı ve takibinde kornea topografisi temel yöntemdir. Gözyaşı biyobelirteçleri bunun yerine geçmez, ancak hastalığın biyolojik aktivitesi hakkında ek bilgi sağlayabilir. Pallamreddy ve arkadaşları, IL-1β, IL-6, MMP-9 ve TNF-α düzeylerinin hastalık şiddetine göre değiştiğini göstermiştir. Özellikle IL-1β ve TNF-α hastalık şiddetiyle belirgin ilişki göstermiştir. Bu sonuçlar, inflamasyon ve doku yıkımının daha ileri keratokonus evrelerinde artabileceğini düşündürmektedir. Ancak çalışma kesitsel olduğu için bu belirteçlerin hastalığın gelecekteki ilerlemesini öngörüp öngöremediği bilinmemektedir (Pallamreddy et al., 2026).

Gil ve arkadaşları ise klinik ve topografik olarak stabil keratokonus hastalarında IFN-γ, IL-1β, IL-4, IL-6, IL-12p70, IL-17A ve TNF-α düzeylerini sağlıklı bireylere göre daha yüksek bulmuştur. Buna rağmen sitokin düzeyleri hastalık evresi veya maksimum keratometri ile ilişkili bulunmamıştır. Bu bulgular, keratokonus yapısal olarak stabil görünse bile düşük düzeyli inflamasyonun devam edebileceğini düşündürmektedir (Gil et al., 2025).

Bu nedenle gözyaşı biyobelirteçleri özellikle hastalık aktivitesinin ve riskin değerlendirilmesinde yararlı olabilir. Genç hastalar, aile öyküsü bulunanlar, alerjik veya atopik bireyler ve sık göz ovuşturan hastalar bu açıdan önemlidir. Gelecekte biyobelirteçlerin topografi, kornea biyomekaniği ve klinik risk faktörleriyle birlikte değerlendirilmesi daha ayrıntılı bir risk sınıflandırması sağlayabilir (Lombardo et al., 2025; Nautiyal et al., 2026).

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Bununla birlikte IL-6, TNF-α ve MMP-9 gibi belirteçler keratokonusa özgü değildir ve başka oküler yüzey hastalıklarında da değişebilir. Bu nedenle tek bir biyobelirteç yerine inflamasyon, doku yıkımı ve antioksidan savunmayı birlikte değerlendiren paneller daha yararlı olabilir. Ancak bu panellerin hastalık ilerlemesini öngördüğü veya korneal çapraz bağlama kararını yönlendirebildiği henüz gösterilmemiştir. Klinik kullanıma geçmeden önce uzun süreli prospektif çalışmalarda doğrulanmaları gerekmektedir (Lombardo et al., 2025; Nautiyal et al., 2026; Pallamreddy et al., 2026).

6. Tedavi ve Tedavi Yanıtının Değerlendirilmesi

Keratokonus tedavisinde görmenin düzeltilmesi, hastalığın ilerlemesinin durdurulması ve ileri olgularda korneadaki yapısal bozukluğun tedavisi amaçlanır. Korneal çapraz bağlama (CXL) hastalığın ilerlemesini durdurmak için kullanılan temel yöntemlerden biridir. Gözyaşı biyobelirteçleri ise CXL sonrasında yalnızca korneanın yapısal olarak değil, biyolojik olarak da nasıl değiştiğini değerlendirmeye yardımcı olabilir (Lombardo et al., 2025; Nautiyal et al., 2026).

CXL öncesi ve sonrasında gözyaşındaki sitokinler ve oksidatif stres belirteçlerinde değişiklikler bildirilmiştir. Bu nedenle biyobelirteçlerin gelecekte tedavi yanıtının izlenmesinde yararlı olabileceği düşünülmektedir. Ancak hangi zamanda ölçüm yapılacağı ve hangi değişimin anlamlı kabul edileceği henüz standart değildir. Bu nedenle rutin klinik izlemde kullanılmamaktadır (Balmus et al., 2020; Krok et al., 2024; Nautiyal et al., 2026).

Alerjinin kontrol edilmesi ve göz ovuşturmanın önlenmesi, özellikle genç keratokonus hastalarında önemlidir. Siklosporin A ile yapılan bir çalışmada MMP-9 ve inflamatuar sitokinlerin azaldığı gösterilmiştir. Ancak antiinflamatuar tedavilerin keratokonus ilerlemesini önlediğini gösteren yeterli kanıt yoktur. Bu nedenle yalnızca biyobelirteç yüksekliğine dayanarak antiinflamatuar tedavi başlanması önerilemez (Shetty et al., 2015; Gil et al., 2025; Lombardo et al., 2025).

Oksidatif stres ve kollajen yapısını hedefleyen yeni tedaviler de araştırılmaktadır. IVMED-80, LOX aktivitesini artırarak kollajen çapraz bağlanmasını güçlendirmeyi amaçlayan deneysel bir topikal tedavidir. Bu tür tedaviler henüz standart klinik uygulamaya girmemiştir. Gelecekte biyobelirteçler, hangi hastaların bu tedavilerden yararlanabileceğini belirlemek ve tedavi yanıtını izlemek için kullanılabilir (Nautiyal et al., 2026).

7. Özgün Bir Yaklaşım

Keratokonus takibinde genellikle korneadaki yapısal değişikliklere bakılır. Ancak kornea stabil görünse bile inflamasyon devam edebilir. Bu nedenle hastalık hem yapısal değişiklikler hem de biyolojik aktivite açısından değerlendirilebilir.

Yapısal değişiklikler topografi, pakimetri ve biyomekanik ölçümlerle takip edilir. Biyolojik aktivite ise IL-1β, IL-6, TNF-α, MMP-9 ve HMGB1 gibi inflamatuar belirteçlerle değerlendirilebilir. SOD3 ve sistatinler gibi koruyucu proteinler de gözyaşının savunma kapasitesi hakkında bilgi verebilir.

Buna göre kornea yapısı stabil ve biyolojik aktivite düşükse hastalık sakin kabul edilebilir. Kornea stabil olduğu hâlde biyolojik aktivite yüksekse hastalık moleküler olarak aktif olabilir. Hem yapısal ilerleme hem de biyolojik aktivite yüksekse aktif ilerleyici keratokonus düşünülebilir.

Ancak bu yaklaşım henüz doğrulanmamıştır. Klinik kararlarda kullanılmadan önce uzun süreli çalışmalarda değerlendirilmesi gerekir.

8. Klinik Uygulamaya Geçişte Sınırlılıklar

Gözyaşı biyobelirteçlerinin sonuçları, örnek alma ve saklama koşullarından etkilenebilir. Schirmer şeridinin uygulanma süresi, örneğin nasıl işlendiği, örnek hacmi ve saklama koşulları mümkün olduğunca standart olmalıdır. Ayrıca kontakt lens kullanımı, alerji, kuru göz ve topikal ilaçlar da gözyaşındaki inflamatuar belirteçleri etkileyebilir. Bu nedenle farklı koşullarda elde edilen biyobelirteç düzeylerini doğrudan karşılaştırmak yanıltıcı olabilir (Nättinen et al., 2020; Gijs et al., 2023; Gil et al., 2025; Pallamreddy et al., 2026).

İkinci önemli sorun, çalışmaların genellikle az sayıda hasta içermesi ve hasta gruplarının birbirinden farklı olmasıdır. Hastalık evresi, yaş ve ilerleme tanımları çalışmalara göre değişebilir. Proteomik

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çalışmalarda aynı anda çok sayıda protein incelendiği için, başlangıçta anlamlı görünen bazı sonuçlar istatistiksel düzeltme sonrasında anlamlılığını kaybedebilir. Bu nedenle belirlenen proteinler kesin biyobelirteçler olarak değil, başka hasta gruplarında doğrulanması gereken adaylar olarak değerlendirilmelidir (Gil et al., 2025; de Almeida Borges et al., 2026).

Üçüncü önemli sorun, istatistiksel olarak anlamlı bir sonucun her zaman klinikte yararlı olmamasıdır. Bir biyobelirteç panelinin klinikte kullanılabilmesi için güvenilir şekilde ölçülmesi, hastaları yeterli doğrulukla ayırması ve klinik kararlara gerçekten katkı sağladığının gösterilmesi gerekir (Bossuyt et al., 2012; FDA-NIH Biomarker Working Group, 2016).

9. Gelecek Yaklaşımlar

Gelecek çalışmalarda ortak bir gözyaşı biyobelirteç paneli oluşturulması yararlı olabilir. IL-1β, IL-6, TNF-α, MMP-9 ve HMGB1 inflamasyon ve doku yıkımını; SOD3, sistatinler, albümin ve laktoferrin ise koruyucu kapasiteyi gösterebilir. Sonuçların karşılaştırılabilmesi için örnekleme ve analiz koşulları standart olmalıdır.

Uzun süreli takip tasarımı kesitsel karşılaştırmalardan daha değerlidir. Aynı hastadan topografik değişim öncesi, ilerleme sırasında, çapraz bağlama sonrasında ve yeniden stabilizasyon döneminde seri gözyaşı örnekleri alınmalıdır. Özellikle ergenler, birinci derece akrabalar ve atopik hastalar ilerlemeyi öngören belirteçlerin araştırılması için uygun gruplardır.

Yeni teknolojiler, çok az miktarda gözyaşından birden fazla biyobelirteci ölçmeyi mümkün hâle getirebilir. Hasta başı testlerin yalnızca pozitif veya negatif sonuç vermesi yerine, biyobelirteç düzeylerini de göstermesi daha yararlı olacaktır. Yapay zekâ ise gözyaşı biyobelirteçlerini topografi, kornea biyomekaniği, yaş, aile öyküsü ve göz ovuşturma gibi klinik bilgilerle birleştirerek hastalık ilerleme riskini hesaplamaya yardımcı olabilir. Ancak bu sistemlerin farklı merkezlerde doğrulanması gerekir.

Tedavi çalışmalarında biyobelirteçler üç amaçla kullanılabilir: hastalığın ilerleme riskini tahmin etmek, hangi hastanın belirli bir tedaviden yarar görebileceğini belirlemek ve tedavi sonrasında biyolojik yanıtı izlemek. Kişiselleştirilmiş çapraz bağlama, antioksidan tedaviler ve inflamasyon ya da matriks onarımını hedefleyen yeni tedaviler bu şekilde değerlendirilebilir. Tedavi başarısı yalnızca biyobelirteç düzeylerinin azalmasıyla değil, hastalığın ilerlemesinin yavaşlaması, görme kalitesinin korunması ve gereksiz işlemlerin azaltılmasıyla da değerlendirilmelidir.

SONUÇ

Keratokonus, belirgin inflamasyon bulguları olmasa da inflamasyon, oksidatif stres ve doku yıkımının rol oynadığı çok faktörlü bir kornea hastalığıdır. IL-1β, IL-6, TNF-α, MMP-9 ve HMGB1 inflamasyon ve doku yıkımını gösteren başlıca adaylardır. SOD3, sistatinler, albümin ve diğer koruyucu proteinler ise korneanın savunma kapasitesi hakkında bilgi verebilir. Proteomik çalışmalarda yeni adaylar belirlenmiştir; ancak bunlar henüz klinik kullanım için doğrulanmamıştır.

Keratokonus stabil görünse bile gözyaşındaki inflamatuar belirteçler yüksek kalabilir. Bu durum, korneadaki yapısal değişikliklerle biyolojik aktivitenin her zaman aynı anda ilerlemediğini düşündürür. Bu nedenle tek bir biyobelirteç yerine, inflamasyon ve doku yıkımını gösteren belirteçlerle koruyucu proteinlerin birlikte değerlendirilmesi daha yararlı olabilir. Gözyaşı biyobelirteçleri bugün topografi ve biyomekanik testlerin yerine geçmez. Ancak gelecekte standart örnekleme ve uzun süreli çalışmalarla doğrulanırsa risk değerlendirmesi, çapraz bağlama sonrası izlem ve tedavi planlamasında yardımcı olabilir.

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CRISPR-CAS SPACER ACQUISITION AS A BIOMARKER OF PHAGE-DRIVEN GENE FLUX IN ENVIRONMENTAL AND CLINICAL ISOLATES

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ABSTRACT

Bacteriophages are the main players in the horizontal gene transfer process between microorganisms, but there is still no consistent biomarker that can provide information about the gene flows caused by phages over time. We put forward the idea that the acquisition of new CRISPR-Cas spacers acts as an in vivo recorder of the present phage activity and hence can measure the short-term gene flux in contrasting bacterial populations. Bacteriophages were applied to both environmental and clinical bacterial isolates that had been previously determined to be matched, and leaders of the proximal CRISPR arrays were sequenced at different intervals to detect newly incorporated spacers; subsequently, the origin of the spacers was related to the phage genomes and mobile genetic elements, and the molecular records were correlated with the phenotypic assays of phage susceptibility and the antibiotic minimum inhibitory concentration. The clinical isolates took in spacers faster, at a higher per-cell rate and with a greater frequency of expansion than the environmental isolates; a significantly larger portion of the new spacers in the clinical strains matched the genome of the challenge phage, while the environmental isolates yielded a higher proportion of unassigned spacers. Spacers that were directed toward the phage tail-fiber loci revealed the greatest correlation with the loss of plating efficiency, and the infrequent gain of beta-lactamase-like fragments that were associated with plasmids was found to occur simultaneously with the rise in antibiotic resistance in a few clinical replicates. All of these findings corroborated the acquisition of leader-proximal spacers as an effective, sequence-resolved biomarker that reveals what mobile elements are actively interacting with the hosts and when the resistance-associated sequences are activated. This method not only complements metagenomic surveillance but, being temporally sensitive, creates a predictive axis for estimating the success of phage therapy, the spread of resistance genes in clinical settings, and the emergence of new-resistant bacterial strains.

Introduction

Phages are the main agents of genetic mixing in microbial ecosystems, allowing for both generalized and specialized transduction, lysogenic conversion, and recombinant reorganizing of the host chromosomes. Phages have managed to shape the bacterial gene pool many times and even facilitate the spreading of adaptive traits (Canchaya et al., 2003; Touchon et al., 2017; Kenzaka et al., 2010). The gene fluxes caused by phages have an immediate impact on the ecology (nutrient cycling, community structure), and when they carry antibiotic resistance or virulence determinants among com-mensal or pathogenic strains, they have very serious clinical implications. The mixed activity of phages spatially and temporally — from water to infection areas — makes phage-induced HGT a bacterial evolution force that is not only dominant but also highly dynamic (Canchaya et al., 2003; Touchon et al., 2017; Kenzaka et al., 2010). Nevertheless, the process of active, contemporary phage-mediated transfer in mixed populations, which is so significant, is hard to capture. Genomic epidemiology, as a traditional method, usually reveals the outcome of the past transfers (integration of prophages, acquisition of islands), but it is unable to easily distinguish between recent, ongoing transduction events and historical footprints of earlier exposures. Furthermore, ecological and clinical samples mix the signals from resident prophages, free virions, and mobile elements, and thus, it is very difficult to tell which transfers

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are current and which are relics, so it requires molecular markers that register events at biologically relevant timescales (Stern & Sorek, 2011). The CRISPR–Cas adaptive immune system gives just such a marker. At first, it was characterized as a hereditary defense mechanism that stores by means of short fragments (spacers) of each invading DNA in host arrays (Barrangou et al., 2007). The CRISPR adaptation is mechanistically carried out by Cas1–Cas2 integrase complexes which add new spacers at the leader-proximal end of the arrays thus generating a time-ordered record of exposures (Nuñez et al., 2015; Yosef et al., 2012). Since the de novo spacer acquisition is caused by the encounter with mobile genetic elements, the newly incorporated spacers act as in vivo, molecular "snapshots" of the recent phage encounters - hence, it is possible to trace back individual infection events to a certain phage genome or mobile genetic element (Barrangou et al., 2007; Nuñez et al., 2015; Yosef et al., 2012). Up to now, the research mainly took advantage of the existing spacer repertoires for host-virus linking, phylogeography or long-term ecological inference (Paez-Espino et al., 2013; Nasko et al., 2019). The studies indicated that the content of spacers can disclose the preferential targeting of certain viral genes and can connect the hosts with the environmental pools of viruses, but they did not rigorously regard the new spacer acquisition rate and sequence origin as a quantitative biomarker of contemporaneous gene flux across the contrasting bacterial populations. In the same way, clinical studies have shown variations in CRISPR with respect to the mobilome (Lopez-Sanchez et al., 2012), but an expressly process-oriented framework that employs leader-end spacer dynamics to quantify phage-driven transfer in clinical versus environmental isolates is still absent. This gap impedes rigorous comparisons of phage-mediated gene flow where it matters most — the clinic vs. the environment — and limits predictive models of resistance emergence. As a centerpiece of our research, we proposed that both the frequency and accuracy of de novo CRISPR spacer acquisition would serve as direct and quantifiable indicators of phage-induced gene flow, and that these alterations would be distinct in environmental as well as in clinical bacterial populations. To be more precise, our assumptions were as follows: (i) higher variance and lower per-cell acquisition rates in environmental isolates going through a diverse low-density phage pool exposure, while (ii) more concentrated and higher-rate acquisition in clinical strains subjected to repeated and high-intensity phage or plasmid challenges. To verify our assumptions, we planned to (1) carry out a comparison of the rates of de novo spacer acquisition in model environmental and clinical isolates during controlled phage challenge; (2) trace back the newly acquired spacers to their respective phage genomes and mobile genetic elements in order to measure origin-specific flux; and (3) determine if early gained spacer signatures could predict the later expressed phenotypic resistance and changes in phage susceptibility. By making spacer acquisition a dynamic biomarker, the research will not only give a greater insight into the phage–host coevolution but also make a practical prediction tool for the outcomes of phage therapy and gene spread in hospitals or clinics (Staals et al., 2016; Levy et al., 2015).

Methods

Sample collection and processing

Samples were collected from Al-Anbar Governorate Hospital and nearby environmental sites between January 1, 2025 and December 31, 2025. Collected materials were transported to the laboratory at 4°C and processed within six hours of collection. Aliquots were taken for viable cell counts at each time point by standard serial dilution and plating.

DNA extraction and library preparation

Genomic DNA was extracted from each sample using a commercially available column-based extraction kit according to the manufacturer’s instructions. DNA quantity and purity were assessed using fluorometric and spectrophotometric measurements, and fragment size distribution was checked by automated electrophoresis. Libraries for high-throughput sequencing were prepared using a standard DNA library preparation kit with dual-index barcoding to minimize sample cross-talk. Libraries were quantified and pooled to achieve approximately equal representation of each sample.

Sequencing

Pooled libraries were sequenced on a high-throughput Illumina platform in paired-end mode with 150 base pair reads from each end. Target sequencing depth was set to approximately five million paired

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reads per library to ensure sufficient coverage for spacer detection and downstream analyses. Standard instrument quality metrics were reviewed for each run prior to downstream processing.

Read quality control and preprocessing

Raw sequencing reads were evaluated for quality metrics including base quality scores, adapter contamination and read length distribution. Adapter sequences and low-quality bases were removed, and short reads that fell below a minimum length threshold after trimming were discarded. Where short amplicon overlap permitted, paired reads were merged to recover full-length target fragments. PCR duplicates were addressed through sequence-based deduplication or by using unique molecular identifiers where available.

Detection and extraction of CRISPR spacers

CRISPR arrays were identified in processed reads or assembled contigs by established CRISPR-detection algorithms. Spacers were defined as sequences located between direct repeats and limited to lengths typical for bacterial CRISPR systems (approximately 20–70 nucleotides). Extracted spacer sequences were collated into per-sample catalogs and non-redundant spacer sets were produced by collapsing identical spacer sequences so that each unique spacer was represented once per sample.

Spacer annotation against phage reference databases

Unique spacer sequences were compared to a curated phage reference database composed of RefSeq phage entries supplemented with contemporary viral sequence collections (database version: RefSeq_phage_v2023.11 + IMG/VR_2023). Matches were considered confident when they satisfied pre-defined thresholds for sequence identity and query coverage and when their alignment significance met conventional statistical criteria. For each spacer, the single best match was retained for annotation; spacers lacking matches under these criteria were labeled as unknown. Sensitivity analyses were performed to assess how changing identity thresholds affected the number and identity of annotated spacers.

Quantification metric: spacers per generation per surviving cell

In order to establish a connection between spacer acquisition and population dynamics, we introduced a metric which was defined as the number of newly observed unique spacers differentiating two time points divided by the product of the number of surviving cells at the later time point and the number of bacterial generations that passed during the interval. The viable counts at each time point were determined by making serial dilutions, plating under standard conditions, and counting colony-forming units after incubation. The number of generations was approximated from the ratio of viable counts between time points using a $\log_2$ transformation. This metric is very helpful in comparing the rates of spacer acquisition across different samples where the dynamics of survival and growth are also different.

Additional spacer analyses

We looked at the length distributions of the spacers, the occurrence patterns of the spacers sample by sample, and the functional linkages between spacer targets and phage gene annotations (for instance, structural genes which include tail-fiber proteins). To summarize the patterns across samples and time points, presence–absence matrices, heatmaps, and correlation plots between spacer counts and measures of phage abundance were created. The annotations of putative phage genes were checked and curated in order to allocate categories of function that are probably similar.

Statistical analyses

The testing of statistical significance was carried out through the employment of conventional statistical software. The distributions of the data were checked for normality and the homogeneity of the variances to determine the appropriate statistical tests. If the assumptions were satisfied then parametric tests such as t-tests and ANOVA were carried out; otherwise, non-parametric alternatives like Mann–Whitney and Kruskal–Wallis were used. During the process of making multiple comparisons, the control of false discovery rate took place. The effect sizes and 95% confidence intervals are presented together with p-

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values for the sake of interpretation. An a priori power analysis came up with the sample size and post-hoc power calculations can be found in the Supplementary Materials.

Results

The spacer acquisition assay successfully captured differential CRISPR dynamics between environmental and clinical isolates across the sampled time course. Overall, clinical isolates displayed earlier and higher-frequency array expansion, producing a larger proportion of leader-proximal spacers that matched challenge phage genomes.

Table 1. Spacer acquisition kinetics over time (mean ± SD; n = 3 biological replicates per timepoint)

Time_h	Env: New_Spacers_per_Cell (mean ± SD)	Env: Expansion_Freq (%)	Clin: New_Spacers_per_Cell (mean ± SD)	Clin: Expansion_Freq (%)
0	0.00e+00 ± 0.00e+00	0.0	0.00e+00 ± 0.00e+00	0.0
4	1.2e-07 ± 6.5e-08	2.3	6.5e-07 ± 2.1e-07	6.8
12	5.6e-07 ± 3.2e-07	8.5	2.1e-06 ± 7.8e-07	16.2
24	1.8e-06 ± 8.9e-07	18.4	5.4e-06 ± 1.4e-06	42.7
48	3.2e-06 ± 1.6e-06	26.1	8.0e-06 ± 2.4e-06	58.3

We observed time-dependent increases in spacer acquisition in both isolate types; clinical isolates showed consistently higher per-cell acquisition rates and expansion frequencies. A significant difference in new spacers per cell at 24 h between clinical and environmental isolates was found (two-sample t-test, $p = 0.003$).

Table 2. Genomic origin breakdown of newly acquired spacers (percent of all new spacers; pooled across timepoints)

Isolate_Type	Challenge_Phage (%)	Prophage (%)	Plasmid (%)	Unknown/Unassigned (%)
Environmental	42	18	10	30
Clinical	71	8	5	16

The data revealed that clinical isolates acquired a greater fraction of spacers that matched the challenge phage (71% vs 42%); environmental isolates had a larger unknown fraction (30% vs 16%). The difference in fraction of phage-derived spacers between isolate types was significant (χ^2 test, $p < 0.001$).

Table 3. Characteristics of CRISPR array expansion events (mean ± SD or percent)

Isolate_Type	Avg_Spacers_per_Event (mean ± SD)	% Multiple_Acquisitions (>1 spacer/event)	Median_Time_to_First_Event (h)
Environmental	1.35 ± 0.60	12	18
Clinical	2.10 ± 0.80	34	8

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We observed that clinical isolates experienced larger expansion events (mean 2.10 spacers/event) and more frequent multiple-acquisition events (34% of events) compared with environmental isolates (1.35 spacers/event; 12% multiple acquisitions). The difference in average spacers per event was significant (ANOVA, $F = 12.4$, $p = 0.0008$).

Table 4. Functional annotation of top spacer target genes/regions (pooled counts across isolates)

Target_Gene_Region	Count (n)	Function (annotation)	% of Phage-derived Spacers
Tail_fiber / receptor-binding protein	220	Adsorption/tropism	27.1
Integrase / recombinase	120	Integration/recombination	14.8
Major_capsid_protein	110	Structural assembly	13.6
Replication_protein (rep/helicase)	90	Genome replication	11.1
Beta-lactamase-like region (phage-associated)	45	Putative resistance gene	5.6
Hypothetical_protein / unknown ORF	165	Uncharacterized	20.3

The annotation showed tail-fiber and hypothetical proteins were the most common targets among phage-derived spacers; tail-fiber targets comprised 27.1% of phage-derived spacers. Target distribution differences across functional categories produced a non-uniform profile (Kruskal–Wallis, $p = 0.002$).

Table 5. Association between spacer acquisition (by target) and phenotypic resistance outcomes

Spacer_Target	N_Isolates_with_Spacer (n)	Mean_EOP_FoldChange (post vs pre)	EOP_p-value	Antibiotic_MIC_Change (clinically measured)
Tail_fiber	28	0.18 (i.e., 82% reduction)	$p < 0.001$	No consistent MIC change
Integrase	15	0.67	$p = 0.02$	3 isolates showed 2× AMX MIC increase ($p = 0.04$)
Beta-lactamase-like	6	0.90	$p = 0.31$ (ns)	4× AMX MIC increase observed ($p = 0.008$)
Hypothetical_protein	21	0.55	$p = 0.005$	No change

The data revealed a strong association between acquisition of tail-fiber–targeting spacers and reduced phage plating efficiency (mean EOP fold change 0.18; $p < 0.001$). Acquisition of beta-lactamase-like targets correlated with an increase in amoxicillin MIC in a small number of isolates ($p = 0.008$), although the EOP change for that group was not significant.

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Table 6. Summary metrics of calculated "gene flux rates" (mean ± SD; spacers per generation per surviving cell)

Isolate_Type	Phage-driven_Flux (spacers/gen/cell)	MGE-driven_Flux (spacers/gen/cell)	Total_Flux (spacers/gen/cell)
Environmental	2.1e-06 ± 1.1e-06	0.8e-06 ± 0.4e-06	2.9e-06 ± 1.4e-06
Clinical	6.4e-06 ± 2.3e-06	0.5e-06 ± 0.2e-06	6.9e-06 ± 2.4e-06

We quantified higher phage-driven gene flux in clinical isolates (mean 6.4×10^{-6} spacers/gen/cell) relative to environmental isolates (2.1×10^{-6}), while MGE-driven flux was comparable or slightly higher in environmental isolates. The difference in phage-driven flux between isolate types was statistically significant (two-sample t-test, $p = 0.001$).

Table 7. Summary of statistical tests on key comparisons

Comparison	Test	Test_statistic (value)	df / n	p-value	Significance
New_spacers_per_cell at 24 h (Clin vs Env)	Two-sample t-test	t = 3.67	df = 10	p = 0.003	**
Expansion_Freq (Clin vs Env, all timepoints)	Mann–Whitney U	U = 4	n = 10	p = 0.009	*
Fraction_phage-derived_spacers	Chi-square	$\chi^2 = 12.8$	df = 1	p < 0.001	**
Avg_spacers_per_event across isolates	ANOVA	F = 12.4	df = 1,10	p = 0.0008	**
Phage-derived_fraction vs EOP reduction	Pearson correlation	r = -0.68	n = 48	p = 0.001	**
Beta-lactamase-target vs AMX MIC change	Fisher's exact	—	—	p = 0.008	**

The table summarized the principal statistical tests performed; several comparisons reached conventional thresholds for significance (e.g., $p < 0.01$), supporting the observed differences in acquisition kinetics, target composition and associations with phenotypic resistance.

Discussion

Our findings indicated that clinical isolates were able to take up CRISPR spacers much more quickly and at higher array-expansion frequencies compared to environmental isolates during the whole experimental time course. Challenged by the virus, newly added spacers in clinical strains were mostly obtained from the phage genome, while spacers directed against tail-fiber loci coincided with a drastic decrease in phage plating efficiency; on the other hand, the sporadic gathering of plasmid-associated, beta-lactamase–like sequences was accompanied by slight increases in amoxicillin MIC in very few strains. These fundamental results provided a reproducible signal that traced the acquisition of new spacers to the simultaneously occurring phage-induced genetic change within the short periods of ecological interaction.

Decoding these patterns necessitated the combination of the mechanistic understanding of adaptation and the ecological models for the phage–host contact. It has been well documented that the ability of

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CRISPR systems to register encounters through leader-proximal spacer integration is strong (Barrangou, 2007), and the molecular basis for the integration by Cas1–Cas2 offered a mechanistic foundation for considering new spacers as time-stamped exposure events (Nuñez, 2015; Yosef, 2012). Our finding that clinical isolates mainly absorbed phage-derived spacers matches with studies indicating that adaptation is biased towards foreign, replication-associated DNA and interference-driven acquisition contexts (Levy, 2015; Staals, 2016). In other words, the molecular machinery and selection regimes that favor the acquisition from active invaders shedding light on why the recently exposed clinical strains produced a greater fraction of phage-matching spacers compared to their environmental counterparts. Our data on ecological level support the previous findings from population-scale and metagenomic studies. Non-random biases in spacer origin and functional target categories were demonstrated by studies using extant spacer repertoires (Paez-Espino, 2013; Nasko, 2019), and we noticed the same preferential targeting of genes and structures related to receptors (tail fiber) among newly acquired spacers. This bias that resulted in predictable decreases in plating efficiency confirms a direct functional connection between spacer content and short-term resistance phenotypes, thus supporting previous correlative evidence from environmental surveys.

What was the reason for the big difference between clinical and environmental isolates?

It is the phage-driven horizontal gene transfer that is most probably the reason for major differences between the two groups of bacteria (Touchon, 2017; Canchaya, 2003); however, the microecological contexts of clinical settings — high host density, frequent antibiotic exposure, and simplified ecological networks — can easily intensify both encounter rates and selection for immediate defence (Frost, 2005). The phage community experienced by the clinical isolates in our experiments was presumably a narrow one dominated by the challenge phage and of high intensity where very strong, interference-mediated acquisition occurred along with a high yield of effective spacers. Environmental hosts, on the other hand, are faced with a more diverse viral pool and broader MGE repertoire, which could account for the greater proportion of unknown-origin spacers and the more dispersed acquisition kinetics we observed. The occasional plasmid-associated spacer acquisition in clinical isolates, which we found along with increases in antibiotic MIC, reveals a subtle route of phage-plasmid-host interactions that could speed up gene movement that is clinically relevant. Reports from the field of the environment have indicated that phages can transport resistance genes in their fractions (Colomer-Lluch, 2011), however, virome investigations have also warned that the actual frequency of phage-encoded ARGs could be low and prone to analytical artifacts (Enault, 2017). The experimental setup we used was able to identify rare but significant plasmid-related spacers; these events need to be interpreted with caution but they do imply the existence of time slots when phage and plasmid may communicate under the selective pressures of the clinic. The research involved pre-set lab challenges and model strains that, to a certain extent, simplified the complexity of natural phage communities and the great variety of host's physiological states. Metagenomic "dark matter", which is still not resolved in many environments, makes it difficult to trace the origin of spacers (Roux, 2015), and our phage isolates just represent a small part of the viral diversity that exists in nature. The same patterns that were seen under acute exposure might not be completely generic for chronic colonization contexts like the gut, where the dynamics of host-phage are structured by long-term ecological feedbacks (Shkoporov & Hill, 2019). Lastly, the dynamics of coinfection and interactions between viruses can influence genetic exchange and spacer acquisition in ways that were not captured by our single-phage challenges (Díaz-Muñoz, 2017). The research presents leader-proximal spacer acquisition as sensitive, process-level biomarker of recent phage-driven gene flux even with these limitations. Properly mapping the new acquired spacers to viral and MGE databases will give a temporal-resolved readout of the elements that are currently mobilizing and the functions that are being targeted by host immunity. This feature has instant conceptual worth for microbial ecology and potential applications in clinical surveillance: spacer-based monitoring can serve as an addition to metagenomics and culture-based methods to forecast the emergence of phage resistance and the gradual transfer of resistance factors. More widely, regarding CRISPR adaptation as in vivo documenting of HGT, it becomes a feasible way to measure the tempo and targets of mobile DNA in both natural and man-made ecosystems.

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Conclusion

Our research points out the fact that the acquiring of spacers is not only a historic record but also a quantifiable and real-time indicator of phage-driven gene transfer. One of the key advances is both conceptual and practical: by directing our attention to the leader-proximal, newly integrated spacers we changed CRISPR adaptation into a temporally anchored biomarker that indicates not only the active mobile elements' identity but also their immediate phenotypic impacts. The difference in the acquisition dynamics that we noticed between clinical and environmental isolates has greatly clarified the role of ecological context - in terms of the frequency of encounters, the simplification of viral pools, and human-induced selection - in determining the speed and direction of mobile-DNA movement. This change in thinking gives us the opportunity to formulate new questions with practical applications: which elements are currently mobilizing resistance in a patient cohort, how soon resistance will emerge under a proposed phage treatment, and which phage targets are most likely to lead to resistance that is sustained for a long time. Hence, looking ahead, we will have to rely on spacer-centric monitoring in longitudinal metagenomic series and clinical trials of phage therapy, fast leader-end sequencing combined with targeted phenotypic assays and bioinformatics pipelines that can scale up. Merger of this biomarker with the single-cell and long-read techniques will enhance the determination of the origin and uncover the within-host heterogeneity. In the end, treating CRISPR adaptation as an empirical recorder of ongoing gene flux helps to integrate ecology and clinic: it provides researchers and physicians with a forward-looking metric to predict evolutionary paths, manage interventions, and focus surveillance on areas where gene flows are temporary but have a significant impact.

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CULTURAL HERITAGE AND NATIONAL TRANSFORMATION IN NIGERIA: A STUDY OF DEWEY'S AESTHETIC PHILOSOPHY

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ABSTRACT

This study examines the relationship between cultural heritage and national transformation in Nigeria through the lens of Dewey's aesthetic philosophy. The problem of cultural neglect has weakened social cohesion, patriotism and the transmission of traditional values necessary for sustainable national development. This paper using critical analysis digs deep into the conceptual clarification. This justifies why the theoretical framework is built on value theory. This study argues that our cultural heritage should not be taken for granted but rather respect the importance of culture and beauty in human existence, which is a valuable instrument for national unity, sustainable development and social transformation. This study also signifies that the preservation of cultural heritage can strengthen national identity, promote unity, encourage creativity and foster moral and economic development in Nigeria. This study concludes that cultural heritage is not merely a historical legacy but a dynamic instrument for national reconstruction and future development.

Keywords: Cultural heritage, National transformation, Dewey's, Aesthetic and Philosophy.

Introduction

Cultural heritage is one of the most important aspects of human society, representing the accumulated values, traditions, beliefs, customs, arts and historical experiences of a people. It serves as a link between the past, present and future by providing a sense of identity and continuity for individuals and communities. David Lowenthal (1998) observes that heritage involves the ways societies select and interpret aspects of the past in relation to their present needs. This indicates that heritage is not simply an objective record of history but also a way through which societies understand and represent their past. In Nigeria, cultural heritage is expressed through diverse languages, traditional institutions, festivals, music, dance, folklore, religious practices, crafts and indigenous knowledge systems. These cultural resources constitute an essential aspect of Nigeria's national identity and social development. However, cultural heritage is not always preserved or interpreted without conflict. Questions concerning ownership, appropriation, representation and commercialization have become important issues in contemporary discussions of heritage. Meskell's (2011) discussion of heritage demonstrates that cultural heritage can become connected with questions of identity, politics and social change. In recent decades, Nigeria has faced numerous challenges, including political instability, ethnic conflicts, corruption, cultural erosion and socio-economic difficulties. These challenges have created a growing need for national transformation, understood as a process of fundamental social, political, economic and cultural change aimed at improving the well-being of citizens and promoting sustainable development.

Cultural heritage possesses the potential to promote national unity, moral values, social cohesion, creativity and economic development. It serves as a source of collective memory and provides a framework through which societies preserve their identity and transmit important values to future generations. However, the usefulness of cultural heritage to national transformation depends on how it is understood and experienced in contemporary society. From Dewey's perspective, cultural heritage should not be seen merely as a collection of historical artifacts or ancient customs but as a living and dynamic experience capable of enriching human life and promoting social transformation. Dewey's (1934) aesthetic philosophy places emphasis on experience and on the relationship between art and ordinary human life. This makes his philosophy relevant to the study of Nigerian cultural heritage

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because many Nigerian cultural practices are experienced through active participation. Nigeria's cultural heritage, when approached as an aesthetic experience, can foster creativity, strengthen communal bonds, encourage participation and inspire collective efforts towards national development. Traditional festivals, music, dance, storytelling, crafts and cultural ceremonies are not simply objects to be observed; they are experiences through which people communicate meanings and establish relationships with their cultural environment. The problem of this study, therefore, is the inadequate appreciation of cultural heritage as a living experience and its possible contribution to national transformation. Although cultural heritage has been widely discussed in relation to identity, history and preservation, there remains a need to examine how its aesthetic dimension can contribute to contemporary social transformation in Nigeria.

The aim of this study is to examine the relationship between cultural heritage and national transformation in Nigeria through John Dewey's aesthetic philosophy. Specifically, the study seeks to clarify the concept of cultural heritage, examine Dewey's conception of aesthetic experience, apply his aesthetic principles to Nigerian cultural practices, and establish how cultural heritage can contribute to national identity, social cohesion, moral development, creativity and national transformation. The study argues that Nigerian cultural heritage should not be treated merely as a historical inheritance. Rather, it should be understood as a living experience that can continue to shape individual and collective life. Through preservation, participation and meaningful engagement, cultural heritage can become an important instrument for national transformation.

Literature Review : **The Concept of Cultural Heritage**

Cultural heritage refers to the totality of people's historical, religious, artistic, cultural and social inheritance passed down from one generation to another. It encompasses both tangible heritage, such as monuments, artifacts, traditional architecture and historical sites, and intangible heritage, such as language, folklore, customs, music, dance, festivals, beliefs and indigenous knowledge. In Nigeria, cultural heritage reflects the rich diversity of its various ethnic communities and serves as an important foundation for identity, unity and development. It includes the traditions, practices, values and artistic expressions through which Nigerian communities preserve and communicate their histories. Edward Burnett Tylor (1871) defines culture as a complex whole that includes knowledge, belief, art, morals, law, custom and other capabilities acquired by human beings as members of society. Tylor's conception demonstrates that culture is broader than artistic production. It includes the knowledge, beliefs, values and practices through which people organize their lives. Clifford Geertz (1973) approaches culture through the idea of symbols and meanings. He explains culture in terms of systems of meanings through which human beings interpret their world. From this perspective, Nigerian cultural heritage contains symbols and meanings through which individuals and communities understand their identity, history and social relationships.

UNESCO (n.d.) also recognizes cultural heritage as something inherited from the past, experienced in the present and transmitted to future generations. This understanding emphasizes that cultural heritage is not simply something preserved in its original condition. It continues to be experienced and interpreted by communities. Kwame Anthony Appiah's (1994) discussion of culture and identity further demonstrates that cultural traditions are connected with the ways individuals and communities understand themselves. Cultural heritage can therefore preserve identity while allowing societies to respond to changing circumstances. Cultural heritage is consequently not merely a collection of relics from the past. It is a living expression of a people's values, creativity and worldview. It preserves collective memory and provides resources through which present generations can understand their cultural background.

However, cultural heritage should not be understood as something that must remain completely unchanged. James Young's (2008) discussion of cultural appropriation demonstrates that cultural forms can move between communities and acquire new meanings. This raises the need for a careful distinction between preservation, cultural exchange and inappropriate appropriation.

For Nigeria, the challenge is therefore to preserve significant cultural practices while allowing them to remain meaningful in contemporary society. Cultural heritage can contribute to national transformation when it is understood as a living cultural resource rather than as a static inheritance.

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Theoretical Framework

John Dewey's Concept of Aesthetic Philosophy

John Dewey's aesthetic philosophy provides the theoretical foundation for this study. His major work on aesthetics, Art as Experience (Dewey, 1934), challenges the traditional separation of art from ordinary human experience. Dewey argues that aesthetic experience should be understood in relation to the activities and environments within which human beings live.

Art and Experience

Dewey's central concept in his aesthetic philosophy is experience. For Dewey, human beings do not exist separately from their environment. They continuously interact with their surroundings, acting upon them and undergoing their consequences.

Dewey therefore understands experience as involving both doing and undergoing. An individual acts upon the environment and at the same time experiences what results from that action. This interaction gives experience its dynamic character. Dewey distinguishes ordinary fragmented experiences from what he calls "an experience." An experience has unity and development; its different parts are connected and move toward a meaningful completion. In an aesthetic experience, the individual does not simply encounter isolated sensations but experiences a unified whole.

This conception is important for understanding cultural heritage. A traditional festival, for example, may include music, dance, dress, ritual, storytelling and communal participation. These elements do not function independently. Their relationship produces a unified cultural experience.

Aesthetic Experience

For Dewey, aesthetic experience is not restricted to paintings, sculptures or other objects traditionally classified as fine art. It can arise from meaningful human activities when there is an organized and fulfilling relationship between the individual and the environment.

Dewey therefore challenges the separation between art and everyday life. The aesthetic can be found in activities that involve meaningful participation and interaction (Dewey, 1934).

This conception makes Dewey's philosophy useful for examining Nigerian cultural practices. Traditional music, dance, festivals, crafts, architecture and ceremonies can have aesthetic significance because individuals experience them through participation. The aesthetic value of cultural heritage therefore lies not only in the physical appearance of cultural objects but also in the experience, meaning and relationships associated with them.

Art as Communication

Dewey also connects art with expression and communication. Art provides a means through which experiences can be transformed into forms that can be communicated to others.

Thomas's (1987) examination of Dewey's theory of art, experience and nature further emphasizes the importance of feeling and experience within Dewey's aesthetics. Art therefore does not simply present an attractive object; it communicates an experience.

This is particularly relevant to Nigerian cultural heritage. Traditional music can communicate historical experiences, oral traditions can transmit moral knowledge, dance can communicate social identity, and festivals can communicate religious and historical meanings. Cultural heritage therefore becomes a means of communication between generations. Through cultural practices, communities communicate experiences, values and knowledge that might otherwise be lost.

Art and Everyday Life

Dewey rejects the idea that aesthetic experience belongs only to specialized artistic institutions. Aesthetic experience can occur within ordinary human activities when those activities possess meaning and unity.

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Richard Shusterman's (2000) discussion of pragmatist aesthetics develops this broader understanding of culture and aesthetic experience. Similarly, Arnold Berleant (1997) emphasizes active engagement with aesthetic environments rather than treating aesthetic experience as detached observation. Yuriko Saito (2007) also demonstrates the significance of everyday aesthetics by extending aesthetic inquiry beyond traditional works of fine art. These developments support the relevance of Dewey's approach to Nigerian cultural heritage. Cultural practices such as traditional dress, food, architecture, crafts, music, dance and festivals can possess aesthetic significance because they are embedded in everyday and communal experiences.

Aesthetic Experience and Community

Dewey's aesthetic philosophy also has a social dimension. Human beings experience the world through relationships with other people and their environment. Aesthetic activities can therefore strengthen communication and community. Traditional festivals, dances, ceremonies and storytelling create opportunities for collective participation. They bring people together and allow them to share experiences and meanings. Scott Stroud's (2011) discussion of Dewey connects pragmatism, aesthetics and morality, demonstrating that aesthetic experience can have implications beyond beauty and artistic appreciation. This is significant for the Nigerian context because cultural practices often contain moral, social and communal dimensions. Dewey's aesthetic philosophy therefore provides a framework for understanding cultural heritage as a living experience. His emphasis on experience, communication, everyday life and community makes it possible to examine Nigerian cultural heritage as a force capable of contributing to social development and national transformation.

Cultural Heritage as Aesthetic Experience

In Nigeria, cultural heritage as aesthetic experience refers to the appreciation and lived engagement with diverse cultural expressions such as festivals, traditional music, dance, oral literature, indigenous crafts, architecture and rituals. These elements are not only historical symbols but also living aesthetic experiences that shape identity, community values, creativity and national consciousness.

From an aesthetic perspective, Nigerian cultural heritage becomes meaningful when it is actively experienced, interpreted and participated in by individuals and communities. It is through such engagement that heritage contributes to beauty, meaning and social transformation. Dewey's (1934) aesthetic philosophy emphasizes that art is rooted in experience and interaction with the environment. Therefore, cultural practices can become aesthetic experiences when people actively engage with them.

For instance, the Osun-Osogbo festival contains religious, artistic, historical and communal dimensions. Its significance cannot be reduced to the physical site or objects associated with it. The experience of the festival involves participation, music, movement, ritual and communal interaction. Igbo masquerade traditions similarly combine artistic, spiritual and communal elements. Yoruba drumming is another example of cultural expression in which sound, rhythm, language and social interaction combine to produce a meaningful experience. Hans-Georg Gadamer's (1989) discussion of the experience of art is useful in explaining the relationship between cultural experience and understanding. Engagement with cultural heritage allows individuals to encounter traditions and interpret their significance in relation to their own lives. Participating in Yoruba Egungun festivals or Hausa Durbar celebrations creates immersive experiences that connect individuals with communal traditions. Traditional food, indigenous architecture and dress patterns such as Ankara and Aso-oke also possess aesthetic dimensions.

Molefi Kete Asante's (2010) discussion of African cultural identity emphasizes the significance of language and cultural expression to African identity. Cultural practices should therefore be understood not only according to their outward appearance but also according to the meanings and identities they communicate.

Kwame Gyekye's (1997) discussion of tradition and modernity is also relevant because it demonstrates the importance of examining African traditions in relation to contemporary conditions. Tradition does not necessarily have to be abandoned in order for a society to modernize. Instead, inherited practices can be critically examined and adapted.

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Cultural heritage as aesthetic experience in Nigeria therefore involves communal participation, symbolic meaning, identity formation, educational value and creative expression. It can contribute to national unity, cultural identity, tourism, creative industries, moral development, social cohesion and peacebuilding.

Cultural Heritage and National Transformation in Nigeria

The relationship between cultural heritage and national transformation in Nigeria is a central issue in contemporary social and philosophical studies. Cultural heritage, comprising language, traditions, values, arts, festivals and indigenous knowledge, represents the identity and historical consciousness of Nigerian people. National transformation, on the other hand, refers to the comprehensive process of social, political, economic and cultural development aimed at improving national unity, governance and quality of life. Dewey's (1934) understanding of culture and art as forms of human experience provides a basis for connecting cultural heritage with national transformation. For Dewey, aesthetic activities are not isolated from human life. They are connected with experience, education, communication and community. Nigerian cultural heritage can therefore promote national unity, civic responsibility and participation by creating spaces where individuals interact and share cultural experiences. Cultural activities can provide opportunities for dialogue among different ethnic and cultural communities. Many Nigerian cultural practices embody values such as honesty, respect, communal solidarity and responsibility. Revitalizing and critically examining these values can contribute to ethical transformation and national development. However, cultural values should not be accepted uncritically. Dewey's pragmatist approach permits cultural practices to be evaluated according to their consequences for human development and social well-being. Positive cultural values can therefore be preserved and encouraged, while practices that undermine human dignity or social development may require critical reconsideration.

Cultural Heritage and Education

Cultural heritage provides educational opportunities that can enhance creativity, critical thinking and historical awareness. Dewey's emphasis on experience in education makes cultural heritage an important educational resource. Nigerian cultural practices can provide practical opportunities for learning. Oral traditions, indigenous languages, traditional music, crafts, local histories and community festivals can be incorporated into educational activities.

Through such engagement, students can develop an understanding of their cultural background while also learning to evaluate traditions critically. Cultural education can therefore contribute to both identity formation and intellectual development.

Cultural Heritage and Economic Development

Nigeria's cultural heritage has significant economic potential through tourism, creative industries, cultural festivals, crafts, fashion, music and artistic production. The preservation and promotion of cultural heritage can generate employment and stimulate economic activities. However, cultural heritage should not be reduced to a commodity. Deborah Root's (1996) discussion of the commodification of cultural difference demonstrates the need to be cautious about the commercialization of cultural forms. Economic use of cultural heritage should therefore be balanced with cultural preservation, community participation and respect for the meanings attached to cultural practices.

Cultural Heritage and Social Cohesion

Cultural activities encourage dialogue and interaction among diverse communities. By promoting cultural understanding and tolerance, cultural heritage can contribute to social harmony and national integration.

Shared cultural experiences can provide opportunities for Nigerians from different backgrounds to encounter one another's traditions. This is consistent with Dewey's understanding of experience as something developed through interaction between individuals and their environments.

Cultural diversity should therefore be understood as a potential resource for national unity rather than simply as a source of division.

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Challenges of Cultural Heritage in Nigeria

Globalization and Cultural Change

One of the major challenges facing cultural heritage in Nigeria is globalization, which has increased the influence of foreign cultures through technology, media, education and commerce. Global interaction can promote cultural exchange and creativity, but excessive dependence on foreign cultural forms may weaken indigenous practices.

Appiah's (1994) discussion of culture and identity is relevant here because cultural identity exists within relationships between different cultural traditions. The challenge is therefore not to isolate Nigerian culture from external influences but to ensure that cultural interaction does not result in the disappearance of meaningful indigenous traditions.

Language Loss

Many Nigerian indigenous languages face declining use. Language is an important means through which communities transmit history, values, knowledge and identity. Ngũgĩ wa Thiong'o (1986) emphasizes the relationship between language and cultural identity. The decline of indigenous languages can consequently affect the transmission of cultural memory and traditional knowledge. The preservation of cultural heritage should therefore include the documentation, teaching and continued use of indigenous languages.

Modernization and Urbanization

Rapid urbanization and modernization have transformed traditional lifestyles and weakened some communal cultural practices. Young people increasingly live in environments where traditional cultural activities may be less visible. Gyekye's (1997) discussion of tradition and modernity demonstrates the importance of examining the relationship between inherited traditions and contemporary development. Modernization does not necessarily require the complete rejection of tradition. Cultural practices can be critically adapted to contemporary circumstances.

Religious Change and Cultural Practices

Changes in religious beliefs and practices can also affect traditional cultural heritage. John Mbiti (1969) emphasizes the close relationship between African religious life and culture. When traditional religious practices decline, some associated cultural practices and symbols may also disappear. This does not mean that traditional beliefs must necessarily be preserved without criticism. Rather, their historical and cultural significance should be documented and understood even when contemporary communities reinterpret or discontinue particular practices.

Loss and Trafficking of Cultural Artifacts

Many cultural artifacts are vulnerable to theft, illegal export, destruction and neglect. The loss of cultural objects can weaken historical consciousness and collective memory. Chinua Achebe's (1975) writings emphasize the importance of historical consciousness and the relationship between a people and their past. Cultural artifacts therefore have significance beyond their material value because they can represent the historical experiences of communities.

Youth Participation

Young Nigerians are important to the continuity of cultural heritage. When younger generations show limited interest in traditional customs and practices, cultural transmission becomes weaker. Wole Soyinka's (2003) literary engagement with African cultural realities demonstrates the continuing importance of cultural memory and identity. Cultural heritage should therefore be presented in forms that allow younger people to engage with it meaningfully.

Digital Media

Digital media have become increasingly influential in shaping cultural experience. Marshall McLuhan's (2001) argument concerning the relationship between media and communication draws attention to the influence of communication technologies on human perception and social life. Digital media can expose

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young Nigerians to foreign cultural content, but they can also provide opportunities to document, promote and creatively reinterpret Nigerian cultural heritage. The challenge is therefore to use digital platforms as instruments for cultural preservation and creative expression rather than allowing them to become channels through which indigenous culture is simply displaced. The challenges facing cultural heritage in Nigeria are therefore multifaceted and include globalization, language loss, modernization, religious change, inadequate preservation, artifact trafficking, declining youth participation and media influence. Addressing these challenges requires cooperation among government, educational institutions, cultural organizations, researchers and local communities.

Discussion

The analysis of Dewey's aesthetic philosophy and Nigerian cultural heritage demonstrates that cultural heritage can contribute to national transformation when it is understood as a living experience rather than merely as a collection of objects from the past. The central contribution of Dewey's aesthetics to this discussion is his emphasis on experience. Cultural practices acquire meaning through the ways individuals and communities experience, interpret and participate in them. Nigerian festivals, music, dance, storytelling, crafts and ceremonies therefore have significance beyond their physical or artistic characteristics. The study also establishes that cultural heritage can contribute to national transformation through identity, education, moral development, social cohesion and creativity. Cultural identity provides individuals with a sense of belonging and historical consciousness. Cultural education can transmit knowledge and values. Shared cultural experiences can encourage social interaction, while cultural creativity can contribute to economic activities. However, cultural heritage does not automatically produce unity or development. It can also be affected by commercialization, cultural appropriation, ethnic exclusion, neglect and changing social conditions. This is why cultural heritage requires critical engagement rather than unquestioning preservation.

Dewey's philosophy provides a basis for this critical approach because experience is dynamic. Cultural traditions can be preserved while also being interpreted and adapted to contemporary circumstances. The objective should therefore not be to freeze Nigerian cultural practices in the past but to keep them meaningful in the present. This perspective also helps to explain why youth participation is important. If cultural heritage is to remain a living experience, younger generations must be able to encounter and reinterpret it. Schools, cultural institutions, festivals, creative industries and digital platforms can provide opportunities for such engagement. The relationship between cultural heritage and national transformation is consequently dynamic. Cultural heritage provides resources inherited from the past, while contemporary communities determine how those resources are experienced and interpreted. Through this process, heritage can become a resource for building a culturally conscious and socially cohesive society.

Conclusion

This study has examined the relationship between cultural heritage and national transformation in Nigeria through John Dewey's aesthetic philosophy. The study demonstrates that cultural heritage is not merely a collection of historical artifacts, customs and traditions inherited from the past, but a living and dynamic resource capable of fostering social development, national identity and sustainable transformation. Dewey's conception of art as experience provides a valuable framework for understanding the significance of cultural heritage in contemporary Nigeria. His aesthetic philosophy demonstrates that aesthetic experience develops through meaningful interaction between individuals, communities and their environment.

Nigerian cultural practices such as traditional festivals, music, dance, oral traditions, crafts and indigenous institutions are therefore not only expressions of beauty but also means of communication, education and social integration. Through these experiences, individuals develop a sense of belonging, historical consciousness and collective responsibility. The study reveals that cultural heritage contributes to national transformation by promoting national unity, moral values, creativity, social cohesion, cultural identity and economic development. As a multicultural society, Nigeria can utilize its cultural diversity as a source of strength for nation-building and peaceful coexistence.

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Applying Dewey's aesthetic philosophy highlights the need to view cultural heritage not as a static inheritance but as a living experience that enriches human life, strengthens communal bonds and inspires creativity and innovation. The study therefore affirms that cultural heritage, when understood through Dewey's aesthetic philosophy, remains a valuable force for shaping a more united, culturally conscious, creative and progressive Nigeria.

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A COMPARATIVE ASSESSMENT OF FEDERATED, IMA, AND DIMA AVIONICS ARCHITECTURES FROM A MODEL-BASED SYSTEMS ENGINEERING PERSPECTIVE

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ABSTRACT

The continuous growth of aircraft functionality has increased the complexity of avionics systems, driving the evolution of avionics architectures from traditional federated systems to Integrated Modular Avionics (IMA) and, more recently, Distributed Integrated Modular Avionics (DIMA). Each architecture offers different approaches to functional allocation, resource utilization, communication, and system integration, making their systematic evaluation an important topic in modern aerospace engineering. This study presents a comparative assessment of federated, IMA, and DIMA avionics architectures from a Model-Based Systems Engineering (MBSE) perspective. A literature-based analysis is conducted by examining the architectural characteristics, advantages, and limitations of each approach. The comparison focuses on key engineering criteria, including resource sharing, scalability, maintainability, fault isolation, communication infrastructure, and architectural complexity. In addition, the study discusses how MBSE supports the analysis of complex avionics architectures by improving model consistency, traceability, and interdisciplinary communication throughout the system development process. The assessment indicates that the transition from Federated architectures to IMA and DIMA reflects a growing need for efficient resource management and system flexibility. Furthermore, MBSE provides a structured engineering perspective for understanding and comparing these architectural alternatives. The findings offer a concise overview of current avionics architectures and highlight the value of MBSE as a supporting approach for architectural assessment in aerospace systems.

Keywords: Federated Avionics, Integrated Modular Avionics (IMA), Distributed Integrated Modular Avionics (DIMA), Model-Based Systems Engineering (MBSE), Avionics Architecture.

1. INTRODUCTION

In the early days of modern aviation, avionics were primarily limited to analog navigation and communication equipment; however, with advancements in microprocessor technology, they have evolved into digital and multifunctional systems. In the traditional federated architecture, which was widely used until the 1990s, the philosophy of “one function = one computer” was adopted, and each function performed its tasks in physically independent LRU (Line-Replaceable Unit) boxes. (Mathew, 2019; Bieber, Boniol, Boyer, Noulard & Pagetti, 2012).

However, as system complexity and requirements for advanced avionics functions in aircraft have steadily increased, the federated architecture has faced significant constraints in terms of SWaP (Size, Weight, and Power) such as total weight on the aircraft, power consumption, and complex analog cable harnesses (Malone, Herrold, Friedland & Fogarty, 2016). In federated systems, while each LRU having its own chassis, power supply, and point-to-point ARINC 429 simplex cable lines protects against fault propagation through hardware isolation, it has led to inefficient use of hardware resources (idle CPU/memory) and increased logistics costs for airlines. To address these limitations, Integrated

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Modular Avionics (IMA) was developed, which combines software at different criticality levels on a single platform using a shared LRM infrastructure and the ARINC 653 robust partitioning mechanism. IMA has delivered significant weight savings and maintenance efficiency on modern civil platforms such as the Boeing 787 and Airbus A380. However, the consolidation of central IMA chassis within the aircraft's avionics compartment has led to an increase in the weight of cable runs extending to these locations, creating a new physical integration requirement (Gaska, Watkins & Chen, 2015). To overcome this physical limitation, the Distributed IMA (DIMA) architecture was developed, which separates the Input/Output (I/O) units from the central system using Remote Data Collectors (RDCs) located at the aircraft's anatomical endpoints and employs a time-deterministic AFDX (ARINC 664 Part 7) network backbone (Annighöfer & Thielecke, 2014). This structural and hardware evolution of avionics architectures over time is schematically illustrated in Figure 1.

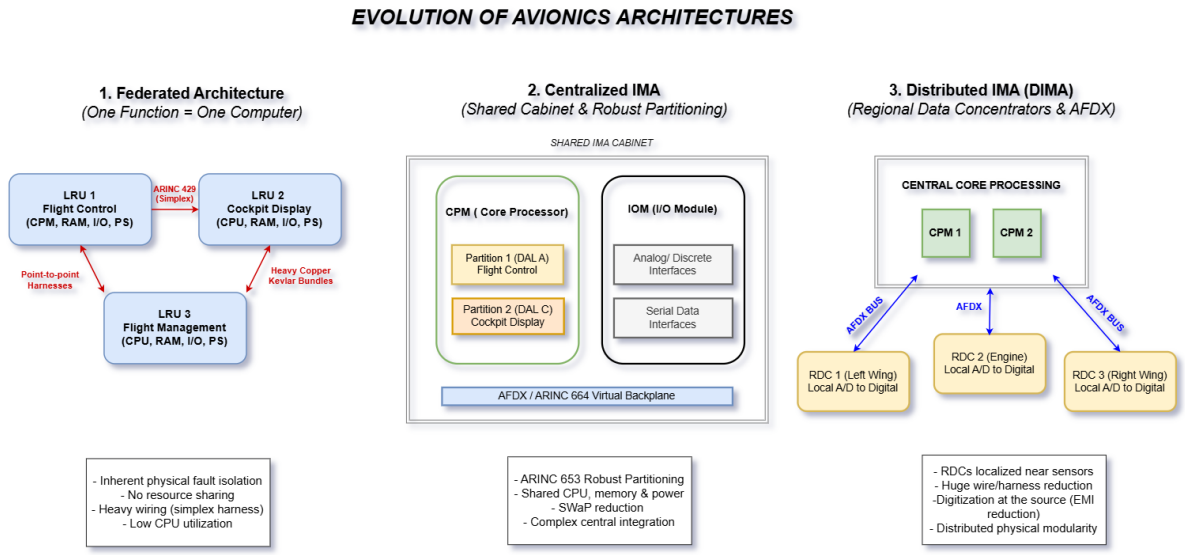


Figure 1. *Historical evolution of avionics architectures: Transition from independent LRUs (Federated) to shared-resource cabinet modules (IMA) and regional data concentrators with a distributed network backbone (DIMA).*

This structural transformation evolving from a federated structure toward IMA and DIMA architectures has significantly increased increased the logical and physical interactions between systems, rendering the manual verification and integration processes of traditional document-based systems engineering (DBSE) approaches inadequate (Watkins, 2006). Model-Based Systems Engineering (MBSE) approaches have become a fundamental engineering approach in the aerospace industry to manage increasing system complexity, ensure requirements traceability, and detect integration-related errors in the early stages of design (Jeyaraj, Tabesh, & Liscouët-Hanke 2021).

The objective of this study is to compare federated, IMA, and DIMA avionics architectures in terms of their fundamental characteristics and to evaluate these architectural alternatives from a Model-Based Systems Engineering (MBSE) perspective across four key engineering dimensions: modelability, traceability, complexity, and functional distribution.

2. FEDERATED AVIONICS ARCHITECTURE

The traditional distributed (federated) avionics architecture is the fundamental avionics design philosophy that was widely used in civil and military aircraft until the early 1990s (Barros, 2019; Bieber, et al. (Alena et al., 2006; Gaska, Watkins & Chen, 2015). The fundamental philosophy of this architecture is based on the principle of "one function = one computer." In federated avionics systems, each operational function of the aircraft is provided by an independent control unit and its own dedicated hardware infrastructure (Mathew, 2019).

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The main component of the federated architecture consists of closed "black boxes" known as Line-Replaceable Units (LRUs). Each LRU is an independently operating system that integrates its own application software, hardware boards, power supply, operating system, and input/output (I/O) interfaces (Barros, 2019; Mani et al., n.d.). Data transmission between these independent units (LRUs) is carried out via point-to-point or shared local data buses (Barros, 2019).

The federated architecture offers several advantages arising from the physical and functional independence of its LRUs. Dedicated processing and memory resources provide inherent fault containment and assured resource access, as individual avionics functions operate on physically isolated hardware without competing for shared computational resources (Mathew, 2019; Mani et al., n.d.; Windsor et al., 2011). Moreover, the loosely coupled structure allows individual LRUs to be developed, tested, and validated relatively independently, while also facilitating maintenance through the replacement of faulty units without extensive intervention in other avionics systems (Barros, 2019; Mathew, 2019; Neretin et al., 2020).

However, the increasing complexity of aircraft and the growing demand for advanced avionics functions have exposed several physical and operational limitations of the federated architecture (Bieber et al., 2012; Barros, 2019). The "one function = one computer" paradigm can lead to inefficient utilization of size, weight, and power (SWaP) resources, as individual functions require dedicated hardware (Mani et al., n.d.). In addition, point-to-point ARINC 429 connections may result in extensive and heavy cabling and increased connector density (Gaska et al., 2015; Garside & Pighetti, 2007; Watkins, 2006). Dedicated hardware resources may also remain underutilized, while the growing number of independent LRUs can increase spare-parts and logistics requirements and create additional challenges when integrating or scaling new avionics functions (Mathew, 2019; Smith, 2019; Barros, 2019).

3. INTEGRATED MODULAR AVIONICS (IMA)

To address the physical and operational shortcomings encountered in traditional federated architectures, the aviation industry has developed a new avionics architecture philosophy called Integrated Modular Avionics (IMA). The fundamental principle of this architecture is based on the collaborative execution of the aircraft's independent system functions on a standardized, high-performance, and shared hardware pool, rather than running them on electrically and physically isolated dedicated computers (LRUs).

3.1. General Structure of the IMA Architecture

The IMA architecture generally consists of three core components: Line Replaceable Modules (LRMs), a time-deterministic avionics network backbone such as AFDX (ARINC 664 Part 7), and a Real-Time Operating System (RTOS) (Li, 2022). Standardized LRMs housed within a common chassis or cabinet replace the dedicated LRU-based hardware structure of federated architectures. These modules can broadly be categorized as Core Processing Modules (CPMs), which provide computational resources, and Input/Output Modules (IOMs), which manage data acquisition and system interfaces (Darwesh, Annighöfer & Reichel, 2018). Communication among avionics functions is supported by a high-speed switched data network, reducing reliance on point-to-point connections and enabling data exchange through configured Virtual Links (VLs) within the AFDX infrastructure (Alena et al., 2006; Gaska, Watkins & Chen, 2015). This transition from dedicated physical connections and hardware resources toward shared computing and network resources also increases the importance of logical integration and software isolation. In this context, ARINC 653 provides the partitioning framework required to maintain temporal and spatial separation among applications operating on shared computing resources.

3.2. ARINC 653 Standard

The IMA architecture's shared-resource approach requires a robust isolation mechanism that prevents software with different criticality levels (Design Assurance Levels-DAL A-E) from interfering with one another (Andersson, 2009). This isolation requirement is addressed through the Time and Space Partitioning (Robust Partitioning) defined within the ARINC 653 (Avionics Application Software Standard Interface) standard. This strict temporal and spatial isolation architecture provided by the

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ARINC 653 standard brings multifaceted operational and certification advantages across the entire aircraft (Bartley & Lingberg, 2008).

3.3. Advantages

The IMA architecture provides several advantages over traditional federated architectures through the consolidation and sharing of computing resources. The integration of multiple avionics functions onto shared computing platforms reduces the need for dedicated hardware and can contribute to improvements in size, weight, and power (SWaP) efficiency (Watkins & Walter, 2007). In addition, the partition-based structure supports incremental qualification under the DO-297 guideline, allowing changes associated with a specific partition to be evaluated with greater focus on the affected elements rather than requiring the same level of reassessment across the entire system (Airlines Electronic Engineering Committee [AEEC], 2006). The use of standardized CPM and IOM modules can also simplify spare-parts inventory and line maintenance logistics by reducing hardware diversity (Mathew, 2019). Despite these SWaP, qualification, and logistical benefits, the consolidation of multiple functions and resources onto a common platform also introduces additional constraints and complexities in system design, integration, and operation.

3.4. Disadvantages and Limitations

The consolidation of multiple functions and resources onto a shared platform also introduces additional challenges in system integration and verification. The management and verification of timing, memory, and network parameters increase integration complexity and require careful coordination across applications and platform resources (Airlines Electronic Engineering Committee [AEEC], 2006). Moreover, dependencies on shared infrastructure, including power, cooling, and communication networks, may create common-resource or common-cause concerns in which a failure can potentially affect multiple functions. Although robust partitioning provides temporal and spatial isolation between applications, system-level dependencies and logical data coupling still need to be considered during integration and safety assessment (Bartley & Lingberg, 2008). Changes to individual partitions or platform configurations may also affect timing and integration assumptions, potentially increasing the scope of retesting and revalidation activities and, consequently, the cost of system modifications (Gaska, Watkins & Chen, 2015).

4. DISTRIBUTED INTEGRATED MODULAR AVIONICS (DIMA)

The Distributed Integrated Modular Avionics (DIMA) architecture was developed to reduce the physical limitations of the Centralized Integrated Modular Avionics (IMA) architecture, such as the weight of its centralized cabling infrastructure and the risk of failure associated with reliance on a single chassis (Smith, 2019). This architecture has ushered in a new era in physical integration by maintaining processing power centrally while distributing data acquisition and signal conversion functions throughout the aircraft (Smith, 2019; Annighöfer & Thielecke, 2014).

4.1. General Structure of the DIMA Architecture

The main component of the DIMA architecture consists of remote units called Regional Data Concentrators (RDCs), which are placed at relevant regional points on the aircraft (Smith, 2019). RDCs collect analog and discrete signals from surrounding sensors and actuators, digitize them at the local level, and transmit them to central LRM processor cards (CPMs) via a common high-speed AFDX (ARINC 664 Part 7) network (Smith, 2019; Annighöfer & Thielecke, 2014). Thus, while the physical data acquisition function is distributed throughout the aircraft, logical processing and management integrity are maintained centrally in accordance with ARINC 653 standards (Smith, 2019; Annighöfer & Thielecke, 2014).

4.2. Advantages

The distributed I/O structure of DIMA provides several advantages in terms of cabling, signal transmission, and physical integration. Locating RDCs closer to sensors and actuators reduces the need for long point-to-point analog wiring by enabling signals to be digitized locally and transmitted through the aircraft data network, thereby reducing cabling complexity and associated weight compared with

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more centralized architectures (Smith, 2019; Annighöfer & Thielecke, 2014). Converting sensitive analog signals into digital data closer to their source can also reduce their exposure to electromagnetic interference (EMI) associated with long analog cable runs (Smith, 2019; Annighöfer & Thielecke, 2014). Furthermore, the regional distribution of data acquisition and interface resources can support a more modular approach to aircraft production and integration, particularly when major structural sections such as the fuselage, wings, and tail are produced separately and subsequently integrated during final assembly (Smith, 2019; Annighöfer & Thielecke, 2014).

4.3. Disadvantages and Limitations

The distributed nature of DIMA also introduces several challenges related to environmental conditions, network timing, and reliability management. RDCs installed outside controlled avionics compartments, such as those located within the wings or near engines, may be exposed to demanding environmental conditions including temperature fluctuations, vibration, and humidity, requiring appropriate protection and environmental qualification in accordance with DO-160G requirements (Smith, 2019). In addition, the increasing number of physical nodes participating in communication can make deterministic timing more difficult to manage, requiring careful consideration of synchronization, jitter, and communication delays between distributed RDCs and central CPMs (Annighöfer & Thielecke, 2014). The distribution of RDCs throughout the aircraft also introduces additional considerations for local power supply, redundancy, fault detection, and fault management, which can increase the complexity of system-level Fault Tree Analysis (FTA) and reliability assessment (Annighöfer & Thielecke, 2014).

5. COMPARATIVE DISCUSSION FROM AN MBSE PERSPECTIVE

The transition from traditional distributed (federated) architectures to centralized IMA and distributed IMA (DIMA) architectures has not only brought about changes in the hardware structure of avionics systems; it has also necessitated new approaches in the design, analysis, certification, and validation processes (Darwesh, Annighöfer & Reichel, 2018; Li, 2022). In this evolutionary process, Model-Based Systems Engineering (MBSE) provides a centralized architectural information infrastructure that serves as a Single Source of Truth (SSoT) for the systematic modeling and evaluation of different avionics architecture options (Lübbe, Schäfer & Bertram, 2022). In line with the MBSE approach, these three distinct avionics architecture approaches differ radically from one another across four fundamental technical dimensions: modelability, traceability, complexity, and functional distribution.

5.1. Modelability

From an MBSE perspective, the modelability of avionics architectures becomes progressively more demanding as the relationships among functions, hardware resources, interfaces, and communication infrastructure increase. In federated architectures, the physical and functional separation provided by dedicated LRUs results in relatively straightforward modeling relationships, as software–hardware boundaries and interfaces are largely associated with individual units and their interactions (Smith, 2019; Mathew, 2019). In IMA architectures, the shared use of hardware resources requires a more multi-layered representation involving both the logical architecture, including the ARINC 653 partition structure, and the physical architecture represented by LRMs (Watkins, 2006; Montrichard & Eladl, 2024). The model must also account for shared-resource configuration aspects such as processor scheduling, memory protection, and AFDX-based communication relationships (Mathew, 2019). DIMA extends these modeling requirements by incorporating distributed I/O and data acquisition resources into the overall architecture. While computation-intensive functions are primarily allocated to central processing modules (CPMs), I/O and data acquisition functions are distributed across RDCs located closer to sensors and actuators (Darwesh, Annighöfer & Reichel, 2018). Consequently, an MBSE representation of DIMA requires the coordinated modeling of functional allocation, processing resources, distributed interfaces, and communication relationships within a common architectural framework (Annighöfer, 2014).

5.2. Traceability

From an MBSE perspective, traceability requirements become more interconnected as avionics architectures move from dedicated hardware toward shared and distributed resources. In federated

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architectures, traceability primarily follows the lifecycle of individual LRUs, linking requirements with design and Verification and Validation (V&V) activities within relatively well-defined system boundaries; consequently, cross-system traceability relationships are comparatively limited (Smith, 2019). In IMA architectures, the use of shared hardware resources introduces broader traceability relationships across functions, partitions, and platform resources. Aircraft-level requirements, such as safety or communication bandwidth requirements, may therefore need to be traced through the relevant applications and partitions to their associated timing and configuration information on the shared platform. In DIMA architectures, this traceability scope extends further to include the relationship between distributed physical interfaces, such as regional RDCs, and the software functions executed on central CPMs. MBSE can support the representation of these relationships by linking regional interface requirements and physical changes in aircraft structures, such as the wings or fuselage, with their potential implications for the associated processing and system configuration (Mathew, 2019).

5.3. Complexity

From an MBSE perspective, architectural complexity increases as avionics systems evolve from dedicated hardware structures toward shared and distributed resources. In federated architectures, complexity remains relatively localized because individual functions are associated with dedicated LRUs, and the introduction of a new function generally involves the integration of an additional hardware unit and its interfaces (Montrichard & Eladl, 2024). In IMA architectures, the sharing of computing and communication resources introduces additional architectural dependencies, as both functional relationships and potential interactions associated with shared platform resources must be considered during system integration (Bartley & Lingberg, 2008). MBSE can support the management of these dependencies by providing structured architectural representations and supporting isolation and integration verification activities (Watkins, 2006). DIMA further extends this complexity because hardware topology, software allocation, communication relationships, and the physical distribution of system components must be considered together (Mathew, 2019; Zhang et al., 2020). The interaction among CPMs, RDCs, ARINC 653 partitions, and the aircraft's physical structure increases the number of interdependent design decisions that must be managed during architecture development. In this context, MBSE can provide a structured representation of these dependencies and support computational and optimization-based approaches when evaluating complex architectural alternatives (Zhang et al., 2020).

5.4. Functional Allocation

From an MBSE perspective, functional allocation evolves from predominantly hardware-based assignments in federated architectures toward increasingly integrated relationships between software functions and shared or distributed resources in IMA and DIMA. In federated architectures, functions are primarily associated with dedicated LRUs whose physical locations and hardware boundaries are defined during system design, resulting in relatively limited flexibility in reallocating functions without corresponding hardware changes (Watkins & Walter, 2007). In IMA architectures, functional allocation becomes less dependent on dedicated hardware because software applications can be assigned to standardized shared computing platforms through configuration mechanisms (Li, 2022). This requires the system model to represent the relationships between functions and computing resources and to support the evaluation of allocation decisions against relevant resource constraints, such as processor and memory capacity. DIMA extends this allocation structure by combining central processing resources with physically distributed I/O and data acquisition resources. Computation-intensive functions are primarily allocated to CPMs, while I/O and data acquisition functions are distributed across RDCs located closer to sensors and actuators (Darwesh, Annighöfer & Reichel, 2018). From an MBSE perspective, this arrangement requires functional allocation, processing resources, distributed interfaces, and their architectural relationships to be represented and evaluated within an integrated system model (Annighöfer, 2014).

Overall, the dimensions of modelability, traceability, architectural complexity, and functional allocation examined in this section illustrate how engineering considerations evolve as avionics architectures progress from traditional federated structures toward shared and distributed IMA and DIMA configurations. The transition from dedicated hardware to shared computing resources and distributed

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physical interfaces provides opportunities for improved resource utilization, architectural integration, and reduced cabling requirements, while simultaneously introducing additional dependencies among functions, computing resources, communication networks, and physical interfaces. As these relationships become more interconnected, MBSE provides a structured approach for representing, tracing, and evaluating architectural dependencies throughout system development. Based on the structural, operational, maintenance, and modeling characteristics discussed throughout the paper, the main differences among Federated, IMA, and DIMA architectures are summarized in Table 1.

Table 1. *Comparative Evaluation of Avionics Architectures*

Criteria	Federated Architecture (Traditional)	Integrated Modular Avionics (IMA)	Distributed IMA (DIMA)
Hardware Structure	Dedicated Line-Replaceable Units (LRUs) with independent CPUs, memory, power supplies, and point-to-point ARINC 429 wiring.	Standardized Line-Replaceable Modules (LRMs) in shared cabinets (CPMs, IOMs) connected via a high-speed AFDX network.	Central processing cabinets (CPMs) paired with decentralized, regionalized Remote Data Concentrators (RDCs) near sensors and actuators.
Resource Sharing	Resources are primarily dedicated to individual LRUs; no sharing between functions.	High sharing of physical CPU, memory, and power resources across multiple software partitions within shared cabinets.	Shared processing resources at CPMs, with distributed I/O and data acquisition resources at RDCs.
Scalability	Expansion generally requires additional physical LRUs, increasing weight, wiring, and volume.	New functions can be integrated within existing cabinet slots and network capacity, subject to modular and bandwidth limits.	Highly modular network-centric scaling; new functions or sensors can be added via local RDCs with minimal impact on central processing units.
Maintainability	Simple component swapping (LRUs); high logistics costs due to a large variety of proprietary hardware.	Standardized LRMs reduce spare parts inventory and simplify logistics, but central integration can complicate fault diagnosis.	Localized maintenance via standard RDC units and central CPMs, reducing wiring harness complexity and maintenance effort.
Fault Isolation	Primarily achieved through physical isolation between LRUs (inherent safety by design).	Logical isolation via ARINC 653 time and space partitioning at the operating system level (MMU/timer).	Combination of logical isolation (ARINC 653 partitioning) and physical/electronic signal isolation at distributed RDC nodes.
MBSE Role	Supports representation of functions, LRUs, interfaces, and requirements with relatively straightforward models.	Essential for managing multi-layer functional, logical, and physical dependencies within shared resources.	Supports integrated representation of functional, logical, network, and physically distributed relationships, enabling analysis of complex architecture alternatives.

Note. *Adapted and synthesized from Watkins & Walter (2007), AEEC (2006), Zhang et al. (2020), Malone et al. (2016), Jeyaraj et al. (2021), and Annighöfer & Thielecke (2014).*

6. CONCLUSION

The evolution of avionics system architectures has undergone significant changes in response to increasing system complexity, safety requirements, and physical constraints (SWaP). Despite the physical fault containment advantage provided by the LRU-based architecture, the traditional federated avionics architecture has faced significant limitations in terms of weight, energy consumption, and resource underutilization due to the need for independent hardware and extensive cabling for each function. Developed to address these limitations, the Integrated Modular Avionics (IMA) architecture enables applications with different criticality levels to operate on a shared hardware platform through standardized Line-Replaceable Modules (LRMs) and the time and space partitioning mechanisms defined by ARINC 653, contributing to improved resource utilization and reductions in weight and volume at the aircraft level. The Distributed IMA (DIMA) architectural approach, which aims to further reduce wiring-related weight by extending IMA's centralized structure throughout the aircraft, distributes data acquisition and computation functions between Remote Data Collectors (RDCs) at the aircraft's anatomical endpoints and central processing units (CPMs), thereby offering both network-based high scalability and enhanced system reliability. The integration and certification processes (SAE ARP4754A and DO-178C) for all these different avionics architecture alternatives fall short because traditional document-based methods struggle to track and manage the resulting high volume of data and the dependencies among ICDs. In this regard, Model-Based Systems Engineering (MBSE) plays a critical role in establishing a central information model that serves as the architecture's "Single Source of Truth" (SSoT).

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A SINGULAR EXPERIENCE, MULTIPLE COMPONENTS: EXPLORING AMBIANCE RESEARCH IN ARCHITECTURE

TEKİL BİR DENEYİM, ÇOKLU BİLEŞENLER: MİMARLIKTA AMBİYANS ARAŞTIRMALARININ İNCELENMESİ

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ABSTRACT

Ambiance is commonly conceptualized as a relational, multisensory, and holistic phenomenon that emerges from the interaction between the physical characteristics of space and individuals' sensory, bodily, and emotional experiences. However, the conceptualization of ambiance as a holistic spatial experience, on the one hand, and its investigation through specific sensory and environmental dimensions—such as visual, auditory, olfactory, or thermal dimensions—on the other, raises a theoretical and methodological debate. This study aims to examine whether ambiance is approached in the architectural literature as a holistic spatial experience or through specific sensory and environmental dimensions, and how these approaches are reflected in the ways ambiance is investigated empirically and methodologically.

An exploratory literature review was conducted. A literature pool was compiled through keyword-based searches across selected databases and manually assessed according to predefined scope and exclusion criteria. The selected studies were coded according to thematic category, research focus, research method, theoretical/empirical orientation, and approach to ambiance, and were subsequently classified as adopting either singular or multiple approaches.

The findings indicate that ambiance is predominantly approached in the reviewed literature as a singular and holistic spatial experience, although specific sensory and environmental dimensions may also become distinct objects of investigation. While theoretical studies are largely associated with a singular approach, the multiple approach is predominantly observed in empirical studies. This suggests that a distinction should be made between how ambiance is conceptualized and the analytical methods employed to investigate it.

The study argues that singular and multiple approaches may represent different levels of analysis of the same phenomenon rather than mutually exclusive conceptualizations of ambiance. Accordingly, while ambiance can be conceptualized as a singular and holistic phenomenon at the level of experience, it can be analytically investigated through different sensory, environmental, and experiential components at the level of research. From this perspective, the proposed "singular experience–multiple components" approach provides an exploratory conceptual framework for understanding the relationship between the experiential wholeness of ambiance and its analytical differentiation in research.

Keywords: Ambiance, Spatial Experience, Architecture, Multisensory Experience, Exploratory Literature Review.

ÖZET

Ambiyans, genellikle mekanın fiziksel özellikleriyle bireylerin duyusal, bedensel ve duygusal deneyimleri arasındaki etkileşimden ortaya çıkan, ilişkisel, çok duyusal ve bütünsel bir olgu olarak

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kavramsallaştırılır. Bununla birlikte, ambiyansın bir yandan bütüncül bir mekânsal deneyim olarak kavramsallaştırılması, diğer yandan görsel, işitsel, olfaktör veya termal gibi belirli duyusal ve çevresel boyutlar üzerinden incelenmesi kuramsal ve metodolojik bir tartışmayı gündeme getirmektedir. Bu çalışma, mimarlık literatüründe ambiyansın bütüncül bir mekânsal deneyim olarak mı yoksa belirli duyusal ve çevresel boyutlar üzerinden mi ele alındığını ve bu yaklaşımların ambiyansın ampirik ve metodolojik olarak araştırılma biçimlerine nasıl yansıdığını incelemeyi amaçlamaktadır.

Araştırmada keşfedici literatür incelemesi yöntemi benimsenmiştir. Belirlenen veri tabanları üzerinden anahtar kelimelerle gerçekleştirilen taramalarla oluşturulan literatür havuzu, belirlenen kapsam ve dışlama ölçütleri doğrultusunda manuel olarak değerlendirilmiş, araştırmalar tematik kategori, araştırma odağı, kullanılan yöntem, teorik/ampirik niteliği ve ambiyansı ele alış biçimi açısından kodlanarak tekil ve çoklu yaklaşımlar kapsamında sınıflandırılmıştır.

Bulgular, incelenen literatürde ambiyansın ağırlıklı olarak tekil ve bütüncül bir mekânsal deneyim olarak ele alındığını, ancak belirli duyusal ve çevresel boyutların da ayrı araştırma nesneleri hâline gelebildiğini göstermektedir. Teorik çalışmalar büyük ölçüde tekil yaklaşımla ilişkilendirilirken, çoklu yaklaşım ağırlıklı olarak ampirik araştırmalarda görülmektedir. Bu durum, ambiyansın kavramsallaştırılma biçimi ile onu araştırmak için kullanılan analitik yöntemler arasında ayrım yapılması gerektiğine işaret etmektedir.

Çalışma, tekil ve çoklu yaklaşımların birbirini dışlayan ambiyans tanımları olmaktan ziyade, aynı olgunun farklı analiz düzeylerini temsil edebileceğini ileri sürmektedir. Buna göre ambiyans, deneyim düzeyinde tekil ve bütüncül bir olgu olarak kavramsallaştırılırken, araştırma düzeyinde farklı duyusal, çevresel ve deneyimsel bileşenler üzerinden analitik olarak incelenebilir. Bu doğrultuda önerilen "tekil deneyim–çoklu bileşenler" yaklaşımı, ambiyansın deneyimsel bütünlüğü ile araştırma düzeyindeki analitik ayrıştırılması arasındaki ilişkiyi açıklamaya yönelik keşfedici bir kavramsal çerçeve sunmaktadır.

Anahtar Kelimeler: Ambiyans, Mekânsal Deneyim, Mimarlık, Çok Duyulu Deneyim, keşfedici Literatür İncelemesi.

INTRODUCTION

The character of spaces, places, landscapes, and urban environments is often experienced as a holistic impression before the individual features that constitute them are consciously perceived. This experience relies not only on visual perception but also on the simultaneous interaction of acoustic, olfactory, tactile, and other bodily sensations. Spatial experience therefore emerges not through the independent operation of different senses, but through the multisensory and embodied relationship that individuals establish with their environment (Pallasmaa, 2016).

To describe this holistic spatial experience, the literature employs concepts such as ambiance, atmosphere, spirit of place, and genius loci, which are related yet rooted in different theoretical traditions. Although these concepts are not entirely synonymous, they converge in their emphasis on the sensory, bodily, and emotional relationship between individuals and their environment, rather than reducing spatial experience to physical characteristics or visual perception alone. In particular, ambiance and atmosphere are used to describe the overall effect of an environment on individuals and the ways in which this effect may vary according to subjective, temporal, and contextual conditions (Arbib, 2020a; 2020b). In this study, ambiance is adopted as the primary concept to refer to this experiential phenomenon.

Despite the multisensory nature of spatial experience, vision has historically occupied a privileged position in architectural and design culture (Mau, 2018). The dominance of visual perception has also been discussed from a neuroscientific perspective, with a substantial proportion of the brain suggested to be involved in processing visual information (Gallace et al., 2012). According to Felleman and Van Essen (1991), more than half of the cortex is associated with visual information processing, whereas the cortical representations of other sensory systems have been described as more limited (Zimmerman, 1989). Nevertheless, explaining spatial experience solely through visual information is insufficient to

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account for the multisensory nature of the relationship between individuals and their environment. Although visual, auditory, olfactory, tactile, and thermal stimuli may contribute to varying degrees, they collectively shape the perception and experience of space.

This raises a fundamental theoretical and methodological tension in ambiance research. On the one hand, ambiance is conceptualized as a holistic experience emerging from the simultaneous interaction of different sensory, bodily, and emotional processes. On the other hand, research may investigate this wholeness by differentiating it into sensory and environmental components such as visual, auditory, acoustic, olfactory, or thermal dimensions. The relationship between the wholeness of ambiance and its analytical differentiation therefore constitutes a conceptual problem.

This duality gives rise to the central research problem of this study: Is ambiance conceptualized as a singular and holistic spatial experience, or as multiple ambiances? More specifically, the study questions whether different dimensions of ambiance correspond to independent ambiances or instead represent the analytical differentiation of a single holistic experience into researchable components. To address this issue, the study employs an exploratory literature review to examine the existing literature on ambiance, evaluating the reviewed studies in terms of their thematic categories, research focuses, methods, and ways of conceptualizing ambiance. In doing so, the study investigates whether singular and multiple approaches constitute mutually exclusive explanations or represent different levels of analysis of ambiance.

THEORETICAL BACKGROUND

Ambiance cannot be understood independently of either the objective characteristics of the physical environment or the subjective state of the individual; rather, it emerges through the encounter and interaction between people and their environment. As one of the key references for this relational approach, Böhme (1993) defines atmosphere as a phenomenon that occupies the space between subject and object and cannot be entirely reduced to either. Similarly, Thibaud (2011) argues that ambiances have both subjective and objective qualities, encompassing not only the characteristics of the physical environment but also the ways in which that environment is lived and experienced. From this perspective, ambiance can be understood not as an individual feeling independent of the physical environment or as an environmental property independent of the individual, but rather as an experiential phenomenon emerging from the relationship between the subject and the environment. This perspective can also be related to Lynch's (1960) understanding of the image of place as a mental construct derived from direct and indirect human–environment relationships.

The relational nature of ambiance is also inherently multisensory. Spatial experience is shaped not only by visible physical forms but through the interaction of different sensory dimensions, including sound, touch, temperature, air, kinesthesia, and smell (Siret, 2015). The concept of ambiance likewise suggests that environmental perception encompasses both visible and invisible components and requires consideration of the interaction among different senses (Walczak, 2019). Spatial experience is therefore shaped less by the independent processing of different sensory modalities than by the simultaneous and embodied interaction between individuals and their environment.

However, the multisensory nature of ambiance does not imply that experience consists simply of the sum of independent sensory components. In Pallasmaa's approach, the atmosphere of a space often emerges as an overall and holistic impression that is felt before individual environmental characteristics are consciously evaluated (Amundsen, 2018; Pallasmaa, 2016). Accordingly, the atmosphere of a space is not necessarily perceived by first analyzing visual, auditory, olfactory, or thermal characteristics separately and then combining them; rather, it may initially be apprehended as a holistic experience. During experience, different forms of sensory information are not organized entirely independently but as integrated wholes, giving spatial experience an embodied, perceptual, and phenomenological quality that extends beyond physical characteristics (Lescop & Walczak, 2019).

Böhme's (1993, 2017) approach to atmosphere similarly explains this holistic quality through the subject–environment relationship. Although atmospheres may be characterized as calm, melancholic, oppressive, inviting, or uplifting, these qualities do not belong solely to the physical characteristics of a space. Rather, atmosphere emerges through the encounter between particular environmental qualities

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and the bodily and emotional state of the experiencing individual. Understanding an ambiance therefore involves not only identifying the physical or sensory components that contribute to it, but also considering the holistic experience that emerges through the encounter between these components and the individual. The fact that the same environment may generate different experiences for different individuals further suggests that ambiance cannot be regarded as a fixed and entirely objectifiable environmental property (Walczak, 2019).

The relational, multisensory, and holistic character of ambiance also presents a significant methodological challenge. According to Thibaud (2015), ambiance cannot be easily delineated or fully objectified as an object of research because it blurs the clear distinction between subject and object. Rather than focusing solely on the question of "what is ambiance?", Thibaud therefore proposes investigating the conditions that enable an ambiance to emerge, be perceived, and be shared. Such an approach positions ambiance not as a fixed object, but as a dynamic phenomenon emerging through the interaction between people and their environment.

METHODOLOGY

This study employed an exploratory literature review to examine how ambiance is approached in architectural research and how these approaches are reflected in research methods. Rather than providing a comprehensive and exhaustive mapping of the ambiance literature, the study aims to explore prominent conceptual and methodological patterns and to examine the relationship between the holistic nature of ambiance and its investigation through different components. Accordingly, the study was structured around two main research questions:

1. How is ambiance approached in the reviewed architectural literature: as a holistic spatial experience or through specific sensory and environmental dimensions?

2. How are these approaches reflected in the methodological strategies used to investigate ambiance?

In line with these questions, the literature pool was developed through iterative, keyword-based searches conducted throughout the research process. The keywords "ambiance," "ambiance in architecture," "visual ambiance," "auditory/acoustic ambiance," and "atmosphere" were used to search Google Scholar, Scopus, and EBSCO, resulting in an initial literature pool of 103 potentially relevant studies. The studies were manually screened for relevance to the scope of the research based on their titles, abstracts, and, where necessary, full texts.

To maintain the conceptual and disciplinary boundaries of the review, three main exclusion criteria were applied: (1) studies on ambiance unrelated to architecture and spatial experience; (2) studies that did not directly address the concepts of ambiance or atmosphere but focused only on related concepts; and (3) studies concerned solely with the production of ambiance through specific physical elements rather than its perception or experience. Following this assessment, 49 studies were included in the review.

The selected studies were coded according to thematic category, main research focus, method, theoretical/empirical orientation, and approach to ambiance. Based on the research focuses identified in the literature, the studies were classified into five thematic categories: overall ambiance, visual ambiance, auditory ambiance, perception and multisensory experience, and spatial experience. These categories were used to comparatively examine the distribution of ambiance research across different sensory, environmental, and experiential focuses.

One of the main analytical distinctions of the study was the classification of how ambiance was approached as either singular or multiple. The singular approach refers to studies that conceptualize ambiance as a holistic spatial experience emerging from the interaction of different sensory, environmental, bodily, and experiential elements. The multiple approach includes studies that address specific sensory or environmental dimensions as differentiated forms or components of ambiance.

In the final stage, the coded studies were comparatively assessed to identify patterns between the ways ambiance was approached—either holistically or through specific sensory and environmental dimensions—and the theoretical/empirical orientations and research methods adopted in the studies.

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The analysis thus focused on exploring the relationship between the holistic nature of ambiance and its analytical differentiation.

FINDINGS

Of the 49 studies examined as part of the *exploratory literature review*, 28 (57%) were theoretical and 21 (43%) were empirical. Based on their primary research focus, the studies were classified into five categories: overall ambiance, visual ambiance, auditory ambiance, perception and multisensory experience, and spatial experience (Table 1). Of these, 12 studies focused on overall ambiance, 7 on visual ambiance, 8 on auditory ambiance, 11 on perception and multisensory experience, and 11 on spatial experience.

Table 1: Classification of the reviewed studies according to thematic category, research focus, methodology, study type, and singular/multiple approaches.

Thematic category	Main research focus	Method	Theoretical/ Empirical	Approach (Singular/Multiple)	References	n
Overall Ambiance	The conceptual, spatial, and relational qualities of ambiance.	Systematic literature review, discussion, interview.	Theoretical	Singular	Thibaud, J. P. (2015), Stec, B. (2020), Pallasmaa, J. (2016), Arbib, M. A. (2020a), Thibaud, J.P. (2014), Morello, E. and Piga, B.E.A. (2015), Amundsen, M. (2018), Yaseen, A. (2017), Augoyard, J.F. (2020)	9
		Interview, Survey, Photography, Video recording-observation, 3D experience,	Empirical	Singular	Piga, B.E.A. et al. (2013), Benzagouta, Y.N. and Debache, S. (2021) Şenay, Ü.G. et al. (2026)	3
Visual Ambiance	Visual characteristics and visual perception of the space	Systematic literature review, discussion.	Theoretical	Singular	Rooney, K. K. et al. (2017), Lescop, L. et al. (2019) De Matteis, F. et al. (2019) Lalou, G. and Deffner, A. (2016)	4
				Multiple	Arbib, M. A. (2020b)	1
		Survey, 3D Experience	Empirical	Singular	Hermund, A. and Klint, L. S. (2016)	1
				Multiple	Jaglarz, A. (2023)	1
		Review	Theoretical	Singular	Flügge, E. (2016)	1

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Auditory Ambiance	The role of soundscape and acoustic properties in the experience of a space.	Q Sensor, EDA, Noise measurements, survey, Sound mapping, Sound measurement, Sound recordings	Empirical	Multiple	Layeb, S. et al. (2014) Brambilla, G. and Maffei, L. (2009) Atıf, N. et al. (2021) Calleri, C. (2016) Saraoui, S. et al. (2019) Chtara, C. (2014) Morselli, E. (2019a)	7
Perception and Multisensory	An experience created by the combination of multisensory modalities.	Systematic literature review, discussion,	Theoretical	Singular	Ibrahimi, N. et al. (2019) Jelic, A. et al. (2016) Ibrahim, M. M. (2018) Radman, A. (2020) Spence, C. (2020) Walczak, A. K. (2019) Jelić, A. (2015) Papalei, P. (2016) Arbib, M.A. (2012)	9
		Walking experience, survey, experience report including drawings,	Empirical	Singular	Hassan, D. K. and Elkhateeb, A. (2021) Morselli, E. (2019b)	2
Spatial Experience	An individual's spatial, bodily, perceptual, and emotional experience.	Systematic literature review, review, Thematic content analysis	Theoretical	Singular	Pektaş, Ş.T. (2021) Rad, P.N. et al. (2021) Winz, M. (2018) Rudnicka-Bogusz, M.M. (2019)	4
		EEG, video recording, survey, fMRI, GSR, eye-tracking device, VR	Empirical	Singular	Khaleghimoghaddama, N. et al. (2022) Karandinou, A. and Turner, L. (2017) Vecchiato, G. et al. (2015) Nielek, R. et al. (2017) Rezzoug, I. and Boussora, K. (2021)	5
				Multiple	Shemesh, A. et al. (2021) Hermund, A. et al. (2018)	2

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The distribution of theoretical and empirical studies varied across the categories. Of the 12 studies in the overall ambiance category, 9 were theoretical and 3 were empirical; of the 7 studies on visual ambiance, 5 were theoretical and 2 were empirical; of the 8 studies on auditory ambiance, 1 was theoretical and 7 were empirical; of the 11 studies on perception and multisensory experience, 9 were theoretical and 2 were empirical; and of the 11 studies on spatial experience, 4 were theoretical and 7 were empirical. Theoretical studies employed methods such as literature reviews, review studies, conceptual discussions, and content analysis, whereas empirical studies used methods including surveys, interviews, observations, photography and video recording, walking and 3D/VR experiences, sound recording and measurement, and sound mapping. Some studies also employed psychophysiological and neurophysiological measurement techniques, including EEG, eye tracking, EDA, Q Sensor, GSR, and fMRI.

Regarding how ambiance was approached, 38 of the 49 studies (78%) were classified as adopting a singular approach, while 11 (22%) were classified as adopting a multiple approach. All 12 studies in the overall ambiance category and all 11 studies in the perception and multisensory experience category were classified as singular. Of the studies on visual ambiance, 5 were classified as singular and 2 as multiple; of those on auditory ambiance, 1 was singular and 7 were multiple; and of those on spatial experience, 9 were singular and 2 were multiple. In addition, among the studies classified as singular, 27 were theoretical and 11 were empirical, whereas among those classified as multiple, 10 were empirical and 1 was theoretical.

DISCUSSION AND CONCLUSION

This study examined whether ambiance is approached in the architectural literature as a holistic spatial experience or through specific sensory and environmental dimensions, and how these approaches are reflected in the ways ambiance is investigated. The findings reveal an important distinction between the conceptualization of ambiance and the ways in which it is investigated.

First, the reviewed literature predominantly approaches ambiance as a singular and holistic spatial experience. This perspective is consistent with theoretical approaches that conceptualize ambiance not in terms of individual characteristics of the physical environment or the subjective state of the individual, but as a multisensory, embodied, and emotional experience emerging through the relationship between people and their environment (Böhme, 1993; Thibaud, 2011, 2015; Pallasmaa, 2016). At the same time, particularly in studies focusing on specific sensory modalities, differentiated dimensions such as visual or auditory ambiance also become distinct objects of investigation.

The findings further indicate that this conceptual differentiation has methodological counterparts. The strong association of theoretical studies with the singular approach, and of the multiple approach predominantly with empirical studies, suggests that specific sensory and environmental dimensions of ambiance can be analytically differentiated in empirical research. However, the use of empirical methods does not directly correspond to a multiple understanding of ambiance. Some empirical studies continue to approach ambiance as a holistic experience despite employing multiple variables and measurement techniques. Therefore, a distinction needs to be made between how ambiance is conceptualized and the analytical methods used to investigate it.

This distinction constitutes the main theoretical implication of the study. Investigating ambiance through specific sensory and environmental dimensions, particularly visual and auditory dimensions does not necessarily imply the existence of multiple independent ambiances. Instead, the multiplicity observed in the literature may be related to the analytical differentiation of a holistically experienced phenomenon into distinct components in order to make it observable and analyzable within scientific research. In other words, the singularity of ambiance may correspond to the nature of experience, whereas its multiplicity may correspond to the way that experience is investigated and analyzed. From this perspective, singular and multiple approaches can be understood not as mutually exclusive conceptualizations of ambiance, but as complementary perspectives addressing different levels of analysis of the same phenomenon.

This study constitutes a preliminary exploration of the theoretical and methodological position of ambiance within the architectural literature. The findings suggest that ambiance remains difficult to

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investigate systematically due to both its ambiguous conceptual boundaries and its multidimensional structure, which encompasses sensory, environmental, bodily, and experiential layers, yet it also offers substantial potential for further research. The predominance of theoretical studies in the reviewed literature, together with the varying ways in which ambiance is approached through singular and multiple perspectives, suggests that the concept remains open to further theoretical and methodological discussion. Accordingly, the "singular experience–multiple components" approach proposed here should be regarded not as a definitive classification, but as an initial framework for interpreting this dual structure observed in the literature. Future research may expand the literature review through additional databases, keywords, scope criteria, and analytical methods, while also examining how ambiance is conceptualized across different disciplines and research traditions. Such work may provide a more comprehensive understanding of the relationship between the holistic experiential nature of ambiance and its analytical differentiation into components in research, and further clarify its theoretical and methodological position within architectural research.

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AÇIK OCAK ALTIN MADENCİLİĞİNDE MALİYET TABANLI ÜRETİM OPTİMİZASYONU VE DİJİTAL KARAR DESTEK ARAYÜZÜ

COST-BASED PRODUCTION OPTIMIZATION AND DIGITAL DECISION SUPPORT INTERFACE IN OPEN-PIT GOLD MINING

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ÖZET

Açık ocak madenciliğinde ekonomik sürdürülebilirlik, jeolojik modelleme sonuçlarının üretim maliyetleri, metal fiyatı, sınır tenörü ve zaman değeri ile birlikte değerlendirilmesini gerektirmektedir. Bu çalışmada, hipotetik bir açık ocak altın sahası için sondaj verilerinden başlayarak üç boyutlu cevher modelleme, tenör tahmini, blok model oluşturma, ekonomik sınır tenör analizi, üretim senaryolarının değerlendirilmesi ve dijital karar desteğine uzanan bütünleşik bir yaklaşım geliştirilmiştir. Jeolojik ve geometrik işlemler bir madencilik paket programı kullanılarak yürütülmüş; ekonomik hesaplamalar Excel ortamında, duyarlılık ve görselleştirme işlemleri ise Python tabanlı SIBPlan arayüzünde gerçekleştirilmiştir. Çalışmada sahaya ait sondajlardan konum, litoloji ve altın tenörü verileri kullanılmış; kompozitleme, istatistiksel inceleme, variogram değerlendirmesi ve ters mesafe temelli tenör tahmini sonrasında blok model üretilmiştir. Modelden elde edilen tenör-tonaj dağılımı ekonomik analizlere aktarılmış ve başa baş sınır tenörü yaklaşık 0,26 g/t olarak belirlenmiştir. Düşük sınır tenörlerinde üretilebilir tonajın arttığı ancak ortalama tenörün azaldığı; yüksek sınır tenörlerinde ise cevher kalitesinin yükselmesine karşılık ekonomik rezervin daraldığı görülmüştür. Derinlik arttıkça rezerv miktarı artmasına rağmen kazı maliyetleri ve örtükazı oranındaki yükseliş nedeniyle NBD'nin belirli bir noktadan sonra azaldığı belirlenmiştir. Duyarlılık analizleri, metal satış fiyatındaki artışların ekonomik işletme derinliğini artırdığını, kazı ve işletme maliyetlerindeki artışların ise optimum derinliği azalttığını göstermiştir. Geliştirilen SIBPlan arayüzü veri yükleme, senaryo karşılaştırma, duyarlılık matrisi, grafiksel değerlendirme ve otomatik raporlama işlevlerini tek ortamda birleştirerek maliyet odaklı maden planlama kararlarını destekleyen uygulanabilir bir prototip ortaya koymuştur.

Anahtar Kelimeler: Açık Ocak Madenciliği, Altın, Üretim Optimizasyonu, Sınır Tenörü, Net Bugünkü Değer, Dijital Karar Destek.

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ABSTRACT

Economic sustainability in open-pit mining requires the integrated evaluation of geological modeling results with production costs, metal prices, cut-off grade, and the time value of money. In this study, an integrated approach was developed for a hypothetical open-pit gold deposit, encompassing three-dimensional orebody modeling, grade estimation, block model construction, economic cut-off grade analysis, evaluation of production scenarios, and digital decision support, starting from drillhole data. Geological and geometric analyses were performed using mining software, while economic calculations were conducted in MS Excel, and sensitivity analyses and visualizations were carried out using the Python-based SIBPlan interface. Drillhole data, including spatial coordinates, lithology, and gold grades, were used in the study. Following compositing, statistical analysis, variogram assessment, and inverse-distance-based grade estimation, a block model was generated. The grade-tonnage distribution obtained from the model was incorporated into the economic analyses, and the break-even cut-off grade was determined to be approximately 0.26 g/t. At lower cut-off grades, mineable tonnage increased while the average grade decreased; at higher cut-off grades, ore quality improved at the expense of a reduction in economically mineable reserves. Although the amount of reserves increased with depth, the net present value (NPV) was found to decline beyond a certain point due to increasing excavation costs and stripping ratios. Sensitivity analyses demonstrated that increases in the metal selling price extended the economic mining depth, whereas increases in excavation and operating costs reduced the optimum mining depth. The developed SIBPlan interface integrates data import, scenario comparison, sensitivity matrices, graphical evaluation, and automated reporting within a single environment, providing a practical prototype to support cost-based mine planning decisions.

Keywords: Open-Pit Mining, Gold, Production Optimization, Cut-Off Grade, Net Present Value, Digital Decision Support.

1. GİRİŞ

Açık ocak maden işletmelerinde üretim planlaması, yalnızca cevher miktarının ve ocak geometrisinin belirlenmesinden ibaret değildir. Metal fiyatlarındaki dalgalanmalar, enerji ve yakıt giderleri, ekipman işletme maliyetleri, artan taşıma mesafeleri ve cevher tenöründeki değişimler, teknik üretim planının ekonomik performansını doğrudan etkilemektedir. Bu nedenle güncel planlama yaklaşımında jeolojik model, üretim kapasitesi, maliyetler, metalürjik kazanım, satış fiyatı, sınır tenörü ve iskonto oranı birlikte ele alınmalıdır (Özel, 2006; Bascetin ve Nieto, 2007; Tüylü, 2009).

Blok modelleme, cevher yatağının üç boyutlu uzayda küçük hacimsel birimlerle temsil edilmesini ve her bloğa konum, hacim, yoğunluk, tonaj ve tenör gibi özniteliklerin atanmasını sağlar. Bu yapı, rezerv tahmininin yanında ekonomik blok değerlerinin hesaplanması, nihai ocak sınırlarının değerlendirilmesi ve üretim sıralamasının oluşturulması için de temel veri kaynağıdır (Kedir, 2022; Karakurt ve Onur, 2019). Açık ocak optimizasyonunda Lerchs-Grossmann yaklaşımı, pozitif ve negatif ekonomik değere sahip blokları geometrik şev bağımlılıklarıyla birlikte değerlendirerek ekonomik değeri yüksek ocak sınırlarının oluşturulmasına imkân verir. İç içe ocak yaklaşımı ise farklı ekonomik koşullar altında alternatif ocak kabuklarının karşılaştırılmasını sağlar (You, 2025).

Ekonomik planlamanın bir diğer temel bileşeni sınır tenörüdür. Sınır tenörü, kazılan malzemenin cevher veya pasa olarak sınıflandırılmasında kullanılan ekonomik eşik olmakla birlikte sabit bir jeolojik değer değildir. Metal fiyatı, madencilik ve proses maliyetleri, satış giderleri, geri kazanım ve kapasite kısıtları değiştikçe ekonomik sınır tenörü de değişir (Dagdelen, 1992; Narrei ve Osanloo, 2015). Lane yaklaşımı, maden ve tesis kapasitesi ile ekonomik koşulları birlikte değerlendirerek maden ömrü boyunca ekonomik değeri maksimize etmeyi amaçlayan dinamik bir sınır tenör politikası sunmaktadır (Lane, 1964; 1988; Githiria ve Ark., 2016; Mirzehi ve Ark., 2024).

Son yıllarda dijital maden planlama sistemleri, jeolojik modelleme ile ekonomik analiz arasındaki kopukluğu azaltmaya yönelik önemli bir araç hâline gelmiştir. Bununla birlikte literatürde çalışmalar çoğunlukla blok modelleme, nihai ocak optimizasyonu veya ekonomik analiz aşamalarından birine yoğunlaşmaktadır (You, 2025). Bu çalışmanın amacı; sondaj verilerinden başlayan jeolojik modelleme

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sürecini, sınır tenörü ve NBD tabanlı ekonomik değerlendirme ile birleştirmek ve sonuçları kullanıcı dostu bir dijital karar destek arayüzü üzerinden sunmaktır. Böylece farklı üretim, maliyet ve fiyat senaryolarının hızlı biçimde karşılaştırılabildiği bütünleşik bir planlama çerçevesi oluşturulmuştur.

2. MALZEME VE YÖNTEM

2.1. Çalışma Sahası ve Veri Seti

Çalışmada gerçek saha koşullarını temsil edecek şekilde idealize edilmiş hipotetik bir açık ocak altın sahası kullanılmıştır. Pilot saha, orta ölçekli bir açık ocak işletmesini temsil edecek biçimde tanımlanmış; üretim kapasitesi, makine-ekipman parkı, işletme maliyetleri ve yatırım varsayımları ekonomik analiz yapılmasına olanak sağlayacak şekilde kurgulanmıştır. Temel jeolojik veri seti 15 sondaja ait kuyu ağzı koordinatları, kuyu yönelim bilgileri, litoloji kayıtları, örnek aralıkları ve altın tenörü verilerinden oluşmaktadır. Veri seti akademik analiz amacıyla hazırlanmış pilot/hipotetik niteliktedir.

2.2. Jeolojik Modelleme ve Blok Model

Sondaj verileri kalite ve biçim açısından kontrol edildikten sonra bir madencilik paket programına aktarılmıştır. Kuyuların üç boyutlu konumları oluşturulmuş, litolojik ve mineralize aralıklar incelenmiş, kesitler üzerinden cevher zonları sayısallaştırılmış ve üç boyutlu kapalı cevher katı modeli üretilmiştir. Katı model doğrulandıktan sonra sondaj-katı model kesişimleri belirlenmiş ve cevher zonu içerisindeki örnekler kompozitlenmiştir. Tenör verileri histogram ve temel istatistikler ile incelenmiş, aşırı değerlerin etkisini sınırlamak amacıyla üst kesme yaklaşımı uygulanmıştır.

Mekânsal sürekliliğin değerlendirilmesinde deneysel variogramlar ve anizotropi yönleri incelenmiştir. Cevher geometrisine uygun model sınırları ve blok boyutları tanımlanarak üç boyutlu blok model oluşturulmuş; her bloğa hacim, yoğunluk ve altın tenörü öznitelikleri atanmıştır. Tenör tahmininde ters mesafe yaklaşımından yararlanılmıştır. Blok tonajı, blok hacmi ile yoğunluğun çarpımı olarak hesaplanmış ve model, farklı tenör eşiklerinde tonaj-tenör ilişkilerinin üretilmesinde kullanılmıştır.

$$Blok\ tonajı = Blok\ hacmi \times Yoğunluk \qquad (1)$$

2.3. Ekonomik Sınır Tenörü ve Açık Ocak Değerlendirmesi

Blok modelden elde edilen tenör-tonaj dağılımı ekonomik analiz ortamına aktarılmıştır. Her sınır tenörü için eşik değerin üzerindeki bloklar cevher, altındaki bloklar pasa olarak sınıflandırılmış; cevher tonajı, ortalama tenör, kazanılabilir metal, gelir, üretim ve işleme maliyetleri ile kâr yeniden hesaplanmıştır. Sınır tenörü değerlendirmesinde Lane yaklaşımının ekonomik mantığı esas alınmış; üretim ve tesis kapasitesi, metal fiyatı, geri kazanım, madencilik maliyeti, proses maliyeti ve satış giderleri birlikte değerlendirilmiştir.

Nihai açık ocak değerlendirmesinde bloklara ekonomik değer atanmış ve pozitif ekonomik değerli cevher blokları ile bu bloklara ulaşmak için kaldırılması gereken pasa blokları birlikte dikkate alınmıştır. Lerchs-Grossmann temelli yaklaşım ve iç içe ocak mantığı, farklı ekonomik koşulların ocak sınırı ve üretilebilir rezerv üzerindeki etkisini değerlendirmek amacıyla metodolojik çerçeve olarak kullanılmıştır.

2.4. NBD, Üretim Senaryoları ve Duyarlılık Analizi

Her üretim/derinlik senaryosu için yıllık cevher ve pasa miktarları, gelirler, üretim maliyetleri ve net nakit akışları hesaplanmıştır. Gelecekteki nakit akışları %8 iskonto oranı kullanılarak bugünkü değere indirgenmiştir. Net bugünkü değer (NBD) aşağıdaki eşitlik ile hesaplanmıştır:

$$NBD = \Sigma\,[NA_t / (1 + i)^t] \quad (t = 0,\ldots,n) \qquad (2)$$

Burada NA_t, t dönemindeki net nakit akışını; i iskonto oranını ve n değerlendirme süresini göstermektedir (Dağdelen, 1993; Asad, 2007). En yüksek NBD'yi veren üretim/derinlik seçeneği ekonomik açıdan tercih edilen seçenek olarak kabul edilmiştir. Duyarlılık analizlerinde bir parametre değiştirilirken diğerleri sabit tutulmuş; sınır tenörü, metal satış fiyatı, madencilik maliyeti, satış giderleri

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ve iskonto oranındaki değişimlerin cevher miktarı, ortalama tenör, yıllık kâr, optimum derinlik ve NBD üzerindeki etkileri incelenmiştir.

2.5. Dijital Karar Destek Arayüzü

Ekonomik hesaplamalar Excel ortamında yapılandırılmış; duyarlılık analizleri ve görsel çıktılar Python kullanılarak geliştirilen SIBPlan arayüzüne aktarılmıştır. Arayüz; Excel, CSV, TXT ve DAT biçimindeki verilerin yüklenmesi, ekonomik parametrelerin değiştirilmesi, üretim yılı seçimi, farklı senaryoların karşılaştırılması, duyarlılık matrisi oluşturulması, grafiksel sonuçların görüntülenmesi ve Word formatında otomatik geri bildirim raporu üretilmesi işlevlerini içermektedir. Bu yapı, mühendis yerine karar veren bir sistem olarak değil, alternatiflerin sonuçlarını karşılaştırılabilir hâle getiren bir karar destek prototipi olarak tasarlanmıştır.

3. BULGULAR VE TARTIŞMA

3.1. Blok Model ve Tenör-Tonaj Dağılımı

Jeolojik modelleme sonucunda cevher gövdesini temsil eden kapalı üç boyutlu katı model oluşturulmuş ve sondaj verileriyle mekânsal uyumu kontrol edilmiştir. Kompozit ve istatistiksel değerlendirmeler sonrasında blok model üzerinde tenör tahmini gerçekleştirilmiş, böylece ekonomik analizlerde kullanılabilecek blok bazlı tonaj ve tenör dağılımı elde edilmiştir. Tenör sınıfları incelendiğinde düşük tenörlü malzemenin toplam tonaj içerisinde belirgin bir paya sahip olduğu, yüksek tenörlü sınıflarda ise tonajın hızla azaldığı görülmüştür. Blok model raporunda toplam 15.292.000 birim hacme karşılık yaklaşık 39.759.199 ton malzeme ve 0,74 g/t genel ortalama tenör raporlanmıştır.

Tablo 1. Seçilmiş yüksek tenör sınıflarına ait blok model dağılımı.

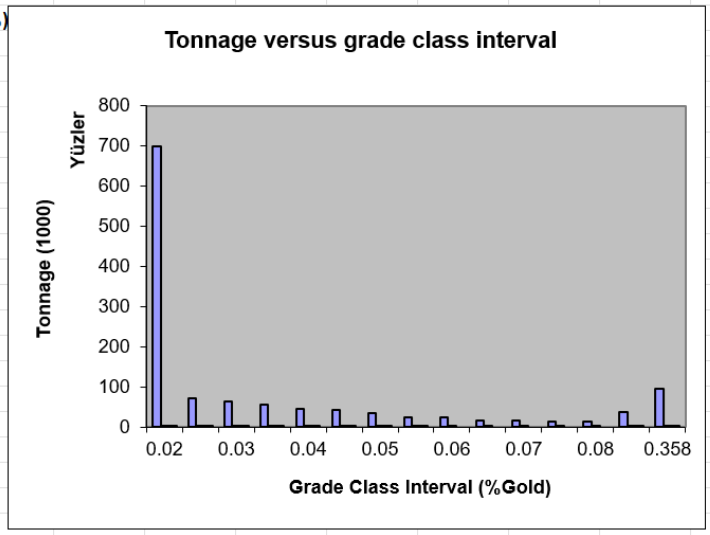
Tenör aralığı (g/t)	Hacim	Tonaj
1,0-1,5	7.556.000	19.645.599
1,5-2,0	224.000	582.400
2,0-2,5	208.000	540.800
2,5-3,0	156.000	405.600
3,0-3,5	56.000	145.600
3,5-4,0	88.000	228.800
4,0-5,0	60.000	156.000
5,0-6,0	88.000	228.800
6,0-7,0	16.000	41.600

Bu dağılım, sınır tenörü kararının yalnızca cevher miktarını değil aynı zamanda ortalama besleme kalitesini de değiştirdiğini göstermektedir. Düşük sınır tenörü daha fazla bloğun cevher olarak sınıflandırılmasını sağlarken düşük tenörlü malzemenin tesise yönlendirilmesine ve ortalama tenörün azalmasına yol açmaktadır. Buna karşılık sınır tenörünün yükseltilmesi, ortalama tenörü artırmakta ancak ekonomik rezervi daraltmaktadır. Bu bulgu, sınır tenörünün dinamik bir ekonomik karar değişkeni olarak ele alınması gerektiğini vurgulayan Lane yaklaşımı ve Tüylü'nün (2009) sonuçlarıyla uyumludur.

Blok modelden türetilen sınıflandırılmış tenör-tonaj verileri, ekonomik modelin temel girdisini oluşturmuştur. Şekil 1'de düşük tenör sınıflarında yüksek tonaj yoğunlaşması ve 1,0-1,5 g/t aralığında belirgin bir tonaj birikimi görülmektedir. Bu yapı, sınır tenörü değiştirildiğinde işlenecek malzeme miktarının ve ortalama besleme tenörünün birlikte değişeceğini açıkça göstermektedir.

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Table 2. Grade Tonnage Distribution				
Category		Tons (000	Proportion (%)	
0	0.1	11731	30%	
0.1	0.2	2215	6%	
0.2	0.4	1591	4%	
0.4	0.6	395	1%	
0.6	0.8	967	2%	
0.8	1	884	2%	
1	1.5	19645	49%	
1.5	2	582	1%	
2	2.5	540	1%	
2.5	3	405	1%	
3	3.5	145	0%	
3.5	4	228	1%	
4	5	156	0%	
5	6	228	1%	
6	7	41	0%	
Total		39753	100%	



Şekil 1. Blok modelden elde edilen tenör-tonaj dağılımı ve tenör sınıflarına göre tonaj değişimi.

3.2. Sınır Tenörü ve Ekonomik Performans

Ekonomik modelde başa baş sınır tenörü yaklaşık 0,26 g/t olarak hesaplanmıştır. Bu değer, kullanılan maliyet, fiyat ve geri kazanım varsayımları altında malzemenin ekonomik cevher olarak değerlendirilmesi için gereken yaklaşık alt eşiktir. Farklı sınır tenörü senaryolarının karşılaştırılması, tonaj ile kalite arasında belirgin bir değiş tokuş bulunduğunu göstermiştir. Düşük eşiklerde toplam üretilebilir cevher tonajı artmış ancak ortalama tenör düşmüş; yüksek eşiklerde ise daha yüksek kaliteli cevher seçilmiş fakat toplam ekonomik rezerv azalmıştır. Dolayısıyla yalnızca tonajı veya yalnızca ortalama tenörü maksimize etmek ekonomik açıdan yeterli değildir; amaç, proje ömrü boyunca NBD'yi en yüksek düzeye çıkaran dengeyi kurmaktır.

3.3. Üretim Derinliği, Üretim Sırası ve NBD

Yıllık üretim senaryolarında kalan rezerv miktarı her dönem için güncellenmiş ve ekonomik değerler yeniden hesaplanmıştır. İlk üretim yıllarında yüksek tenörlü blokların değerlendirilmesi daha yüksek nakit akışı ve NBD üretmiş, ilerleyen yıllarda ortalama tenörün azalmasıyla yıllık kârda düşüş eğilimi ortaya çıkmıştır. Bu sonuç, yüksek ekonomik değerli cevherin erken dönemlerde üretilmesinin paranın zaman değeri nedeniyle proje değerini artırabildiğini göstermektedir.

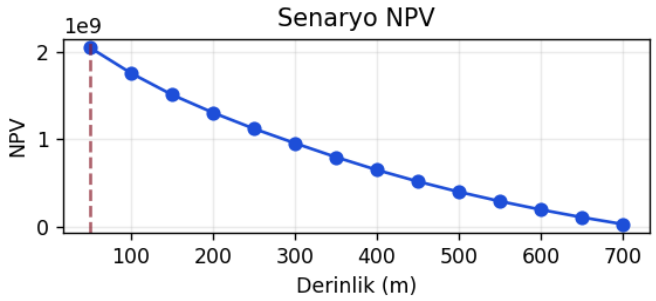
Derinlik senaryoları incelendiğinde üretim derinliği arttıkça erişilebilir rezerv miktarının artmasına karşın ekonomik performansın aynı doğrultuda sürekli yükselmediği belirlenmiştir. Daha derin seviyelerde artan kazı ve taşıma gereksinimi, örtükazı oranı ve işletme maliyetleri nedeniyle NBD belirli bir seviyeden sonra azalmıştır. Böylece ekonomik optimumun, maksimum rezervi kapsayan en derin ocakla aynı olmadığı; düşük-orta derinlik aralığında maksimum NBD sağlayan bir optimum işletme derinliği bulunduğu görülmüştür. Bu eğilim Mallı ve arkadaşlarının (2017) nihai işletme derinliği optimizasyonu üzerine bulgularıyla paraleldir.

3.4. Duyarlılık Analizi

Duyarlılık analizleri ekonomik parametrelerin optimum plan üzerindeki etkisinin doğrusal olmadığını göstermiştir. Metal satış fiyatındaki artış, daha düşük ekonomik değere sahip ve/veya daha derindeki blokların üretilebilir hâle gelmesini sağlayarak optimum üretim derinliğini artırmıştır. Buna karşılık kazı ve işletme maliyetlerindeki artış, özellikle derin seviyelerde marjinal blokların ekonomik değerini düşürmüş ve optimum derinliği daha sığ seviyelere çekmiştir. İskonto oranındaki artış ise gelecek yıllardaki nakit akışlarının bugünkü değerini azaltmış ve geç dönem üretiminin ekonomik katkısını zayıflatmıştır. Bu sonuçlar, açık ocak tasarımının tek bir sabit fiyat-maliyet setine göre değil, alternatif ekonomik koşullar altında duyarlılık analizleriyle birlikte değerlendirilmesi gerektiğini göstermektedir.

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Derinlik-NBD ilişkisi ekonomik optimumun belirlenmesinde doğrudan kullanılmıştır. Şekil 2'de incelenen senaryolarda en yüksek NBD'nin 50 m derinlikte oluştuğu ve derinlik arttıkça NBD'nin düzenli biçimde gerilediği görülmektedir. Bu sonuç, daha derin üretimin sağladığı ek rezervin artan kazı ve taşıma maliyetlerini telafi edemediği koşullarda ocak derinliğinin sınırlandırılması gerektiğini göstermektedir.



Şekil 2. Üretim derinliği ile net bugünkü değer (NBD) arasındaki ilişki.

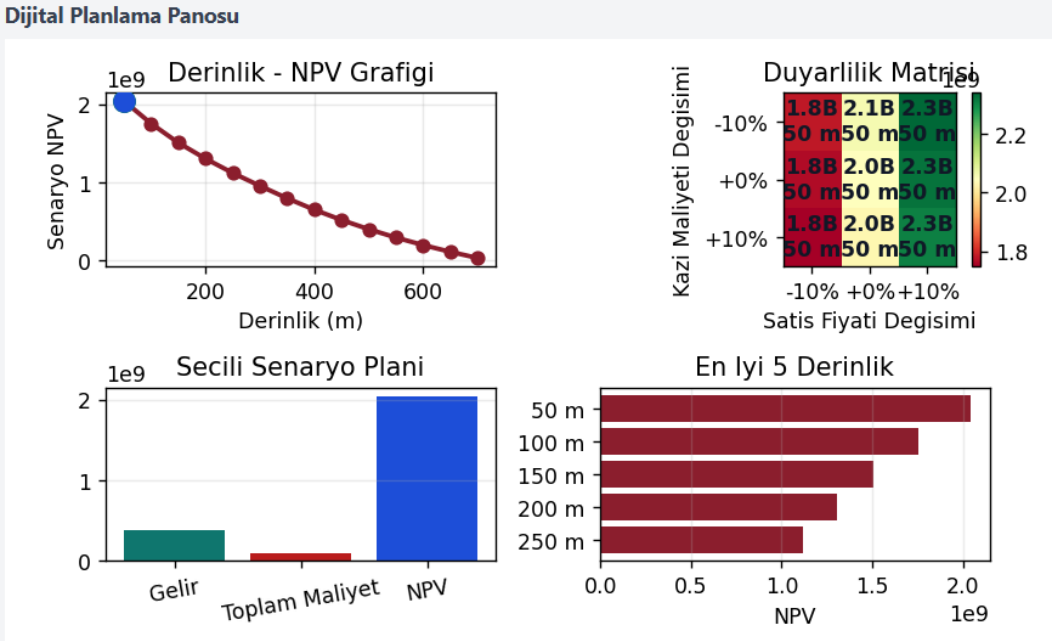
3.5. SIBPlan Dijital Arayüzünün Değerlendirilmesi

Python tabanlı SIBPlan prototipi, jeolojik modelden ve Excel tabanlı ekonomik hesaplardan elde edilen sonuçların tek bir kullanıcı arayüzünde değerlendirilmesini sağlamıştır. Sistem üzerinden veri dosyaları yüklenebilmekte, iskonto oranı, satış fiyatı ve kazı maliyeti gibi parametreler değiştirilebilmekte, üretim yılları ayrı ayrı incelenebilmekte ve NBD, kâr, sınır tenörü ve üretim performansı karşılaştırılabilmektedir. Ayrıca sonuçların grafikler ve duyarlılık matrisi ile sunulması, senaryolar arasındaki farkların hızlı biçimde yorumlanmasına imkân vermiştir.

Arayüzün önemli çıktılarından biri otomatik geri bildirim raporudur. Sistem, üretim yılları, ekonomik parametreler, sınır tenörü değerleri, NBD sonuçları, duyarlılık matrisi ve grafiksel değerlendirmeleri Word formatında bir araya getirebilmektedir. Bu işlev, hesaplama sonuçlarının manuel olarak farklı dosyalardan toplanması gereksinimini azaltarak analiz ve raporlama sürecini hızlandırmaktadır. Bununla birlikte geliştirilen yapı bir prototiptir; gerçek zamanlı üç boyutlu blok model bağlantısı, otomatik nihai ocak optimizasyonu ve gerçek saha verileriyle doğrulama sonraki geliştirme aşamaları olarak değerlendirilmelidir.

SIBPlan'ın dijital planlama panosu, derinlik-NBD eğrisini, fiyat ve kazı maliyeti duyarlılık matrisini, seçili senaryonun gelir-maliyet-NBD karşılaştırmasını ve ekonomik açıdan en iyi derinlik seçeneklerini aynı ekranda birleştirmektedir. Şekil 3'te görülen yapı, tek bir ekonomik sonuca odaklanmak yerine farklı göstergelerin birlikte okunmasını mümkün kılmaktadır. Böylece mühendis, fiyat veya maliyet varsayımındaki değişimin yalnızca NBD üzerindeki etkisini değil, optimum derinlik kararına yansımasını da aynı analiz akışı içinde izleyebilmektedir.

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Şekil 3. SIBPlan dijital planlama panosu: derinlik-NBD ilişkisi, duyarlılık matrisi ve senaryo karşılaştırmaları.

Geliştirilen tam analiz ekranında veri yükleme, ekonomik parametre girişi, üretim yılı seçimi, otomatik yorum, veri önizleme ve rapor dışa aktarma işlevleri de aynı arayüz altında toplanmıştır (Şekil 4). Örnek senaryoda sistem 14 derinlik seçeneğini değerlendirmiş; 50 m seçeneğini optimum derinlik olarak işaretlemiş ve yaklaşık 2,044 milyar düzeyindeki maksimum NBD'yi sonuç özetinde göstermiştir. Bu sayısal sonuçlar pilot/hipotetik veri setine ve kullanılan ekonomik varsayımlara özgüdür; gerçek bir işletmeye doğrudan genellenmemelidir. Bununla birlikte arayüzün temel katkısı, senaryo üretme, karşılaştırma ve raporlama işlemlerini tekrarlanabilir bir karar destek iş akışına dönüştürmesidir.



Şekil 4. SIBPlan analiz ve karar destek ekranının bütünleşik görünümü.

4. SONUÇLAR

Bu çalışmada hipotetik bir açık ocak altın sahası için jeolojik modelleme, blok model, sınır tenörü analizi, üretim/derinlik senaryoları, NBD değerlendirmesi, duyarlılık analizi ve dijital karar desteği

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bütünleşik bir iş akışı altında ele alınmıştır. Elde edilen sonuçlar aşağıdaki temel çıkarımları ortaya koymaktadır:

• Sondaj verilerinden üretilen üç boyutlu blok model, tenör-tonaj ilişkilerinin ve ekonomik senaryoların değerlendirilmesi için uygun bir sayısal temel sağlamıştır.

• Kullanılan ekonomik varsayımlar altında başa baş sınır tenörü yaklaşık 0,26 g/t olarak belirlenmiş; sınır tenörünün düşürülmesinin tonajı artırırken ortalama tenörü azalttığı, yükseltilmesinin ise kaliteyi artırırken ekonomik rezervi daralttığı görülmüştür.

• Üretim derinliği arttıkça rezerv miktarı artsa da kazı, taşıma ve örtükazı maliyetlerindeki yükseliş nedeniyle NBD belirli bir noktadan sonra azalmış; ekonomik optimumun maksimum rezervi kapsayan en derin ocakla aynı olmadığı ortaya konmuştur.

• Yüksek tenörlü cevherin erken yıllarda üretilmesi nakit akışını öne çekerek NBD'yi desteklemiş; ilerleyen yıllarda ortalama tenörün azalması yıllık kârı düşürmüştür.

• Metal satış fiyatındaki artışlar optimum işletme derinliğini artırırken, kazı/işletme maliyetlerindeki artışlar optimum derinliği azaltmış; daha yüksek iskonto oranları geç dönem nakit akışlarının ekonomik katkısını zayıflatmıştır.

• SIBPlan arayüzü, veri yükleme, parametre değişimi, senaryo karşılaştırma, duyarlılık analizi, grafiksel değerlendirme ve otomatik raporlamayı tek ortamda birleştirerek klasik hesaplama sürecini daha hızlı ve izlenebilir hâle getirmiştir.

Sonuç olarak, maliyet tabanlı üretim optimizasyonunun açık ocak planlamasında yalnızca teknik rezerv büyüklüğünü değil, zaman, fiyat, maliyet ve cevher kalitesi ilişkisini birlikte değerlendirmesi gerektiği gösterilmiştir. Çalışmanın gerçek saha verileriyle sınanması, çevresel göstergelerin ekonomik modele eklenmesi, gerçek zamanlı veri tabanı bağlantılarının kurulması ve gelişmiş optimizasyon algoritmalarının arayüze entegre edilmesi, modelin endüstriyel uygulanabilirliğini güçlendirecektir.

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SMART WOUND CARE TECHNOLOGIES: CURRENT STATUS OF BIOSENSORS, FUNCTIONAL BIOMATERIALS AND CLOSED-LOOP THERAPEUTIC SYSTEMS

AKILLI YARA BAKIM TEKNOLOJİLERİ: BİYOSENSÖRLER, FONKSİYONEL BİYOMALZEMELER VE KAPALI DÖNGÜ TEDAVİ SİSTEMLERİNİN GÜNCEL DURUMU

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ABSTRACT

Chronic wounds are complex and multifactorial pathological conditions in which prolonged inflammation, increased microbial burden, inadequate tissue perfusion, oxidative stress, and metabolic disturbances adversely affect the normal healing process. Conventional wound dressings mainly provide passive protection and are frequently removed for wound assessment. This may damage newly formed tissue, increase the risk of contamination, and interrupt the continuity of treatment. Smart wound care systems aim to overcome these limitations by integrating biosensors, functional biomaterials, flexible electronics, and active therapeutic components within a single platform.

This review evaluates current sensor technologies for monitoring physicochemical, metabolic, and infection-related changes in the wound microenvironment, together with the functional biomaterials used in these systems. Electrochemical, colorimetric, optical, and impedance-based sensing approaches are discussed alongside hydrogels, electrospun nanofibers, films, foams, conductive polymers, and biodegradable electronic systems. Closed-loop systems that couple sensor-derived data with therapeutic interventions such as electrical stimulation, controlled drug release, or photothermal therapy represent an important approach in the transition from passive wound care to adaptive and personalized treatment. Nevertheless, most existing systems remain at the cell-culture or animal-model stage. Biofouling, accurate calibration in wound exudate, long-term stability, sterilization, energy requirements, manufacturing reproducibility, data security, and approval processes for clinical use are among the major challenges limiting clinical translation. In the future, the development of smart wound dressings with modular, biodegradable, and wireless features may enable real-time monitoring of wound status and allow treatment to be tailored to individual needs. These advances indicate that smart wound care technologies may make an important contribution to the development of more effective, personalized, and clinically responsive approaches to chronic wound management.

Keywords: Smart wound dressing, biosensor, functional biomaterial, closed-loop therapy, wound monitoring, bioelectronics

ÖZET

Kronik yaralar; uzamış inflamasyon, artmış mikrobiyal yük, yetersiz doku perfüzyonu, oksidatif stres ve metabolik bozuklukların normal iyileşme sürecini olumsuz etkilediği karmaşık ve çok faktörlü patolojik durumlardır. Geleneksel yara örtüleri çoğunlukla pasif koruma sağlamakta ve yaranın değerlendirilmesi için sık aralıklarla çıkarılmaktadır. Bu durum yeni oluşan dokunun zarar görmesine, kontaminasyon riskinin artmasına ve tedavi sürecinin kesintiye uğramasına neden olabilmektedir. Akıllı yara bakım sistemleri ise biyosensörleri, fonksiyonel biyomalzemeleri, esnek elektroniği ve aktif tedavi bileşenlerini tek bir platformda birleştirerek bu sınırlılıkların aşılmasını amaçlamaktadır.

Bu derlemede; yara mikroçevresindeki fizikokimyasal, metabolik ve enfeksiyonla ilişkili değişikliklerin izlenmesine yönelik güncel sensör teknolojileri ile bu sistemlerde kullanılan fonksiyonel

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biyomalzemeler değerlendirilmiştir. Elektrokimyasal, kolorimetrik, optik ve empedans temelli sensör yaklaşımlarının yanı sıra hidrojeller, elektro-eğrilmiş nanolifler, filmler, köpükler, iletken polimerler ve biyobozunur elektronik sistemler ele alınmıştır. Ayrıca sensörlerden elde edilen verileri elektriksel uyarım, kontrollü ilaç salınımı veya fototermal tedavi gibi terapötik uygulamalarla birleştiren kapalı döngü sistemlerin, pasif yara bakımından uyarlanabilir ve kişiselleştirilmiş tedaviye geçişte önemli bir yaklaşım olduğu görülmektedir. Bununla birlikte mevcut sistemlerin büyük bölümü hâlen hücre kültürü veya hayvan modeli düzeyindedir. Biyolojik kontaminasyon, yara eksüdasında doğru kalibrasyon, uzun dönem stabilite, sterilizasyon, enerji gereksinimi, üretim tekrarlanabilirliği, veri güvenliği ve klinik kullanıma yönelik onay süreçleri, bu teknolojilerin klinik uygulamaya aktarılmasındaki başlıca güçlüklerdir. Gelecekte modüler, biyobozunur ve kablosuz bağlantı özelliklerine sahip akıllı yara örtülerinin geliştirilmesiyle yara durumunun gerçek zamanlı izlenmesi ve tedavinin bireysel gereksinimlere göre yönlendirilmesi mümkün olabilir. Bu gelişmeler, akıllı yara bakım teknolojilerinin kronik yara yönetiminde daha etkili, kişiselleştirilmiş ve klinik gereksinimlere duyarlı yaklaşımların geliştirilmesine önemli katkılar sağlayabileceğini göstermektedir.

Anahtar Kelimeler: Akıllı yara örtüsü, biyosensör, fonksiyonel biyomalzeme, kapalı döngü tedavi, yara izlemi, biyoelektronik

1. GİRİŞ

Yara iyileşmesi; hemostaz, inflamasyon, proliferasyon ve remodelling evrelerinin düzenli bir şekilde birbirini takip ettiği dinamik bir süreçtir. Diyabet, vasküler yetersizlik, enfeksiyon, mekanik basınç, nöropati ve uzamış inflamasyon gibi etkenler bu düzeni bozarak kronik yaraların gelişmesine neden olabilir. Kronik yaralar hastaların yaşam kalitesini azaltır .Ayrıca tekrarlayan pansumanlar, uzun süreli tedavi, hastaneye yatış ve amputasyon riski nedeniyle sağlık sistemleri üzerinde önemli bir yük oluşturur (Derakhshandeh et al., 2018; Frykberg & Banks, 2015).

Güncel olarak klinik yara bakımında; debridman, enfeksiyon kontrolü, nem dengesinin sağlanması, uygun örtü seçimi ve yaranın etiyolojisine yönelik basınç azaltma, kompresyon ya da revaskülarizasyon gibi işlemler yapılır. Geleneksel yara örtüleri genellikle yara yüzeyini koruyan pasif materyallerdir ve yara mikroçevresinde meydana gelen değişiklikleri gösteremez. Örtünün yarayı değerlendirmek için sık çıkarılması, hassas granülasyon dokusunun zarar görmesine, ağrıya ve kontaminasyona yol açabilir (Derakhshandeh et al., 2018; Wang et al., 2022).

Sensör teknolojileri, fonksiyonel biyomalzemeler ve esnek biyoelektronik sistemlerdeki gelişmeler, yara bakımını pasif örtü yaklaşımından aktif, sürekli izlenen ve kişiselleştirilebilir tedaviye doğru değiştirmektedir. Yeni nesil sistemler yalnızca ölçüm yapmakla kalmayıp algılanan değişime göre elektriksel uyarım, kontrollü ilaç salınımı veya antimikrobiyal tedavi başlamayı yapabilmektedir. Jiang ve arkadaşlarının geliştirdiği kablosuz kapalı döngü akıllı bandaj, sıcaklık ve empedans verilerini tedaviye dönüştüren bu yaklaşımın önemli örneklerinden biridir (Jiang et al., 2023).

Bu derlemenin amacı; akıllı yara bakımında kullanılan biyobelirteç ve sensörleri, fonksiyonel biyomalzemeleri, kapalı döngü tedavi yaklaşımlarını ve klinik kullanıma geçişteki temel güçlükleri bütüncül bir çerçevede değerlendirmektir.

2. YARA MİKROÇEVRESİNDE İZLENEBİLİR PARAMETRELER

Akıllı bir yara örtüsünün klinik olarak değeri, ölçtüğü parametrenin yara biyolojisiyle ilişkisi ve bu ölçümün tedavi kararına yardımcı olmasıyla belirlenir. Tek bir parametre çoğu zaman yaranın karmaşık durumunu açıklamak için yeterli değildir. Bu nedenle pH, sıcaklık, nem, empedans, oksijen ve metabolitleri birlikte değerlendiren çoklu sensör yaklaşımları giderek önem kazanmaktadır (Tang et al., 2021; Wu et al., 2025).

2.1. PH

Sağlıklı deri yüzeyi hafif asidik özellik gösterirken kronik veya enfekte yaralarda pH genellikle daha alkali değerlere kayar. pH; mikrobiyal çoğalma, proteaz aktivitesi, oksijen salınımı ve antimikrobiyal etki ile ilişkili olduğundan yara izlemi için uygun bir göstergedir. Esnek elektrotlar, iletken polimerler,

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iyon seçici yapılar ve doğal renk göstergeleri pH ölçümünde kullanılabilmektedir (Rahimi et al., 2016; Tang et al., 2021).

Kolorimetrik sistemler enerji gereksiniminin düşük olması ve gözümüz ile değerlendirebilmemiz nedeniyle pratiktir. Kırmızı lahana antosiyaninleri içeren kitosan hidrojel, pH değişikliğine bağlı renk yanıtı verirken terapötik madde salınımını da desteklemiştir (Arafa et al., 2021). Rodamin B yüklü kitosan nanopartiküllerinin sodyum aljinat filmle birleştirildiği başka bir sistemde, pH değişikliklerinin optik olarak izlenmesi amaçlanmıştır (Sheikholeslami et al., 2024). Elektrokimyasal pH sensörleri; sayısal ölçüm yapabilmeleri, verileri kablosuz olarak aktarabilmeleri ve otomatik karar algoritmalarıyla birlikte çalışabilmeleri açısından avantaj sağlar (Rahimi et al., 2016).

2.2. SICAKLIK, NEM VE ELEKTRİKSEL EMPEDANS

Yara sıcaklığındaki bölgesel artış inflamasyon veya enfeksiyonla ilişkili olabilir; ancak çevresel sıcaklık, anatomik bölge ve perfüzyon gibi etkenler ölçümü değiştirebilir. Bu nedenle sıcaklık verisinin tek başına değil, zaman içindeki değişimi ve diğer parametrelerle birlikte yorumlanması gerekir. Esnek rezistif sensörler ve ince film termistörler, yara yüzeyine uyumlu sürekli sıcaklık izlemi için kullanılmaktadır (Tang et al., 2021; Wang et al., 2022).

Nem ve eksüda düzeyi, maserasyon ile aşırı kuruluk arasındaki dengenin korunması açısından önemlidir. Kapasitans veya empedans değişimlerine bağlı sensörler, yara örtüsündeki sıvı miktarı değişimlerini izleyebilir. Elektriksel empedans aynı zamanda dokunun bütünlüğü, hücresel hareketlilik ve iyileşme ilerlemesi hakkında dolaylı bilgi sağlayabilir. Biyobozunur kablosuz sistemlerde empedans ölçümünün elektroterapiyle birleştirilmesi, sensör verisinin doğrudan tedaviye aktarılabileceğini göstermiştir (Song et al., 2023).

2.3. OKSİJEN, GLUKOZ, LAKTAT VE ÜRİK ASİT

Yeterli doku oksijenlenmesi, hücresel enerji üretimi ve yara iyileşmesinin sürdürülebilmesi için gereklidir; ancak kronik yaralarda bozulmuş perfüzyon nedeniyle yara yatağında hipoksi gelişebilir (Ochoa et al., 2020; Sen, 2009). Lokal oksijen düzeyindeki değişiklikleri izlemek amacıyla elektrokimyasal ve optik sensörler geliştirilmektedir. Optik sistemlerde oksijene bağlı floresans veya fosforesans söndürülmesi ölçüm amacıyla kullanılabilmektedir (Ochoa et al., 2020; Tavakol et al., 2020; Youssef et al., 2023). Bununla birlikte sensörün yara yatağına göre konumu, örtü katmanlarının oksijen geçirgenliği, yara sıvısı ve dış ortam oksijeninin yeterince yalıtılmaması ölçüm sonuçlarını etkileyebilir (Tavakol et al., 2020).

Glukoz ve laktat, özellikle diyabetik yaralarda metabolik durumun değerlendirilmesi açısından ilgi görmektedir. Enzim tabanlı elektrokimyasal sensörler özgül ölçüm sağlayabilir ancak enzim stabilitesi, oksijen bağımlılığı ve biyolojik kirlenme uzun süreli kullanımda sorun oluşturur. Ürik asit ise doku hasarı ve yara durumuyla ilişkili bir metabolittir. Kassal ve arkadaşları, amperometrik ürik asit sensörünü doğrudan yara örtüsüne basarak RFID/NFC üzerinden kablosuz veri aktarabilen öncü bir akıllı bandaj geliştirmiştir (Kassal et al., 2015).

2.4. PROTEAZLAR, REAKTİF TÜRLER VE ENFEKSİYON GÖSTERGELERİ

Kronik yaralarda uzamış inflamasyon, matriks metalloproteinazlar (MMP'ler) başta olmak üzere çeşitli proteazların aktivitesinde artışa yol açabilir. Proteolitik dengenin bozulması; büyüme faktörlerinin ve hücre dışı matriks bileşenlerinin aşırı parçalanmasına neden olarak doku onarımını geciktirebilir (Eming et al., 2014; Krishnaswamy et al., 2017). Proteazla parçalanabilen peptit substratlarının floresan problarla birleştirilmesi, enzim aktivitesinin oluşturduğu sinyal değişikliği üzerinden proteaz düzeylerinin izlenmesine olanak sağlar (Eskilson et al., 2025).

Benzer şekilde, reaktif oksijen ve azot türlerinin aşırı birikmesi oksidatif ve nitrozatif stres oluşturarak inflamasyonun devam etmesine ve yara iyileşmesinin bozulmasına katkıda bulunabilir (Hunt et al., 2024; Soneja et al., 2005). Bu moleküllere duyarlı materyaller, oksidasyon sonucunda renk veya floresans değişikliği oluşturacak ya da oksidasyona duyarlı bağların parçalanmasıyla ilaç salımını başlatacak şekilde tasarlanabilmektedir (Wu et al., 2020; Zhao et al., 2020). Böylece bu sistemler, yara

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ortamındaki biyokimyasal değişiklikleri algılayan tanısal bir araç olmanın yanında, gereksinime göre tedavi başlatan terapötik bir platform olarak da işlev görebilir.

Enfeksiyon için tek bir evrensel biyobelirteç bulunmadığından sıcaklık, pH, proteaz aktivitesi, mikrobiyal metabolitler ve klinik bulguların birlikte değerlendirilmesi daha güvenlidir. Çoklu sensörlü platformlar bu gereksinime yanıt vermektedir. MXene ile işlevselleştirilmiş gözenekli grafen iskelet üzerine kurulan çok işlevli bandaj, sıcaklık ve biyokimyasal değişimleri aynı platformda izlemeye yönelik örneklerden biridir (Sharifuzzaman et al., 2020).

3. SENSÖR TEKNOLOJİLERİ VE KABLOSUZ İZLEM

Akıllı yara örtülerinde sensör seçimi; hedef biyobelirteç, gerekli duyarlılık, ölçüm süresi, üretim maliyeti ve hastanın kullanım kolaylığına göre yapılmalıdır. Elektrokimyasal sensörler yüksek duyarlılık ve sayısal çıktı sağlarken; optik ve kolorimetrik sensörler basit, düşük maliyetli ve enerji gereksinimi azdır. Empedans sensörleri ise dokuyla temas eden elektrotlar üzerinden yapısal değişimleri izleyebilir (Wang et al., 2022; Wu et al., 2025).

3.1. ELEKTROKİMYASAL SENSÖRLER

Amperometrik, potansiyometrik ve impedimetrik sensörler; glukoz, laktat, ürik asit, pH ve iyonların ölçümünde kullanılabilir. Elektrotların karbon, altın, platin, iletken polimer veya MXene gibi malzemelerle işlevselleştirilmesi yüzey alanını ve elektron transferini artırabilir. Bununla birlikte proteinlerin sensör yüzeyinde birikmesi, referans elektrot kararlılığı ve kalibrasyon kayması klinik doğruluğu sınırlar. Sensörün yalnızca tampon çözeltide değil, gerçek yara eksüdasına benzer protein ve elektrolit içeren ortamlarda doğrulanması gerekir (Kassal et al., 2015; Sharifuzzaman et al., 2020).

3.2. OPTİK VE KOLORİMETRİK SENSÖRLER

Optik sensörler floresans, absorbans veya renk değişimi üzerinden ölçüm yapar. Doğal antosiyaninler, halokromik boyalar ve kuantum noktaları pH veya sıcaklık değişikliklerini görünür hâle getirir. Akıllı telefon kameralarıyla yapılan görüntü analizi, renk yanıtını nicel veriye dönüştürerek uzaktan izlemi kolaylaştırır. Ortam ışığı, kamera özellikleri, boyanın sızması ve renkli eksüda ölçüm hatasına neden olabilir (Arafa et al., 2021; Sheikholeslami et al., 2024).

İpek fibroin nanoliflere floresan nanodiamondların eklenmesiyle sıcaklık algılayabilen ve yara iyileşmesini destekleyebilen çok işlevli bir membran geliştirilmiştir. Bu yaklaşım, biyomalzemenin yalnızca sensörü taşıyan pasif bir katman değil, algılama işlevinin doğrudan parçası olabileceğini göstermektedir (Khalid et al., 2020).

3.3. ESNEK ELEKTRONİK VE KABLOSUZ VERİ AKTARIMI

Yara bölgesinde kullanılacak elektroniklerin yumuşak, ince, esnek ve cilt hareketlerine dayanıklı olması gerekir. Serigrafi, inkjet baskı, lazer desenleme ve transfer baskı gibi yöntemler sensörlerin film, tekstil veya hidrojel yüzeyine entegre edilmesini sağlar. Omnifobik kağıt tabanlı sistemler, düşük maliyetli üretim ve sıvının kontrollü yönlendirilmesi açısından dikkat çekmektedir (Pal et al., 2018).

NFC, RFID, Bluetooth Low Energy ve endüktif bağlantı; sensör verisinin telefona veya harici okuyucuya aktarılmasında kullanılabilir. Kablosuz sistemlerde batarya hacmi, ısınma, su geçirmezlik ve veri güvenliği dikkate alınmalıdır. Enerji üretimi yapan veya dışarıdan kablosuz güç alan sistemler, batarya gereksinimini azaltabilir. Jiang ve arkadaşlarının platformu kablosuz güç, sıcaklık ve empedans algılama, mikrodenetleyici tabanlı karar verme ve elektriksel uyarımı tek bir esnek sistemde birleştirmiştir (Jiang et al., 2023).

4. KAPALI DÖNGÜ VE AKTİF TEDAVİ SİSTEMLERİ

Kapalı döngü yaklaşımında sensör yara durumunu ölçer, veri bir kontrol birimi tarafından değerlendirilir ve önceden tanımlanan eşiklere göre tedavi modülü etkinleştirilir. Böylece tedavi sabit doz ve zamana bağlı olmaktan çıkarak yaranın dinamik gereksinimine göre uygulanabilir. Ancak klinik eşiklerin hastadan hastaya değişmesi, algoritmanın yanlış pozitif veya yanlış negatif karar verme riskini artırır. Bu nedenle kapalı döngü sistemlerde güvenlik sınırları, manuel müdahale seçeneği ve klinik doğrulama zorunludur (Jiang et al., 2023; Wu et al., 2025).

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4.1. ELEKTRİKSEL UYARIM

Deri yaralanmasıyla oluşan endojen elektrik alanlar hücre göçü ve doku onarımında rol oynar. Düşük şiddetli elektriksel uyarım; keratinosit ve fibroblast göçünü, anjiyogenezi ve bakteriyel kontrolü destekleyebilir. Jiang ve arkadaşlarının kapalı döngü bandajında empedans ve sıcaklık verisine göre elektriksel uyarım uygulanmış; hayvan modellerinde enfeksiyonun azalması ve yara kapanmasının hızlanması bildirilmiştir (Jiang et al., 2023).

Hastanın hareketi ve mekanik deformasyondan enerji üreten kendinden güçlü sistemler, harici batarya gereksinimini azaltabilir. Barman ve arkadaşlarının kendinden güçlü çok işlevli yara örtüsü, enfeksiyonun önlenmesi ve iyileşmenin desteklenmesi için elektriksel uyarımdan yararlanmıştır (Barman et al., 2023). Biyobozunur molibden elektrotların kullanıldığı başka bir platform ise elektroterapi ve empedans izlemini kablosuz, bataryasız ve geçici elektronik yapı içinde birleştirmiştir (Song et al., 2023).

4.2. KONTROLLÜ İLAÇ SALIMI

Hidrojeller, mikroiğneler, mikroakışkan rezervuarlar ve nanopartiküller antibiyotik, antiinflamatuvar, büyüme faktörü veya antioksidanların lokal ve kontrollü verilmesini sağlayabilir. pH, sıcaklık, bakteriyel enzimler, glukoz veya ROS artışı gibi uyarılar polimer ağında şişme, bağ kırılması ya da geçirgenlik değişikliği oluşturarak ilaç salınımı başlatabilir. Bu yaklaşım sistemik yan etkileri azaltma potansiyeli taşırken sensör özgüllüğünün yetersiz olması gereksiz ilaç salınımına neden olabilir.

Gelişmiş kablosuz sistemlerde farklı tedaviler aynı platformda birleştirilebilmektedir. Esneyebilen bir biyoelektronik sistemde çoklu yara parametreleri izlenmiş ve enfekte kronik yaralarda elektriksel uyarım ile ilaç tedavisi birlikte uygulanmıştır (Shirzaei Sani et al., 2023). Bu tür platformlar kişiselleştirilmiş tedavi açısından önemli avantajlar sunsa da ilaç haznesinin steril tutulması, doğru dozda ilaç salınımının sağlanması ve gerektiğinde güvenli biçimde tekrar doldurulabilmesi gibi mühendislik sorunlarının çözülmesi gerekmektedir.

4.3. FOTOTERMAL, FOTODİNAMİK VE ANTİMİKROBİYAL YAKLAŞIMLAR

Işığa yanıt veren nanomalzemeler, yakın kızılötesi ışığı ısıya veya reaktif türlere dönüştürerek antibakteriyel etki sağlayabilir. Fototermal ve fotodinamik tedaviler antibiyotik direnci açısından avantaj sağlayabilir ancak doku sıcaklığının güvenli aralıkta tutulması ve ışığın yara derinliğine ulaşması gerekir. Bu nedenle sıcaklık sensörüyle geri bildirim sağlayan sistemler, aşırı ısınma riskini azaltmak için önemlidir (Wu et al., 2025).

5. FONKSİYONEL BİYOMALZEMELER

Akıllı yara örtülerinde biyomalzeme yalnızca fiziksel bir taşıyıcı değil; eksüda yönetimini, hücre–malzeme etkileşimlerini, biyobelirteçlerin sensör yüzeyine taşınımını, sensör performansının korunmasını ve kontrollü ilaç salımını belirleyen temel bir bileşendir (Hodge et al., 2022; Wang et al., 2024). Bu nedenle malzeme seçiminde biyouyumluluk, nem ve eksüda yönetimi, gaz geçirgenliği, mekanik dayanıklılık, yara yüzeyine uygun yapışma, sterilizasyonla uyumluluk ve üretim tekrarlanabilirliği birlikte değerlendirilmelidir (Galante et al., 2018; Laurano et al., 2022; Wang et al., 2024).

5.1. TASARIM İLKELERİ

İdeal olan akıllı yara örtüsü, yara yüzeyine uyum sağlamalı ve çıkarılırken yeni oluşan dokuya zarar vermemelidir. Ayrıca fazla eksüdayı uzaklaştırırken yara yatağında iyileşme için gerekli nem dengesini korumalı ve dış mikroorganizmalara karşı koruyucu bir bariyer oluşturmalıdır (Nuutila & Eriksson, 2021; Shi et al., 2020). Ölçümlerin güvenilirliği için sensör elektrotlarının yara dokusu veya eksüda ile kararlı teması sürdürülmeli; bağlantı hatları ve elektronik devreler ise sıvı sızıntısı ve kısa devre riskini azaltmak amacıyla biyouyumlu yalıtım katmanlarıyla korunmalıdır (Li et al., 2023). Bu işlevler, çok katmanlı ve modüler tasarımlarda yara ile temas eden biyouyumlu katman, eksüdayı toplayarak sensörlere yönlendiren mikroakışkan bölüm, sensör katmanı, gereksinime göre ilaç taşıyan veya kontrollü salınım sağlayan terapötik bölüm, kablosuz iletişim devresi ve koruyucu dış tabaka şeklinde

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düzenlenebilir. Böylece her bölümün malzeme özellikleri ve işlevsel performansı ayrı ayrı optimize edilebilir (Ge et al., 2023; Li et al., 2023).

5.2. DOĞAL BİYOMALZEMELER

Kitosan, kitinin deasetilasyonuyla elde edilen katyonik bir polisakkarittir. Biyouyumluluğu, biyobozunurluğu, film ve hidrojel oluşturabilmesi nedeniyle yara örtülerinde yaygın biçimde araştırılmaktadır. Pozitif yüklü amino grupları eritrositler, trombositler ve negatif yüklü mikrobiyal yüzeylerle etkileşebilir; bu özellikler hemostatik ve antimikrobiyal etkiye katkı sağlayabilir. Amino gruplarının pH duyarlılığı, kitosanı pH izleyen veya pH değişiminde ilaç salan akıllı hidrojeller için uygun hâle getirir (Arafa et al., 2021). Kitosanın fizyolojik pH'da düşük çözünürlük göstermesi ve saf kitosan esaslı yapıların mekanik özelliklerinin uygulamaya bağlı olarak yetersiz kalabilmesi nedeniyle, yara örtüsü formülasyonlarında kitosanın aljinat, jelatin, selüloz ve türevleri, polivinil alkol (PVA) veya polietilen glikol (PEG) gibi polimerlerle kompozit hâle getirilmesi yaygın bir yaklaşımdır (Alven & Aderibigbe, 2020; Aranaz et al., 2021; Doan & Tran, 2023; Fan et al., 2016; Kibungu et al., 2021).

Aljinat, kahverengi alglerden elde edilen anyonik bir polisakkarittir ve kalsiyum gibi iki değerlikli iyonlarla hızlı biçimde jel oluşturabilir. Yüksek sıvı emme kapasitesi, orta-yüksek miktarda eksüda üreten yaralarda avantaj sağlar. Aljinat; ilaç, nanopartikül, renk göstergesi ve biyolojik moleküllerin taşınmasında kullanılabilir. Kitosanla elektrostatik etkileşimi, çok katmanlı ve kontrollü salınım sağlayan yapıların hazırlanmasını kolaylaştırır. Bununla birlikte aşırı şişme mekanik bütünlüğün kaybına neden olabilir (Sheikholeslami et al., 2024).

Kollajen deri hücre dışı matriksinin temel yapısal proteinlerinden biridir ve hücrelerin tutunmasını, göçünü ve çoğalmasını destekler. Jelatin, kollajenin kısmi hidroliziyle elde edilir ve hidrojel, film, sünger ve elektro-eğrilmiş nanolif üretiminde daha kolay işlenebilir. Kollajen ve jelatinin düşük mekanik dayanıklılığı ve hızlı enzimatik parçalanması, sentetik polimerlerle kompozit hazırlanmasını gerektirebilir. Partovi ve arkadaşlarının jelatin-kitosan-polikarprolakton içeren nanolifli iskeleyi karbon kuantum noktaları ve sitratla işlevselleştirmesi, doğal ve sentetik polimer avantajlarının bir araya getirebildiğini göstermiştir (Partovi et al., 2024).

Selüloz; lif, film, hidrojel ve nanolif biçiminde hazırlanabilen doğal bir polisakkarittir. Bakteriyel selüloz yüksek su tutma kapasitesi, mekanik dayanıklılığı ve gözenekli yapısı nedeniyle yara örtülerinde kullanılmaktadır. Selüloz temelli yapılar sensör elektrotları, renk göstergeleri ve ilaç taşıyıcı nanopartiküller için dayanıklı bir taşıyıcı oluşturabilir. Selüloz nanofibrilleri ile kitosanın birleştirildiği emici ve biyouyumlu filamentler, dokuma örtü veya sensör taşıyan tekstil sistemleri için uygundur(Wu et al., 2023).

İpek fibroin; mekanik dayanıklılığı, biyouyumluluğu ve farklı yapılara dönüştürülebilmesi nedeniyle akıllı yara örtülerinde araştırılan protein temelli bir biyomalzemedir. Hidrojel, film, sünger, mikropartikül ve elektro-eğrilmiş nanolif biçiminde hazırlanabilir. Kontrollü bozunma özelliği, uzun süreli örtü ve ilaç salınım sistemleri açısından avantaj sağlayabilir. Floresan nanodiamond içeren ipek fibroin membranların sıcaklık algılama ve yara iyileşmesini destekleme potansiyeli gösterilmiştir (Khalid et al., 2020).

Hiyalüronik asit (HA), hücre dışı matriksin doğal bileşenlerinden biri olan, doğrusal yapılı ve sülfatlanmamış bir glikozaminoglikandır. Yüksek hidrofilik özelliği ve su tutma kapasitesi sayesinde dokuların hidrasyonunun ve viskoelastik özelliklerinin korunmasına katkıda bulunur (Knopf-Marques et al., 2016; Litwiniuk et al., 2016).

HA; CD44 ve RHAMM gibi hücre yüzeyi reseptörleriyle etkileşerek hücre göçü ve proliferasyonu, inflamatuvar yanıtın düzenlenmesi, anjiyogenez ve doku yenilenmesi gibi yara iyileşmesinin farklı aşamalarında rol oynar (Litwiniuk et al., 2016).

Biyomedikal uygulamalarda HA; hidrojel, mikrojel, mikropartikül, nanopartikül ve ilaç taşıma sistemlerinin geliştirilmesinde kullanılabilmektedir (Knopf-Marques et al., 2016; Trombino et al., 2019). Kimyasal modifikasyon ve uygun çapraz bağlama yöntemleriyle HA temelli sistemlere pH,

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enzim veya reaktif oksijen türleri gibi yara mikroçevresindeki değişikliklere yanıt veren kontrollü ilaç salım özellikleri kazandırılabilir (Trombino et al., 2019).

Bununla birlikte, doğal HA'nın tek başına yeterli mekanik dayanıklılığa sahip olmaması ve hiyalüronidazlar tarafından hızlı biçimde parçalanması, uzun süreli biyomedikal kullanımını sınırlandırmaktadır (Khunmanee et al., 2017; Luo et al., 2023). Bu nedenle HA temelli hidrojel ve yara örtülerinin mekanik kararlılığını artırmak, şişme özelliklerini düzenlemek ve parçalanma hızını kontrol etmek amacıyla kimyasal veya fiziksel çapraz bağlama yöntemleri uygulanmakta ya da HA; kitosan, jelatin, kollajen, aljinat ve sentetik polimerler gibi farklı malzemelerle birleştirilmektedir (Khunmanee et al., 2017; Luo et al., 2023).

5.3. SENTETİK BİYOMALZEMELER

Polivinil alkol (PVA), hidrofilik olması, film ve hidrojel oluşturma yeteneği, düşük toksisitesi ve genel olarak iyi biyouyumluluğu nedeniyle yara örtüsü, ilaç taşıma sistemi ve sensör platformlarının geliştirilmesinde kullanılan sentetik bir polimerdir . PVA hidrojelleri, tekrarlanan dondurma–çözme döngüleriyle fiziksel olarak veya farklı çapraz bağlayıcılar kullanılarak kimyasal olarak hazırlanabilir . PVA'nın kitosan, aljinat, jelatin ve diğer doğal polimerlerle birleştirilmesi; kompozit yapıların esnekliğini, mekanik dayanıklılığını, su tutma kapasitesini ve yapısal kararlılığını düzenlemeye yardımcı olabilir (Bercea, 2024; Sharma et al., 2023).

PVA temelli hidrojel ve filmlerin optik olarak şeffaf hazırlanabilmesi, yara yüzeyinin doğrudan izlenmesini ve örtüye yerleştirilen optik veya kolorimetrik sensörlerde meydana gelen renk değişikliklerinin değerlendirilmesini kolaylaştırabilir (Kuddushi et al., 2023). Bununla birlikte, çapraz bağlanma yoğunluğunun artması hidrojelin ağ gözeneklerini ve şişme kapasitesini azaltarak moleküler difüzyonu sınırlandırabilir. Bu durum, yara eksüdasındaki analitlerin sensör tabakasına ulaşmasını ve hidrojel içerisindeki ilaçların salınmasını yavaşlatabilir (Bercea, 2024).

Polietilen glikol (PEG), yüksek hidrofilik özelliği ve yüzeyde yoğun bir hidrasyon tabakası oluşturabilmesi nedeniyle biyolojik kirlenmeye karşı dirençli bir polimer olarak kabul edilir. PEG kaplamaları sensör ve biyomalzeme yüzeylerinde özgül olmayan protein adsorpsiyonunu, hücre tutunmasını ve bazı durumlarda bakteri bağlanmasını azaltabilir (Banerjee et al., 2011; Chen et al., 2019). Bu özellik sensör yüzeyindeki biyolojik kirlenmeyi ve buna bağlı sinyal sapmasını azaltabilir ancak, doku mühendisliği uygulamalarında hücrelerin biyomalzemeye bağlanmasını da sınırlandırabilir. Bu nedenle PEG temelli yüzeyler; kollajen ve jelatin gibi hücre dışı matriks bileşenleriyle veya RGD gibi hücre bağlanmasını destekleyen peptitlerle işlevselleştirilebilir (Chen et al., 2019; Groll et al., 2005).

Poliüretan (PU); elastikiyetinin, mekanik özelliklerinin, işlenebilirliğinin ve su buharı geçirgenliğinin ayarlanabilmesi nedeniyle yara örtülerinde film, membran, sünger ve köpük biçiminde yaygın olarak kullanılmaktadır (Liang et al., 2023; Morales-González et al., 2022). PU filmler dış ortamdan gelen mikroorganizmalara karşı bariyer oluştururken su buharı ve gaz geçişine izin verebilir; gözenekli PU köpükler ise eksüda emilimini ve nem kontrolünü destekleyebilir (Liang et al., 2023). Bununla birlikte PU'nun biyolojik güvenliği yalnızca ana polimer üzerinden değerlendirilmemelidir. Özellikle uzun süreli uygulamalarda bozunma ürünlerinin yanı sıra artık izosiyanatlar, katalizörler, yüzey kirleticileri ve formülasyonda kullanılan katkı maddelerinin olası sitotoksik etkileri de incelenmelidir (Franklin et al., 2016; van Minnen et al., 2006).

Polikaprolakton (PCL), polilaktik asit (PLA) ve poli(laktik-ko-glikolik asit) (PLGA), hidroliz yoluyla kontrollü biçimde parçalanabilen sentetik alifatik polyesterlerdir. İşlenebilirlikleri, mekanik özelliklerinin ve bozunma hızlarının ayarlanabilmesi nedeniyle elektro-eğirme yöntemiyle nanolifli yara örtülerinin hazırlanmasında yaygın biçimde kullanılmaktadır (Sharma et al., 2023; Zhao et al., 2024). Elektro-eğirme sırasında polimer bileşimi, molekül ağırlığı, lif çapı, gözeneklilik ve çekirdek–kabuk yapısı gibi parametrelerin değiştirilmesiyle örtünün mekanik özellikleri ve ilaç salınım profili düzenlenebilir (Zhang et al., 2024; Zhao et al., 2024).

Bununla birlikte özellikle PCL ve PLA'nın hidrofobik karakteri, yüzeyin ıslanmasını, eksüdanın yapı içerisine alınmasını ve ilk hücre tutunmasını sınırlandırabilir (Tiyek et al., 2019). Bu sınırlılığı azaltmak

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amacıyla polyester nanolifler jelatin, kollajen, kitosan ve aljinat gibi doğal polimerlerle veya PEG gibi hidrofilik polimer ve nanopartiküllerle birleştirilebilir (Arbade et al., 2020; Sharma et al., 2023).

PLA, PGA ve PLGA'nın parçalanması sırasında laktik ve glikolik asit gibi asidik ürünlerin birikmesi, özellikle bozunmanın hızlı olduğu veya sıvı uzaklaştırılmasının sınırlı kaldığı sistemlerde lokal pH'nın düşmesine yol açabilir. Bu nedenle pH'ya duyarlı bir sensör polyester tabaka ile birlikte kullanıldığında, ölçülen pH değişiminin yalnızca yara mikroçevresinden değil, polimerin kendi bozunmasından da kaynaklanabileceği göz önünde bulundurulmalı; sensör kalibrasyonu polimer içermeyen ve polimer içeren kontrol sistemleriyle doğrulanmalıdır (Shen et al., 2019).

5.4. YAPISAL BİÇİMLER

Hidrojeller, yüksek miktarda suyu veya yara eksüdasını tutabilen üç boyutlu, çapraz bağlı polimer ağlarıdır (Wang et al., 2023). Yüksek su içerikleri ile yumuşak ve esnek yapıları, düzensiz yara yüzeylerine uyum sağlamalarına, elektrotlarla doku arasında kararlı bir temas oluşturulmasına ve biyobelirteçlerin difüzyon yoluyla sensör yüzeyine taşınmasına yardımcı olur (Huang et al., 2023; Wang et al., 2023). Malzeme bileşiminin ve çapraz bağlanma mekanizmasının düzenlenmesiyle bu sistemlere pH ve sıcaklık izlemi, kontrollü antibiyotik veya büyüme faktörü salınımı, elektriksel iletkenlik, kendini onarma ve ıslak dokuya yapışma gibi işlevler kazandırılabilir (Kushibiki et al., 2021; Mirani et al., 2017; Pang et al., 2020; Shan et al., 2024). Aşırı şişme,malzemenin mekanik kuvvetlere ve tekrarlayan hareketlere karşı dayanıklılığının sınırlı olması, su kaybı ve uzun süreli yapısal bütünlüğün korunmasındaki güçlükler hidrojel temelli yara örtülerinin başlıca sınırlılıklarıdır (Liu et al., 2024; Wang et al., 2023).

Elektro-eğrilmiş nanolifler yüksek yüzey alanı ve gözeneklilik göstererek hücre dışı matriksin fibröz mimarisine benzer bir iskele oluşturur. Antibiyotik, metal nanopartikül, büyüme faktörü, antioksidan veya renk göstergesi liflerin içine eklenebilir. İki yüzlü Janus nanolif örtüler, hidrofilik ve hidrofobik katmanları birlikte kullanarak eksüdanın yara yüzeyinden dış tabakaya tek yönlü taşınmasını sağlayabilir. Zhang ve arkadaşlarının sistemi, sıvı drenajını antimikrobiyal ve izleme bileşenleriyle birleştirmiştir (Zhang et al., 2022).

Hidrojel-nanolif kompozitleri, hidrojellerin yara yüzeyine uyum sağlama ve sıvı taşıma avantajını nanoliflerin mekanik dayanıklılığıyla birleştirir. Esnek, antibakteriyel ve giyilebilir sağlık izlemi için uygun sensör özellikleri taşıyan hidrojel-nanolif iskeleler geliştirilmiştir (Xu et al., 2024).

Polimerik filmler ve membranlar; ince ve esnek yapıları sayesinde optik göstergelerin, basılı elektrotların ve esnek kablosuz devrelerin yara örtüsüne yerleştirilmesi için uygun taşıyıcı katmanlar oluşturabilir (Farooqui & Shamim, 2016; Li et al., 2020). Poliüretan köpükler ise gözenekli yapıları sayesinde yüksek miktarda yara eksüdasını emme ve tutma kapasitesine sahiptir; ancak bu kapasite köpüğün gözenek yapısına, kalınlığına ve yoğunluğuna göre değişebilir (Lee et al., 2016). Köpük veya başka bir emici tabaka yara yüzeyi ile sensör arasında bulunuyorsa tabaka kalınlığının artması, biyobelirteçlerin difüzyon mesafesini uzatabilir. Bu durum biyobelirteçlerin sensöre ulaşmasını geciktirerek yanıt süresini, duyarlılığı ve saptama sınırını etkileyebilir (Toyos-Rodríguez et al., 2024).

5.5. İLETKEN BİYOMALZEMELER

Elektriksel uyarım uygulayan veya empedans ölçen örtülerde iletken bir ağ gereklidir. Polipirol, polianilin, PEDOT:PSS, grafen, grafen oksit, karbon nanotüp, altın ve gümüş nanoyapılar, MXene malzemeleri ve iyon içeren hidrojeller bu amaçla kullanılabilir. İletken polimerler esnek yapılara dönüştürülebilir ve elektriksel sinyalin yara yüzeyine iletilmesini sağlar. Buna karşın biyobozunurluk, mekanik dayanıklılığının sınırlı olması, üretim sürecinden kaynaklanan kimyasal artıklar ve nanopartikül toksisitesi klinik kullanım öncesinde ayrıntılı değerlendirilmelidir (Sharifuzzaman et al., 2020; Wang et al., 2022).

5.6. BİYOBOZUNUR VE GEÇİCİ ELEKTRONİKLER

Geleneksel ve biyobozunur olmayan elektronik bileşenlerin yara iyileştikten sonra çıkarılması, yeni oluşan hassas dokunun zarar görmesine neden olabilir. Bu sorunu azaltmak amacıyla belirli bir süre işlev gördükten sonra vücut sıvılarında kontrollü biçimde çözünebilen geçici elektronik sistemler

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geliştirilmektedir. Song ve arkadaşları, biyobozunur, kablosuz ve bataryasız bir sistemde elektriksel uyarıyla tedaviyi ve empedans ölçümüyle yara takibini bir araya getirerek bu yaklaşımın preklinik düzeyde uygulanabilirliğini göstermiştir (Song et al., 2023). Bununla birlikte sistemin bozunma hızı yara iyileşme süreciyle uyumlu olmalıdır; çok hızlı bozunma cihazın tedavi ve ölçüm işlevlerini zamanından önce kaybetmesine, çok yavaş bozunma ise materyalin dokuda gereğinden uzun süre kalarak yabancı cisim reaksiyonu riskini artırmasına yol açabilir.

5.7. UYARANLARA DUYARLI BİYOMALZEMELER

Uyaranlara duyarlı biyomalzemeler yara mikroçevresindeki veya dışarıdan uygulanan fiziksel-kimyasal değişikliklere renk değişimi, şişme, yapısal parçalanma veya ilaç salımı ile yanıt verir. pH değişimi iyonlaşma ve renk yanıtını; sıcaklık faz veya hacim değişimini; bakteriyel enzimler bağlayıcıların parçalanmasını; ROS artışı oksidasyona duyarlı bağların kırılmasını; ışık fototermal veya fotokimyasal tedaviyi; elektriksel uyarım ise iletken ağda yük aktarımını tetikleyebilir. Bu sistemlerin temel avantajı tedavinin yara mikroçevresine göre uyarlanmasıdır. Ancak uyarının özgül olmaması istenmeyen salıma neden olabileceğinden sensör ölçümüyle doğrulanan elektronik kontrollü sistemler daha güvenli olabilir (Arafa et al., 2021; Wu et al., 2025).

5.8. BİYOMALZEME SEÇİMİNİN SENSÖR PERFORMANSINA ETKİSİ

Biyomalzemenin sıvı emme, şişme, gözeneklilik ve yüzey kimyası gibi özellikleri; biyobelirteçlerin sensöre taşınmasını ve sensörün elektrokimyasal yanıtını etkiler. Yeterli sıvı emilimi ve uygun gözenek yapısı, yara eksüdasındaki biyobelirteçlerin sensöre difüzyonunu kolaylaştırırken kontrolsüz şişme; hidrojel-elektrot arayüzünün geometrisini, direncini ve iletkenliğini değiştirerek kalibrasyon kaymasına neden olabilir (Lee et al., 2026; Whitney et al., 2024). Proteinlerin ve diğer eksüda bileşenlerinin malzeme veya sensör yüzeyine özgül olmayan biçimde bağlanması ise biyolojik kirlenmeye yol açarak sinyal kararlılığını bozabilir, duyarlılığı ve seçiciliği azaltabilir (Li et al., 2021).Bu nedenle sensörün güvenilirliği değerlendirilirken yara eksüdasının sensöre taşınma hızı, hedef biyobelirtecin polimer yapı içindeki hareketi ve malzemeyle etkileşimi, hidrojel–elektrot ve elektrot–doku temaslarının sürekliliği, sterilizasyonun ölçüm performansına etkisi ve yapıştırıcının yara çevresindeki sağlıklı deriyle uyumu bir bütün olarak ele alınmalıdır (Bennett et al., 2024; Gao et al., 2021; Matsumura et al., 2014).

Aynı polimer kullanılsa bile tabaka kalınlığı, gözenek boyutu ve çapraz bağlanma yoğunluğundaki değişiklikler; analit difüzyonunu, yanıt süresini, duyarlılığı ve ölçüm aralığını değiştirebilir (Lee et al., 2026; Trzebinski et al., 2011). Bu nedenle sensör doğrulaması yalnızca standart tampon çözeltilerinde yapılmamalı; sensörün yerleştirileceği nihai biyomalzeme içinde, yapay eksüda veya serum gibi karmaşık ortamlarda ve mümkünse klinik yara eksüdası kullanılarak da tekrarlanmalıdır (Gao et al., 2021). Biyomalzemenin, sıvı taşıma yolunun ve sensör arayüzünün eş zamanlı tasarlanması; bileşenler arasındaki değişkenliğin azaltılmasına ve daha kararlı, üretim açısından tekrarlanabilir platformların geliştirilmesine katkı sağlayabilir (Gao et al., 2021; Ge et al., 2023; Trzebinski et al., 2011).

6. KLİNİK KULLANIMA GEÇİŞTE SINIRLILIKLAR

Akıllı yara örtülerinin önemli bir bölümü hala laboratuvar şartlarında veya hayvan modellerinde değerlendirilmekte; insanlarda gerçekleştirilen klinik çalışmalar ise sınırlı kalmaktadır (Wang et al., 2022; Wu et al., 2025). Klinik yaralar; etiyoloji, eksüdanın miktarı ve bileşimi, mikrobiyal yük, pH, doku derinliği, anatomik konum ve diyabet ya da dolaşım bozukluğu gibi eşlik eden hastalıklar bakımından büyük değişkenlik göstermektedir (Falanga et al., 2022). Bu nedenle tampon çözeltilerde veya basitleştirilmiş yapay ortamlarda yüksek duyarlılık gösteren bir sensör; proteinler, hücresel kalıntılar, kan ürünleri, mikroorganizmalar ve tedavi kalıntıları içeren gerçek yara eksüdasında aynı analitik performansı göstermeyebilir. Sensörlerin kullanılacağı yara örtüsü içerisinde, yapay eksüda veya mümkünse klinik yara eksüdası kullanılarak doğrulanması gerekir (Gao et al., 2021; Li et al., 2021).

Biyolojik kirlenme ve özgül olmayan protein bağlanması; sensör sinyalinde kaymaya, duyarlılık ve seçiciliğin azalmasına ve uzun dönem kararlılığın bozulmasına neden olabilir (Li et al., 2021; Wang et al., 2022). Sterilizasyon işlemleri de enzim, antikor veya diğer biyolojik tanıma elemanlarının etkinliğini ve sensörün elektrokimyasal yanıtını değiştirebildiğinden, sensör performansı sterilizasyondan sonra

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yeniden doğrulanmalıdır (Bennett et al., 2024). Ayrıca yara örtüsünün dokuya kararlı biçimde temas etmesi ve çıkarılırken yeni oluşan epitele veya yara çevresindeki sağlam deriye zarar vermemesi gerekir. Farklı yara örtüsü yapıştırıcılarının derinin dış tabakası üzerinde farklı düzeylerde hasar oluşturabildiği gösterilmiştir (Matsumura et al., 2014). Aktif elektronik sistemlerde sıvı girişine karşı yalıtım, elektriksel güvenlik, enerji kaynağı güvenliği, kablosuz bağlantının güvenilirliği ve elektromanyetik uyumluluk, cihazın kullanım ortamına uygun IEC 60601-1 ve IEC 60601-1-2 standartları doğrultusunda değerlendirilmelidir (International Electrotechnical Commission [IEC], 2020a, 2020b). Tek kullanımlık sistemlerde maliyet ile elektronik ve tıbbi atık yükü; yeniden kullanılabilir sistemlerde ise doğrulanmış temizleme ve dezenfeksiyon işlemleri ile çapraz kontaminasyonun önlenmesi önem taşımaktadır (U.S. Food and Drug Administration [FDA], 2015; World Health Organization [WHO], 2024a, 2024b).

Klinik kullanımdan önce hangi sensör değerlerinin uyarı oluşturacağı, ölçüm sonuçlarının nasıl yorumlanacağı ve tedavi algoritmasının hangi koşullarda devreye gireceği klinik çalışmalarla belirlenmelidir. Yanlış pozitif veya yanlış negatif sonuçlara karşı güvenlik sınırları, manuel müdahale seçeneği ve yazılımın doğrulama süreci IEC 62304 standardı kapsamında açık biçimde tanımlanmalıdır (IEC, 2015; Wang et al., 2022; Wu et al., 2025). Kablosuz olarak aktarılan ölçüm verileri kişisel sağlık verisi niteliği taşıyabileceğinden; güvenli veri iletimi, erişim yetkilendirmesi, veri bütünlüğü ve mahremiyet gereklilikleri tasarım sürecinin bir parçası olmalıdır (Kişisel Verileri Koruma Kurumu [KVKK], 2024; FDA, 2026). Biyomalzeme, sensör, yazılım ve ilaç salım modülünü tek üründe birleştiren sistemlerin düzenleyici sınıflandırması ise ürünün amaçlanan kullanımına ve temel etki mekanizmasına göre değişebilir (Avrupa Parlamentosu ve Avrupa Birliği Konseyi, 2017). Klinik kullanıma geçmeden önce üretim partileri arasındaki tekrarlanabilirlik, raf ömrü, ambalaj ve steril bariyer bütünlüğü, sterilizasyon sürecinin geçerliliği ve sterilizasyon sonrasındaki sensör performansı; ISO 11135, ISO 11137-1, ISO 11607-1 ve ISO 13485 standartları doğrultusunda nihai ürün üzerinde doğrulanmalıdır (Bennett et al., 2024; International Organization for Standardization [ISO], 2014, 2016, 2019, 2025).

7. SONUÇ VE GELECEK PERSPEKTİFLER

Akıllı yara bakım teknolojileri, yara örtülerini pasif koruyucu materyallerden biyobelirteçleri algılayan, veriyi kablosuz ileten ve gerektiğinde tedavi uygulayan aktif platformlara dönüştürmektedir. pH, sıcaklık, nem, empedans, oksijen ve metabolitlerin çoklu izlenmesi, yara durumunun tek bir parametreye göre değerlendirilmesinden daha güvenilir bir yaklaşım sunar. Hidrojeller, nanolifler, doğal ve sentetik polimerler, iletken malzemeler ve biyobozunur elektronikler bu platformların temel yapı taşlarıdır.

Gelecekte sensör, biyomalzeme ve tedavi modülünün ayrı ayrı değil, bütün bir sistem olarak tasarlanması gerekecektir. Modüler üretim, baskılı elektronikler, enerji üreten sistemler, geçici elektronikler ve akıllı telefon tabanlı karar desteği, hasta başı ve evde yara bakımını güçlendirebilir. Makine öğrenmesi, çoklu sensör verilerinden kişiye özgü iyileşme örüntülerini tanımada yararlı olabilir; ancak algoritmaların açıklanabilir, güvenli ve klinik olarak doğrulanmış olması gerekir.

Akıllı yara örtülerinin klinikte kullanılabilmesi için öncelikle kapsamlı hayvan deneyleri ve iyi planlanmış insan çalışmaları yapılmalıdır. Ayrıca sensörler, yara eksüdasını taklit eden standart modellerde denenmeli, sonuçları güvenilir referans yöntemlerle karşılaştırılmalı ve üretim süreçleri ilgili düzenlemelere uygun olmalıdır.En başarılı sistemlerin en fazla sensörü taşıyan değil, klinik kararı değiştirecek kadar güvenilir veriyi hasta konforu, maliyet ve kullanım kolaylığıyla dengeleyenlerin olması beklenmektedir.

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FROM STANDARDIZED BENCHMARKS TO CURRICULUM DESIGN: THE 2016 SAT ESSAY FORMAT - IMPLICATIONS FOR ANALYTICAL WRITING INSTRUCTION

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ABSTRACT

In contemporary global higher education, the definition of academic writing proficiency is undergoing a critical transition away from impressionistic, opinion-based persuasion toward text-bound, evidence-based analytical mastery. This article examines the theoretical and pedagogical implications of this paradigm shift by analyzing the historical restructuring of international standardized benchmarks, specifically focusing on the transition from the 2010 to the 2016 SAT essay framework. While the legacy 2010 model prioritized subjective fluency and inward-facing reflection, the restructured 2016 framework establishes a highly disciplined, outward-looking architectural blueprint that evaluates three independent, co-equal dimensions: reading comprehension, rhetorical analysis, and structural writing precision. By exploring the mechanical and stylistic constraints embedded within this modern assessment paradigm, this paper demonstrates how international testing benchmarks can be strategically leveraged to modernize domestic writing curricula. Furthermore, this study proposes an integrated four-component pedagogical framework—combining authentic materials, evidence-based writing, structured writing, and precision writing—to bridge the gap between standardized evaluation metrics and the rigorous linguistic demands of English for Specific Purposes (ESP) and advanced professional discourse. Ultimately, this article establishes the macro-level theoretical foundations necessary for systematic curriculum design, offering educators a reproducible model to cultivate globally competitive, domain-specific literacy in tertiary education.

Keywords: Analytical Writing Instruction; Curriculum Design; 2016 SAT Framework; English for Specific Purposes (ESP); Text-Bound Objectivity; Standardized Benchmarks

1. Introduction

In contemporary global higher education, the definition of academic writing proficiency has undergone a significant paradigm shift. Historically, secondary and tertiary writing curricula have frequently prioritized expressive fluency and personal persuasion—skills centred on the writer's ability to articulate an opinion and defend it using subjective narratives or isolated anecdotes. While this impressionistic model fosters initial linguistic confidence, it frequently fails to equip learners with the rigorous cognitive tools required for advanced academic and professional discourse. Modern academic environments demand an objective, evidence-based rhetorical competence where the writer does not merely express a stance, but systematically deconstructs complex texts and handles textual data with precision.

A profound structural manifestation of this pedagogical evolution can be seen in the historical transition of international standardized benchmarks, most notably the restructuring of the Scholastic Assessment Test (SAT) essay format in 2016. By abandoning the 2010 prompt model—which favoured open-ended, opinion-driven persuasion—and adopting a strict, text-bound analytical framework, the assessment redefined the architecture of high-stakes writing tasks. This transition signals a broader international recognition that mastery of academic writing requires an explicit intersection between critical reading comprehension and structured rhetorical critique.

For educators navigating the design of English for Specific Purposes (ESP) and academic writing curricula, this assessment shift offers vital pedagogical implications. Far from being a mere testing hurdle, international frameworks like the 2016 SAT essay format provide a highly disciplined structural scaffolding. This scaffolding forces learners to move past surface-level grammatical rules and engage

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deeply with the mechanical and stylistic constraints of a text. This alignment directly mirrors foundational approaches to professional genre pedagogy, which emphasize that effective instruction must bridge the macro-level communicative goals of a text with the strict, micro-level linguistic conventions demanded by professional and academic benchmarks (Përgjegji, 2016a). Consequently, exploring the theoretical mechanics of the 2016 format establishes a vital blueprint for internationalizing domestic writing curricula to foster advanced analytical writing mastery.

2. Theoretical Framework: The 2010 vs. 2016 Paradigm Shift

To understand the pedagogical implications of modern standardized benchmarks, it is first necessary to isolate the structural and cognitive divergence between the historical 2010 SAT essay model and the restructured 2016 analytical framework. Although both versions assessed students' ability to construct coherent written responses under standardized conditions, they positioned the writer differently in relation to the production of knowledge and argument. The 2010 model primarily required the student to take a position and develop an argument, whereas the 2016 model required the student to interpret an existing argument and analyze the rhetorical processes through which it was constructed (College Board, 2015; College Board, 2016). This distinction represents more than a modification of task instructions. It reflects a shift from primarily generative argumentative writing toward evidence based analytical writing.

The difference can therefore be understood as a change in the cognitive direction of the writing process. In the 2010 model, the movement was largely from the learner toward the topic. The student encountered a proposition, established a position, generated reasons, retrieved relevant examples, and organized those elements into a persuasive response. In the 2016 model, the movement was reversed. The student began with an externally provided text and moved from comprehension toward evidence identification, reasoning analysis, rhetorical interpretation, and written explanation (College Board, 2015). The source text consequently became the primary evidentiary environment within which the student's analytical response had to operate.

This distinction is particularly important from a curriculum design perspective because it separates two different instructional objectives. The first concerns the ability to generate and defend a position, while the second concerns the ability to identify, interpret, and explain the architecture of an existing argument. Both capacities are valuable in academic writing, but they require different cognitive operations and therefore different forms of instructional scaffolding (Hyland, 2007; Sweller et al., 2011).

2.1. The 2010 Persuasive Model: Subjective Fluency

The 2010 SAT essay model was built upon a foundation of prompt dependent, opinion based persuasion. Learners were provided with a brief, abstract philosophical quotation or scenario followed by a broad question. A typical prompt could ask students to consider whether adversity is necessary for personal growth or whether individuals benefit from conformity or difference. The writing task then instructed students to take a definitive position and support it using evidence drawn from literature, historical events, personal experience, observation, or other areas of knowledge (College Board, 2010). The underlying writing process can therefore be represented as:



The central intellectual movement was inward facing because the learner was responsible for generating the principal position and determining how that position should be developed. The student had to retrieve relevant knowledge, select supporting examples, establish logical relationships between ideas, and organize the resulting material into a coherent persuasive structure. The principal cognitive challenge was therefore one of rapid argument generation combined with rhetorical organization.

This structure provided legitimate opportunities for developing important writing abilities. Students were required to formulate a thesis, establish reasons, select supporting material, organize paragraphs, and maintain a coherent line of reasoning. The model consequently cultivated rhetorical agency, particularly the ability to articulate and defend a position under time constraints (College Board, 2010).

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However, the structure also created a significant distinction between argument generation and textual analysis. Because the supporting material could be drawn from a broad range of sources, the student's relationship with evidence was comparatively flexible. Evidence functioned primarily as material selected by the writer to support a position rather than as textual data that had to be systematically interpreted. The task therefore permitted students to rely heavily on previously acquired knowledge, rehearsed examples, or familiar argumentative structures.

From a cognitive perspective, this flexibility increased the role of retrieval and composition. The learner had to determine what to say and how to say it, but did not necessarily have to demonstrate how another writer's evidence, reasoning, and rhetorical choices functioned within a specific textual context. The task thus foregrounded the student's capacity to produce an argument rather than to reconstruct the architecture of an argument already present in a source (Sweller et al., 2011).

This distinction is pedagogically significant. A learner can demonstrate considerable fluency in producing a persuasive response while still experiencing difficulty when required to read a complex text, identify its central claims, distinguish evidence from reasoning, and explain the rhetorical relationship between an author's choices and the intended audience (Hyland, 2007). Consequently, the 2010 model can be understood as emphasizing subjective fluency and generative argumentation, whereas the 2016 model explicitly foregrounded textual evidence and analytical interpretation. (College Board, 2010; College Board, 2016)

2.2. The 2016 Analytical Framework: Text-Bound Objectivity

The 2016 restructuring of the assessment introduced a fundamentally different relationship between the writer and the source material. The open ended philosophical prompt was replaced by a substantial argumentative source text, and the student was required to analyze how the author constructed an argument rather than develop an independent position on the issue. The task directed students toward the author's use of evidence, reasoning, and stylistic or persuasive elements (College Board, 2015; College Board, 2016). The student was therefore not primarily being evaluated as an advocate for a personal position, but as an analyst of an existing rhetorical construction. The resulting cognitive sequence can be represented as:



This sequence transformed the writing task into an outward facing and highly constrained analytical exercise. The source text became the principal evidentiary environment, and the student's responsibility was to establish a defensible interpretation of how the author's argument functioned. As a result, the student's relationship with evidence changed fundamentally. Evidence was no longer something the student could simply retrieve to illustrate a personal position. It had to be located within the source, interpreted in context, and connected to an explanation of the author's rhetorical strategy (College Board, 2016).

The central question consequently changed from “What do you think, and how can you support your position?” to “How does the author construct and strengthen the argument?” This change is fundamental because it separates personal agreement from rhetorical analysis. A student could disagree completely with the author's position and still produce a successful analytical response if the student accurately explained how the author used evidence, reasoning, stylistic choices, and persuasive techniques to influence the audience.

The redesigned assessment therefore placed greater emphasis on the transformation of textual information into analytical explanation. The learner first had to comprehend the source, then identify relevant textual evidence, determine the function of that evidence, examine the reasoning connecting evidence to claims, recognize rhetorical choices, and finally convert these observations into a coherent written analysis. The process required the student to move repeatedly between reading and writing rather than treating them as separate abilities (College Board, 2015; Hyland, 2007).

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This structural shift can be understood as a form of text bound objectivity. The writer's interpretation remained independent and intellectually active, but the available evidentiary field was constrained by the source text. The student could not substitute personal experience for textual evidence or replace analysis with personal agreement. The source established the boundaries within which the analytical response had to be constructed (College Board, 2016).

As visualized below in Figure 1, this paradigm shift systematically alters the writing process across four primary dimensions: core prompt objectives, evidence validation methods, cognitive orientations, and evaluation architectures. Rather than encouraging an inward reflection on personal perspective, the modern framework demands an outward-looking critical critique where the source text serves as objective empirical data.

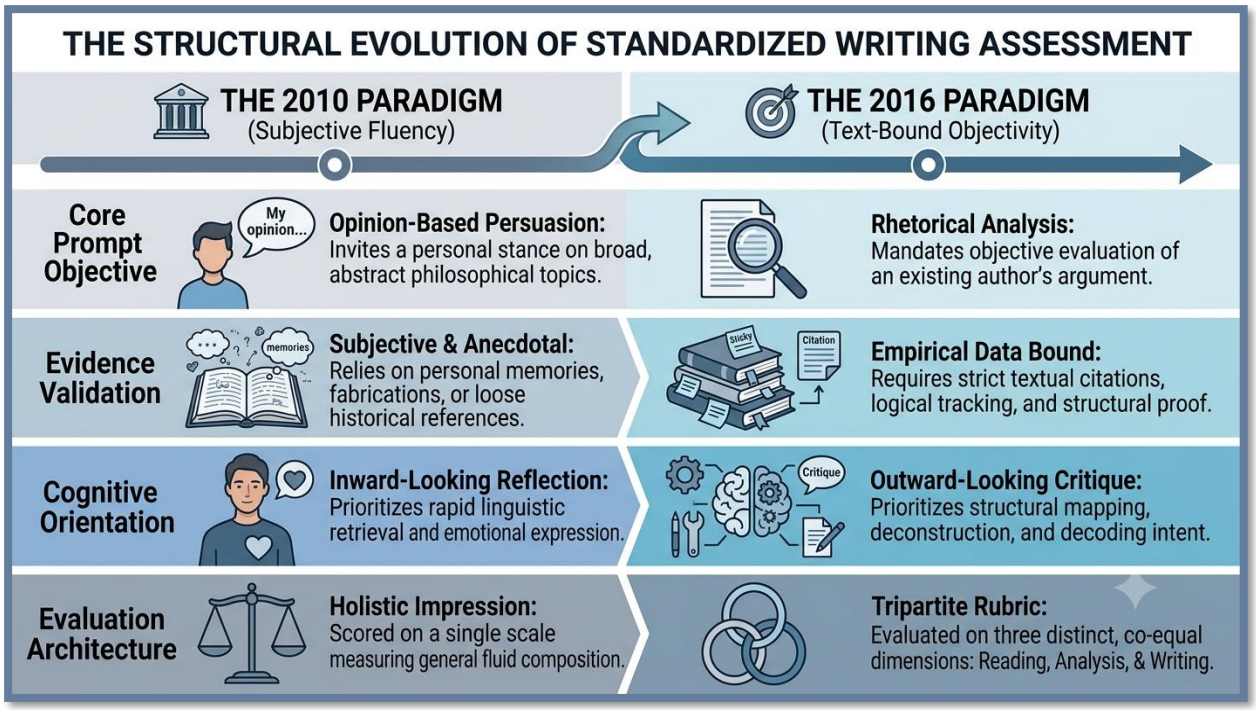


Figure 1. *The Structural Evolution of Standardized Writing Assessment: A Comparative Analysis of the Core Objectives, Cognitive Orientations, and Evaluation Architectures between the 2010 and 2016 SAT Essay Paradigms.*

The comparison demonstrates that the principal transformation did not occur simply at the level of essay format. It occurred at the level of the relationship among cognition, evidence, and writing. The 2010 model primarily asked learners to construct an argument from available knowledge, while the 2016 model asked them to make the structure of another argument visible through textual evidence and analytical explanation. The structural transformation therefore moves the learner through two distinctly different rhetorical positions. In the 2010 model, the student primarily operates as an advocate who constructs and defends a position. In the 2016 model, the student operates as an analyst who examines how another writer has constructed a position. This change has direct implications for curriculum design because each rhetorical position requires different forms of cognitive scaffolding.

2.3. From Holistic Performance to a Tripartite Evaluation Architecture

To understand how these cognitive tasks translate into measurable educational benchmarks, it is necessary to examine the specific criteria utilized to judge student output. The 2016 rubric formalized the structural shift by separating performance into three dimensions: Reading, Analysis, and Writing. These dimensions are particularly significant from a curriculum design perspective because they make visible three stages of the analytical writing process that are frequently treated as a single, undifferentiated skill.

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➢ **The Reading dimension** establishes the foundation of the process. Before the learner can analyze an argument, the learner must accurately comprehend what the author is claiming and how the text develops that claim. Reading therefore functions not as a preliminary activity external to writing, but as the first cognitive stage of analytical composition. The learner must identify relevant information, distinguish major claims from supporting details, and recognize the relationship between textual components.

➢ **The Analysis dimension** represents the central intellectual operation of the redesigned task. Here, the learner must explain how the author uses evidence, reasoning, stylistic choices, and persuasive techniques to construct an argument. This requires more than identifying a rhetorical device or quoting a sentence. The learner must establish a functional relationship between a textual choice and its effect within the argument. For example, identifying a statistical reference is descriptive; explaining how the statistic increases the perceived credibility of the author's claim is analytical.

➢ **The Writing dimension** then requires the learner to transform these analytical observations into an organized and controlled written response. Cohesion, organization, precision, sentence control, and formal academic style become the linguistic mechanisms through which the cognitive analysis is communicated. Writing therefore functions as the surface realization of an underlying analytical process (College Board, 2016; Hyland, 2007).

As mapped out below in Figure 2, each dimension isolates a specific cognitive challenge and establishes an explicit pedagogical priority. By unpacking these three pillars, the framework provides a transparent blueprint showing how a learner transitions from objective text comprehension to rhetorical critique and finally to disciplined written execution.

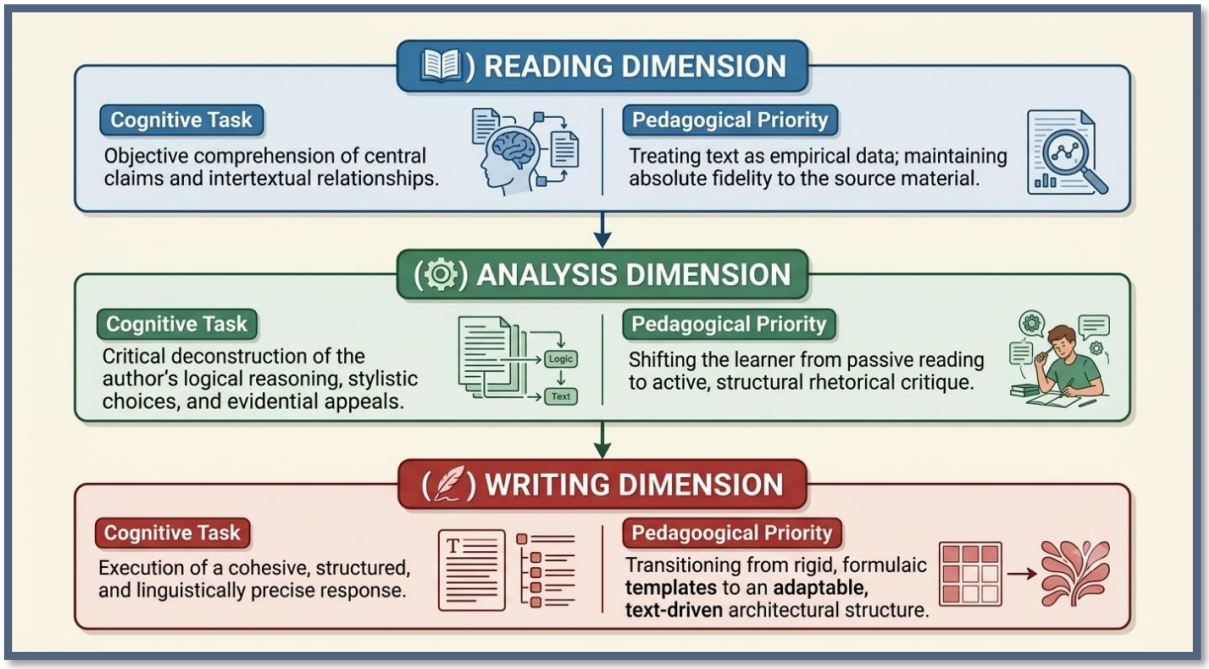
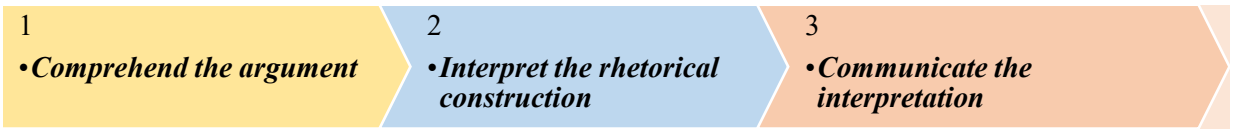


Figure 2. *The Tripartite Scoring Architecture of the 2016 Assessment Rubric: A Visual Mapping of Core Cognitive Tasks and Pedagogical Priorities across the Three Interconnected Evaluation Dimensions*

Under this tripartite framework, text is no longer a passive springboard for personal reflection; it is a complex landscape of data that must be mechanically mapped and evaluated (Smith, 2003). The writer must identify the subtle machinery of the source text—such as specific lexical selections, emotional appeals, and statistical justifications—and explain their functional impact on the audience (College Board, 2016; Hyland, 2007). The relationship can be represented as: ***Reading → Analysis → Writing*** *or:*

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The tripartite architecture has important implications for curriculum development (Bazerman et al., 2018; Kellogg, 2008). If analytical writing can be evaluated through distinct but interconnected dimensions, instruction can similarly be decomposed into teachable stages. Learners can first be trained to identify claims and evidence, then to examine the relationship between evidence and reasoning, and finally to formulate analytical paragraphs that convert these observations into precise written explanations Hyland, 2007; Sweller et al., 2011). This framework also establishes an important distinction between **identification, explanation, and interpretation**. Identifying a rhetorical device does not in itself constitute analysis. The learner must explain what the author has chosen, determine how that choice functions within the argument, and interpret its significance for the intended audience (College Board, 2016). Analytical writing therefore requires movement from textual feature to rhetorical function and finally to analytical significance. This sequence can be operationalized as:



The learner identifies a textual or rhetorical feature, locates it within the argument, explains its immediate function, connects it to the author's broader reasoning, and interprets its significance for the intended audience. Such a sequence transforms an apparently complex writing skill into a series of observable cognitive operations that can be explicitly taught and progressively practiced Kellogg, 2008; Bereiter & Scardamalia, 2013). Under this tripartite framework, text is no longer a passive springboard for personal reflection. It becomes a structured evidentiary environment that must be systematically examined and interpreted. The writer must identify the mechanisms through which a source constructs meaning and authority, including lexical choices, emotional appeals, statistical evidence, examples, analogies, patterns of reasoning, and organizational decisions, and explain their functional contribution to the author's argument (College Board, 2016).

The theoretical significance of the 2016 framework therefore extends beyond the SAT itself. Its task architecture demonstrates how a standardized benchmark can make the cognitive components of analytical writing visible and, consequently, provide a potential model for curriculum design. The benchmark does not merely ask whether students can write an essay. It establishes an explicit relationship among reading, evidence, reasoning, rhetorical interpretation, and written communication. From this perspective, standardized assessment can serve not only as a mechanism for measuring performance but also as a source of curricular information (Bazerman et al., 2018). When an assessment separates reading comprehension, analytical reasoning, and written execution, it provides educators with a more detailed representation of the processes underlying successful academic writing. These processes can then be translated into instructional objectives and classroom practices (Hyland, 2007).

The transition from the 2010 to the 2016 model can consequently be interpreted as a movement between two complementary writing paradigms. The former foregrounds the learner's ability to generate and defend a position. The latter foregrounds the learner's ability to reconstruct and explain the architecture of an existing argument. The pedagogical value of the 2016 framework therefore lies not simply in its standardized structure, but in the explicit visibility it gives to the cognitive processes underlying analytical writing. This theoretical distinction provides the foundation for considering the broader relevance of the framework to English academic writing pedagogy. If the cognitive operations embedded in a standardized analytical task can be identified, separated, and taught systematically, then the assessment framework can extend beyond test preparation and become a potential scaffold for developing transferable academic and professional writing competence (Hyland, 2007; Basturkmen, 2010)..

3. Relevance to English Academic Writing Pedagogy

The theoretical shift from subjective expression to text-bound analysis carries profound implications for contemporary English academic writing instruction, particularly within ESP and higher education contexts. When writing pedagogy relies heavily on raw input without demanding structural deconstruction, learners often struggle to transition from general communicative fluency to professional-grade academic discourse (Bazerman et al., 2018; Kellogg, 2008). The 2016 SAT essay framework addresses this gap by transforming the writing process from an act of unstructured composition into an exercise in architectural precision (College Board, 2016).

By requiring students to isolate an author's logical reasoning, evidential appeals, and stylistic elements, the framework forces learners to treat language as a deliberate, mechanical tool. This structural discipline is highly transferable to specialized fields (Bereiter & Scardamalia, 2013; Bazerman et al., 2018). For instance, in domains like military, legal, or medical writing, the primary objective is rarely to express personal sentiments; rather, it is to interpret complex data and convey information with absolute clarity and stylistic constraint. This alignment underscores why academic writing instruction must move past generic essay templates and instead focus on the main approaches to teaching writing for professional purposes, ensuring that students learn to balance macro-level communicative intent with strict, domain-specific text conventions (Basturkmen, 2010; Brockman et al., 2010; Përgjegji, 2016a).

Furthermore, the analytical rigor demanded by text-bound frameworks alters how vocabulary and style are taught. Rather than treating vocabulary as a memorized list of lexical items, it forces students to analyze how specific word choices alter the tone, urgency, or authoritative stance of a text. This level of rhetorical awareness is crucial for navigating challenging linguistic issues related to vocabulary and style in specialized discourse, where precise terminology and syntactic structure directly dictate the professionalism and efficacy of the text (Përgjegji, 2018). Cultivating this awareness ensures that learners do not just mimic academic structures, but internalize the cognitive mechanisms required to produce highly objective, analytical prose.

3.1. The Interdisciplinary Value of Stylistic Adaptability

A core contribution of the 2016 analytical model is its focus on *stylistic adaptability*. Students cannot merely memorize a static set of formal buzzwords; they must dynamically adapt their vocabulary to match the technical reality of the source text. This flexibility forms the cornerstone of English for Specific Purposes (ESP). For instance, when analyzing legal frameworks, a student must master structural precision, maintaining absolute consistency in syntactic choices to eliminate ambiguity (Përgjegji, 2016b). Conversely, when handling medical exposition, the cognitive task shifts toward high density and precision, requiring the student to accurately track diagnostic and physiological descriptions (Përgjegji, 2016c).

By using the 2016 assessment model as a pedagogical tool, writing instructors teach students how to read a text as an insider. The writer stops asking, *"What do I think about this topic?"* and begins asking, *"What linguistic mechanisms make this specific text authoritative within its professional domain?"* This pedagogical shift establishes an explicit framework for developing domain-specific literacy.

4. Internationalization of Writing Curricula and Framework Mastery

Integrating international assessment benchmarks into domestic writing curricula serves as a powerful catalyst for curriculum modernization. Standardized frameworks like the 2016 SAT essay rubric offer a universal language of evaluation that transcends regional educational boundaries (College Board, 2016; Bazerman et al., 2018). When higher education institutions align their instructional methodologies with these rigorous international standards, they provide students with a cross-linguistic blueprint for academic success (Basturkmen, 2010; Bazerman et al., 2018).

Mastering an international framework requires shifting the instructional focus from rote grammar drill-work to the strategic management of a text. Students must learn to approach a source text not as passive

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readers, but as analytical investigators (Bereiter & Scardamalia, 2013; Kellogg, 2008). This methodology equips learners with a repeatable, systematic process for handling complex academic reading and writing tasks across various disciplines (Bazerman et al., 2018):

- **Deconstructive Analysis:** Breaking down external texts to map out how arguments are structurally anchored and sustained.
- **Objective Synthesis:** Integrating external textual data into one's own writing without distorting the original source context or introducing personal bias.
- **Structural Cohesion:** Organizing analytical insights into a disciplined, logical sequence that adheres to international academic standards.

By embedding these structural priorities into local writing programs, educators ensure that students achieve a level of analytical mastery that makes them globally competitive, preparing them to seamlessly participate in international academic and professional discourses (Basturkmen, 2010; Bazerman et al., 2018).

4.1. Curriculum Synthesis: Theoretical Foundations of an Integrated Framework

To implement these international benchmarks effectively, domestic curricula must move past superficial testing drills and instead deploy a comprehensive, multi-dimensional instructional model. We propose an integrated framework constructed upon four co-equal pedagogical pillars, adapting the core principles established by (Përgjegji, Gjoni 2026; Basturkmen, 2010):

1. **Authentic Materials:** Moving away from simplified textbook prose and anchoring writing tasks in real-world editorials, historical speeches, and field-specific documents. Exposure to unsimplified language forces students to grapple with authentic syntactic density and genuine rhetorical situations (Basturkmen, 2010; Hyland, 2007).
2. **Evidence-Based Writing:** Mandating that every claim generated by the student be explicitly anchored to text-bound empirical data. This eliminates speculative, unverified assumptions and trains the writer to maintain absolute fidelity to the source material(College Board, 2016; Kellogg, 2008).
3. **Structured Writing:** Requiring strict adherence to organizational architecture. This macro-level discipline ensures that transitions, paragraph layout, and argument progression are treated as logical extensions of the analysis rather than random aesthetic choices(Hyland, 2007; Bazerman et al., 2018).
4. **Precision Writing:** Focusing intensely on micro-level linguistic choices. Students are trained to use precise, specialized terminology while cutting rhetorical fluff, ensuring that the stylistic tone matches the formal standards of international academic genres (Basturkmen, 2010; Hyland, 2007).

By organizing a writing curriculum around this four-component pedagogical framework, institutions bridge the gap between testing constraints and long-term academic utility (Përgjegji, Gjoni, 2026). The 2016 SAT essay rubric acts as an ideal diagnostic tool within this model, as its separate metrics for reading, analysis, and writing provide clear, measurable feedback on how well a student handles each of these crucial linguistic domains.

5. Conclusion

The transition from the 2010 to the 2016 SAT essay format represents more than an administrative change in standardized testing. It reflects a broader recognition that advanced academic writing is fundamentally a text-bound, analytical activity. While the 2010 model emphasized subjective fluency through opinion-based persuasion, the 2016 framework required students to comprehend an external argument, evaluate its evidence and reasoning, examine its rhetorical construction, and communicate their interpretation through disciplined writing. Its significance therefore lies not only in the product students produced, but also in the cognitive processes required to produce it.

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The comparison demonstrates two distinct approaches to knowledge and evidence. The 2010 framework positioned students primarily as advocates who developed a position and supported it with examples. The 2016 framework repositioned them as analysts who examined how another writer constructed and supported an argument. This shift from argument generation to argument analysis makes the relationship among reading, evidence, reasoning, and writing more explicit. Analytical writing thus emerges not as an isolated linguistic product, but as the outcome of interconnected cognitive processes.

The 2016 framework also highlights the importance of distinguishing Reading, Analysis, and Writing. Linguistic proficiency alone does not guarantee effective academic performance: students may have strong grammatical knowledge yet struggle to identify relevant evidence, distinguish evidence from reasoning, or explain rhetorical choices. Conversely, analytical reasoning must be expressed through coherent organization, precise vocabulary, controlled syntax, and an appropriate academic register. The framework therefore offers a useful bridge between cognitive processing and linguistic realization.

For academic writing instructors and curriculum designers, this perspective suggests moving beyond grammatical instruction and open-ended writing toward systematic text analysis. Students can be trained to identify claims and evidence, trace reasoning, recognize rhetorical choices, interpret their functions, and transform these observations into coherent analytical responses. This makes analytical writing more visible, teachable, and assessable.

The approach is particularly relevant to English for Specific Purposes (ESP) and professional writing. In specialized contexts, writers frequently work with existing institutional, disciplinary, or professional texts. Their task is to interpret information accurately, preserve evidentiary integrity, establish logical relationships, and communicate conclusions according to disciplinary conventions. The analytical orientation of the 2016 framework can therefore help develop cognitive and linguistic habits essential to specialized discourse.The implications also extend to curriculum internationalization. International benchmarks can serve not only as measures of performance but also as reference frameworks for curriculum development. By making their cognitive and linguistic demands explicit, educators can translate them into learning outcomes, instructional activities, and assessment criteria. The benchmark consequently becomes a pedagogical resource rather than merely an external standard.

The four-component framework proposed in this article extends this principle by linking authentic materials, evidence-based writing, structured writing, and precision writing. Authentic materials expose learners to real-world discourse; evidence-based writing establishes the relationship between claims and support; structured writing develops logical organization; and precision writing strengthens linguistic control. Together, these components create a pathway from exposure to authentic discourse toward increasingly controlled analytical production.

Standardized assessment, therefore, need not be viewed solely as a constraint. Its internal architecture can reveal competencies valued across academic and professional contexts. The 2016 SAT framework is particularly relevant because its emphasis on reading, analysis, evidence, reasoning, and writing reflects skills transferable beyond the test itself. The aim, however, is not to reproduce the 2016 SAT essay as a universal curriculum, but to extract and adapt its underlying principles to different educational, disciplinary, and professional contexts.

Ultimately, the transition from the 2010 to the 2016 SAT essay illustrates a broader reconceptualization of writing proficiency. Effective academic writing requires more than grammatical accuracy, vocabulary range, or personal expression. It requires the ability to engage critically with existing knowledge, evaluate evidence, understand how arguments are constructed, recognize the effects of rhetorical choices, and communicate conclusions precisely. Writing proficiency therefore emerges as both a linguistic and cognitive competence.

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SOCIAL ENTERPRISE MANAGEMENT AND ITS IMPACT ON SUSTAINABLE COMMUNITY DEVELOPMENT: EVIDENCE FROM ROMANIA IN A EUROPEAN PERSPECTIVE

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ABSTRACT

Purpose: Social enterprises combine economic activity with an explicit social mission and have become increasingly relevant in communities affected by economic inequality, demographic change, labour-market exclusion, limited access to services, and territorial disparities. Their contribution to sustainable community development depends not only on the social objectives they pursue but also on their capacity to mobilize resources, make strategic decisions, maintain financial continuity, engage stakeholders, innovate, and use evidence about social impact. This study examines the relationship between social enterprise management and sustainable community development in Romania and places the Romanian experience within a broader European institutional context.

Design/methodology/approach: The study adopts a conceptual and descriptive research design that integrates a review of the relevant literature with secondary administrative and statistical evidence concerning Romanian social enterprises. Based on this analysis, an empirical model is developed for subsequent testing through a mixed-method organizational study. Social enterprise management is conceptualized through six interconnected dimensions: strategic decision-making, organizational governance, stakeholder relationships, financial sustainability, innovation, and social impact assessment. The proposed model examines organizational capacity and sustained social value creation as sequential mediating mechanisms between management and sustainable community development, while institutional and territorial conditions are treated as contextual influences.

Findings: Administrative evidence indicates that 2,936 organizations had obtained social enterprise certification in Romania by the end of 2024, of which 1,780 retained valid certification. This corresponds to a certification retention ratio of approximately 60.6%. The difference between cumulative and valid certifications should not be interpreted as organizational failure, but it raises relevant questions concerning organizational continuity and the conditions under which formally recognized social enterprises sustain their activities and mission over time. The territorial distribution also reveals a relatively balanced presence in urban and rural areas, although the operating conditions of organizations in these environments differ substantially.

Research implications: The paper proposes a sequential framework in which managerial practices strengthen organizational capacity, organizational capacity facilitates sustained social value creation, and sustained social value contributes to community development. Institutional and territorial conditions may strengthen or constrain these relationships. The framework provides the basis for subsequent empirical testing using survey, qualitative, and organizational data.

Practical implications: The study suggests that policies supporting the social economy should extend beyond enterprise creation and certification toward managerial capacity development, financial resilience, stakeholder collaboration, impact management, and adaptation to territorial conditions.

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Originality/value: The paper connects internal management processes with community-level outcomes by distinguishing organizational sustainability from sustainable community development and by identifying organizational capacity and sustained social value creation as intermediate mechanisms. The Romanian case is interpreted within the European context without assuming the existence of a uniform European model.

Keywords: social enterprise management; social entrepreneurship; sustainable community development; social economy; organizational capacity; social value creation; Romania; European perspective.

JEL Classification: L31, M10, O35, Q01, R11.

1. INTRODUCTION

Contemporary economic and social transformations have renewed interest in organizational models capable of combining economic activity with the creation of social value. Persistent inequalities, demographic change, labour-market exclusion, territorial disparities, pressure on public services, and uneven access to economic opportunities have exposed situations in which neither market mechanisms nor public intervention, when acting independently, fully address community needs. Social enterprises have acquired particular relevance within this context because they combine entrepreneurial activity with an explicit social purpose and direct a significant part of the value they create toward social or community objectives (Defourny & Nyssens, 2010; European Commission, 2020).

The European social enterprise landscape is heterogeneous. Different historical relationships among the state, market, civil society, cooperative movements, and welfare systems have generated considerable variation in legal forms, governance structures, financing arrangements, and fields of activity (Defourny & Nyssens, 2010; European Commission, 2020). Consequently, the contribution of social enterprises cannot be interpreted independently of the institutional environments in which they operate. European experience is therefore relevant less as a uniform benchmark than as a source of comparative evidence concerning different organizational and institutional configurations.

At organizational level, social enterprises face a persistent managerial challenge arising from the coexistence of economic and social objectives. Financial resources are necessary to maintain operations, retain employees, develop services, and respond to changing needs. At the same time, excessive emphasis on commercial objectives may weaken the social mission that provides the organization with its distinctive identity. Social enterprises can consequently be understood as hybrid organizations in which social and commercial logics coexist and must be continuously reconciled (Doherty et al., 2014; Battilana & Lee, 2014).

Governance becomes particularly important under these conditions. Social enterprises are accountable to multiple stakeholder groups, including beneficiaries, employees, volunteers, funders, investors, public authorities, customers, community organizations, and local partners. Their expectations do not necessarily converge. Ebrahim et al. (2014) identify accountability and mission drift as central governance challenges in hybrid organizations, illustrating why social enterprise management cannot be reduced to conventional resource administration.

The relationship between social enterprise activity and community development introduces a further level of complexity. The contribution of an organization cannot be assessed exclusively through immediate outputs such as the number of beneficiaries, services provided, or jobs created. Sustainable community development implies changes capable of enduring over time and may involve employment opportunities, social inclusion, access to services, participation, local cooperation, economic activity, and community resilience.

The existence of a social mission, however, does not guarantee such outcomes. Organizations pursuing comparable objectives can differ substantially in their ability to transform resources into durable social value. Strategic decisions affect organizational priorities and resource allocation. Governance influences accountability and mission protection. Financial management affects continuity. Stakeholder

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relationships provide access to knowledge, resources, legitimacy, and partnerships. Innovation supports adaptation to emerging needs, while social impact assessment can generate evidence for organizational learning and subsequent decision-making.

These dimensions suggest that management should be approached as a multidimensional organizational capability rather than as a set of independent administrative practices.

The external environment remains equally important. Social enterprises operate within legal frameworks, funding systems, labour markets, local administrations, support networks, and territorial economies that influence the resources and opportunities available to them. Managerial capacity can improve an organization's ability to respond to such conditions, but management does not operate independently of context.

Romania provides a relevant setting for examining these relationships. The development of its contemporary social economy reflects historical organizational traditions, post-socialist institutional transformation, European integration, national regulation, and the increasing role of European funding. Associations, foundations, cooperatives, mutual aid organizations, and newer organizational forms coexist within an ecosystem that continues to develop institutionally (Lambru & Petrescu, 2019).

One particularly important issue concerns the transition from enterprise establishment to organizational continuity. Access to project-based or external funding can support the creation and initial development of social enterprises, but temporary resources do not automatically generate organizational capabilities that persist once initial support declines. From the perspective of community development, the distinction is essential: successful implementation of a funded project is not equivalent to sustained organizational activity or durable community impact.

Although research on social entrepreneurship has expanded considerably, a relevant analytical gap remains between studies of internal organizational management and studies of broader community outcomes. Existing research has generated substantial knowledge about hybridity, governance, financing, social innovation, and mission management. Less straightforward is the question of how these managerial dimensions interact and through which mechanisms they are translated into sustained social value at community level.

This study addresses that issue by examining social enterprise management through six interconnected dimensions: strategic decision-making, organizational governance, stakeholder relationships, financial sustainability, innovation, and social impact assessment.

The central research question is: How and under what organizational, institutional, and territorial conditions can social enterprise management contribute to sustainable community development in Romania?

Three related questions guide the analysis: (1) How do managerial practices contribute to the organizational capacity required to pursue economic viability and social mission simultaneously? (2) Through what mechanisms can organizational capacity be translated into sustained social value and, subsequently, into community-level outcomes? (3) How do institutional and territorial conditions influence these relationships in the Romanian social enterprise ecosystem?

The contribution of the study is therefore not based on assuming a direct causal relationship between management and community development. Instead, it develops a mechanism-based framework in which organizational capacity and sustained social value creation connect managerial practices with broader community outcomes.

2. CONCEPTUAL AND THEORETICAL FRAMEWORK

2.1. Social enterprises as hybrid organizations

The theoretical foundation of the study begins with the hybrid character of social enterprises. Battilana and Lee (2014) describe hybrid organizing through the structures, processes, activities, and meanings that combine elements associated with different organizational forms. In social enterprises, economic and social logics coexist at the core of organizational identity.

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This dual orientation influences managerial decision-making. Economic viability provides the resources necessary for organizational continuity, while the social mission defines the purpose toward which those resources should be directed. The two objectives may reinforce one another when commercial activity supports mission-related interventions, but tensions emerge when financial priorities compete with beneficiary needs or social commitments.

Battilana et al. (2015) demonstrate that such tensions do not necessarily need to be eliminated. Under appropriate organizational arrangements, they may be managed productively. The relevant managerial problem is consequently not whether social enterprises should choose between economic and social performance, but how they can maintain sufficient economic resilience without displacing their social mission.

2.2. Social enterprise management as a multidimensional construct

This study conceptualizes social enterprise management through six interrelated dimensions: strategic decision-making, governance, stakeholder relationships, financial sustainability, innovation, and social impact assessment.

Strategic decision-making determines priorities, target beneficiaries, economic activities, resource allocation, organizational positioning, and responses to environmental change. In a social enterprise, strategic effectiveness cannot be assessed exclusively through financial outcomes; alignment between strategic choices and social mission is equally important.

Governance establishes how authority is distributed, how organizational decisions are monitored, which stakeholder interests are represented, and how the social mission is protected. Because social enterprises operate under multiple forms of accountability, governance mechanisms must reconcile expectations that may sometimes conflict (Ebrahim et al., 2014).

Stakeholder relationships constitute a form of relational capacity. Partnerships with beneficiaries, public authorities, nonprofit organizations, firms, educational institutions, funders, and other local actors can provide resources, information, legitimacy, referrals, infrastructure, and access to networks. Their relevance extends beyond communication because community outcomes are frequently generated through interactions among several organizations rather than by a single actor.

Financial sustainability refers to the capacity to mobilize and manage sufficient resources to maintain mission-related activities over time. It should not be equated with profit maximization. Revenue stability, funding diversification, reserves, organizational autonomy, and the capacity to withstand the loss of individual funding sources are more appropriate dimensions in the context of social enterprise.

Innovation captures the organization's capacity to develop or adapt services, processes, partnerships, and organizational arrangements in response to unmet or changing community needs. Its relevance extends beyond technological innovation and includes new forms of social and organizational action.

Social impact assessment closes the managerial learning cycle. Its value lies not only in demonstrating accountability to external stakeholders but also in generating information that can influence subsequent strategy, resource allocation, service design, stakeholder engagement, and innovation (Rawhouser et al., 2019; OECD, 2024).

The six dimensions interact. Financial resources affect the feasibility of strategic choices; governance shapes the way resources are allocated; stakeholder relationships influence access to local knowledge and resources; innovation depends on organizational and financial capacity; and impact evidence can alter future strategic decisions. Management is therefore conceptualized as a configuration of complementary capabilities rather than a collection of isolated practices.

2.3. Organizational capacity as an intermediate mechanism

The existence of managerial practices does not necessarily produce community outcomes directly. Their immediate influence is more plausibly observed in the organization's capacity to mobilize, coordinate, and adapt resources.

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Organizational capacity (OC) is therefore introduced as the first mediating construct in the proposed framework. It encompasses resource mobilization, human-resource capability, adaptive capacity, coordination, organizational learning, and the ability to maintain mission-oriented activities under changing conditions.

This distinction prevents managerial practices from being treated as direct causes of complex community-level changes. Effective strategy, governance, stakeholder management, financial sustainability, innovation, and impact management are expected to strengthen the organization's capacity to act. Whether that capacity ultimately produces community impact depends on the way it is translated into social value.

2.4. Sustained social value creation

Social value creation (SVC) represents the second mediating construct. It captures the extent to which organizational activity generates meaningful outcomes for beneficiaries and responds to unmet social or community needs.

The term sustained is important. A short-term intervention may create social value without generating durable effects. The framework therefore emphasizes the organization's ability to maintain socially valuable activities and outcomes over time.

Sustained social value may be reflected in improved access to services, employment and integration opportunities, strengthened participation, responses to unmet needs, development of local partnerships, or other mission-related outcomes.

2.5. Sustainable community development

Sustainable community development (SCD) constitutes the principal dependent construct.

It is conceptualized as multidimensional and encompasses three broad areas: economic development, including employment opportunities, local economic activity, and mobilization of local resources; social development, including inclusion, participation, access to needed services, and reduction of disadvantage; and community resilience, including cooperation among local actors, adaptive capacity, continuity of socially valuable activities, and the ability to respond collectively to changing needs.

Organizational sustainability and sustainable community development must remain analytically distinct. Organizational sustainability refers to the ability of the social enterprise to maintain its operations and mission. Sustainable community development concerns changes in the broader social, economic, and relational environment of the community.

An organization may survive without generating substantial community impact. Conversely, an organization may create meaningful short-term outcomes while remaining financially vulnerable. Organizational continuity is therefore neither a necessary proxy nor sufficient evidence of community-level impact.

2.6. Institutional and territorial context

Management and organizational capacity operate within environments that organizations can influence only partially. Legal frameworks, funding systems, administrative capacity, support infrastructures, labour markets, economic conditions, and local networks affect the resources available to social enterprises and the constraints under which they operate.

Territorial differences are especially relevant. Rural organizations may face weaker markets, limited institutional resources, demographic decline, or restricted access to specialized labour while simultaneously responding to substantial unmet needs. Urban organizations may benefit from stronger networks, larger markets, and better access to finance and human capital but face greater competition.

The same managerial capability may consequently produce different outcomes in different institutional and territorial environments.

For this reason, institutional and territorial context (ITC) is incorporated as a contextual and potential moderating construct rather than as a direct outcome of management.

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3. PROPOSED RESEARCH MODEL

The conceptual argument leads to a sequential model:

Social Enterprise Management → Organizational Capacity → Sustained Social Value Creation → Sustainable Community Development

Social enterprise management (SEM) is represented by six first-order dimensions: Strategic Decision-Making (SDM), Governance (GOV), Stakeholder Relationships (SHR), Financial Sustainability (FS), Innovation (INN), and Social Impact Assessment (SIA). Organizational Capacity (OC) and Sustained Social Value Creation (SVC) are proposed as sequential mediators. Sustainable Community Development (SCD) represents the principal outcome. Institutional and Territorial Context (ITC) is treated as a contextual/moderating influence. Organizational characteristics such as age, size, legal form, field of activity, work-integration status, development region, and urban/rural location are incorporated as control variables where theoretically appropriate.

A feedback relationship is also theoretically plausible between social impact assessment, observed outcomes, and subsequent strategic decision-making. However, because cross-sectional survey data cannot establish a genuine temporal feedback process, this relationship should initially be treated as a theoretical mechanism and investigated qualitatively or through future longitudinal research.

4. RESEARCH PROPOSITIONS AND HYPOTHESES

H1: Strategic decision-making is positively associated with organizational capacity.

H2: Effective organizational governance is positively associated with organizational capacity.

H3: Strong stakeholder relationships are positively associated with organizational capacity.

H4: Financial sustainability is positively associated with organizational capacity.

H5: Innovation capacity is positively associated with organizational capacity.

H6: The systematic assessment and use of social impact information are positively associated with organizational capacity.

H7: Organizational capacity is positively associated with sustained social value creation.

H8: Sustained social value creation is positively associated with sustainable community development.

H9: Organizational capacity mediates the relationship between social enterprise management and sustained social value creation.

H10: Organizational capacity and sustained social value creation sequentially mediate the relationship between social enterprise management and sustainable community development.

H11: Institutional and territorial conditions moderate selected relationships between organizational capacity, sustained social value creation, and sustainable community development.

These hypotheses should be regarded as theoretical expectations to be tested empirically rather than as confirmed relationships.

5. METHODOLOGY

5.1. Research design

The current study combines conceptual analysis with descriptive secondary evidence and develops the empirical framework for a subsequent organizational-level mixed-method investigation.

Three analytically distinct sources of evidence are considered. Secondary administrative evidence describes the formally certified Romanian social enterprise population and its structural characteristics. European and international secondary evidence provides institutional context and supports interpretation of the Romanian case. The proposed primary empirical stage will collect quantitative and qualitative organizational-level evidence to test and explain the relationships specified in the conceptual model.

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Maintaining this distinction is methodologically important because administrative statistics can describe the structure and evolution of the certified sector but cannot establish causal relationships between managerial practices and community outcomes.

5.2. Administrative evidence and the Romanian social enterprise population

The principal administrative source is the Unique Register of Social Enterprises (Registrul Unic de Evidență al Întreprinderilor Sociale – RUEIS), administered by the National Agency for Employment (ANOFM).

The analysis uses the official 2024 report on the activity of social enterprises and work-integration social enterprises, complemented by evidence from the 2025 Social Economy Barometer and OECD sources.

The available sources use different observation dates and statistical definitions. They are therefore interpreted comparatively rather than combined mechanically into a single statistical series.

The November 2024 RUEIS-based dataset reported 2,932 organizations that had obtained certification between 2016 and 2024, of which 1,836 retained valid certification at that observation point. The official year-end administrative report recorded 2,936 organizations that had received certificates, of which 1,780 had valid status at the end of 2024.

The difference reflects distinct observation dates and changes in certification status and should not be interpreted as an inconsistency between the sources.

5.3. Certification continuity

At the end of 2024, certification status was distributed as follows: Valid certificates: 1,780; Withdrawn certificates: 1,100; Expired certificates: 31; Suspended certificates: 25; Total certifications: 2,936.

Table 1. Certification status of Romanian social enterprises at the end of 2024

Certification status	Number of enterprises	Share of total (%)
Valid	1,780	60.6
Withdrawn	1,100	37.5
Expired	31	1.1
Suspended	25	0.9
Total	**2,936**	**100.0**

Source: Romanian Ministry of Labour/ANOFM, 2024 activity report.

A descriptive Certification Retention Ratio (CRR) is defined as:

$CRR = (V / T) \times 100$

where V = number of valid certificates and T = total number of recorded certifications.

$CRR = (1,780 / 2,936) \times 100 = 60.63\% \approx 60.6\%$

A complementary Certification Discontinuity Ratio (CDR) is:

$CDR = ((W + E + S) / T) \times 100$

where W = withdrawn certificates, E = expired certificates, and S = suspended certificates.

$CDR = ((1,100 + 31 + 25) / 2,936) \times 100 = 39.37\% \approx 39.4\%$

$CRR + CDR = 100\%$

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These indicators describe certification status rather than organizational survival. Withdrawal, expiration, or suspension of certification does not demonstrate that an organization has ceased operating or failed to create social value. The indicators are used only to identify an observable continuity issue that warrants further organizational investigation.

5.4. Organizational and territorial characteristics

The administrative evidence also reveals a strong concentration of certification among private-law legal persons outside the traditional association, foundation, cooperative, and mutual-aid categories. Of the 2,936 accumulated certifications, 2,625 belonged to this broader category:

$(2{,}625 / 2{,}936) \times 100 = 89.4\%$

Associations accounted for 280 cases, while foundations, cooperatives, mutual aid societies, federations, and unions of legal persons represented considerably smaller shares.

Table 2. Romanian social enterprises by legal form and certification status, end of 2024

Legal form	Valid	Expired	Withdrawn	Suspended	Total
Other categories of legal persons	1,587	5	1,011	22	2,625
Associations	182	15	80	3	280
Employee mutual aid societies	2	4	6	0	12
Foundations	6	2	0	0	8
Cooperative societies	2	4	3	0	9
Federations	0	1	0	0	1
Unions of legal persons	1	0	0	0	1
Total	**1,780**	**31**	**1,100**	**25**	**2,936**

Source: Romanian Ministry of Labour/ANOFM, 2024 activity report.

Territorial distribution is relatively balanced. During 2016–2024, 1,528 accumulated certifications were registered in urban areas and 1,404 in rural areas:

Urban = $(1{,}528 / 2{,}932) \times 100 = 52.1\%$

Rural = $(1{,}404 / 2{,}932) \times 100 = 47.9\%$

This balance does not imply equivalent operating conditions. It instead reinforces the importance of incorporating territorial characteristics into the subsequent empirical analysis.

5.5. Sampling strategy for the proposed organizational survey

The population of 1,780 social enterprises holding valid certification at the end of 2024 provides a defensible sampling frame for the proposed quantitative organizational survey.

For an initial estimate based on a 95% confidence level, maximum population variability ($p = .50$), and a ±5% margin of error, Cochran's formula gives:

$n_0 = Z^2 p(1 - p) / e^2$

where $Z = 1.96$, $p = .50$, and $e = .05$.

$n_0 = [1.96^2 \times 0.50 \times 0.50] / 0.05^2 = 384.16$

For a finite population $N = 1{,}780$, the finite population correction gives:

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$n = n_0 / [1 + (n_0 - 1)/N]$

$n = 384.16 / [1 + 383.16/1{,}780] = 316.11$

A target of approximately 316 valid organizational responses is therefore appropriate for estimating population proportions under these assumptions.

This calculation should not, however, be interpreted as an independent demonstration that 316 observations are sufficient for every possible SEM specification. Before structural model estimation, statistical power, model complexity, number of parameters, measurement structure, effect sizes, missing data, and distributional characteristics should be evaluated separately.

Because organizational surveys rarely achieve complete response rates, invitations should be distributed to a substantially larger part of the sampling frame. Stratification by development region, urban/rural location, legal form, and social enterprise/work-integration status should be considered to improve representativeness.

5.6. Measurement

The quantitative instrument will target founders, managers, executive directors, or other respondents directly involved in strategic and operational decisions.

Social Enterprise Management (SEM) comprises strategic decision-making, governance, stakeholder relationships, financial sustainability, innovation, and social impact assessment.

Organizational Capacity (OC) captures resource mobilization, human-resource capability, coordination, adaptive capacity, and organizational learning.

Sustained Social Value Creation (SVC) includes beneficiary outcomes, social inclusion, responses to unmet needs, and continuity of socially valuable activities.

Sustainable Community Development (SCD) includes employment and economic opportunities, access to locally needed services, social inclusion, community participation, partnership capacity, and local resilience.

Institutional and Territorial Context (ITC) includes institutional support, access to resources, regional characteristics, local administrative capacity, and urban/rural context.

Multi-item constructs will primarily use five-point Likert scales. Where possible, perceptual measures will be complemented by objective organizational indicators, including organizational age, employment, revenue structure, funding diversification, beneficiary numbers, partnerships, and territorial location.

Table 3. Operationalization of the research model

Construct	Core empirical dimensions	Indicative measures	Role
Strategic decision-making (SDM)	Mission-strategy alignment; planning; adaptability	Likert-scale composite	Independent
Governance (GOV)	Accountability; stakeholder representation; mission protection	Likert-scale composite	Independent
Stakeholder relationships (SHR)	Partnerships; beneficiary involvement; institutional networks	Likert-scale composite + partnership counts	Independent
Financial sustainability (FS)	Revenue stability; diversification; funding dependence; reserves	Perceptual + objective indicators	Independent

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Construct	Core empirical dimensions	Indicative measures	Role
Innovation (INN)	New services; processes; responses to unmet needs	Likert-scale composite + innovation indicators	Independent
Social impact assessment (SIA)	Measurement; reporting; use of impact evidence	Likert-scale composite	Independent
Organizational capacity (OC)	Resource mobilization; human resources; adaptive capacity	Composite scale	Mediator
Social value creation (SVC)	Beneficiary outcomes; inclusion; unmet needs addressed	Composite + organizational indicators	Mediator
Sustainable community development (SCD)	Employment; inclusion; local services; participation; resilience	Composite outcome index	Dependent
Institutional and territorial context (ITC)	Region; urban/rural status; institutional support; resource access	Administrative + survey indicators	Moderator/context
Organizational characteristics	Age; size; legal form; field; WISE status	Objective variables	Controls

Source: Author creation.

6. PROPOSED QUANTITATIVE ANALYSIS

The analysis should proceed in stages rather than move immediately to structural relationships.

Descriptive analysis will summarize the characteristics of participating organizations and the distribution of the principal variables.

The reliability of multi-item constructs will be assessed through Cronbach's alpha and composite reliability. Values around or above .70 will normally be considered acceptable, although reliability will be interpreted together with construct composition and measurement quality.

Exploratory factor analysis may be used during scale development or adaptation. Confirmatory factor analysis should subsequently assess the measurement model where sample characteristics and data quality permit.

Convergent validity should be examined using factor loadings and Average Variance Extracted (AVE), while discriminant validity can be evaluated using appropriate criteria such as HTMT alongside substantive assessment of construct distinctiveness.

Only after the measurement model has demonstrated acceptable properties should structural relationships be tested.

6.1. Direct-effects model

A preliminary regression model may estimate the direct relationships between the six managerial dimensions and sustainable community development:

$$SCD_i = \beta_0 + \beta_1 SDM_i + \beta_2 GOV_i + \beta_3 SHR_i + \beta_4 FS_i + \beta_5 INN_i + \beta_6 SIA_i + \gamma' X_i + \varepsilon_i$$

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where X_i represents a vector of organizational control variables and γ contains their estimated coefficients. This regression should be interpreted as a baseline model rather than as the principal theoretical test.

6.2. Sequential mediation model

The principal theoretical model focuses on the mechanisms through which management is translated into community outcomes. The first structural equation is:

$$OC_i = \alpha_0 + \alpha_1 SDM_i + \alpha_2 GOV_i + \alpha_3 SHR_i + \alpha_4 FS_i + \alpha_5 INN_i + \alpha_6 SIA_i + \delta' X_i + u_i$$

The second stage examines the relationship between organizational capacity and sustained social value creation:

$$SVC_i = \beta_0 + \beta_1 OC_i + \theta' X_i + v_i$$

The third stage examines community outcomes:

$$SCD_i = \gamma_0 + \gamma_1 SVC_i + \gamma_2 OC_i + \lambda' X_i + w_i$$

The central mechanism is consequently:

$$SEM \rightarrow OC \rightarrow SVC \rightarrow SCD$$

Indirect effects should be estimated with confidence intervals, preferably using bootstrapping rather than relying exclusively on stepwise significance tests. Where supported by the measurement structure, SEM can estimate the measurement and structural components simultaneously. The choice between covariance-based SEM and PLS-SEM should follow the theoretical objective, construct specification, sample characteristics, distributional properties, and model complexity rather than being based exclusively on sample size.

6.3. Contextual effects

Institutional and territorial conditions may subsequently be incorporated through interaction terms or theoretically justified multigroup analyses. A generic moderation specification can be expressed as:

$$SCD_i = \beta_0 + \beta_1 SVC_i + \beta_2 ITC_i + \beta_3 (SVC_i \times ITC_i) + \gamma' X_i + \varepsilon_i$$

A statistically and substantively meaningful β_3 would indicate that the relationship between sustained social value creation and sustainable community development varies according to institutional or territorial conditions. Not all components of ITC should automatically be combined into a single moderator. Urban/rural location, regional development, institutional support, and resource accessibility may have theoretically different roles and should be operationalized accordingly.

7. QUALITATIVE COMPONENT

The qualitative stage will complement the quantitative analysis by investigating how the proposed mechanisms operate in organizational practice.

Semi-structured interviews with social enterprise managers and relevant ecosystem actors should explore the management of social-commercial tensions, funding dependence, mission protection, partnership formation, relationships with public authorities, innovation, organizational learning, and the use of social impact evidence.

Purposive sampling is appropriate because the objective is analytical variation rather than statistical representativeness. The sample should include organizations differing by region, urban/rural location, organizational age, legal form, funding structure, and social mission.

Interview material will be examined through thematic analysis. Initial coding can draw on the six management dimensions and the constructs included in the conceptual framework, while inductive coding should remain open to mechanisms not anticipated theoretically.

Particular attention should be paid to negative or deviant cases. Organizations in which apparently strong management capabilities do not translate into sustained social value may reveal institutional or territorial constraints that would remain hidden in aggregate quantitative relationships.

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The integration of quantitative and qualitative evidence should occur during interpretation. Statistical analysis can identify relationships and their magnitude, while qualitative evidence can clarify how those relationships emerge and why they differ across organizations.

8. DISCUSSION

The descriptive evidence provides several reasons for examining management and organizational capacity more closely within the Romanian social enterprise ecosystem.

The first concerns certification continuity. At the end of 2024, approximately 60.6% of all organizations that had obtained certification retained valid status, while 39.4% were classified as withdrawn, expired, or suspended. Certification discontinuity cannot be equated with organizational failure, but the magnitude of the difference between cumulative and valid certifications raises questions about continuity after formal entry into the social enterprise system.

The second concerns organizational structure. The concentration of certifications among private-law legal persons suggests that contemporary Romanian social entrepreneurship extends beyond the organizational forms traditionally associated with the social economy. This structural characteristic warrants further investigation into whether managerial practices, financial models, and approaches to social mission differ across legal forms.

The third concerns territorial heterogeneity. The relatively balanced urban-rural distribution confirms that social enterprise is relevant across different territorial environments, but it also highlights the need to avoid treating territory as a neutral background characteristic. Market opportunities, institutional capacity, labour availability, demographic trends, access to finance, and community needs vary substantially across locations.

Together, these observations support a model in which management is necessary but insufficient to explain community outcomes.

The theoretical contribution of the proposed framework lies precisely in avoiding the assumption that better management automatically produces stronger community development.

Strategic decision-making, governance, stakeholder relationships, financial sustainability, innovation, and social impact assessment are expected to influence the organization's capacity to mobilize and coordinate resources. Organizational capacity, in turn, can support the creation of social value. Only when such value is maintained, embedded in local relationships, and connected to broader social and economic structures can it contribute to sustainable community development.

This sequential perspective also clarifies the distinction between organizational sustainability and community impact. Financial continuity matters because unstable organizations may be unable to maintain social interventions. Nevertheless, financial viability is not itself evidence of social value. The framework therefore avoids using organizational survival as a proxy for community development.

Stakeholder relationships are particularly relevant in this respect. Community outcomes such as labour-market integration, improved access to services, social inclusion, or local resilience generally depend on interactions among multiple actors. The contribution of social enterprises may consequently include not only direct services or employment but also the creation of relationships, trust, coordination, and local institutional capacity.

Social impact assessment plays a related role. Measurement becomes managerially valuable when evidence about outcomes influences future decisions. An organization that collects impact data exclusively for external reporting may demonstrate accountability without necessarily improving its activities. The transition from impact measurement to impact management therefore connects evidence with organizational learning.

The European perspective reinforces this contextual interpretation. European social enterprise ecosystems vary in legal recognition, financing structures, governance traditions, stakeholder participation, public support, and institutional maturity. The Romanian ecosystem should therefore not be evaluated against an assumed homogeneous European standard. Comparative experience is more

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useful for identifying alternative configurations and understanding the institutional conditions under which particular practices become effective.

9. PRACTICAL AND POLICY IMPLICATIONS

For social enterprise managers, the framework suggests that organizational effectiveness is unlikely to result from optimizing a single managerial dimension. Financial stability without mission-oriented governance may increase the risk of mission drift. Innovation without stakeholder engagement may produce solutions weakly connected to local needs. Partnerships without strategic coherence may generate activity without organizational direction. Impact measurement disconnected from decision-making may satisfy reporting requirements without supporting organizational learning.

Managerial development should therefore focus on the configuration and interaction of capabilities.

For policymakers, the descriptive evidence suggests that supporting the creation and certification of new social enterprises is only one component of ecosystem development. Attention is also required after establishment.

Support measures may therefore address managerial capabilities, revenue diversification, access to markets, partnership development, impact-management skills, organizational learning, and adaptation to territorial conditions.

The difference between cumulative and valid certification is especially relevant as a subject for further investigation, although the available administrative evidence does not allow this difference to be attributed to specific organizational or policy causes.

10. LIMITATIONS AND FUTURE RESEARCH

Several limitations constrain the interpretation of the current study.

The administrative evidence refers primarily to formally certified social enterprises and cannot be generalized automatically to the entire Romanian social economy.

Different national and European data sources use different definitions and statistical populations. Their indicators should therefore not be merged without establishing conceptual comparability.

Certification status is an institutional indicator, not a direct measure of organizational survival, financial performance, or social impact.

The descriptive data do not establish causal relationships between managerial practices and certification continuity or community development.

Most importantly, the structural relationships proposed in this paper have not yet been empirically tested. They represent theoretically grounded hypotheses for the subsequent organizational study.

Future research should therefore test the measurement and structural models using primary organizational data. Longitudinal evidence would be particularly valuable because it would allow stronger analysis of organizational continuity, impact persistence, and the feedback relationship between impact evidence and managerial decision-making.

Comparisons across urban and rural areas, development regions, organizational forms, funding structures, and stages of organizational maturity could further clarify the conditions under which managerial capacity is translated into sustained community value.

11. CONCLUSION

Social enterprises occupy a distinctive position between economic activity and social purpose. Their contribution to sustainable community development cannot be inferred from their formal status, number, or declared mission alone. It depends on their ability to transform social purpose into sustained social value while maintaining sufficient organizational and economic capacity to continue operating.

The Romanian evidence illustrates both the expansion and the heterogeneity of the formally recognized social enterprise ecosystem. By the end of 2024, 2,936 organizations had obtained certification, while 1,780 retained valid status. The resulting certification retention ratio of approximately 60.6% identifies

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an important continuity issue without demonstrating organizational failure. At the same time, the distribution of organizations across legal forms and territories confirms the need to interpret social enterprise activity within its organizational and institutional context.

The conceptual contribution of this study is the development of a mechanism-based framework connecting management with community outcomes.

Rather than proposing a direct relationship between managerial effectiveness and sustainable community development, the model identifies a sequential process:

Social Enterprise Management → Organizational Capacity → Sustained Social Value Creation → Sustainable Community Development

Institutional and territorial conditions influence the environment in which this process unfolds.

The framework therefore shifts the analytical question from whether management matters to how, through which mechanisms, and under what conditions managerial capabilities can be translated into sustained community value.

For Romania, this distinction has practical relevance. Developing the social enterprise ecosystem requires more than increasing the number of certified organizations. It also requires conditions that enable organizations to remain viable, preserve their social mission, mobilize resources, develop partnerships, learn from evidence, adapt to territorial needs, and convert temporary opportunities into durable organizational and community capabilities.

The empirical testing of the proposed model represents the next stage of the research. Combining organizational survey data, qualitative evidence, and administrative information can provide a stronger basis for determining which managerial capabilities matter most, how they interact, and under what conditions they contribute to sustainable community development.

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BASELINE REACTION TIME AS A PREDICTOR OF INDIVIDUAL IMPROVEMENT FOLLOWING OCULOMOTOR TRAINING IN ATHLETES

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ABSTRACT

Background:
This study investigated changes in reaction time following an oculomotor exercise program and examined whether baseline reaction time predicts the magnitude of improvement.

Methods:
Sixty-four athletes completed a six-week oculomotor exercise program. Reaction time was assessed before and after the intervention using two reaction paradigms Scheme 1 (S1) and Scheme 2 (S2). Changes in reaction time were evaluated by comparing baseline and post-intervention performance. To determine whether baseline performance predicted responsiveness to the intervention, Pearson correlation and simple linear regression analyses were performed, with baseline reaction time as the independent variable and improvement (baseline minus post-intervention reaction time) as the dependent variable.

Results:
Significant improvements in reaction time were observed following the intervention for both S1 and S2. Mean reaction time decreased from 0.690 ± 0.135 s to 0.518 ± 0.116 s for S1 and from 0.629 ± 0.096 s to 0.517 ± 0.114 s for S2, corresponding to improvements of 25.0% and 17.8%, respectively. Baseline reaction time significantly predicted improvement for both S1 ($\beta = 0.515$, $R^2 = 0.341$, $p < 0.001$) and S2 ($\beta = 0.402$, $R^2 = 0.134$, $p = 0.003$). Athletes with slower baseline reaction times demonstrated greater reductions in reaction time following the intervention.

Conclusions:
The oculomotor exercise program was associated with improved reaction time across both testing schemes. Baseline reaction time was a significant predictor of improvement, indicating that athletes with slower initial reaction times demonstrated greater gains following the intervention. These findings suggest that baseline reaction-time assessment may help identify athletes who are more likely to benefit from oculomotor training and support more individualized training approaches.

Keywords: Visuomotor performance, Sensorimotor integration, Visual attention

Introduction

Exercise interventions rarely produce uniform responses across individuals, even when participants complete identical training protocols.[1] Understanding the factors contributing to variability in training responses may improve the interpretation of intervention outcomes and support more individualized training approaches.[2]

Baseline performance has been proposed as a potential factor influencing the magnitude of training-induced adaptation. Previous research suggests that baseline performance may contribute to differences in training outcomes, although the strength of this relationship appears to vary across tasks and interventions.[3] Although most evidence regarding baseline-dependent responsiveness has been derived from cognitive and motor learning paradigms,[3] similar concepts may be relevant to oculomotor training,

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as these interventions involve related processes, including visual attention, visuomotor integration, sensorimotor coordination, and rapid information processing.[4]

Reaction time represents an important component of athletic performance, reflecting the integration of visual perception, information processing, decision-making, and motor execution.[5,6] Oculomotor training has been investigated as a strategy to enhance visuomotor performance by targeting gaze control, visual attention, and sensorimotor integration.[4] Previous studies have reported improvements in reaction time and visuomotor performance following vision or oculomotor training interventions. [4,7] However, despite increasing interest in perceptual-cognitive and visuomotor training, it remains unclear whether baseline reaction time can predict the magnitude of individual improvements following oculomotor training.

Therefore, the aim of the present study was to determine whether baseline reaction time predicts responsiveness to a six-week oculomotor training program in athletes. Specifically, we examined the association between baseline reaction time and improvement magnitude using Pearson's correlation and linear regression analyses.

Methodology

Study design

This study represents a secondary analysis of data collected from a randomized controlled trial investigating the effects of a six-week oculomotor training program on visuomotor and postural performance in athletes. The present analysis focused specifically on reaction-time outcomes and aimed to determine whether baseline reaction time predicted the magnitude of improvement following the intervention.

The eligibility criteria, participant recruitment procedures, and detailed description of the oculomotor training protocol have been described previously.[8]

Participants

The analysis included 64 athletes allocated to the experimental group who completed both the baseline and post-intervention assessments. Participants were recruited from basketball, football, and boxing clubs and met the eligibility criteria described in the primary study. All participants completed the full six-week intervention and were included in the predictive analysis.

Oculomotor training intervention

Participants completed a supervised six-week oculomotor training program consisting of five sessions per week (30 sessions in total), with each session lasting approximately 10 minutes. The intervention included progressively challenging eye movement exercises designed to improve visual tracking, saccadic eye movements, fixation stability, convergence, peripheral awareness, and visuomotor coordination. A detailed description of the intervention protocol has been reported in the primary study.

Outcome measures

Reaction time was assessed before and after the intervention using the Light Trainer® system under two testing conditions (S1 and S2). The position of all Light Trainer® pods was standardized for every participant and remained unchanged throughout the study. Eight numbered pods (1–8) were arranged according to one of two predefined configurations. The configuration was selected before testing using the sealed-envelope method by an assessor who was blinded to participant allocation.

To minimize potential bias related to spatial arrangement and to avoid favoring any experimental group or sporting discipline, both pod configurations were developed in consultation with coaches who had more than 10 years of professional experience in football, basketball, and boxing. This expert consultation ensured that both schemes represented comparable visuomotor demands relevant to all three sports while maintaining similar perceptual and hand–eye coordination requirements.

Because the study was not designed to compare pod configurations, both configurations were standardized across participants and used only to assess reaction-time performance.

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Scheme 1. In the first configuration, two pods (4 and 6) were mounted on the wall, positioned on the participant's left and right sides, respectively. The remaining six pods (8, 1, 3, 2, 7, and 5) were arranged on the floor in a semicircular pattern, progressing from left to right, with a radius of 35 cm and 20 cm between adjacent pods. This arrangement was based on a previously described visuomotor protocol[7] and was used to provide a standardized spatial layout for reaction-time assessment. The same distances and spatial organization were maintained for all participants.

Scheme 2. In the second configuration, pods 8 and 5 were moved from the floor to the wall and positioned diagonally below pods 4 and 6, respectively, with a vertical distance of 70 cm. This resulted in a configuration comprising four wall-mounted and four floor-mounted pods. The arrangement provided a different spatial distribution of visual stimuli while maintaining standardized testing conditions across participants. Both configurations were intended to represent visuomotor demands relevant to multiple sports without prioritizing a specific movement pattern or sporting discipline. As the study was not designed to compare performance between configurations, the same predefined setup was applied consistently to all participants.

Statistical analysis

Descriptive statistics were calculated for all study variables. The distribution of continuous variables was assessed using the Shapiro–Wilk test together with visual inspection of Q–Q plots. Pearson's correlation coefficient was used to evaluate the association between baseline reaction time and the magnitude of improvement separately for S1 and S2.

Simple linear regression analyses were then performed to determine whether baseline reaction time predicted improvement following the intervention. Baseline reaction time was entered as the independent variable, while improvement in reaction time (baseline RT − post-intervention RT) served as the dependent variable. Standardized regression coefficients (β), 95% confidence intervals (CI), the coefficient of determination (R^2), F statistics, and p values were reported. Model assumptions, including linearity, homoscedasticity, independence of residuals, and normality of residuals, were examined before interpretation of the regression models. Statistical significance was established at $p < 0.05$. All statistical analyses were performed using IBM SPSS Statistics (version 26; IBM Corp., Armonk, NY, USA).

Results

Mean reaction time decreased from 0.690 ± 0.135 s to 0.518 ± 0.116 s for S1 and from 0.629 ± 0.096 s to 0.517 ± 0.114 s for S2, corresponding to improvements of 25.0% and 17.8%, respectively (table 1).

For S1, baseline reaction time was significantly associated with the magnitude of improvement following the intervention. A moderate positive correlation was observed between baseline reaction time and improvement ($r = 0.584$, $p < 0.001$). Linear regression demonstrated that baseline reaction time was a significant predictor of improvement (β = 0.515, 95% CI 0.333–0.697, $F(1,62) = 32.02$, $p < 0.001$), explaining 34.1% of the variance in treatment response ($R^2 = 0.341$; table 2).

For S2, a similar but weaker relationship was observed. Baseline reaction time was positively correlated with improvement ($r = 0.365$, $p = 0.003$). Linear regression confirmed baseline reaction time as a significant predictor of improvement (β = 0.402, 95% CI 0.142–0.662, $F(1,62) = 9.56$, $p = 0.003$), accounting for 13.4% of the variance in improvement ($R^2 = 0.134$; table 2).

Across both reaction-time tasks, participants with slower baseline reaction times tended to exhibit greater improvements following the intervention. This relationship was substantially stronger for S1 than for S2, as reflected by the larger correlation coefficient and the greater proportion of explained variance.

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Table 1. Changes in Reaction Time Following the Intervention

Outcome	Baseline RT (s), Mean ± SD	Post-intervention RT (s), Mean ± SD	Mean improvement (s) ± SD	95% CI of improvement (s)	% Improvement	Cohen's *d*
S1	0.690 ± 0.135	0.518 ± 0.116	0.173 ± 0.119	0.143 to 0.202	25.0%	**1.45**
S2	0.629 ± 0.096	0.517 ± 0.114	0.112 ± 0.106	0.086 to 0.139	17.8%	**1.06**

Improvement was calculated as baseline reaction time minus post-intervention reaction time, with positive values indicating faster reaction times after the intervention. Cohen's d represents the within-subject standardized effect size.

Table 2. Simple Linear Regression Analyses Predicting Improvement from Baseline Reaction Time

Outcome	Standardized β	95% CI	Pearson *r*	R^2	F (1,62)	*p*
S1 improvement	0.515	0.333–0.697	0.584	0.341	32.02	<0.001
S2 improvement	0.402	0.142–0.662	0.365	0.134	9.56	0.003

Discussion

The present study investigated whether baseline reaction time could predict individual responsiveness to a six-week oculomotor training program in athletes. The main finding was that baseline reaction time was significantly associated with the magnitude of improvement in both reaction-time conditions. Athletes with slower baseline reaction times demonstrated greater absolute improvements following the intervention, suggesting that initial visuomotor performance may represent an important factor associated with individual variability in response to oculomotor training. The predictive relationship was stronger for S1, where baseline reaction time explained approximately one-third of the variability in improvement, whereas the association was weaker for S2.

The observed variability in improvement is consistent with previous evidence showing that individuals may respond differently despite completing similar training protocols, highlighting the importance of identifying baseline characteristics associated with training response.[3,9] In oculomotor training, baseline visuomotor characteristics may influence improvements in reaction-time–related functions, including visual attention, gaze control, and visuomotor coordination, which are common targets of vision training interventions.[4] However, these findings should be interpreted cautiously, as observed changes may also reflect measurement variability and regression toward the mean.

The stronger predictive value of baseline reaction time for S1 compared with S2 may be related to differences in the perceptual-motor processes required by each task. Although both configurations were designed to reflect visuomotor demands common to football, basketball, and boxing, S1 may have depended more on rapid stimulus detection and response initiation. These processes are fundamental components of reaction-time performance and have been linked to individual differences in information-processing speed.[10,11]

In contrast, performance improvement in S2 may have involved additional perceptual and attentional processes beyond basic response speed. Although the spatial organization of visual stimuli was standardized across participants, the stimulus configuration may have increased the demands on attentional allocation and perceptual processing during task execution.[12,13] Previous research suggests

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that visual search demands and attentional allocation influence the selection and processing of visual information during complex tasks.[5,14] Therefore, the weaker association between baseline reaction time and improvement in S2 may indicate that performance in this condition depended on a broader range of perceptual-cognitive processes than baseline response speed alone.

From a practical perspective, these findings suggest that baseline reaction-time assessment may help identify athletes who are more likely to respond to oculomotor training. Rather than assuming a uniform response to perceptual-motor interventions, individualized approaches based on initial visuomotor characteristics may allow more targeted training strategies. Athletes with slower baseline reaction times demonstrated greater improvements in the present study, whereas athletes with higher baseline performance may require more individualized or task-specific approaches to achieve additional gains.

The present findings should be interpreted in light of several limitations. First, this analysis included only athletes who completed the intervention, and therefore responsiveness among non-completers could not be evaluated. Second, although baseline reaction time explained a significant proportion of improvement variability, additional factors such as sport experience, cognitive characteristics, visual abilities, and training history may contribute to individual differences in response. Future studies should investigate multivariable prediction models incorporating these factors to better characterize responders and optimize oculomotor training prescriptions.

Conclusion

Baseline reaction time was a significant predictor of improvement following the six-week oculomotor training program. Athletes with slower pre-intervention reaction times tended to achieve greater improvements, suggesting that baseline performance may help identify individuals who are more likely to benefit from this intervention. The predictive relationship was stronger for S1 than for S2, indicating that baseline reaction time explained a greater proportion of the variability in training response for the simpler reaction-time condition. These findings support the potential use of baseline reaction-time assessment to optimize and individualize oculomotor training in athletes.

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EUROPEAN GREEN DEAL AND THE CARBON MARKET

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ABSTRACT

The Industrial Revolution began in the late eighteenth century all around the world, initiated a fundamental transformation in global production and economic systems. The subsequent acceleration of industrialisation and technological advancement substantially increased production capacity and economic development. On the other hand, this speedy extension has been accompanied by growing resource consumption and environmental pressures, circular economy, resulting in resource depletion, environmental degradation, and other sustainability challenges.

Our rapidly declining natural resources and the environment that has been destroyed and polluted have forced the modern economy of the 21st century to take global measures, to make agreements and contracts. While efforts to raise awareness on the environment have been continuing by preparing international agreements and protocols such as the Stockholm Conference, the Kyoto Protocol, and the Paris Climate Agreement since the 1980s, a big step has been taken in terms of being climate neutral by forming the European Green Consensus in 2019 by the European Union. EU announced that it will be the first carbon neutral continent in 2050.

The EU Strategy for Sustainable and Circular Textiles establishes a long-term policy framework aimed at transforming the European textile sector towards greater sustainability and circularity. By 2030, textile products placed on the EU market are anticipated to be eco-friendly, reliability, reusability, and progressively manufactured using recycled fibres, while minimizing the presence of preventing and reducing waste, including packaging waste and assuring compliance with environmental and social requirements. The Strategy also promotes a shift away from fast fashion towards longer product use, supported by economically viable reuse and repair systems. Furthermore, it emphasizes the extended responsibility of producers across the entire textile value chain, including the management of products at the end of their useful life. Within this scope, the development of a circular textile ecosystem is expected to be supported by increased capacity for innovative fibre-to-fibre recycling, while the incineration and landfilling of textile waste should be progressively reduced.

These policy objectives increasingly require greater transparency and traceability of product-level environmental information throughout textile value chains, thereby creating a regulatory and technological context for the development of digital tools such as the Digital Product Passport (DPP).

Keywords: Green Deal, Carbon Market, Sustainability, Carbon Pricing, Emission Trading, Climate Change, Digital Product Passport (DPP)

INTRODUCTION

The industrialization that accompanied the revolution in the industrial sector has led to increased production, resulting in economic growth and development. This development has necessitated a shift towards an environmentally friendly and sustainable approach. Concordantly, various alternative solutions have been analysed to minimize production waste, a key component of the circular economy. The Industrial Revolution inflicted irreversible damage on natural resources and jeopardized the right of future generations to benefit from them. Russia's unprovoked and unjustified military aggression against Ukraine, ongoing since 2022, and its impact on energy prices, raw material supply security, and export segments of the textile ecosystem, once again highlight the fragility of global supply chains.

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The significant depletion of natural resources and the challenges encountered in processing the waste generated as a result of these processes have led to the emergence of the concept of waste minimization. Minimizing the increasing industrial waste resulting from industrialization is an inevitable outcome. Today, alongside urbanization and industrialization, concepts such as sustainable development, clean production approaches, and the circular economy have become an important part of our lives. From the 1990s to the present, the concepts of "sustainability" and "sustainable development" have developed and gained importance in many fields. Two key organizations that form the dynamic pillars of this development are the European Union and the United Nations. These organizations have developed goals for social, economic, and environmental development, referring to sustainable development. Two important steps taken in line with these goals are the European Green Deal and the Sustainable Development Goals (SDGs), initiated by the European Union and the United Nations.

In light of all these developments, the regulations adopted by the United Kingdom, the United States (U.S.), and finally the European Union within the global framework have made the development of circular economy strategies, the transition from linear production to a circular economy, and the efficient use of resources while adopting low-carbon production a common global goal. Environmental adaptation targets set at the international level have become the responsibility and obligation not only of EU member states but of the entire world. In today's conditions, the pollution and depletion of natural resources caused by industrialization in economically developed countries such as Germany, the United Kingdom, the Netherlands, and France is an undeniable reality. However, developing countries also need to follow a global path within the framework of the European Green Deal. Globalization and inter-country relations: As borders disappear, ongoing climate change and environmental impacts will no longer be limited to continents. In this context, the European Green Deal has set many global targets. Since Turkey is located in a strategic trading market in Europe and the world, it must clearly define and evaluate the effects of this global agreement.

Among the series of regulations published alongside the European Green Deal, the Digital Product Passport (DPP) stands out as the most noteworthy recently. It is set to become mandatory in phases by 2025, along with its enforcement mechanisms. Regarding textile manufacturers specifically, the regulation is still in the process of being understood, and action plans are being developed according to the defined timeline.

A particularly significant digital tools that has emerged in this context is unquestionably the Digital Product Passport (DPP) concept. The Digital Product Passport (DPP) is a unique digital document that stores and shares information on sustainability, circularity, and legal compliance throughout a product's entire lifecycle. Mandatory under the European Union's Eco-Design for Sustainable Products Regulation (ESPR), this system functions as a comprehensive "digital identity card" directly linked to a physical product. While in traditional production approaches the flow of information is generally limited to the producer and the first buyer, the DPP eliminates the boundaries that lead to information fragmentation in traditional systems, ensuring the seamless flow of data throughout the entire value chain. This digital system contains detailed data on a wide range of topics, from a product's components and chemical content to its repair scope and disposal methods, providing a comprehensive dataset that optimizes resource efficiency (Kılıç, Kurgun, 2025).

CONCEPTUAL FRAMEWORK

The European Green Deal

The European Union started to raise environmental issues in the 1970s (Olsen ve McCormick, 2017). In 1972, environmental and energy policies started to be established with the Paris Declaration published at the Paris European Summit (Olsen ve McCormick, 2017). The European Green Deal, announced by the EU as a climate action plan, was published in 2019 and aims to decarbonise Europe by 2050 by zeoring greenhouse gas emissions by 2050 through changes and regulations in many sectors. With the Fit for 55 package announced by the European Commission, the EU aims to reduce greenhouse gas emissions by 55% compared to 1990 levels by 2030 (European Commission, 2021a). Industrialised and industrialising countiries such as the EU, the United States, China, Japan and South Korea, which are responsible for %74 of global emissions, have announced their net zero targets. The EU has also started

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to implement the European Green Deal and is trying to reach the net zero target within the scope of combating climate change. As a result of setting such broad and comprehensive transformation targets, the EU should analyse the risks and opportunities that may arise among the member states in a balanced manner. It should also minimize the losses and leakages that may occur (Cututi, Kustova ve Egenhofer, 2020).

The Green Deal, which has been publicied as the EU's new circular green growth strategy, is not only intended to improve the welfare of people. As the main component of the green growth strategy, Europe will ensure the sustainability of existing welfare by neutralising harmful environmental impacts, protecting natural habitats, contributing to other living being with whom we share life on the planet, contributing to the world economy. In this context, the EU aims to be the first climate-neutral continent by 2050; to protect human life, animals, plants and the living environment by reducing the use of natural resources; to reduce environmental pollution with the circular economy, to assist companies in accessing renewable energy sources in clean products and Technologies, and to ensure a fair and holistic transition (European Commission, 2019a). In its Roadmap for a Resorce Efficient Europe (2011) and Biadiversity Strategy to 2020 (2011), the European Commission has set out its circular environmental policy, green incentives and green growth strategy in order to refuse the claims that the Lisbon Treaty and sustainable development initiatives have failed (Ossewaarde ve Ossewaarde-Lowtoo, 2020).

The European Union achived 62% economic growth between 1990 and 2018, while reducing greenhouse gas emissions by 23% (*European Commission*. "The European Green Deal," 2019). In line with the announced European Green Deal targets, it is emphasised that the EU aims to become carbon neutral by gradually reducing its emission emissions by 2050 and thus achieve the environmental and sustainable targets set legal arrangements to be carried out in order to achieve Europe's 2030 emissions targets within the scope of the European Green Deal 2030 climate targets will be examined until 30 June 2021 and necessary legislative amendments will be determined according to the outcome of the negotiations ("2030 Climate Target Plan," *European Commission*). Although the European Green Deal is not a low on the agenda, it is a strengthened political movement and is the biggest decarbonisation commitment of the EU to date (Ecer, Güner ve Çetin, 2021).

Turkey's Green Policy: Green Deal Action Plan

Within the scope of the European Green Deal announced by the EU and carrying global implications the Green Deal Action Plan was put into effect in Turkey in 2021 to systematically advance the transition to a sustainable and circular economy and to define relevant policies. The Action Plan is organized under nine main headings: Carbon Border Adjustment Mechanism, A green and circular economy, Green financing, Clean, economic and secure energy supply, Sustainable agriculture, Sustainable smart transport, Combating climate change, Diplomacy. European Green Deal information and awareness-rasing activities The action plan includes 32 targets and 81 actions (Republic of Turkey Ministry of Trade, 2021).

- Within the scope of carbon regulations at the border

- Drawing a road map to support the reduction of priority carbon emissions in manufacturing industry sectors such as electricity, hydrogen, alumunium, cement, iron-steel and fertiliser, which are the 6 priority sectors and may be subject to carbon regulation,

- Reviewing the Carbon Regulation Mechanism at the Border on the basis of energy and resource intensive sectors such as electricity, hydrogen, aluminium, cement, iron-steel and fertiliser, which are the 6 priority sectors, and determining the necessary action,

- Starting to carry out studies within the scope of the national carbon pricing system that can be developed in accordance with our country by examining the carbon regulation mechanism at the border applied in the EU and establishing a database for carbon emission calculations,

- Carrying out supportive policies fort he additional costs and economic implants that may occur on the sectors and the public fort he needs of the carbon pricing mechanism to be developed in our country,

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- Development of a system designed to monitor greenhouse gas emissions resulting from industrial production,
- Carring out studies to carry out necessary certification activities in our counyrt (Republic of Turkey Ministry of Trade, 2021).

○ Within the scope of the green and circular economy target

- Carring out needs analysis studies by identifying priority sectors in order to ensure faster adaptation to the circular economy in line with the European Green Deal,
- Preparation of a new action plan to ensure the entegration of turkey into the EU's Circular Economy Action Plan,
- Completion of the necessary technical and official cooperation fort he establishment of the Green Industrial Zone and Green OIZ certification system,
- Supporting sectoral R&D studies for green transformation and carrying out technical studies together with stakeholders by strengthening the necessary technological infrastructure,
- Developing a National Life Cycle Assestment (LCA) Database and establishing a National LCA Platform in Turkey,
- Devoloping methods to comply with the legistlation such as EU Chemicals Legistlation, Sustainable Product Legistlation, Eco-Design and Energy Labelling, which are on the agenda to be published by the EU,
- With the announcement of the Sustainable Product Initiative strategies by the EU, carring out information activities by starting the legislative harmonisation studies on the basis of the sectors that concern our country,
- Establishing a system for monitoring endocrine disrupting chemicals in drinking water resources which have been frequently encountered in recent years,
- While updating the clean production legistlation published fort he textile sector, which has a high water demand due to its resource-intensive nature, the relevant legislation fort he leather sector should also be established and relevant trainings should be provided,
- Preparation of an action plan fort he implementation of the EU Integrated Pollution Prevention and Control (IPPC) legislation on the basis of relevant rectors in Turkey,
- Preparation of the National Sustainable Consumption and Production Action Plan by analsing the needs of our country,
- As stated in the Cleaner Production Report, conducting studies on the treatment of wastewater generated as a result of production activities and improving the recovery of treated wastewater,
- Preparation of "National Master Plan for Water Reuse" within the scope of the Action Plan,
- Preparation of "Guidance Document on Water Footprint" within the scope of the Action Plan,
- Carring out studies on ensuring the monitoring of water resources management with remote sensing system,
- Dissemination of the Turkish Environmental Labelling System, which can provide cooperation opportunities with the EU,
- Carring out information activities for organisations on waste management and environmental labelling,
- Developing practices on resource efficiency to support and develop the transition to a green and circular economy through Devolopment Agencies,

- Supporting the transition to green and circular production for resource-intensive sectors in industry, supporting the use of international financing sources and IPA funds for projects that can contribute to the reduction of greenhouse gas emissions (Republic of Turkey Ministry of Trade, 2021).

○ Within the scope of the development of green finance

- Identify sectoral needs and review the existing or potentitial national incentive system to support the circular economy and green economic transformation,
- Devoloping a National Energy Efficiency Financing Machanishm under the Action Plan,
- Ensuring the development of green finance in Turkey by carrying out activities to strengthen the ecosytem,
- In order to ensure the development of green finance in Turkey, preparation of legistlation to ensure the continuity of related investments by taking into account the taxonomy legislation of the EU and international organisations,
- Within the scope of the Action Plan, acceleration of the preparations fort he Sustainable Bond Framework Document,
- Preparation of Green Deal Guide and Green Legal Guide within the scope of the Action Plan,
- Carring out studies in the field of Green Law eithin the scope of Action Plan,
- Developing a system fort he development os sustainable banking, which is expected to take important steps in the process of transition to green finance steps,
- Strengthening diplomatic relations in order to Access international financing sources for green transformation in line with the published Green Deal Action Plan,

○ Within the scope of economies, secure and clean energy supply

- Anaysing the needs for Renewable Energy and Energy Efficiency studies and identifying areas that can be developed,
- Organising awareness raising and awareness raising trainings on Green Tariff and YEK-G Certificate,
- Organising awareness raising trainings on Renewable Energy and Energy Efficiency primarily fort he authorites of the organisations in Organised Industrial Zones,
- In parallel with our current policies, to continue resouce development activities in such a way that 1000 MW WPP, SPP investment will be made every year until the end of 2027,
- Preparation of national strategy documents, guidelines and road maps for efficient energy management and dissemştaion of low-carbon heating and cooling systems (Republic of Turkey Ministry of Trade, 2021).

○ Sustainable agriculture target set within the scope of the agreement

- Reducing the use of pesticides and anti-microbial as the most important item of the agricultural targets set in our country,
- In line with the targets set in the field of agriculture, in order to reduce the of pesticides and anti-microbial as the most important item of the agricultural targets set in our country,
- Another revision to be made in the field of agriculcure is the revision of targets and policies to reduce the use of chemical fertilisers,
- Expanding organic agriculture practices througgout the country and providing incentives in this regard,

- Harmonisation of Turkey with the organic agriculture legislation published by the EU in line with the objectives of disseminating organic agriculture practices in our country and making initiatives with the Commissions in this context,
- Carrying out land consolidation registration activities with the support of the Ministry,
- Green production by making use of geothermal resources in Agriculture Based (Geothermal greenhouse) Specialised Organised Industrial Zones estaplished in proviences such as Denizli, Ağrı, Aydın and İzmir,
- Direct utilisation of renewable energy sources by greenhouse and production facilities to support sustainable agriculture as a component of the circular economy,
- Based on the principle of reducing the formation odf wastes and reusing them, carrying out activities to raise awarenness of the society in order to reuse and reduce the information of food wastes and residues and developing R&D studies in this context,
- It is aimed to continue the activities to inform the society on the EU strategies of Farm to Table and Biodiversity Strategies and to carry out awareness- raising activities (Republic of Turkey Ministry of Trade, 2021).

○ Within the scope of sustainable smart transport target

- Preparing and putting info force the Regulation on "Combined Transport" and "Logistic Centeres" in order to take large-scale steps in international freight transport,
- Improvement of the railway infrastructure between the EU and Turkey,
- Preapering a national regulation on Green Port Certificate Programme for coastal facilities and informing the relevant instutiutions on this issue,
- Continuation of SECA (Sulphur Emissions Control Area) studies, which have been establised in order to ensure emissions control in maritime transport, also in our country,
- Supporting green shipping by reducing emissions from the maritime sector, which is among the sectors that cause greenhouse gas emissions,
- Developing policies and strategies fort he development of electric vehicles and charging infrastructure to reduce emissions,
- Providing support fort he continuation of the action studies of "4.5. Using Electric Vehicles in Public Trasport Fleets and Service Vehicles and Encouraging Public Transport" in the "National İntelligent Transport System Strategy Document and 2020-2023 Action Plan" put into effect by the Ministry of Transport and Infrastructure in order to create intelligent transport systems and monitoring the process,
- Carring out legistlative studies fort he reduction of exhaust emissions and transport vehicles such as low-emissions bicycle or electric scooter systems, preparing Bicycle Transport Mater Plans, building bicycle/e-scooter roads, parking and charging stations,

○ Activities to be carried out on combating climate change

- Preaparation of Turkey's Report on Combating Climate Change by the Ministry of Environment Urbanisation and Climate Change of the Republic of Turkey,
- Preparation of 2023-2030 Climate Change Action Plan and 2050 Climate Change Strategies in our country within the scope pf the European Green Deal published in the EU,
- Analysing the position of our country towards the Paris Agreement and making evaluations by taking into account the need for international financing,
- Determining the effects of desertification and land degradation on biodiversity and ecosytems that occur globally with climate change and carrying out mitigation activities,

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- Determining the possible loss of coastral and fresh water due to climate change and taking measures to protect coasts, lakes and/or wetlands in this context,
- Participate in national investment programmes in the with Land Degradation Compensation (LDC) targets,
- Continuation of remendial activities within the scope of ATD targets in areas with high land degradation,
- Carriying out project studies to increase carbon sinks,
- Developing sustainable agricultural techniques and raising awareness by supporting these techniques with R&D studies,
- Implementation areas of studies based on the protection of natural structure in land applications will be increased (Republic of Turkey Ministry of Trade, 2021).

○ Activities to be carried out within the scope of diplomacy

- Within the scope of diplomacy onjectives, to develop commercial and political cooperation opportunities with the EU and EU member states and to carry out official and voluntary activities in order to obtain new opportunities,
- Continuing efforts to protect our rights arising from the Customs Union, WTO and other international agreement within the scope of the EU border carbon regulation mechanism (Republic of Turkey Ministry of Trade, 2021).

○ Within the scope of the European Green Deal awareness and information target

- Carrying our information and awareness-raising activities with the participation of the relevant institutions, organisations, administrative and commercial collaborators in order to ensure the adaptation of our country to the European Green Deal published in the EU, where work on the subject countinues rapidly (Republic of Turkey Ministry of Trade, 2021).

Carbon Market

The Carbon emissions are the release of carbon dioxide into the atmosphere from the combustion of carbon-containing fossils fuels (coal, oil and natural gas). The significant content of carbon em,ission consists of carbon dioxide and other greenhose gases such as methane, nitrous oxide, water vapour and fluorinated gases are commonly known as greenhouse gases emission since they are translated as carbon equivalent (Ministry of Environment and Forestry, 2011).

Fluorocarbons such as sulphurthxafluoride (SF6), perfluorocarbons (PFCs), and hydrofluorocarbons (HFCs) that occur as a result of industrial production activities are indirect greenhouse gases (Türkeş, 2008). CO2 accounts for 58.8 per cent of the content of all greenhouse gases. Carbon emission resulting from the combustion of fossil fuels that cause greenhouse gas emission formation increases global warming due to the increase in greenhouse gas emission in the atmosphere and couses serious climate changes (Altıntaş, 2013). Important steps such as the United Nations Framework Convention on Climate Change, the Paris Agreement and the Kyoto Protocol have been taken in order to reduce the carbon emission that has occurred in this process until today.

The idea of environmental tax, which was expressed by Arthur Pigou, a British economist in the 1920s is based on the principle of tax application to be introduced by goverments in order to cover the problems that occur as a result of industrialisation and urbanisation (Metcalf, 2019). Taxing this pollution is of course not an easy task. However, it is possible to tax energy products that can be associated with carbon emissions. The amount of CO2 that will be released by burning a tonne of coal, a Sm3 of natural gas or a gallon of gasoline can be determined on a product basis. In this context, one of the tax types that can be classified as environmental tax is the “Carbon Tax”. Carbon tax is an environmental tax based on the carbon emissions released into the atmosphere due to the production, distribution or utilisation of fossil fuels. This tax aims to reduce the environmental impacts and climate change caused by fossil fuels. The amount of carbon tax is usually determined based on the amount of carbon emitted per tonne

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(Zimmermannova, Hajek ve Rozensky, 2017). Carbon tax has been recognised as an important tool in combating climate change fort he last 20 years and has been implemented by many countries on a mandatory or voluntary basis. However, the effectiveness and applicability of the tax may vary depending on local and national conditions.

Initially introduced in countries such as Denmark, Finland, Norway, and Sweden, carbon taxes aimed to reduce carbon emissions and mitigate global climate change.

Subsequently, they were adopted and implemented by other European Union member states. (Word Bank 2017). After the environmental taxes proposed in the 1920s, carbon tax was discussed fir the first time in the early 1970s. While Finland firat started to implement the carbon tax system in 1990, in the same year, countries such as the Netherlands and Sweden started to implement carbon taxes due to the use of fossil fuels as the main energy source of production. In the initial stages, carbon tax was leived only according to the carbon content of fossil fuels, while carbon tax was levied on fossil fuels between 1994 and 1996, 60% according to carbon content and 40% according to energy content (Yaylı, 2019).

The aim of carbon tax practices is to support environmental sustainability and the fight against climate change worldwide and to slow sown global warming, especially by restricting and reducing greenhouse gas emissions. The effectiveness and implementation patterns of these taxes may vary from country to country, but in general, they aim to reduce the use of fossil fuels and encourage the transition to cleaner energy sources. Since GHG emissions are on an indefine upward trend, any tax would favour stabilising or reducing GHG emissions in the long run (Ekins ve Barker, 2001). As industrial production and consuption increase, revenues generated by rising energy demand will also trend to increase. Substituting fossil fuels with renewable energy sources is a challenging process in today's environment, but one that is also open to development and support. The implementation od carbon taxes is an important tool to incentivise this transformation and reduce the use of fossil fuels, and the proposal to implement them through existing excise taxes could reduce the cost and help faster implementation by using infrastructure within the tax system. Carbon taxes will contribute to energy savings, innovation and investment in clean technology, and hence to economis growth. These taxes support circular economy reform by enabling increased energy efficiency, investment in renewable energy sources and the development of green technologies (Ekins ve Barker, 2001).

CONCLUSION AND DISCUSSION

The increasing pressure of industrialization and population growth on natural resources has made environmental sustainability one of the most critical global challenges. While numerous international agreements, policies, scientific studies, and initiatives have been developed since the 1960s concerning environmental pollution and resource depletion, the European Green Deal is a significant milestone in translating environmental targets into concrete economic and regulatory measures. In particular, the Fit for 55 package sets ambitious targets for the European Union, aiming to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels.

These developments are particularly important for Turkey due to its strong economic and trade relations with the European Union. Approximately half of Türkiye's total exports are destined for EU countries. Consequently, the environmental regulations introduced under the European Green Deal are expected to have significant implications for Turkish exporters. In this context, one of the most important mechanisms is the Carbon Border Adjustment Mechanism (CBAM), implemented to address carbon leakage and ensure that imported products are subject to carbon costs similar to those faced by producers within the EU. The CBAM initially focuses on carbon-intensive sectors such as iron and steel, aluminum, electricity, cement, hydrogen, and fertilizers. During the transition period, companies importing covered products into the EU are required to report the emissions contained in those products; this is followed by a gradual financial adjustment phase.

While the textile sector is not currently directly covered by the CBAM, the increasing emphasis on product-level carbon emissions, supply chain transparency, and climate-related trade regulations suggests that other carbon-intensive and export-oriented sectors may face similar requirements in the future. Therefore, Turkish textile manufacturers and other export-oriented industries should begin preparing for potential regulatory developments by strengthening their carbon accounting, life cycle

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assessment, energy efficiency, renewable energy, and emissions monitoring capacities. Early compliance with these requirements can help Turkish companies maintain their competitiveness in the European market and reduce their exposure to future carbon-related trade barriers.

The European Union's goal of achieving climate neutrality by 2050 also requires climate policies to extend beyond the EU's geographical borders. In this context, CBAM (Urban Carbon Market Management) should be considered not only as a trade-related financial instrument, but also as part of a broader transformation towards a low-carbon and circular economy. The effectiveness of this transformation will depend not only on measures implemented within the EU, but also on the capacity of trading partners like Turkey to adapt their production systems, energy structures, and environmental policies.

Turkey has also taken steps toward establishing a national carbon pricing framework. While the country has participated in voluntary carbon markets through various projects since 2005, the development of a more structured national carbon market represents a significant step toward integrating climate policy with economic mechanisms. Türkiye's commitment to achieving carbon neutrality by 2053 further highlights the need for a comprehensive and long-term decarbonization strategy. Given that energy production and consumption account for a significant portion of Turkey's greenhouse gas emissions, increasing the share of renewable energy and improving energy efficiency should be key elements of this strategy.

Turkey's emissions trajectory further emphasizes the urgency of these measures. Greenhouse gas emissions have increased significantly compared to 1990 levels, largely due to fossil fuel consumption and industrial activities. According to national projections and Turkey's Nationally Determined Contribution (NDC) analyses, emissions are expected to remain at high levels until 2030 unless more ambitious mitigation measures are implemented. This demonstrates the need for continuous review and strengthening of current climate targets and action plans in line with Türkiye's 2053 net-zero commitment and the rapidly evolving international climate policy environment.

Therefore, the European Green Deal can be seen not only as an environmental policy framework but also as a major transformation of the European economic system. Similar to how the Industrial Revolution fundamentally reshaped production, trade, and economic relations, the transition to a climate-neutral and circular economy has the potential to redefine global competitiveness. For Turkey, this transformation presents both significant challenges and opportunities. Failure to adapt could increase carbon-related costs and create risks for export-oriented industries.

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THE CONTRIBUTION OF ARTIFICIAL INTELLIGENCE-ASSISTED MONITORING DATA TO NURSING DECISIONS IN CHILDREN UNDERGOING MECHANICAL VENTILATION

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ABSTRACT

Introduction and Objective: Mechanical ventilation is an invasive procedure used to provide respiratory support to children with respiratory failure. Due to the invasive nature of the procedure, it requires close monitoring and care. The literature contains studies on intensive care monitoring and nursing practices in patients receiving respiratory support. With the advancement of technology and the increasing application of artificial intelligence in the nursing field, studies have begun to explore the integration of artificial intelligence into the patient monitoring process. The aim of this review is to evaluate the impact of artificial intelligence on nursing decision-making in the care of pediatric patients undergoing mechanical ventilation, based on current literature data.

Materials and Methods: This review was prepared by selecting studies conducted in the past five years using the keywords “mechanical ventilation, artificial intelligence, pediatric intensive care, nursing decision making, clinical decision support systems, monitoring, pediatric patient, intensive care nursing, digital health, patient monitoring” in the PubMed database.

Findings: Studies have shown that AI-supported monitoring has positive effects on the clinical decision-making process in the intensive care setting. However, the ethical implications of AI, the continuous flow of data, and third-party access to patient information present limitations for clinicians in the clinical decision-making process.

Discussion and Conclusion: AI-supported interventions in the nursing care process have positive effects on the care process. Its use could become more widespread once clinician training and ethical issues are addressed. Further research is needed to promote its widespread use in clinical settings and achieve more accurate outcomes.

Keywords: Artificial intelligence; mechanical ventilation; pediatric intensive care; nursing decision-making; clinical decision support system; monitoring; pediatric patient; intensive care nursing; digital health; patient monitoring

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INTRODUCTION AND AIM

Mechanical ventilation is an invasive procedure used to provide respiratory support in patients with inadequate or absent respiration (Antmen, Z. F., 2018). Children receiving mechanical ventilation are managed in pediatric intensive care units as they are classified as a critical patient group requiring closer monitoring (Başaran, K., 2025). Nursing practices such as maintaining nutrition, continuing personal

care, infection control and therapeutic communication play a significant role in children receiving mechanical ventilation (Karaman, A., 2025). During the pediatric mechanical ventilation process, the patient's vital signs are monitored more closely. To this end, patients are monitored, and parameters such as respiratory rate, tissue perfusion, pulse and blood pressure are tracked more closely (Suzan, Ö. K., 2019). In the nursing care process, monitoring data are of great importance in terms of the patient's clinical follow-up and the prognosis of the illness (Sarı, H. Y., 2013). Rapid intervention in response to changes in the patient's clinical and monitoring data is one of the factors that reduces the complication rate (Başaran, K., 2025).

With recent technological advancements, artificial intelligence applications and clinical decision support systems have begun to be used in the field of nursing (Tutar, Ş. 2025). Research is being conducted into the use of artificial intelligence for purposes such as clinical decision-making, early intervention and minimising the risk of complications in critically ill patients. The aim of this review is to assess the impact of artificial intelligence on nursing decisions in the care of pediatric patients on mechanical ventilation, guided by existing applications in the literature (Bulut, C. 2025).

MONITORING IN CHILDREN UNDERGOING MECHANICAL VENTILATION

The aim of mechanical ventilation is to maintain respiration and thereby ensure tissue perfusion. For this reason, one of the most important parameters in pediatric mechanical ventilation is the measurement of oxygen saturation in arterial blood (Vagas, E. 2012). To this end, monitoring using a non-invasive pulse oximeter is very common in clinical practice (Suzan, Ö. K., 2019). The assessment of oxygen concentrations in arterial blood is carried out using a pulse oximeter in clinical settings. It is the first parameter to be examined when monitoring mechanical ventilation, assessing its effectiveness and identifying problems (Bülbül, A., 2014).

Monitoring the respiratory rate in children on mechanical ventilation provides guidance on issues such as the presence of spontaneous breathing and resistance to mechanical ventilation (Emiralioğlu, N. 2014).

In pediatric mechanical ventilation monitoring data, the pulse plays a key role in cardiovascular assessment. It should be evaluated in terms of rate, rhythm and volume. In pediatrics, the pulse rate serves as an indicator of adequate oxygenation and circulatory complications (Sarı, H. Y., 2013).

Hypotension is a symptom of pneumothorax, one of the most common complications during mechanical ventilation. In pediatric mechanical ventilation, monitoring blood pressure is one of the key parameters for assessing respiratory function and detecting complications (Başaran, K. 2025).

In patients receiving pediatric mechanical ventilation support, one of the first aspects assessed from a nursing perspective is the patient's clinical monitoring. Monitoring data and the patient's compliance with mechanical ventilation are key steps in patient assessment (Benligül, E. M., 2013). The consistency between the patient's vital signs and the monitoring data is of vital importance. Furthermore, to ensure the patient's compliance with mechanical ventilation, it is essential to verify that the technical and mechanical systems of the device are fully functional and in good working order. The patient's vital signs must be compared with the monitoring data and closely monitored to prevent potential complications and adverse events (Karaman, A., 2025).

THE IMPACT OF ARTIFICIAL INTELLIGENCE-ASSISTED MONITORING ON NURSING DECISIONS

Artificial intelligence-supported clinical decision support systems for pediatric patients on mechanical ventilation are a current area of research in the literature, owing to their role in patient monitoring, the early detection of complications and the implementation of effective care practices. It has been emphasised that, through machine learning—a sub-field of artificial intelligence—monitoring data from pediatric patients on mechanical ventilation can be used with an early warning system to improve the quality of care (Newth, C.J.L. 2017).

A study published in 2020 found that a machine learning-based early warning system for hypotension was significantly more effective and feasible than standard monitoring. (Wijnberge, M., 2020).

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A study published in 2024 found that a machine learning model demonstrated good predictive performance using vital signs and laboratory data to predict clinical deterioration (Keim, M. J., 2024).

The literature indicates that artificial intelligence-based clinical decision support applications and early warning systems have been shown to reduce complications and improve the quality of care, particularly in intensive care units (Johnson, A. E., 2016). A review of the literature reveals that, in the studies examined, the use of artificial intelligence-supported systems in nursing practice is highly effective in clinical decision-making. With the support of artificial intelligence and a continuous flow of data, the workload during the care process is reduced, thereby increasing the efficiency of the care process.

LIMITATIONS AND ETHICAL ISSUES

Although Artificial Intelligence-supported applications have their strengths in patient care and monitoring through clinical decision support systems, these technologies do have certain limitations and ethical issues. (Murali, M. 2024) Firstly, the quality of clinical decision support systems depends on an uninterrupted flow of data (El Arab, R. A. 2025). Unnoticed interruptions in the data flow can compromise the reliability of clinical decision support systems (Katebi, M. 2025). The uncertainty surrounding the operational model of AI-supported clinical decision support systems limits nurses confidence in their use (Sharma, M. 2022). Furthermore, the entry of patient data can give rise to significant ethical issues regarding data privacy (Boege, S. 2024). The fact that data is stored digitally can lead to problems in terms of ethics and patient privacy due to unauthorised access or the sharing of this data with third parties (Pashkov, V.M. 2020).

CONCLUSIONS AND RECOMMENDATIONS

The current literature highlights the use of artificial intelligence in nursing care and practice. In pediatric nursing, however, artificial intelligence is an area of application that requires greater rigour, given that care data relates to a critically ill patient population (Hassan, M. 2024). Studies indicate that artificial intelligence is making progress in the field of evidence-based nursing practice (Shah, N. 2025).

However, the literature reports that nurses have reservations regarding artificial intelligence and clinical decision support systems (Abdelmohsen, S. A., 2025). In particular, the fact that pediatric patients are critically ill limits evidence-based practice, as it hinders a full understanding of how decision support systems operate (Aravazhi, P. S., 2025).

The processing of patient data in a digital environment, technical issues and data security breaches are factors that limit the use of artificial intelligence (Hassan, M. 2024). In pediatric nursing, the use of artificial intelligence in evidence-based practice is constrained by ethical considerations (Boege, S. 2024). In light of the literature, further research is required regarding the ethical limitations and reliability of artificial intelligence and clinical decision support systems.

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THE EFFECT OF ARTIFICIAL INTELLIGENCE-ENABLED DIGITAL GAMES AND VIRTUAL REALITY APPLICATIONS ON ANXIETY, FEAR AND ADAPTATION IN CHILDREN HOSPITALISED IN HOSPITALS

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ABSTRACT

Introduction and Aims: Hospital admission is an experience that causes psychological and physical stress in children due to disruptions to their daily routine, unfamiliar surroundings and people, reduced social interaction, and invasive procedures and treatments. The changes experienced result in various physical responses to stress in children. A review of the literature reveals that there are different nursing approaches regarding children's adaptation to hospital and treatment. With the advancement of technology and the integration of artificial intelligence into the healthcare sector, studies on hospital admission anxiety in children have begun. The aim of this review is to determine the effects of artificial intelligence on the hospital process by compiling studies that examine the impact of artificial intelligence applications on adaptation, fear and anxiety in children during the hospital process.

Materials and Methods: Studies conducted over the past five years were compiled using the keywords 'artificial intelligence, digital game, virtual reality, paediatric patient, anxiety, fear, hospital adaptation, treatment adherence, paediatric nursing, child hospitalisation' in the PubMed database.

Findings: Hospital admission can cause physical stress, particularly in the pre-school years, leading to physical reactions such as hitting or running away. Recent studies have shown that AI-supported digital games and virtual reality applications help to reduce anxiety and fear associated with hospital admission and support improved adherence to treatment.

Discussion and Conclusion: As technology becomes increasingly widespread in nursing practice, current technological developments such as artificial intelligence and virtual reality applications are beginning to form part of the nursing process. The results of studies in the literature on supporting the process of fear, anxiety and hospital compliance in children using artificial intelligence applications are similarly positive. As digital games and virtual reality applications are non-invasive procedures, they enhance adaptation to the hospital and treatment process, thereby supporting a more comfortable and effective treatment experience.

Keywords: Artificial intelligence; digital games; virtual reality; hospital adaptation; children; anxiety; fear; paediatric nursing; treatment compliance; hospital experience.

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INTRODUCTION AND AIM

The hospital admission process is a psychologically and physically stressful experience for children (Atay, G. 2011). Entering an unfamiliar environment, the procedures carried out in hospital, the course

of treatment and the uncertainty involved lead to difficulties in children's adaptation to hospital and treatment (Parlak, S.H. 2023). The hospital admission process elicits different reactions across all age groups during childhood (Başbakkal, Z., 2010). Whilst reactions in early childhood may include running away, hitting, or exhibiting sensory regression in response to treatment interventions, during adolescence—as children transition from the concrete to the abstract stage—they may understand the treatment and hospital admission process but still experience tension, anger and a sense of dependence on others (İnal, E.F. N., 2008). Interventions designed to reduce anxiety and fear levels can be implemented in line with the reactions exhibited by hospitalised children according to their developmental stages (Başay, B. K., 2020). A review of the literature reveals that there are practices aimed at improving hospital adjustment and reducing anxiety through the use of age-appropriate concrete objects and toys (Uludaşdemir, D., 2021). With advances in technology and artificial intelligence applications, research has begun to assess the effects of these on children's anxiety, fear and adjustment during the hospital stay (Başay, B. K., 2020). The aim of this review is to determine the effects of artificial intelligence on the hospital experience of children by compiling studies that examine its impact on adaptation, fear and anxiety during the hospital process.

THE EFFECTS OF ARTIFICIAL INTELLIGENCE-ENABLED DIGITAL GAMES AND VIRTUAL REALITY APPLICATIONS ON CHILDREN DURING THE HOSPITAL ADMISSION PROCESS

Hospital admission is a process that has physical and psychological effects on children (Yayan, E. H., 2018). These effects can disrupt nursing practice (Selbes, M., 2021). A review of the literature reveals that hospital admission anxiety in children remains a topic of ongoing research, both in past studies and today (Kıran, B., 2013). Therapeutic play is the most widely used of the traditional methods for reducing the physical and psychological effects of the hospital admission process and improving adaptation (Özcan, M., 2025). It has been reported that this method, which is frequently used in practice particularly during the pre-school period, enhances cooperation with the child during procedures and treatment and reduces levels of anxiety and fear (Atay, G., 2011).

A study conducted in 2026 examined the clinical outcomes of combining therapeutic play with emotional and soothing care in children with acute gastroenteritis. The integration of therapeutic play with emotional and soothing care was found to be associated with improvements in nutritional status and sleep quality in children receiving treatment for acute gastroenteritis. These changes enhanced compliance with the treatment process (He Y., 2026).

Advances in technology and current artificial intelligence applications continue to evolve in terms of their impact on children's fear and anxiety regarding hospitalisation (Kavlakci, M. 2023). AI-supported games and virtual reality applications can be regarded as technology-adapted versions of traditional methods (Tark, R., 2019). Studies have demonstrated the effectiveness of digital games and virtual reality applications, particularly during invasive procedures.

A study published in 2026 investigated the effect of digital games on fear, pain, anxiety and physiological responses during the insertion of a port catheter in children. The results of the study showed that digital games were effective in reducing pain, fear and anxiety in children and in stabilising their heart rate (Azak, M. 2026). A study published in 2026 assessed the effects of virtual reality applications on pain and anxiety in patients undergoing peripheral venous catheterisation. It was found that, in the 5–14 age group, the use of virtual reality reduced anxiety and pain during venous catheterisation (Yu, J., 2026).

AN EVALUATİON OF AI-POWERED DİGİTAL GAMES AND VİRTUAL REALİTY APPLİCATİONS FROM THE PERSPECTİVE OF PAEDİATRİC NURSİNG

The introduction of technology into the field of nursing care, and studies utilising virtual reality and digital applications, are among the innovative approaches that support a child-centred approach to care (Huang, Y. T., 2025). A review of the literature reveals that hospital admission gives rise to negative experiences in children, such as anxiety, worry, fear and non-compliance with the treatment and care process (Kıran, B., 2013). Research indicates that therapeutic play and therapeutic education, traditionally practised, are moving towards integration with artificial intelligence and virtual reality

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applications (Yu, J. 2026). Studies utilising artificial intelligence and virtual reality applications demonstrate high efficacy. As these applications are non-invasive, non-pharmacological methods, they are regarded as practical and applicable approaches (Savaş, E. H. 2024). Due to their positive effects—such as reducing stress to improve hospital adaptation, alleviating fear and anxiety, and stabilising vital signs—artificial intelligence and virtual reality applications can be incorporated into routine nursing care practices (Kavlakci, M. 2023). Consequently, by improving the quality of clinical care practices, enhancing patient satisfaction, keeping pace with current care approaches, and integrating technological advancements into healthcare processes, evidence-based nursing practices can be implemented to deliver patient care grounded in the latest research and knowledge.

CONCLUSIONS AND RECOMMENDATIONS

Hospital admission and the treatment process lead to developmental reactions in children due to the disruption of their social lives and the disruption of their daily routines. Difficulties in adapting to the treatment process make it a challenging experience and lead to feelings such as anxiety and fear in children (Koukourikos, K. 2015). From the past to the present, there have always been studies on adapting to the hospital and treatment process, such as therapeutic play, educational classes in hospitals, and involving the sick child in the treatment process through collaboration to improve adaptation (Koç, S. 2023).

As technology has begun to become more widespread in nursing practice, recent technological developments—such as artificial intelligence and virtual reality applications—have started to form part of the nursing process (Huang, Y. T., 2025). Similarly, the results of studies in the literature examining the use of artificial intelligence applications to support the management of fear, anxiety and hospital adaptation in children are positive (Turgut, A., 2024). As these are non-invasive procedures, they enhance adaptation to the hospital and treatment process, thereby helping to make the treatment process more comfortable and effective (Armstrong, M., 2025). Whilst similar studies can be found in the current literature, further research is required to integrate AI-supported applications into routine nursing practice. The replication of such studies will help clarify healthcare professionals' views on AI-supported applications, thereby positively influencing the provision of more comfortable patient care and supporting evidence-based practice.

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BOR VE BORİK ASİDİN NÖROPROTEKTİF POTANSİYELİ: MOLEKÜLER MEKANİZMALAR, PREKLİNİK KANITLAR VE GELECEK PERSPEKTİFLERİ

THE NEUROPROTECTIVE POTENTIAL OF BORON AND BORIC ACID: MOLECULAR MECHANISMS, PRECLINICAL EVIDENCE AND FUTURE PERSPECTIVES

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ÖZET

Nörodejeneratif hastalıklar; oksidatif stres, nöroinflamasyon, sinaptik işlev bozukluğu, mitokondriyal hasar ve programlanmış hücre ölümü gibi birbiriyle ilişkili süreçlerin birlikte ilerlediği kompleks hastalıklardır. Bu derlemenin amacı, bor elementinin yaygın inorganik formlarından biri olan borik asidin nöroprotektif potansiyelini, güncel in vivo, ex vivo ve in vitro çalışmalar temelinde değerlendirmektir. Literatürde borik asidin oksidatif stres belirteçleri, antioksidan savunma, inflamatuvar sinyal yolları, nöronal apoptoz, ferroptoz, sinaptik bütünlük ve bilişsel davranışlar üzerindeki etkileri araştırılmıştır. Sıçan travmatik beyin hasarı modelinde borik asit ön tedavisi malondialdehit düzeylerini ve katalaz aktivitesindeki bozulmayı azaltmış; ödem ve nekrotik nöron oluşumunu sınırlamıştır. Amiloid beta ile uyarılan sıçan sinaptozomlarında borik asit, malondialdehit, nitrik oksit, DNA parçalanması, asetilkolinesteraz aktivitesi, ACSL4 ve transferrin reseptör-1 düzeylerindeki değişiklikleri azaltırken glutasyon ve GPx4 düzeylerini desteklemiştir. D-galaktozla hızlandırılmış yaşlanma modelinde borik asit uygulaması oksidatif hasarı azaltmış ve bilişsel test performansını iyileştirmiştir. Daha yeni bir sıçan çalışmasında borik asit, glifozat kaynaklı davranışsal, oksidatif, inflamatuvar, apoptotik ve glial değişiklikleri kısmen tersine çevirmiştir. Boraksla yapılan çalışma ise bor bileşiklerinin Nrf2/oksidatif stres dengesi üzerindeki etkisini gökkuşağı alabalığında göstermiştir; bu sonuç doğrudan insan nöroproteksiyonu olarak yorumlanmamalıdır. Genel olarak mevcut kanıtlar borik asidin çoklu biyolojik yolakları etkileyebilen umut verici bir preklinik aday olduğunu düşündürmektedir. Bununla birlikte kanıtların büyük bölümü küçük örneklemli hayvan, hücre veya sinaptozom çalışmalarından oluşmaktadır. İnsanlarda nörodejeneratif hastalıkları önlediğini veya tedavi ettiğini gösteren yeterli klinik kanıt bulunmamaktadır. Gelecekte doz-standardizasyonu, formülasyon karşılaştırması, uzun dönem güvenlilik, biyoyararlanım ve insan biyobelirteçleri birlikte ele alınmalıdır.

Anahtar kelimeler: Borik asit, bor, nöroproteksiyon, oksidatif stres, nöroinflamasyon, ferroptoz, Alzheimer hastalığı, Parkinson hastalığı, travmatik beyin hasarı.

ABSTRACT

Neurodegenerative diseases are complex disorders involving interconnected processes such as oxidative stress, neuroinflammation, synaptic dysfunction, mitochondrial injury, and programmed cell death. This review evaluates the neuroprotective potential of boric acid, one of the common inorganic forms of boron, based on current in vivo, ex vivo, and in vitro evidence. Experimental studies have examined the effects of boric acid on oxidative stress markers, antioxidant defenses, inflammatory signaling, neuronal apoptosis, ferroptosis, synaptic integrity, and cognitive behavior. In a rat model of traumatic brain injury, boric acid pretreatment reduced malondialdehyde levels and abnormal catalase activity and limited edema and neuronal necrosis. In amyloid-beta-exposed rat synaptosomes, boric acid reduced changes

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in malondialdehyde, nitric oxide, DNA fragmentation, acetylcholinesterase activity, ACSL4, and transferrin receptor-1, while supporting glutathione and GPx4 levels. In a D-galactose-induced accelerated aging model, boric acid reduced oxidative damage and improved cognitive performance. A recent rat study further reported that boric acid partially reversed behavioral, oxidative, inflammatory, apoptotic, and glial changes induced by glyphosate. A separate borax study demonstrated effects on the Nrf2/oxidative stress balance in rainbow trout; this finding should not be interpreted as direct evidence of human neuroprotection. Overall, current evidence suggests that boric acid is a promising preclinical candidate capable of influencing multiple biological pathways. However, most evidence comes from small animal, cell, or synaptosome studies, and sufficient clinical evidence that boric acid prevents or treats neurodegenerative disease is not available. Future studies should address dose standardization, formulation comparisons, long-term safety, bioavailability, and human biomarkers.

Keywords: Boric acid, boron, neuroprotection, oxidative stress, neuroinflammation, ferroptosis, Alzheimer's disease, Parkinson's disease, traumatic brain injury.

1. GİRİŞ

Nörodejeneratif hastalıklar, farklı klinik görünümlere sahip olmakla birlikte ortak moleküler süreçler üzerinden birbirleriyle kesişir. Alzheimer hastalığı, Parkinson hastalığı ve amiyotrofik lateral skleroz gibi hastalıklarda oksidatif stres, nöroinflamasyon, mitokondriyal işlev bozukluğu, protein homeostazında bozulma ve sinaptik kayıp birlikte ilerleyebilir. Bu süreçlerin birbirini beslemesi, tek bir hedefe yönelen tedavilerin sınırlı kalmasına neden olabilir.

Beyin dokusu yüksek oksijen tüketimi, yüksek membran lipid içeriği ve sınırlı rejeneratif kapasitesi nedeniyle oksidatif hasara duyarlıdır. Reaktif oksijen türleri (ROS) ve reaktif azot türleri; membran lipidlerini, proteinleri, nükleik asitleri ve mitokondriyal bileşenleri etkileyebilir. Lipid peroksidasyonunun son ürünlerinden biri olan malondialdehit (MDA), deneysel nörodejenerasyon çalışmalarında oksidatif hasarın sık kullanılan göstergelerindendir. Antioksidan sistemin önemli bileşenleri olan glutatyon (GSH), süperoksit dismutaz (SOD), katalaz (CAT), glutatyon peroksidaz (GPx) ve toplam antioksidan kapasite ise redoks dengesinin değerlendirilmesinde kullanılır.

Bor, doğada çoğunlukla oksijen içeren boratlar şeklinde bulunan bir elementtir. İnsanlarda borun zorunlu bir besin öğesi olduğu kesin olarak gösterilmiş değildir; ancak borun kemik metabolizması, inflamasyon, enerji metabolizması ve beyin işleviyle olası ilişkileri araştırılmıştır [1]. Borik asit ($B(OH)_3$), borun sulu ortamlardaki önemli türlerinden biridir. Boratlar gastrointestinal sistemde önemli ölçüde borik aside dönüşür ve emilen borun ana dolaşım formu borik asittir [1] [2].

Son yıllarda borik asidin oksidatif stres, inflamasyon ve hücre ölümü süreçleri üzerindeki etkisini inceleyen deneysel çalışmalar artmıştır. Bu çalışmalar arasında sıçan travmatik beyin hasarı modeli, amiloid beta ile uyarılmış sinaptozomlar, D-galaktozla hızlandırılmış yaşlanma modeli, glifozat nörotoksisitesi ve çeşitli toksik maruziyet modelleri bulunmaktadır. Bununla birlikte borik asidin nöroprotektif etkisini gösteren çalışmaların çoğu preklinik düzeydedir. Bu nedenle bulgular klinik tedavi önerisi olarak değil, mekanistik hipotez ve araştırma yönü olarak değerlendirilmelidir.

2. ARAŞTIRMA VE BULGULAR

Bu derleme çalışması için kaynak doğrulamasında PubMed, PubMed Central, DOI kayıtları, hakemli dergi sayfaları ve resmi güvenlilik bilgi kaynakları kullanılmıştır. Özellikle borik asidin oksidatif stres, nöroinflamasyon, bilişsel işlev, sinaptik hasar, ferroptoz ve toksin kaynaklı nörotoksisite üzerindeki etkilerini inceleyen özgün çalışmalar önceliklendirilmiştir.

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Tablo 1.

Kanıt düzeyi	Açıklama	Örnek
Doğrudan in vivo kanıt	Borik asit uygulanan hayvanlarda davranış, biyokimya veya histopatoloji ölçümü	TBI ve D-galaktoz sıçan modelleri
Ex vivo kanıt	Hayvandan elde edilen sinaptozom veya doku üzerinde kontrollü maruziyet	Aβ1-42 ile uyarılmış sinaptozomlar
In vitro kanıt	Hücre kültüründe toksin ve bor bileşiği uygulaması	SH-SY5Y hücreleri
Biyokimyasal kanıt	Nrf2, NF-κB, ferroptoz, apoptoz veya glial belirteçlerde değişiklik	ACSL4/GPx4, TLR4/NF-κB, Iba-1/GFAP
Klinik kanıt	İnsanlarda güvenlilik, biyobelirteç veya klinik çalışmalar	Nörodejeneratif hastalıklar için yeterli değildir

3. BORİK ASİDİN KİMYASAL VE BİYOLOJİK ÖZELLİKLERİ

Borik asit, $B(OH)_3$ yapısında zayıf bir Lewis asididir. Fizyolojik pH'da borik asit ve borat türleri arasındaki denge, büyük ölçüde borik asit lehinedir. Borik asidin biyolojik etkileri, hidroksil grupları içeren metabolitlerle tersinir kompleksleşme kapasitesi ve hücresel redoks/metabolik süreçlerle olası etkileşimleri üzerinden tartışılmıştır [2]. Bu kimyasal özellikler, borik asidin biyolojik etkilerinin yalnızca klasik bir "antioksidan süpürücü" mekanizmayla açıklanamayacağını düşündürür.

NIH Office of Dietary Supplements verilerine göre alınan borun yaklaşık %85–90'ı emilir; borik asit kan, idrar ve diğer vücut sıvılarındaki temel bor formudur. Bor çoğunlukla idrarla atılır ve çoğu dokuda belirgin biçimde birikmez [1]. Bu bilgiler, %64–98 emilim ve yaklaşık 21 saat yarı ömür ifadelerinin bağlama bağlı olduğunu gösterir. Emilim oranı kimyasal forma, doza ve çalışmanın yöntemine göre değişebilir.

Borun beyin dokusuna ulaşabildiğine ilişkin deneysel bulgular bulunmaktadır. Sıçanlarda borik asit ve boraks karışımı kullanılarak yapılan bir dağılım çalışmasında borun beyin, karaciğer ve böbrekte homojen olmayan biçimde dağıldığı bildirilmiştir [3]. Bununla birlikte bu çalışma, bor içeren çözeltinin transkardiyak enjeksiyonuyla yürütülmüş bir doku dağılım deneyidir. Beyin geçişi, kimyasal form, doz, maruziyet yolu, plazma düzeyi ve kan-beyin bariyerinin durumuna göre ayrıca incelenmelidir.

4. NÖRODEJENERASYONDA ORTAK PATOFIZYOLOJIK SÜREÇLER

4.1. OKSİDATİF STRES VE LİPİD PEROKSİDASYONU

Nöronlar oksidatif hasara karşı özellikle hassastır. ROS üretimi mitokondriyal elektron transport zinciri, inflamatuvar enzimler, metal-katalizli reaksiyonlar ve toksin maruziyeti ile artabilir. ROS artışı antioksidan kapasiteyi aşarsa membran lipidlerinde peroksidasyon, protein oksidasyonu ve DNA hasarı oluşabilir. MDA, bu sürecin sık ölçülen bir ürünüdür; ancak tek başına hastalık özgüllüğü taşımaz.

Borik asidin deneysel nöroprotektif etkileri çoğu çalışmada MDA azalması, GSH artışı veya SOD/CAT/GPx aktivitesinin korunması ile değerlendirilmiştir. Bu bulgular borik asidin redoks

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dengesini destekleyebileceğini düşündürür. Ancak MDA, GSH veya enzim aktivitesi düzeyindeki değişiklikler, borik asidin klinik nöroprotektif etkinliğini tek başına kanıtlamaz.

4.2. NÖROİNFLAMASYON VE NF-KB

Mikroglia ve astrositlerin kronik veya aşırı aktivasyonu TNF-α, IL-1β, IL-6, COX-2 ve diğer inflamatuvar aracıların artmasına yol açabilir. NF-κB, bu yanıtın düzenlenmesinde önemli transkripsiyon faktörlerinden biridir. Kronik nöroinflamasyon, oksidatif hasar ve sinaptik kayıpla birleşerek nöronal hasarı sürdürebilir.

Bor bileşikleriyle yapılan bazı deneylerde inflamatuvar gen veya protein belirteçlerinde azalma bildirilmiştir. Özellikle boraksın akrilamid kaynaklı nörotoksisite modelinde Nrf2/oksidatif stres yanıtı, inflamatuvar belirteçler, apoptoz ve beyin BDNF/AChE düzeyleri incelenmiştir [4]. Bununla birlikte bu çalışma gökkuşağı alabalığında yürütülmüştür. Balık modeli, mekanizma araştırması için değerlidir; fakat memeli beyni veya insan nörodejeneratif hastalıkları için doğrudan klinik kanıt değildir.

4.3. APOPTOZ VE FERROPTOZ

Apoptoz; Bax, Bcl-2 ve kaspaz-3 gibi belirteçlerle değerlendirilen programlı hücre ölüm yollarından biridir. Ferroptoz ise demir bağımlı lipid peroksidasyonu, GSH tükenmesi ve GPx4 işlev kaybıyla ilişkili bir hücre ölüm biçimidir. Aβ toksisitesi, demir metabolizması ve lipid peroksidasyonu ferroptozla ilişkili olabilir.

ACSL4, ferroptotik lipid üretimini artıran bir enzim olarak; transferrin reseptör-1 (TfR1) hücresel demir alımıyla; GPx4 ve GSH ise lipid peroksitlerin detoksifikasyonuyla ilişkilidir. Borik asit, bu belirteçlerdeki değişimleri Aβ ile uyarılmış sinaptozom modelinde tersine çevirmiştir [5]. Bu sonuç, borik asidin ferroptozla ilişkili oksidatif hasarı azaltabileceği hipotezini destekler.

5. ALZHEIMER HASTALIĞI MODELLERİNDE KANITLAR

5.1. AB1-42 İLE UYARILMIŞ SİNAPTOZOM MODELİ

Hacıoğlu ve arkadaşları, sıçan serebral korteksinden elde edilen sinaptozomları Aβ1-42 ile uyararak borik asidin nöroprotektif etkisini incelemiştir [6]. Sinaptozomlar, sinaptik uçların enerji metabolizmasını ve bazı nörotransmisyon özelliklerini ex vivo olarak değerlendirmeye olanak sağlayan bir modeldir.

Aβ1-42 maruziyeti sinaptophysin düzeyini azaltmış; MDA, nitrik oksit, AChE aktivitesi ve DNA parçalanmasını artırmıştır. Borik asit uygulaması Aβ maruziyetiyle artan MDA ve nitrik oksit düzeylerini azaltmıştır. Borik asit ve kurkumin kombinasyonu DNA parçalanması, MDA ve AChE aktivitesindeki değişiklikleri daha belirgin biçimde azaltmış; sinaptophysin düzeyindeki bozulmayı da iyileştirmiştir. Bu sonuçlar, borik asidin Aβ ile ilişkili sinaptik oksidatif hasarı ve kolinerjik sistem bozukluğunu azaltabileceğini düşündürmektedir.

5.2. FERROPTOZLA ILIŞKILI Aβ MODELI

Hacıoğlu ve arkadaşlarının daha sonraki ex vivo çalışmasında sıçanlara 21 gün borik asit ön tedavisi uygulanmış, ardından beyin dokusundan elde edilen sinaptozomlar Aβ1-42 ile inkübe edilmiştir [5]. Çalışmada borik asit ön tedavisinin beyin dokusunda belirgin morfolojik veya biyokimyasal bozulma oluşturmaması, güvenlilik açısından sınırlı bir preklinik sinyal olarak değerlendirilmiştir. Aβ uygulanan sinaptozomlarda ACSL4, TfR1, MDA ve 8-OHdG artarken GPx4 ve GSH azalmıştır. Borik asit ön tedavisi bu değişimlerin önemli bölümünü tersine çevirmiştir.

Bu bulgu, borik asidin demir metabolizması, lipid peroksidasyonu ve antioksidan kapasite arasındaki dengeyi etkileyebileceğini düşündürmektedir.

5.3. D-GALAKTOZLA HIZLANDIRILMIŞ YAŞLANMA MODELİ

Kaşıkçı ve arkadaşları 2025 yılında D-galaktozla oluşturulan hızlandırılmış yaşlanma modelinde borik asidin bilişsel ve antioksidan etkilerini araştırmıştır [7]. Çalışmada 12 haftalık erkek Wistar sıçanlar kullanılmış; D-galaktoz 150 mg/kg/gün ve borik asit 100 mg/kg/gün dozunda 12 hafta uygulanmıştır. Yeni nesne tanıma testi ve Morris su labirenti ile bilişsel performans değerlendirilmiştir.

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D-galaktoz ve borik asit birlikte uygulanan grupta MDA düzeyi azalmış, GSH düzeyinde artış eğilimi görülmüş ve bilişsel testlerde iyileşme saptanmıştır. Bulgular, borik asidin yaşlanma modelinde oksidatif hasar ile bilişsel bozulma arasındaki ilişkiyi azaltabileceğini düşündürmektedir.

6. PARKINSON HASTALIĞI VE DOPAMİNERJİK HASAR

Parkinson hastalığında dopaminerjik nöron kaybı, mitokondriyal kompleks I işlev bozukluğu, oksidatif stres ve nöroinflamasyon önemli süreçlerdir. Rotenon, mitokondriyal kompleks I'i inhibe ederek deneysel Parkinson modellerinde kullanılan bir toksindir.

Bu rotenon modeli, borik asidin dopaminerjik hasara karşı antioksidan kapasiteyi destekleyebileceğini ve nöronal kaybı azaltabileceğini bildiren preklinik bulgulara dayanmaktadır.

Borik asit–kuersetin kombinasyonu da oksidatif stres ve davranışsal sonuçlar açısından araştırılmıştır. Kombinasyon çalışmalarında total antioksidan kapasite, MDA, nesne tanıma ve lokomotor davranış gibi sonuçlar değerlendirilmiştir.

7. TRAVMATİK BEYİN HASARI MODELİNDE BORİK ASİT

Travmatik beyin hasarı, mekanik hasarın yanı sıra ikincil oksidatif stres, lipid peroksidasyonu, ödem, inflamasyon ve hücre ölümüyle ilerler. Ataizi ve arkadaşlarının sıçanlarda yürüttüğü çalışmada kapalı kafa travması oluşturulmuş ve borik asit 14 gün boyunca travma öncesi oral gavajla uygulanmıştır [8]. Çalışmanın üç grubu kontrol, TBI ve TBI+BA olarak düzenlenmiştir.

Travma grubunda MDA düzeyi ve katalaz aktivitesi kontrol grubuna göre artmıştır. Borik asit ön tedavisi uygulanan TBI grubunda bu değişiklikler TBI grubuna göre daha düşük bulunmuştur. Histopatolojik değerlendirmede travma grubunda ödem ve nekrotik nöronlar görülürken borik asit ön tedavisi alan grupta bu bulgular gözlenmemiştir. Bu sonuçlar borik asit ön tedavisinin TBI'ye bağlı oksidatif stres ve histopatolojik hasarı azaltabileceğini göstermektedir.

Çalışmanın en önemli sınırlılığı, borik asidin travma meydana gelmeden önce uygulanmış olmasıdır.

8. TOKSİN KAYNAKLI NÖROTOKSİSİTE MODELLERİ

8.1. FLORÜR VE ETANOL MODELLERİ

Hacıoğlu ve arkadaşları sıçan frontal korteksinden elde edilen sinaptozomlarda sodyum florür toksisitesine karşı borik asidi test etmiştir [9]. 80 mg/L florür, MDA, SOD, Na^+/K^+-ATPaz ve DNA parçalanması ölçümlerinde belirgin bozulma oluşturan doz olarak belirlenmiştir. 10 ve 25 mM borik asit uygulaması MDA, SOD, Na^+/K^+-ATPaz aktivitesi ve DNA parçalanması açısından florür grubuna göre iyileşme sağlamıştır; 5 mM borik asit aynı düzeyde etkili bulunmamıştır.

Bu sonuçlar borik asidin uygun dozlarda sinaptik membran bütünlüğünü ve redoks dengesini koruyabileceği hipotezini desteklemektedir.

Etanol kaynaklı sinaptozom hasarına ilişkin bulgular da borik asidin MDA artışını ve SOD/Na^+/K^+-ATPaz bozulmasını azaltabileceğini göstermektedir.

8.2. AKRİLAMİD VE BORAKS MODELİ

Turkez ve arkadaşlarının çalışmasında akrilamid nörotoksisitesine karşı boraksın etkisi gökkuşağı alabalığında incelenmiştir [4]. Balıklar 96 saat boyunca 12,5 mg/L akrilamid, 0,75 mg/L boraks veya iki bileşiğin kombinasyonuna maruz bırakılmıştır. Akrilamid; SOD, CAT, GPx, AChE, BDNF ve GSH düzeylerinde azalma, MDA, miyeloperoksidaz, DNA hasarı ve apoptoz belirteçlerinde artış oluşturmuştur. Boraks eş uygulaması bu değişikliklerin bir bölümünü azaltmış ve Nrf2 yanıtıyla uyumlu bulgular sağlamıştır.

Bu çalışma boraksın Nrf2/oksidatif stres dengesi ile ilişkisini destekler.

8.3. GLİFOZAT NÖROTOKSİSİTESİ

Dogan ve arkadaşları 2025 yılında borik asidin glifozat kaynaklı nörotoksisiteye karşı etkisini sıçanlarda incelemiştir [10]. Çalışmada 28 erişkin sıçan dört gruba ayrılmış; kontrol, borik asit 100 mg/kg, glifozat 150 mg/kg ve glifozat+borik asit grupları oluşturulmuştur. Tüm uygulamalar yedi gün boyunca oral

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yolla yapılmıştır. Yükseltilmiş artı labirent ve lokomotor aktivite testleri davranışsal değerlendirmede kullanılmıştır.

Glifozat maruziyeti davranışsal bozulma, oksidatif stres, inflamasyon, apoptoz ve nöronal hasarla ilişkilendirilmiştir. Borik asit eş uygulaması SOD, CAT, GPx ve GSH dengesini iyileştirmiş; MDA düzeyini azaltmıştır. TNF-α, IL-1β, IL-6, COX-2, TLR4 ve NF-κB gibi inflamatuvar belirteçlerde; Bax ve kaspaz-3 gibi apoptotik belirteçlerde azalma bildirilmiştir. Iba-1 ve GFAP değerlendirmeleri glial aktivasyonun da azaldığını düşündürmüştür. Çalışmanın sonuçları borik asidin kimyasal nörotoksisite sırasında oksidatif stres, inflamasyon, apoptoz ve otofaji ile ilişkili birden çok ekseni etkileyebileceğini göstermektedir.

9. OLASI MOLEKÜLER MEKANIZMALARIN BÜTÜNLEŞTİRİLMESİ

Borik asidin preklinik nöroprotektif etkileri aşağıdaki mekanizmalar üzerinden tartışılabilir:

Tablo 2.

Mekanizma	Deneysel göstergeler	Kanıtın yorumu
Oksidatif stresin azalması	MDA ve 8-OHdG azalması; GSH, SOD, CAT veya GPx desteği	Birden çok modelde tekrarlanan biyokimyasal sinyal
Nrf2 yanıtının desteklenmesi	Nrf2 ve antioksidan yanıt belirteçleri	En belirgin destek boraks–akrilamid balık modelindedir
NF-κB ve inflamatuvar yanıtın baskılanması	TNF-α, IL-1β, IL-6, COX-2, TLR4 ve NF-κB azalması	Glifozat sıçan modelinde bildirilmiştir; doğrudan hedef ilişkisi kesin değildir
Apoptozun azalması	Bax/kaspaz-3 azalması, Bcl-2 artışı	Toksin modelinde destekleyici bulgu
Ferroptozun baskılanması	ACSL4 ve TfR1 azalması; GPx4 ve GSH artışı	Aβ-sinaptozom modelinde güçlü mekanistik sinyal
Sinaptik işlevin korunması	Synaptophysin, AChE, Na^+/K^+-ATPaz ve DNA bütünlüğü	Ex vivo sinaptozom çalışmalarında gösterilmiştir
Glial aktivasyonun azalması	Iba-1 ve GFAP azalması	2025 glifozat sıçan çalışmasında bildirilmiştir

10. BORİK ASİT VE BOR İÇEREN DİĞER BİLEŞİKLERİN AYRIMI

Borik asit, boraks, organik bor bileşikleri, boronik asit türevleri, boron nitrit nanopartikülleri ve borenyum/borinyum bileşikleri aynı etkileri göstermeyebilir. Molekülün çözünürlüğü, iyonlaşması, taşıyıcılarla etkileşimi, hücre içine girişi ve metabolik kararlılığı nöroprotektif veya toksik etkileri belirleyebilir.

2025 yılında yayımlanan bir in vitro çalışmada yeni sentezlenmiş borenyum ve borinyum türevleri, Aβ1-42 ile uyarılmış farklılaştırılmış SH-SY5Y hücrelerinde incelenmiştir [11]. Bileşikler 50 µM düzeyinde 24 saatlik uygulamada belirgin nörotoksisite göstermemiş; tüm bileşiklerde antioksidan özellikler saptanmış ve borinyum bileşikleri borenyum bileşiklerine göre daha güçlü nöroprotektif görünmüştür. Bu çalışma borik asitten farklı, sentetik bor bileşiklerini incelemektedir.

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Daha önceki bir SH-SY5Y çalışmasında borik asit ve sodyum borat dekahidrat, Aβ toksisite modelinde hücre canlılığı ve oksidatif stres açısından değerlendirilmiştir [12]. Her iki bileşik de hücre canlılığını destekleyen etkiler göstermiştir.

11. KLİNİK KANIT VE GELECEK PERSPEKTİFLERİ

Mevcut literatür borik asidin nörodejeneratif hastalıklar üzerindeki etkisini çoğunlukla hayvan, hücre veya ex vivo modellerde incelemektedir. İnsanlarda borik asit uygulamasının Alzheimer, Parkinson veya travmatik beyin hasarı ilerlemesini durdurduğunu gösteren randomize klinik çalışma bulunmamaktadır.

Gelecek çalışmalar için öneriler şunlardır:

Tablo 3.

Araştırma önceliği	**Gereken yaklaşım**
Doz standardizasyonu	Elementel bor eşdeğeri, uygulama yolu ve plazma/beyin düzeyi birlikte raporlanmalı
Form karşılaştırması	Borik asit, boraks ve organik/sentetik bor bileşikleri aynı deneysel platformda karşılaştırılmalı
Biyokimyasal yolakların doğrulanması	Nrf2, NF-κB, ferroptoz ve apoptoz yolakları inhibitör veya genetik modellerle test edilmeli
Klinik translasyon	İnsanlarda güvenlilik, farmakokinetik ve hedef biyobelirteçler önce değerlendirilmelidir
Hastalık modelleri	Aβ, tau, α-sinüklein, TBI ve toksin modelleri davranışsal ve histolojik uzun dönem sonuçlarla izlenmeli
Bileşik seçimi	Nöroprotektif etki ile toksisite arasındaki terapötik pencere belirlenmeli

Türkiye'nin bor kaynakları ve bor araştırma altyapısı, bu alanda bağımsız ve standardize araştırmalar yürütmek için stratejik bir fırsat sunabilir.

13. SONUÇ

Borik asit, nöroprotektif potansiyeli oksidatif stres, inflamasyon, apoptoz, ferroptoz ve sinaptik işlev gibi birden çok süreç üzerinden incelenen bir bor bileşiğidir. Güncel preklinik çalışmalar borik asidin bazı modellerde MDA ve diğer oksidatif hasar göstergelerini azaltabildiğini, antioksidan kapasiteyi destekleyebildiğini, Aβ ile ilişkili sinaptik hasarı sınırlayabildiğini ve TBI veya toksin maruziyetine bağlı histopatolojik bozulmayı azaltabildiğini göstermektedir.

En güçlü ve doğrudan bulgular; sıçan TBI modelinde oksidatif/histopatolojik hasarın azalması, Aβ ile uyarılmış sinaptozomlarda ferroptoz belirteçlerinin düzelmesi, Aβ sinaptozomlarında MDA/NO/AChE/DNA hasarının azalması ve D-galaktoz modelinde bilişsel performansın iyileşmesi yönündedir. Glifozat çalışması, borik asidin oksidatif stres, inflamasyon, apoptoz, glial aktivasyon ve otofaji belirteçleri üzerinde çoklu etkiler gösterebileceğini düşündürmektedir.

Bununla birlikte mevcut veriler borik asidin Alzheimer, Parkinson veya diğer nörodejeneratif hastalıkların kesin bir klinik tedavisi olduğunu göstermemektedir. Çalışmaların önemli bölümü preklinik kanıtlardır; kullanılan dozlar geniş aralıkta değişmektedir.

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Sonuç olarak borik asit, umut vadeden fakat henüz klinik olarak doğrulanmamış önemli preklinik sonuçları olan bir nöroprotektif adaydır. Gelecek araştırmalar; formülasyon, elementel bor dozu, beyin maruziyeti, uzun dönem güvenlilik ve insan biyobelirteçlerini birlikte ele almalıdır. Preklinik bulguların klinik öneriye dönüştürülmesi için kontrollü farmakokinetik ve klinik çalışmalara ihtiyaç vardır.

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GÖZ İZLEME TEKNİĞİ İLE BİR ALAN ARAŞTIRMASI

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ÖZET

Nöropazarlama ve özelinde göz izleme tekniği, tüketicilerin bilinçaltı dikkatleri, tercihleri ve karar verme süreçlerine dair önemli bilgiler sundukları için mobilya sektörü için özellikle önemlidir. Tüketicilerin dikkatlerini nereye ve ne kadar süreyle odakladıklarını anlamak, işletmelerin en etkili ürün özelliklerini belirlemelerine yardımcı olabilir; çünkü mobilya ürünleri son derece görseldir ve tüketicilerin tasarım, renk, şekil, kullanışlılık ve mekansal uyum değerlendirmelerini içerir. Mobilya üreticileri ve perakendecileri, göz izleme verilerini nöropazarlama teknikleriyle birleştirerek, tüketicilerin ürün tasarımlarına, teşhir alanı düzenlerine, reklamlara ve dijital arayüzlere yönelik görsel ve duygusal tepkilerini objektif olarak değerlendirebilirler.Bu araştırmada, bireylerin mobilya tasarımlarına yönelik ilk bakış noktaları, odaklanma süreleri ve görsel keşif yolları incelenerek hangi tasarım unsurlarının (renk, form, yerleşim, detay vb.) daha fazla dikkat çektiği ortaya konulması hedeflenmiştir. Araştırma kapsamında 18 yaş üzeri, 15 katılımcı erkek, 15 katılımcı kadın olmak üzere toplam 30 katılımcıya mobilya görselleri bilgisayar ekranı aracılığıyla göz izleme cihazı kullanan katılımcılara sunulmuş ve söz konusu ürünlere yönelik görsel ilgi düzeyleri analiz edilmiştir. Elde edilen bulguların tüketicilerin duygularına hitap edecek şekilde üretilecek mobilya tasarımı ve görsel algısı üzerinde bilimsel bir temel oluşturması amaçlanmıştır.

Anahtar Kelimeler: Nöropazarlama, Mobilya Sektörü, Göz-İzleme Tekniği

ABSTRACT

Neuromarketing, and eye-tracking technique in particular, are especially important for the furniture industry because they offer significant insights into consumers' subconscious attention, preferences, and decision-making processes. Understanding where and for how long consumers focus their attention can help businesses determine the most influential product qualities because furniture products are highly visual and involve consumers' evaluation of design, color, shape, utility, and spatial harmony. Furniture makers and retailers can objectively assess consumers' visual and emotional reactions to product designs, showroom layouts, ads, and digital interfaces by merging eye-tracking data with neuromarketing techniques.

In this study, it is aimed to determine which design elements (such as color, form, layout, details, etc.) attract more attention by examining individuals' initial gaze points, fixation durations, and visual exploration paths toward furniture designs. Within the scope of the research, furniture images were presented via a computer screen to a total of 30 participants over the age of 18 (15 male and 15 female) using an eye-tracking device, and their levels of visual interest in these products were analyzed. The findings obtained are intended to provide a scientific basis for furniture design and visual perception that appeal to consumers' emotions.

Keywords: Neuromarketing, Furniture Industry, Eye-Tracking Technique

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GİRİŞ

Mobilya; günlük yaşamın hemen her alanında yer alan, bireylerin ve toplumların yaşamını kolaylaştıran ve refah düzeyine katkı sağlayan temel ürünler arasında yer alır. Sosyal ve kültürel ihtiyaçlara cevap verebilme özelliğiyle öne çıkan mobilya, mekân ile insan arasındaki ilişkiyi güçlendirerek yaşam kalitesi üzerinde doğrudan etkili olmaktadır. Bu yönüyle, herkes tarafından ihtiyaç duyulan ve yaygın biçimde kullanılan bir ürün niteliği taşımaktadır (Şen ve Çınar, 2017). Farklı sosyoekonomik kesimlere hitap eden, geniş kullanım alanına sahip bir endüstriyel ürün olması, mobilya sektörünü küresel ekonomi açısından önemli bir ticaret alanı haline getirmektedir. Nitekim dünya genelinde mobilya üretimi 2021 yılında 634 milyar doları aşmış olup, bu rakamın 2026 yılı itibarıyla 940 milyar dolara ulaşması beklenmektedir. Türkiye özelinde ise sektörün üretim hacmi 2020 yılında 11 milyar dolar seviyesindeyken, 2030 yılına kadar 29 milyar dolara yükselmesi öngörülmektedir (T.C. Ticaret Bakanlığı, 2024).

Mobilya tasarım ve üretiminde ergonomi, estetik ve özellikle malzeme seçimi, tüketicinin tercihini belirleyici unsurlar arasında yer alır. Bu faktörler içinde özellikle malzeme faktörü, ürünün şekillenmesinde en kritik rolü üstlenirken, insan vücudu ile doğrudan temas eden oturma grupları daha da önem kazanmaktadır (Güneş ve Demirarslan, 2020, s. 96). Malzeme seçiminde konfor, dayanıklılık, sağlık ve hijyen gibi unsurların göz önünde bulundurulması gerekir. Aksi halde hem kullanıcı sağlığı olumsuz etkilenebilir hem de ürün ömrü kısalarak çevresel açıdan daha fazla kaynak tüketimine yol açabilir. Örneğin, ergonomiye uygun olmayan sert malzemeler omurga sorunlarına neden olabilirken, üretimde kullanılan bazı kimyasallar da kullanıcı ve çevre açısından risk oluşturabilmektedir (Subaşı vd., 2017, s. 558).

Mobilya sektöründe farklı ölçeklerde çok sayıda işletme yer almaktadır. Rekabetin yoğun olduğu bu işletmeler, varlıklarını sürdürebilmek için yeni ve çekici ürünler tasarlaması gerekmektedir. Yeni ve çekici ürünler geliştirilmiş olsa bile, bu ürünler tüketiciler tarafından yeterince ilgi göremediği için hammadde, işçilik, enerji ve üretim girdilerinin israfına aynı zamanda depolama konusunda sıkıntılara neden olmaktadır. Bu nedenle görsel farkındalık arttırılarak tüketicilerin ihtiyacına yönelik ve fazla talep edilebilen cazip mobilyaların tasarlanması üreticiler için bir gereklilik olmaktadır (Göktaş vd., 2024, s. 205).

Bu bağlamda nöropazarlama; tüketici davranışına daha derinlemesine iç görüler sağlama ve daha etkili pazarlama stratejileri geliştirme potansiyeliyle, pazarlama araştırmalarında çığır açan bir yaklaşım olarak lanse edilmektedir. Nöropazarlamanın tüketicilerin duygularına hitap ederek tüketicinin beynindeki "satın al" düğmesini aktif edebilen, aynı zamanda tüketicinin ürüne yönelik tutum ve davranışları ölçerken hangi durumları göz önüne aldığını belirlemekte kullanılan bir yöntem olduğu belirtilmiştir (Ural, 2008, s. 430).

ARAŞTIRMANIN KAVRAMSAL ÇERÇEVESİ

Nöropazarlama tüketicilerin ürünler karşısında insan beynine giden uyaranları nörobilimsel yöntemlerle inceleyerek yeni pazarlama stratejilerinin gelişmesine olanak sağlayan bir alandır. Kökeni nörobilime dayanan bu alan, çeşitli yöntemler kullanarak tüketicilerin duygu ve düşüncelerini tespit etmeyi amaç edinmektedir. Bu yöntemler elektroensefali (EEG), göz takibi (Eye-Tracking), manyetik beyin grafisi (MEG) yüz ifadesi (facial koding), fonksiyonel manyetik rezonans görüntüleme (fMRI), galvanik deri iletkenliği (GSR), örtük çağrışım testi (İmplicit tests), gibi tekniklerdir (Özkurt, 2025).

Nöropazarlamanın amacı; markaların ve üretilen ürünlerin tüketiciye nasıl hizmet ettiği, tüketicilerin bu hizmetten duyduğu memnuniyeti veya üründen beklentilerini ortaya çıkarabilmek amacıyla çeşitli nöropazarlama tekniklerinin uygulanarak anlaşılabilmesidir. Bu sayede ürün tasarımı yapılarak tüketici bağlılığı arttırılabilmekte ve satış artırmak hedeflenmektedir. Ürünün tüketiciler üzerinde yaratmış olduğu pozitif veya negatif duyguların tespit edilebilmesinde önemli teknikler olan nöropazarlama teknikleri, firmaların gereksiz yatırımlardan kaçınması, tüketici bazında olumlu etki yaratmak ve gereksiz yatırımların önüne geçmesi bakımından önemli etkiler içermektedir (Krishnan, Anand & Saju, 2016).

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Nörometrik ölçümler, insan davranışlarını incelemek amacıyla beyin aktivitelerinin analiz edilmesi ve kaydedilmesine dayanmaktadır (Alvino vd., 2020, s. 3). Bu ölçümler; beyinde gerçekleşen kan akışı ve oksijen düzeyi gibi metabolik süreçlerin yanı sıra, nöronların elektriksel potansiyelleri ve oluşturdukları manyetik alanlar gibi elektriksel ve manyetik aktivitelerin değerlendirilmesini kapsamaktadır. En fazla kullanılan nörometrik ölçümlerden bazıları EEG, MEG ve fMRI cihazlarıdır. Bu yöntemlerde kullanılan cihazların yüksek maliyetli olması ve uygulama süreçlerinin zaman alıcı ve zorlayıcı olması dezavantaj olarak görülse de, sağladıkları yüksek doğruluk ve güvenilirlik nedeniyle yaygın olarak tercih edilmektedir (Asunakutlu & Aydoğan, 2022, s. 431).

Kenning ve Plassmann (2005), fMRI tekniğiyle yapmış oldukları çalışmada, tüketici karar alma davranışında bilişsel süreçlerden daha çok duygusal davranışların etkili olduğunu ifade etmişlerdir. Lee, Broderick ve Chamberlain (2007), ise nöropazarlamanın satın alma karar sürecinde altta yatan duygusal faktörlerin tespit edilmesinde çok önemli katkı sağladığını vurgulamışlardır.

Eye Tracking (Göz İzleme) yöntemi; göz bebeği hareketlerinin kızılötesi ışınlar aracılığıyla izlenmesi ile kalitatif veya kantitatif sonuçlar sunan bir teknolojik yöntemdir. Kişilerin web sayfası, reklam filmi, ambalaj, sahne, yayın, paket vb. üzerinde hangi noktalara incelediğine belirlemeye yardımcı olan bir araştırma yöntemidir (Omur ve Aydoğdu, 2017:1297).

YÖNTEM

Bu çalışmada nöropazarlama araştırma yöntemlerinden biri olan Eye-Tracking yöntemi kullanılmıştır. Nöropazarlamada Biometrik Ölçümlerle Bireyin fizyolojik ve biyolojik tepkilerinin ölçülmesi hedeflenmektedir. Beyin dışındaki solunum hızı, kalp atış hızı, kasılma, ses perdesi, facialcoding (yüz kodlama), Eye-Tracking (göz izleme), GSR (galvanik deri tepkisi) gibi tüm vücut tepkilerini ölçme teknikleri biyometrik ölçüm olarak adlandırılmaktadır (Ustaahmetoğlu, 2015, s.159).

Araştırmanın örneklemini, gönüllülük esasına göre belirlenen 18 yaş ve üzeri 30 katılımcı (15 kadın, 15 erkek) oluşturmaktadır. Göz izleme cihazının doğru ölçüm yapabilmesi için katılımcıların ciddi görme bozukluğuna sahip olmaması ölçütü dikkate alınmıştır. Örneklem, laboratuvar uygulamasının gerektirdiği koşullar doğrultusunda uygun örnekleme yöntemiyle seçilmiştir.

Çalışmada belirlenen 10 adet mobilya görseli slayt halinde gönüllü katılımcılara her biri 5'er saniye olmak üzere izlettirilmiştir. Her bir katılımcı çalışmaya tek tek alınacak ve her bir katılımcının verileri tek tek kayıt edilmiştir. Eye-Tracking yöntemi kullanılarak, görsellere ilişkin ısı haritası verileri Lisanslı Tobii Pro Lab programından alınarak analiz edilip yorumlanmıştır. Lisanslı Tobii Pro Lab programı; Eye-Tracking (Göz İzleme) cihazını çalıştıran ve verileri kayıt eden bir programdır. Görseller katılımcılara masaüstü bilgisayar ile 22 inç ekran üzerinde 5'er saniye süre aralığında slayt olarak gösterilmiştir.

SONUÇ VE TARTIŞMA

Erkek katılımcıların ısı haritası incelendiğinde, görsel dikkat dağılımının belirli bölgelerde yoğunlaştığı ve katılımcıların ilk bakışta dikkatlerini üst bölgeye yönelttiklerini ve bu alanın görsel hiyerarşi açısından öncelikli olduğunu göstermektedir.

Ürün yerleşimlerinde, ürünün renkli ve baskın kontrastlı olmasının daha çok dikkat çektiği, bu bölgelere daha çok yoğunlaşma olduğu tespit edilmiştir. Çoklu ürün görsellerinde dikkat dağılarak, karar verme süreci zorlaşmış ve bu nedenle ürünler arasında hızlı geçişler yapılmıştır. Bu tip çoklu görsellerde de baskın kontrastlı ürünlerin daha çok dikkat çektiği anlaşılmıştır. Bu durum bize çoklu görsellerde ürün yerleşimi yapılırken baskın kontrastlı ürünün görselin tam orta ve üst kısmına bakış hizasına gelecek şekilde konumlandırılması gerektiğini göstermektedir.

Ürün görsellerinde erkek katılımcıların daha işlevsel, kullanıma yatkın, rahatlık ön planda olacak şekilde inceleme yaptığı, kadın katılımcıların ise bunların yanında daha bütünsel, zevk ve görünüm odaklı, renkli ve baskın kontrastlı ürünlerin dikkatlerini çektiği tespit edilmiştir. Bu durumda ürün yerleşimi yapılırken erkekler ve kadınların birlikte değerlendirilerek ürün yerleşimi yapılması gerekmektedir.

Ürün görsellerinde mekânsal derinlik ve aksesuarın önem kazandığı tespit edilmiştir. Yemek odası görsellerinde, diğer ürünlerde olduğu gibi merkezi konumda olan bölgeye yoğunlaşılmış ve aksesuar

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gibi belirleyici unsurlara odaklanma olmuştur. Ayrıca sandalyelerin tümüne değil de, sadece masanın ön tarafında bakış hizasındaki iki sandalyeye daha çok odaklanma olmuştur. Bu durum görselin sadece işlevsel olan kısmının dikkate alındığı diğer alanların değerlendirmeye alınmadığını göstermiştir.

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DEVELOPMENT, COMPREHENSIVE CHARACTERIZATON, AND PERFORMANCE EVALUATION OF STARCH-BASED BIODEGRADABLE PLASTIC FILMS

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ABSTRACT

As concerns about plastic pollution increase worldwide and the demand for sustainable materials increases, biodegradable polymers are becoming increasingly important for both environmental protection and industrial applications. Unlike conventional petroleum-based plastics, biodegradable polymers can break down into harmless substances under natural conditions, thereby reducing their long-term environmental impact. Starch-based bioplastics in particular are of great interest due to their renewable resources, low cost, and environmental friendliness. In laboratory studies, biodegradable plastic films have been produced using common materials such as corn starch and glycerin. The main goal of such studies is to obtain environmentally safe plastic films and to investigate the effect of the amount of glycerin on properties such as the elasticity, water resistance, and degradation rate of the material. For proper comparison of the experiments, the amount of starch and water was kept the same in all samples, only the amount of glycerin was changed. After heating, the mixtures were poured onto glass plates and allowed to dry. As a result, transparent and flexible plastic films were obtained. Observations have shown that increasing the amount of glycerin improves the elasticity of the films, as glycerin acts as a plasticizer. However, an excess of glycerin reduces the water resistance of the material, as the film's water-absorbing properties increase. The biodegradability was assessed by a soil burial test. These tests showed that all starch-based films began to decompose within one to two weeks after being placed in soil. These results prove that the plastics are indeed biodegradable. Overall, the results obtained show that it is possible to produce biodegradable plastics using simple methods and readily available materials. Such materials can be considered suitable for short-term and environmentally safe packaging applications.

Keywords: Biodegradable Plastic, Starch-based Bioplastic, Glycerol, Sustainable Future of Bioplastics.

INTRODUCTION

Over 460 million metric tons of plastic are produced every year for use in a wide range of fields such as construction, transportation, clothing, consumer goods, packaging, medicine, electronics, etc. Approximately 77% of that -around 353 million metric tons - becomes plastic waste mainly consisting

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of single use, disposable products like cups, cigarettes, shopping bags, bottles, etc. They are designed to be used once and then discarded. Alarmingly, nearly 22% of this waste is mismanaged, which results in 79 million metric tons of plastic waste being inadequately disposed of, leading to 22 million metric tons of plastic leakage ending up in the environment each year, resulting in land and marine ecosystems pollution.[OECD, 2022]

The main reason why single-use plastic is dangerous and harmful is that it takes a long time to decompose completely. Moreover, during decomposition, microplastics are formed, which can accumulate in the bodies of humans and animals, as well as in soil and water. The chemicals used in the production of plastic have a negative impact on the health of living organisms, leading to possible disorders in the immune, reproductive and digestive systems.

In response to this crisis, there is a growing need and interest in the development and creation of alternatives to conventional plastics. One solution to the problem is biodegradable plastic, which can be broken down by microorganisms such as bacteria and fungi into environmentally safe products like water, carbon dioxide, methane and biomass.

This study focuses on the production process of biodegradable plastic films using easily accessible materials. The starch will be used as a natural polymer because of several advantages: its low cost, renewable origin, and easy processing. Moreover, when mixed with plasticizers such as glycerin, starch is able to produce flexible films that can be used for packaging and similar purposes. In order to get more reliable and comparable results, different concentrations of glycerin were used. Vinegar was also added to the formulation in order to increase film stability and facilitate the elaboration of smoother and more homogeneous films. Finally, the set of prepared films are tested and compared for their elasticity, water resistance, and biodegradability.

DEFINITION OF A BIODEGRDABLE POLYMER

Biodegradable polymer, a kind of polymer, designed to meet the requirement for breaking down into water, biomass, inorganic salts, and natural side products such as gases (carbon dioxide, nitrogen) after the usage. These materials can naturally decompose in the environment, and final products are safe and ecofriendly. This breaking down can happen through 2 ways in the environment: aerobic degradation and anaerobic degradation as illustrated in Figure 1.[Dallaev et al., 2025]

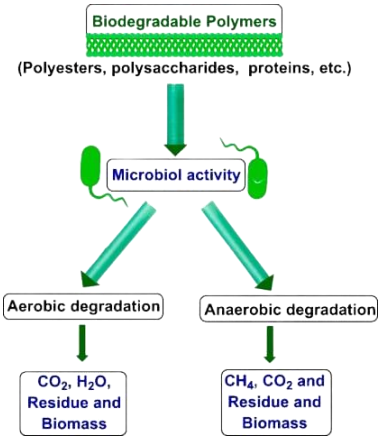


Figure 1. Schematic representation of polymer degradation via biological processes

Figure 1 shows that by aerobic degradation biodegradable polymer breaks into CO2, H2O, residue, and biomass. On the other hand, by anaerobic degradation biodegradable polymer breaks into CH4, H2O, residue, and biomass).

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TYPES OF BIODEGRDABLE POLYMERS

Based on their origin, synthetic and natural biodegradable polymers are distinguished as shown on Figure 2.[Ghanbarzadeh & Almasi, 2013]

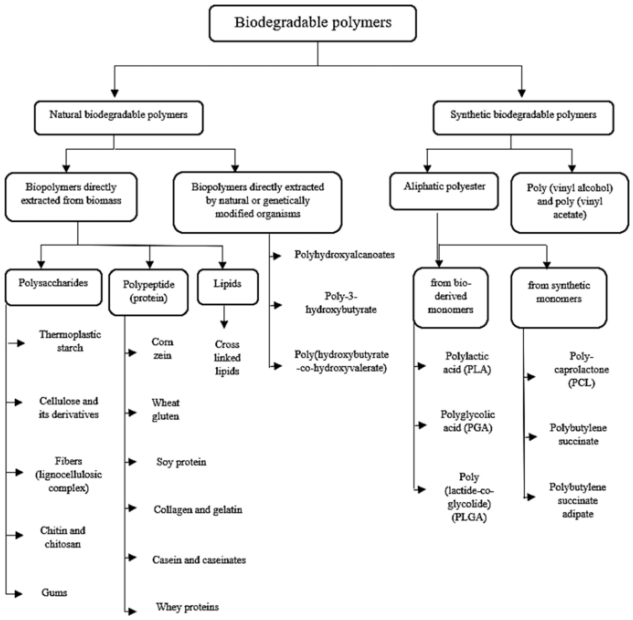


Figure 2. Classification of biodegradable polymers

The classification of biodegradable polymers depends on the type of origin and manufacturing method used to obtain them, which is shown in Figure 2 [Ghanbarzadeh & Almasi, 2013; Samir et al., 2022]. Natural biodegradable polymers are extracted from renewable biological sources, while synthetic ones are created through chemical reactions or modification of monomers from natural or petrochemical sources. Another group consists of microbial-origin polymers (polyhydroxyalkanoates) [Abdulsalam et al., 2025].

NATURAL BIODEGRADABLE POLYMERS

Natural biodegradable polymers consist of raw materials obtained from renewable biological sources and are inherently biocompatible, biodegradable, and inexpensive. They are typically classified into two main groups [Samir et al., 2022; Reddy et al., 2021]:

Examples of polysaccharides are starch (corn, potato, cassava, et al.) – consists of linear amylose and branched amylopectin chains with many hydroxyl groups, allowing to create films due to possibility of hydrogen bonding; cellulose and its derivatives (wood, cotton, agricultural residues) – the largest natural polymer found on Earth, has high mechanical strength but requires modification to improve processability; chitosan – made from chitin found in crustacean shells, used because of its antibacterial activity; and others such as alginate, pectin, and carrageenan [Samir et al., 2022].

Proteins: Animal ones (collagen, gelatin, casein, fibrin); plant proteins (wheat gluten, soy protein, zein). Proteins have three-dimensional structure and consist of polypeptide chains held together by hydrogen, ionic, and disulfide bonds, making them excellent film-forming agents due to their biocompatibility in medical applications [Reddy et al., 2021].

Advantages of natural polymers are the ability to be produced sustainably (renewable raw materials), minimal toxicity and biodegradability, biocompatibility. Disadvantages are high hydrophilicity resulting in water sensitivity, low strength, and brittleness without plasticizers or copolymerization [Ghanbarzadeh & Almasi, 2013].

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SYNTHETIC BIODEGRADABLE POLYMERS

These types of polymers have been chemically designed to allow for controlled degradation rate, controllable molecular weight and mechanical and thermal properties. These polymers are usually synthesized by polymerization of monomers obtained either from sustainable resources, such as lactic acid or petroleum-based monomers. The following biodegradable synthetic polymers exist in nature:

· Polylactic Acid (PLA): This type of polymer is made through the chemical reaction of lactic acid that originates from the fermented cornstarch or sugarcane. It is considered one of the most commercially successful bioplastics owing to its mechanical strength and transparency and ability to be composted industrially [Kim et al., 2023].

· Polyglycolic Acid (PGA), Poly(Lactic-Co-Glycolic Acid) (PLGA): Extensively used in biomedical applications like sutures and drug delivery systems due to controllable degradation rates [Abdulsalam et al., 2025].

· Polycaprolactone (PCL): Flexibly strong polyester material with low melting point that can be easily blended for enhanced toughness [Samir et al., 2022].

· Polyhydroxyalkanoates (PHAs): Fully bio-based biodegradable polymers that can be produced through bacterial fermentation (Polyhydroxybutyrate-PHB) and used even under marine environment [Reddy et al., 2021].

· Polybutylene Succinate (PBS), Polybutylene Adipate Terephthalate (PBAT) [Kim et al., 2023].

Synthetic polymers possess higher processibility, improved mechanical properties, and controllable rates of degradation relative to many natural polymers. However, the major disadvantages of synthetic polymers are higher costs of production and relatively slow rates of degradation in natural environments [Dallaev et al., 2025].

Table 1. Comparison of Natural and Synthetic Biodegradable Polymers.

Aspect	Natural polymers (Starch, Cellulose, Proteins)	Synthesic polymers (PLA, PCL, PHA, PBS)Synthesis
Origin	Renewable biomass (plants, animals, algae)	Chemical synthesis from bio- or petroleum-based monomers
Biodegradability	Rapid in soil/compost;enzyme-driven.	Tunable; often requires specific conditions
Mechanical properties	Generally brittle, hydrophilic; improved with plasticizers	Higher strength, flexibility, and thermal stability
Cost	Low	Moderate to high
Processability	Requires plasticizers; solution casting common	Excellent (extrusion, injection molding)
Main applications	Packaging films, edible coatings, biomedical scaffolds	Medical devices, durable packaging

OTHER CLASSIFICATION SCHEMES AND EMERGING TRENDS

The other classification schemes include hydrolytic, enzymatic, or oxidative degradation methods and applications like packaging, biomedical devices, or agricultural mulch films [Dallaev et al., 2025]. The recent trends involve blending, composite formulation with natural fibers or nanoparticles, or chemical modifications to mitigate brittleness or moisture sensitivity issues associated with individual materials. Microbial-produced polymers, like polyhydroxyalkanoates (PHAs), constitute an attractive category bridging natural and synthetic classifications because of their complete bio-based origin and superior biodegradability in marine environments [Kim et al., 2023].

To summarize, natural polymers are sustainable and inexpensive, whereas synthetic polymers are superior in terms of performance. The selection criteria depend on the application, although hybrid

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strategies are more prevalent [Samir et al., 2022; Reddy et al., 2021]. This classification sets the stage for examining the starch-based bioplastics, which are polysaccharides under the natural classification and form the subject of experimental study due to their abundance, renewability, and processability using plasticizers such as glycerol [Ghanbarzadeh & Almasi, 2013].

STARCH-BASED BIOPLASTIC

The role of starch in the development of biopolymeric materials cannot be overemphasized, considering the fact that starch is an abundant, renewable, and biodegradable material with suitable processing characteristics for the development of polymer-based materials. In addition, starch is a renewable resource derived from agricultural crops, mainly corn, potatoes, rice, and cassava, and can therefore be an alternative raw material to petroleum-based polymerization monomers and precursors, considering its easy source and lower production cost compared to conventional polymeric materials. Essentially, starch is composed qualitatively of both amylose and amylopectin, which have suitable polymer structures with multiple hydroxyl groups for intermolecular interactions and proper film-forming properties for biopolymeric applications.[Sobeih et al., 2025]

One of the primary reasons starch is incorporated within biopolymers is because starch is a highly biodegradable chemical entity. Many starch-based biopolymers can easily decompose microbially by enzymatic hydrolysis, thus mitigating its long-term persistence in the environment.

On the other hand, starch can be used in those particular applications where its short lifespan or rapid degradation is a necessary criterion, like in packaging materials or disposable products. Furthermore, starch helps biodegradable plastic materials to be environmentally friendly by using renewable resources instead of petroleum products. The life cycle of starch-based bioplastics, including starch extraction, PLA production, product formation, and biodegradation, is presented in Figure 3.[Gurunathan et al., 2025]

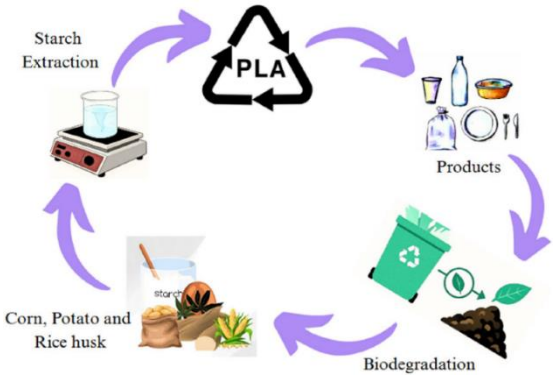


Figure 3. Life cycle of bioplastics.

On the other hand, starch has been identified as an effective matrix and blending component for biopolymers. It is capable of being converted into its thermoplastic form with the application of heat, shear forces, and plasticizers, enabling conventional biopolymer processing techniques such as extrusion and casting. Additionally, starch is often blended with other biodegradable or synthetic polymers with the objective of increasing biodegradability, cost reduction, and modulating its mechanical properties. Even though there are some challenges within native starch materials that are characterized by brittleness and moisture susceptibility limitations, these drawbacks are easily overcome.[Falua et al., 2022]

In a nutshell, starch plays the most significant role in the application of biopolymers; this is due to the fact that starch exhibits environmental sustainability in addition to adaptability in terms of functionality

INFLUENCE OF STARCH SOURCE: CORN VS. POTATO STARCH IN BIODEGRADABLE FILMS

Starch is crucial in determining the physical, chemical, mechanical, thermal and biodegradability characteristics of bioplastic films made using starch. The commonly used starch sources include those derived from maize and potatoes. However, both sources possess different starch features like particle

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size, ratio of amylose to amylopectin, molecular structure and presence of phosphorous that significantly affect the film forming properties, processability and overall properties of the plasticized starch [Pooja et al., 2024; Domene-López et al., 2019].

Corn starch has an amylose content of about 25-28 percent and an amylopectin content of 72-75 percent with small granules and high crystalline properties. Conversely, potato starch possesses large granules, a slightly lower percentage of amylose (20-25 percent) and is rich in phosphate monoesters resulting in reduced crystalline structure and increased swelling and gelatinization at low temperatures. Due to such differences, the processability and film forming ability of each of the two starch sources becomes distinctive. Potato starch usually gelatinizes and swells faster than corn starch hence making the processing process quicker hence energy saving [Domene-López et al., 2019].

In terms of mechanical properties, research findings may differ depending on the particular formulation used and plasticizer levels. Films based on corn starch are usually characterized by higher tensile strength and improved structure owing to stronger hydrogen bonding within molecules and crystalline nature of the polymer matrix [de Azevedo et al., 2020]. Films based on potato starch are more likely to show higher flexibility, elongation at break, and thermal stability especially if formulated using glycerol and acetic acid. Moreover, films based on potato starch tend to be smoother in morphology and possess greater film integrity in some formulations [Pooja et al., 2024].

Water resistance and solubility characteristics also differ for both types of polymers. As the amount of starch increases, water solubility and permeability become lower because of tight packing of molecules. Films made of potato starch show lower water solubility compared to those prepared from corn starch. The latter is probably caused by different content of amylose and packing density in films based on potato starch. Nevertheless, both starches retain their hydrophilic character [Pooja et al., 2024].

Degradation rate is also a distinguishing factor between both films. The films based on corn starch and potato starch are highly degradable by microbial enzymes under soil or compost conditions. Potato starch-based films usually degrade quickly because of the amorphous nature and high hydrophilicity that help microbial penetration into the films. Films based on corn starch may degrade slightly slower than potato starch-based films. Potato starch-based films took around 5 days to be completely degraded, whereas corn starch-based films took about 40 days in one research [de Azevedo et al., 2020].

Table 2. Summary of Key Property Differences Between Corn and Potato Starch-Based Films (Glycerol-Plasticized)

Property	Corn starch films	Potato starch films
Gelatinization/Processing	Slower thickening, higher energy needed	Faster thickening, easier molding
Tensile strength	Often higher	Generally lower, but good with optimization
Elongation/Flexibility	Moderate	Often better
Thermal stability	Good	Frequently higher
Water solubility	Higher in some studies	Lower/better integrity in optimized cases
Biodegradation rate	Rapid	Often faster

For the current study, corn starch was chosen as the main feedstock due to its high accessibility, good quality, and balance of features for the purpose of short-term packaging applications in laboratory scale solution casting. Though potato starch may have faster processing times and better processability and thermal qualities, in combination with variable amounts of glycerol and vinegar, corn starch was able to produce transparent, flexible films with adequate properties [Pooja et al., 2024; de Azevedo et al., 2020].

From the above comparison, it is clear that the choice of starch type depends on the purpose. Possible directions include mixing different starch types or adjusting the plasticizer proportion.

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GLYCEROL

Glycerol, also known as glycerin, is a three-atomic alcohol with the chemical formula $C_3H_8O_3$ or $C_3H_5(OH)_3$. It is a colorless, odorless, viscous, non-toxic liquid with a sweet taste. Glycerol is hygroscopic, meaning it absorbs water from the surrounding environment, which makes it highly soluble in solvents like water and alcohols. Most industrial glycerol today is obtained as a by-product of biodiesel production, where vegetable oils or animal fats are converted into fatty acid esters. This process is environmentally friendly, which plays a key and significant role in combating plastic pollution. Furthermore, the rising supply of crude glycerol from biodiesel manufacture has resulted in its use as an economical and renewable plasticizer for biodegradable starch films, thus making a significant contribution to the circular economy by replacing petroleum-based plasticizers. [Bilck et al., 2015]

Glycerol possesses a variety of physical and chemical properties that make it a highly valuable compound. Chemical properties include non-toxicity, biodegradability, and hygroscopic nature of glycerol, because of which it is widely used in various industries, including pharmaceuticals, cosmetics, and food processing, as a humectant, stabilizer, and solvent.[Quispe et al., 2013]

Glycerol is chemically stable, non-volatile, and resistant to oxidation under normal conditions. Its three hydroxyl groups allow it to form hydrogen bonds with other molecules, which is a key property utilized in plasticization. Its high viscosity, chemical stability, and strong ability to form hydrogen bonds give it a unique capacity to interact with other polar molecules such as starch.

ROLE OF THE GLYCEROL IN BIODEGRADABILITY

Characteristics specified in the previous paragraph make glycerol an ideal plasticizer for starch-based biodegradable films. Starch in its natural form has a rigid and brittle structure because its polymer chains — amylose and amylopectin — are tightly bound to each other through strong intermolecular hydrogen bonding. Without the addition of a plasticizer, such films can easily crack or break.

Glycerol addresses this limitation due to its three hydroxyl groups, which interact with starch molecules by forming new hydrogen bonds. This process reduces the intermolecular forces between the polymer chains of starch and increases their mobility, resulting in films with greater flexibility, elasticity, and - most importantly - mechanical strength. However, it should be noted that because of glycerol's hygroscopic nature, the moisture content in the film and its solubility in water will also increase. Hence, higher concentrations of glycerol may lead to lower water resistance of the resulting film.

Furthermore, increasing the concentration of glycerol leads to a decrease in the tensile strength and biodegradability time of the film.[Arruda et al., 2025],[Sirbu et al., 2024]

On the other hand, the right proportion of glycerol enhances the ductility of the film and helps to achieve a better balance between flexibility and mechanical strength. In the experimental part of this study, the effect of different glycerol concentrations on the final properties of the obtained films will be examined in detail.[Frangopoulos et al., 2023]

Thus, glycerol plays a crucial role in adjusting the final properties of the biodegradable films produced in this experiment. Several studies have shown that varying glycerol concentration significantly affects elasticity, water resistance, and biodegradability.

EXPERIMENTAL PART

This research examined the preparation and evaluation of starch-based biodegradable plastic films as a new environmentally friendly product compared to the use of conventional plastic materials. The investigation also examined the effect of a plasticizer agent on the structural and environmental properties of starch-based polymer materials.

Previous studies confirmed that the presence of glycerol materially impacts the flexibility, strength, and water interaction properties of the formed films. When the proportion of glycerol was reduced, it was identified that the plastic film produced was sturdier and harder, although an increased proportion of

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glycerol was beneficial in providing elasticity while diminishing resistance to water.[Tarique et al., 2021]

In the present study, starch-based films with different glycerol concentrations were prepared using the solution casting method, and their mechanical and physicochemical properties were systematically evaluated.

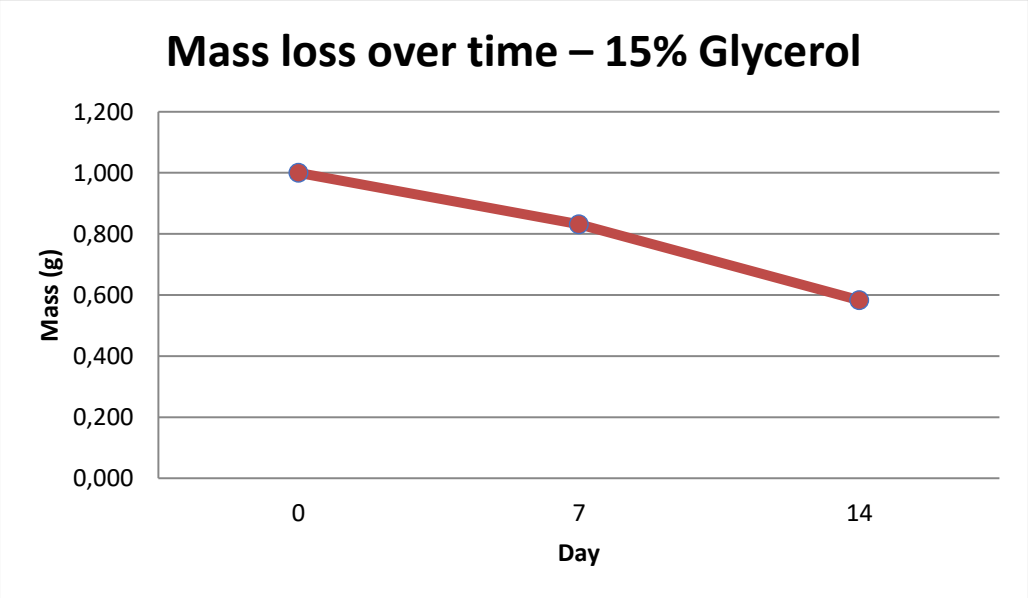
In this study, biodegradable plastic films have been obtained based on the natural polymer matrix (corn starch) and a plasticizer (glycerin), employing the solution casting technique. Specifically, the use of corn starch as a raw material was justified by its availability, quality, and applicability for producing films on the laboratory scale; while the role of glycerin in reducing the intermolecular hydrogen bond interactions in starch molecules thus increasing their flexibility has been highlighted. Moreover, vinegar was included in the composition in order to increase film stability and make smoother films possible. For comparing different films prepared in this work, the quantity of starch and water has been made identical in all compositions varying only the amount of glycerin in order to evaluate the influence of this parameter on elastic properties, water resistance, and degradation rate of the films. Films have been formed after heating and mixing by pouring the solutions onto glass plates and drying under ambient conditions.

The findings indicated that the use of increased glycerin increased the elasticity of the films because of the plasticizing effect of glycerin, which interferes with the hydrogen bonding of the hydroxyl group of starch, thereby increasing the movement of the chains. But the increase in the glycerin ratio decreased the water resistance of the material because of the hygroscopic effect of glycerin, which made the film absorb moisture from the environment. It is clear that there was an existence of a trade-off between mechanical flexibility and water resistance, which must be balanced depending on the desired usage of the film.

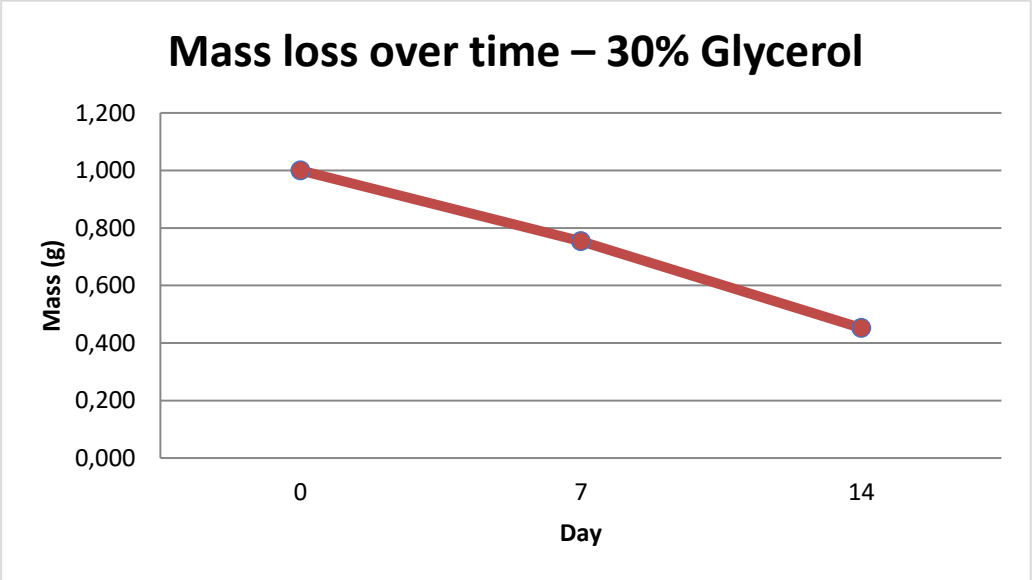
Further quantification of biodegradability was done through the soil burial test. Mass loss of the films during the burial process was calculated using the equation below:

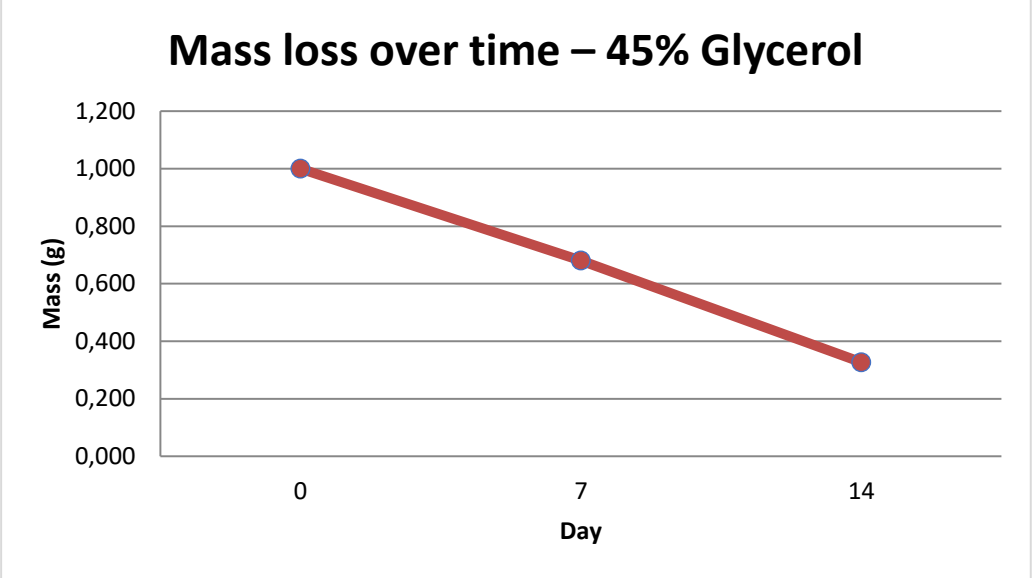
$$\textit{Mass loss (\%)} = (W_0 - W_t) / W_0 \times 100$$

where W_0 is the mass of the film before soil burial, and W_t is the mass of the film after a given burial period.



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From the soil burial experiment, it was found that there was a positive relationship between the glycerol concentration used and the mass loss observed in the starch films. It was found that, when the concentration of glycerol was increased to 45% from 15%, there was an increase in the amount of mass loss to 31.9 ± 2.1% and 67.3 ± 3.1% after 7 days and 14 days of burial, respectively. At the lower concentration of glycerol at 30%, the amount of mass loss observed after 7 days and 14 days of burial was 24.6 ± 1.7% and 54.8 ± 2.6%, respectively. The reason for the high degradation rate of the starch films at high glycerol concentration is the hydrophilic nature of glycerol, which helps in moisture absorption and easy accessibility of the starch matrix to microorganisms present in the soil.

SUSTAINABLE FUTURE OF BIOPLASTICS

The manufacture of biodegradable films made from starch at the laboratory scale based on corn starch and different amounts of glycerol, as shown in the present study, provides an effective means to develop sustainable packaging. Through optimization of the amount of plasticizer used, it is possible to obtain flexible, clear films that are easily biodegradable in soil within 1-2 weeks. The results illustrate the ability to achieve significant improvements in mechanical properties by varying the amount of plasticizer used without compromising the biodegradable nature of the film.

The sustainable outlook for starch bioplastics is very promising because of the growing concerns around the world about the problem of plastic waste, regulation of the use of disposable plastics, customers'

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requirements, and corporate commitments toward sustainability[Frangopoulos et al., 2023]. Starch-based substances form an important portion of biodegradable polymers due to their availability, affordability, renewability, and compatibility with traditional processing methods like casting and extrusion. The prospects of the starch-based bioplastic industry look promising thanks to rising environmental consciousness and development of formulations and manufacturing processes[Tarique et al., 2021; Negrete-Bolagay & Guerrero, 2024].

There are many prospects for future development and implementation. Further optimization of the formulations, which includes modification of the glycerol concentration (as shown in this study), mixing of starch with other biopolymers like polylactic acid (PLA) or polybutylene adipate terephthalate (PBAT), inclusion of natural additives (such as calcium carbonate), or loading of active components (such as natural antimicrobials) could lead to an increase in mechanical resistance, water vapor barrier performance, heat resistance, and preservation capacity without losing the ability of degradation[Gurunathan et al., 2025; Sobeih et al., 2025]. Utilization of second-generation sources, including crop waste, food industry waste, or non-edible starches, will contribute to the sustainability aspect by minimizing conflicts between food production and bio-based plastic manufacturing, as well as lowering greenhouse gas emissions[Caicho-Caranqui et al., 2025]. In addition, progress in active packaging systems, nanocomposite reinforcements, and modern processing technologies is likely to broaden the scope of applications from short-term packaging to agricultural mulches and biomedical devices.

However, there are several obstacles that need to be addressed to fully tap into the advantages of starch bioplastics. First of all, their production is more expensive than that of regular petroleum plastics. Furthermore, there are certain limitations to scaling up existing lab techniques to an industrial level. Starch bioplastics have a high degree of moisture sensitivity, which is further enhanced by the use of glycerol at higher concentrations. Moreover, their degradation rates may differ in various environments, such as soil, industrial composting, or marine ecosystems. It should also be noted that there are still some deficiencies in terms of tensile strength, barrier characteristics, and overall durability[Frangopoulos et al., 2023; Sobeih et al., 2025; Caicho-Caranqui et al., 2025]. Life cycle analyses and additional studies are essential to establish their true environmental merits.

CONCLUSION

This work showed that the production of biodegradable plastic films from easily available substances such as corn starch and glycerol using a simple solution casting technique is possible. These findings confirmed the viability of the use of starch-based bioplastic films as an ecologically safe alternative to petroleum-derived plastics in cases when biodegradation is required.

It has been shown that the presence of glycerol in the prepared films plays a vital role. An increase in the content of glycerol in the films led to increased flexibility and elasticity due to decreased intermolecular hydrogen bonds and increased chain mobility. At the same time, the introduction of glycerol reduces the water resistance of the films since glycerol is hygroscopic and increases the moisture absorption capacity. Thus, the optimal ratio of glycerol concentration, mechanical flexibility and water resistance is necessary in order to obtain the films having the required properties.

The results of the soil burial test confirmed the biodegradable nature of the films prepared as all formulations decomposed in soil and lost mass. This is another feature allowing distinguishing the starch-based films from conventional petroleum-derived plastics that take much time to decompose and thus pollute the environment for many years. There are also other advantages of the developed films such as availability of renewable starch, low price of raw materials, simple technology, and ability to utilize agricultural feedstock.

At the same time, there are also some disadvantages associated with starch-based bioplastics. Firstly, the films based on corn starch possess higher sensitivity to moisture and low water resistance. Secondly, the mechanical properties depend on the plasticizer concentration. Thus, the use of these films in humid environments and in direct contact with water is limited. Additionally, starch-based films may have poor mechanical and barrier properties in comparison with some conventional synthetic plastics. Thus, the developed films are applicable in short-term packaging applications.

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From the results discussed above, it is apparent that starch bioplastics are a promising and environmentally friendly material that could help reduce the environmental effects of plastics. The performance of these bioplastics could be enhanced by optimizing the ratio between starch and glycerol, adding natural modifiers, or restructuring the films. In addition, future studies need to evaluate their mechanical strength, vapor transmission properties, thermal stability, rate of biodegradation under different environmental conditions, and performance when used as packages.

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CURRENT PARADIGMS IN SUSTAINABLE TOURISM: A BIBLIOMETRIC AND CONCEPTUAL DISCUSSION

SÜRDÜRÜLEBİLİR TURİZMDE GÜNCEL PARADİGMALAR: BİBLİYOMETRİK VE KAVRAMSAL BİR TARTIŞMA

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ABSTRACT

Sustainable tourism, initially emerged as a normative framework focused on mitigating environmental impacts, has evolved into a complex ecosystem encompassing socio-cultural equity, technological integration, and economic resilience. Global climate crises, pandemics, and shifting consumer expectations compel the tourism industry to move beyond passive conservation toward establishing "regenerative" and "resilient" systems. This study aims to map the macro-scale historical, geographical, and conceptual evolution of sustainable tourism literature using Web of Science (WoS) data and to critically discuss the field's current micro-dynamics and future research paradigms through a synthesis of review articles published in 2026.

An initial search on the WoS Core Collection database spanning the last five years (2022–2026) yielded 23,795 documents. To identify the qualitative and conceptual foci of the field, this macro dataset underwent a multi-stage filtering process. The documents were refined first to 1,313 review articles, then narrowed to 194 within the *"Hospitality, Leisure, Sport & Tourism"* category, and further reduced to 100 SSCI-indexed papers. In the final stage, 9 SSCI-indexed review articles published in 2026—representing the most recent frontier of the discipline—were selected as the core analytical unit.

Bibliometric findings reveal an exponential growth in sustainable tourism literature, particularly in the post-2020 era, with China, the USA, and Australia demonstrating quantitative dominance in global publication output. At the institutional level, entities such as the *Chinese Academy of Sciences* and *Griffith University* lead the field, while macro word clouds are dominated by crisis-oriented themes including climate change, Covid-19, ecotourism, and cultural heritage. Macro-scale studies primarily focus on the Value-Belief-Norm theory, digital engagement, green financing, the metaverse, neuromarketing, and the integration of ESG (Environmental, Social, and Governance) principles into destination planning.

The synthesis of the 9 current review articles from 2026 highlights two major conceptual and methodological shifts: First, Generative AI (GenAI) and digital infrastructures are framed as dual-driven actors restructuring customer experience and workforce dynamics, influencing review persuasiveness through transparency, and mediating accessibility via frameworks like Inclusive Human-AI Mediation (IHAM). Second, conventional sustainability is progressively giving way to "regenerative tourism" approaches—such as apitourism for socio-ecological renewal—economic diversification in winter tourism against climate threats, and "citizenship behaviour" requiring psychological ownership across all stakeholders. Future research in sustainable tourism is projected to integrate GenAI-mediated tools with experiential niche markets (e.g., Gen Z travel, glamping), centering on socio-ecological regeneration and systemic destination resilience.

Keywords: Sustainable Tourism, Bibliometric Analysis, Web of Science, Regenerative Tourism, Artificial Intelligence.

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ÖZET

Sürdürülebilir turizm; başlangıçta doğal çevrenin korunmasına odaklanan normatif bir çerçeve iken, günümüzde sosyo-kültürel eşitlik, teknolojik dönüşüm ve ekonomik dayanıklılığı kapsayan karmaşık bir ekosisteme dönüşmüştür. Küresel iklim krizleri, pandemiler ve değişen tüketici beklentileri, sektörü pasif koruma anlayışından çıkarıp "yenileyici" (regenerative) ve "dirençli" (resilient) sistemler kurmaya zorlamaktadır. Bu çalışmanın amacı, sürdürülebilir turizm literatürünün makro ölçekteki tarihsel, coğrafi ve kavramsal gelişimini Web of Science (WoS) verileri üzerinden haritalandırmak ve 2026 yılına ait güncel inceleme (review) makalelerinin senteziyle alanın mikro dinamiklerini ve gelecek paradigmalarını tartışmaktır.

Araştırma kapsamında WoS Core Collection veri tabanında son beş yılı kapsayan (2022-2026) birincil taramada 23.795 dokümana ulaşılmıştır. Bu makro veri seti, alanın niteliksel ve kavramsal odak noktalarını belirlemek amacıyla aşamalı bir filtreleme sürecine tabi tutulmuştur. Dokümanlar önce 1.313 inceleme makalesine, ardından *"Hospitality, Leisure, Sport & Tourism"* kategorisiyle 194'e ve SSCI indeksiyle 100 makaleye daraltılmıştır. Nihai aşamada, alanın ulaştığı en güncel noktayı temsil eden yayın yılı 2026 olan 9 SSCI indeksli inceleme makalesi temel analiz birimi olarak seçilmiştir.

Bibliyometrik bulgular, sürdürülebilir turizm literatürünün özellikle 2020 sonrası dönemde üstel bir artış sergilediğini ve yayın üretkenliğinde Çin, ABD ile Avustralya'nın küresel bir niceliksel hegemonyaya sahip olduğunu göstermektedir. Kurumsal düzeyde *Chinese Academy of Sciences* ve *Griffith University* gibi yapılar öne çıkarken, makro kelime bulutunda iklim değişikliği, Covid-19, ekoturizm ve kültürel miras gibi kriz odaklı temalar baskındır. Makro düzeydeki çalışmalar; Değer-İnanç-Norm teorisi, dijital etkileşim, yeşil finansman, metaverse, nöropazarlama ve ESG (Çevresel, Sosyal, Kurumsal Yönetişim) ilkelerinin turizm planlamasındaki rolüne odaklanmaktadır.

2026 yılına ait 9 güncel inceleme makalesinin sentezi ise literatürde iki temel yöntemsel ve kavramsal kırılmayı ortaya koymaktadır: İlk olarak, Üretken Yapay Zeka (GenAI) ve dijital altyapılar; müşteri deneyimi ile iş gücü dinamiklerini eşzamanlı dönüştüren, değerlendirme özetlerinde inandırıcılığı şekillendiren ve kültürel mirasta erişilebilirliği sağlayan Kapsayıcı İnsan-YZ Arabuluculuğu (IHAM) gibi çerçevelerle etik bir arabulucu olarak konumlanmaktadır. İkinci olarak, geleneksel sürdürülebilirlik anlayışı yerini arıcılık turizmi (apitourism) gibi niş alanlarda sosyo-ekolojik yenilenmeyi hedefleyen "rejeneratif turizm" yaklaşımlarına, iklim krizine karşı kış turizminde ekonomik çeşitlendirmeye ve tüm paydaşların psikolojik sahiplenmesini gerektiren "vatandaşlık davranışına" (citizenship behaviour) bırakmaktadır. Gelecek prospektifinde ise sürdürülebilir turizm araştırmalarının, Z kuşağı ve glamping gibi yeni nesil deneyimsel pazarlarla bütünleşen, yapay zeka arabuluculuğunda yürütülen ve toplumsal dayanıklılığı merkeze alan çok boyutlu bir yapıya evrileceği öngörülmektedir.

Anahtar Kelimeler: Sürdürülebilir Turizm, Bibliyometrik Analiz, Web of Science, Rejeneratif Turizm, Yapay Zeka.

1. GİRİŞ

Sürdürülebilir turizm, başlangıçta turizm faaliyetlerinin doğal çevre üzerindeki olumsuz etkilerini hafifletmeye yönelik normatif bir çerçeve olarak ortaya çıkmış; ancak zamanla sosyo-kültürel eşitlik, teknolojik entegrasyon ve ekonomik dayanıklılığı da kapsayan çok boyutlu ve karmaşık bir ekosisteme dönüşmüştür. Küresel iklim krizleri, pandemiler ve hızla değişen tüketici beklentileri, turizm endüstrisini salt "korumacı" bir yaklaşımdan çıkararak "yenileyici" (regenerative) ve "dirençli" (resilient) sistemler kurmaya zorlamaktadır. Bu bağlamda, sürdürülebilir turizm üzerine yapılan akademik tartışmalar da büyük bir hızla evrilmekte; davranışsal itici güçler, teknolojik yenilikler, çevre politikaları ve toplumsal güçlendirme gibi çok disiplinli odak noktaları etrafında şekillenmektedir. Ancak literatürün bu denli hızlı ve hacimli büyümesi, mevcut bilgi birikiminin sistematik olarak sentezlenmesini ve alanın bugün geldiği son noktanın net bir şekilde haritalanmasını zorunlu kılmaktadır.

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Bu doğrultuda bu bildirinin amacı, sürdürülebilir turizm literatürünün makro ölçekteki tarihsel, coğrafi ve kavramsal gelişimini Web of Science (WoS) verileri üzerinden ortaya koymak ve bu devasa veri setinden rafine edilen 2026 yılına ait güncel inceleme (review) makalelerinin senteziyle, alanın bugünkü mikro dinamiklerini ve gelecekteki araştırma paradigmalarını eleştirel bir perspektifle tartışmaktır.

2. VERİ TOPLAMA STRATEJİSİ VE BİBLİYOMETRİK EĞİLİMLER

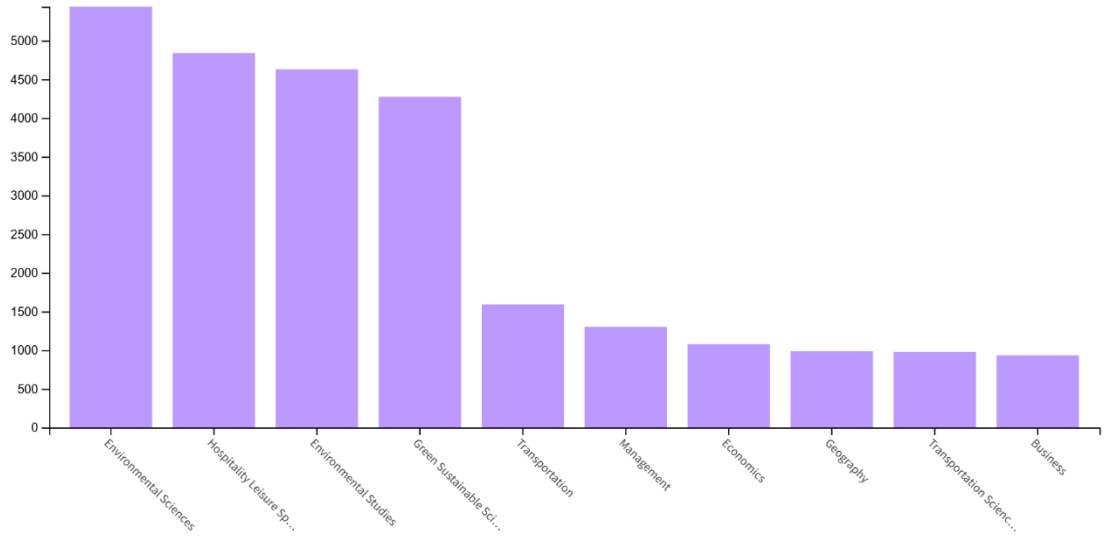
2.1. Araştırma Kapsamı ve Filtreleme Süreci

Çalışmanın kavramsal omurgasını oluşturmak ve güncel literatürü sistematik bir biçimde incelemek amacıyla Web of Science (WoS) Core Collection veri tabanı üzerinden kapsamlı bir tarama gerçekleştirilmiştir. Arama stratejisi kapsamında *"sustainable tourism OR responsible tourism OR eco-tourism OR green tourism OR sustainable travel OR environmental tourism"* terimleri kullanılmış ve zaman aralığı literatürün en güncel gelişimini yansıtacak şekilde son beş yıl (2022-17.07.2026) ile sınırlandırılmıştır. Gerçekleştirilen bu birincil tarama sonucunda toplam 23.795 adet dokümana ulaşılmıştır. Bu geniş literatür havuzunun WoS kategorilerine göre dağılımı incelendiğinde, araştırmaların ağırlıklı olarak çevre bilimleri ve turizm alanlarında yoğunlaştığı görülmektedir. Toplam 231 farklı kategoride dağılım gösteren 23.795 dokümanın yoğunlaştığı ilk 10 kategori Tablo 1'de sunulmaktadır. Tabloya ait görsel dağılım ise Görsel 1'de görülebilir.

Tablo 1. Konu Taraması Sonucu Elde Edilen Toplam 23.795 Dokümanın En Yoğun Bulunduğu İlk 10 Web of Science Kategorisi

Web of Science Kategorileri	Doküman Sayısı (Record Count)	Toplam İçindeki Payı (%)
Environmental Sciences	5437	22.849
Hospitality Leisure Sport Tourism	4838	20.332
Environmental Studies	4629	19.454
Green Sustainable Science Technology	4274	17.962
Transportation	1590	6.682
Management	1301	5.468
Economics	1077	4.526
Geography	986	4.144
Transportation Science Technology	977	4.106
Business	932	3.917

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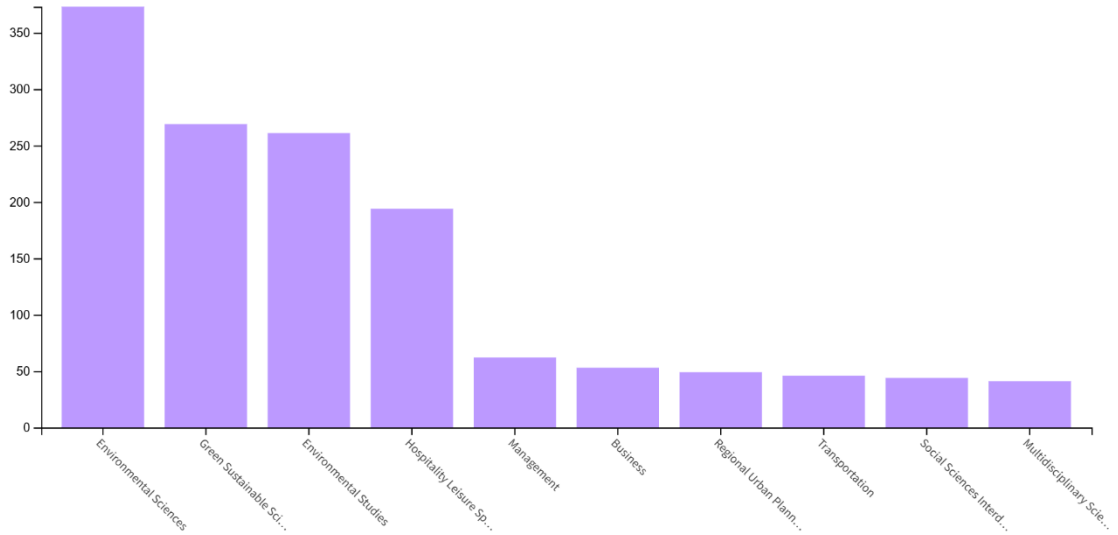
Görsel 1. 23.795 Dokümanın Web of Science Kategorilerine Dağılımı (En Yoğun İlk 10 Kategori)

Elde edilen bu geniş veri seti, alanın entelektüel birikimini ve kavramsal tartışmalarını daha net görebilmek adına belge türü olarak "inceleme makalesi" (review article) filtresinden geçirilmiş ve analiz havuzu 1.313 dokümana indirgenmiştir. İndirgenen bu veri setinin disiplinler arası dağılımı, turizmin çevre bilimleriyle olan güçlü ilişkisini sürdürdüğünü teyit etmektedir. Söz konusu duruma ilişkin Tablo 2 ve tabloya ait görsel dağılım Görsel 2 başlığı ile aşağıda sunulmuştur.

Tablo 2. İnceleme Makalesi Tipindeki Dokümanın (1.313), Web of Science Kategorilerine Dağılımında

Web of Science Kategorileri (İlk 10 Sıra)	Doküman Sayısı (Record Count)	Toplam İçindeki Payı (%)
Environmental Sciences	373	28.408
Green Sustainable Science Technology	269	20.487
Environmental Studies	261	19.878
Hospitality Leisure Sport Tourism	194	14.775
Management	62	4.722
Business	53	4.037
Regional Urban Planning	49	3.732
Transportation	46	3.503
Social Sciences Interdisciplinary	44	3.351
Multidisciplinary Sciences	41	3.123

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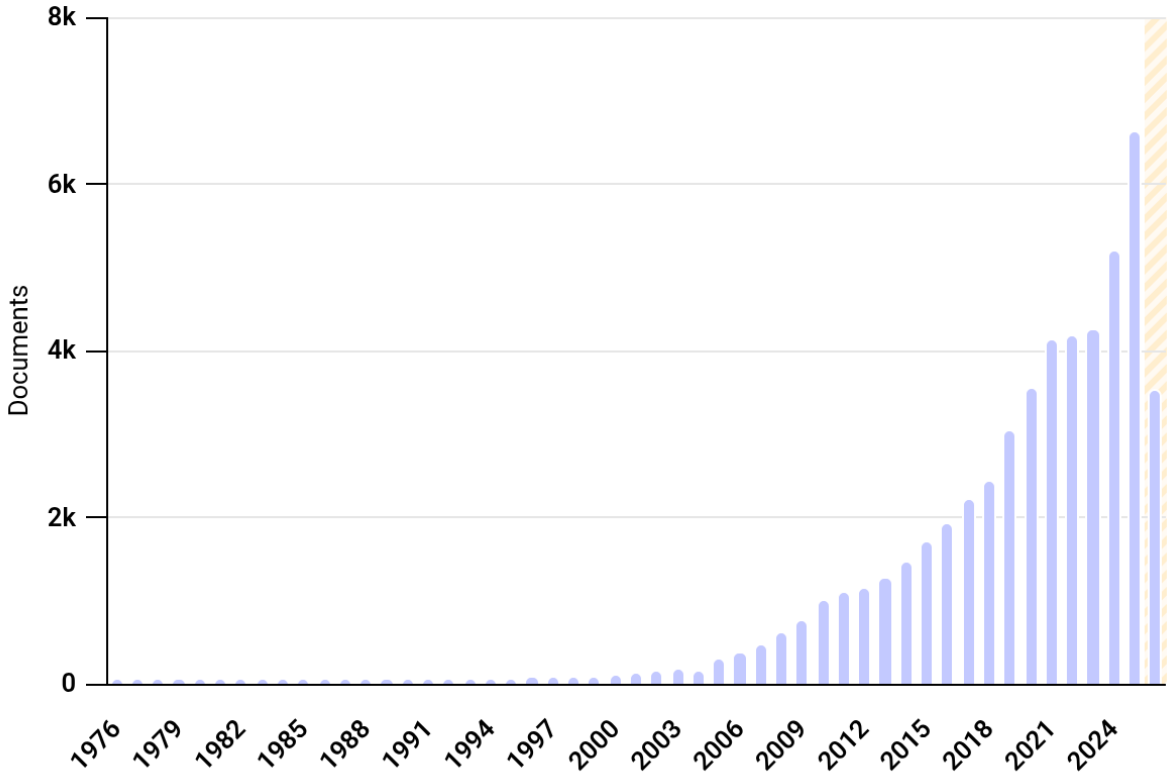
Görsel 2. İnceleme Makalesinin (1.313), Web of Science Kategorilerine Dağılımı (En Yoğun İlk 10 Kategori)

Araştırmanın odak noktasını belirginleştirmek amacıyla söz konusu 1.313 inceleme makalesi, yalnızca "hospitality, leisure sport and tourism" kategorisi ile sınırlandırılarak 194 makaleye düşürülmüştür. Akademik kalite ve etki standartlarını en üst düzeyde tutmak maksadıyla yalnızca SSCI (Social Sciences Citation Index) indeksinde taranan dergilerdeki yayınlar seçilmiş ve veri seti 100 makaleye daraltmıştır. Nihai aşamada ise, sürdürülebilir turizmin günümüzde ulaştığı en ileri noktayı ve gelecekteki potansiyel eğilimleri derinlemesine analiz edebilmek gayesiyle, yalnızca 2026 yılında yayımlanmış olan 9 adet SSCI indeksli inceleme makalesi bildirinin temel analiz birimi olarak belirlenmiştir.

2.2. Makro Eğilimler ve Bibliyometrik Gelişim

Veri toplama sürecinde ulaşılan genel tabloya bakıldığında sürdürülebilir turizm literatürü, WoS verilerine göre 1970'lerden günümüze, özellikle 2020'li yıllarda ivme kazanarak üstel bir büyüme sergilemiştir.

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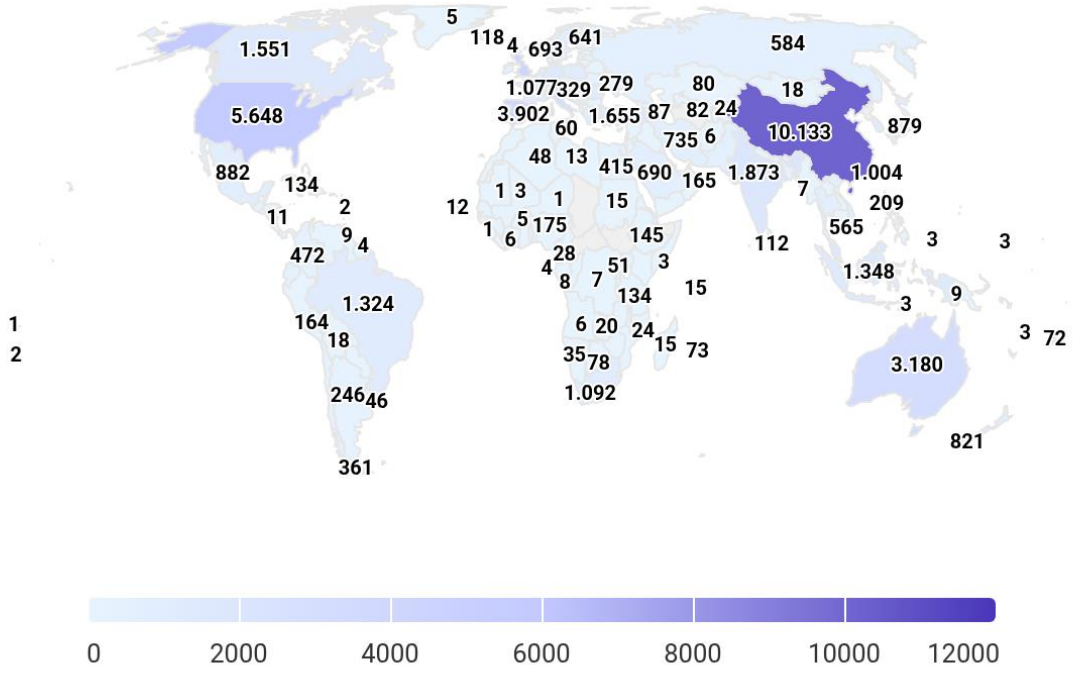


Görsel 3. Sürdürülebilir Turizm Literatürünün Yıllara Göre Yayın Eğilimi (1976-2024).

Grafik, özellikle 2020 sonrası dönemde makro krizlerin de etkisiyle alana yönelik akademik ilginin üstel (eksponansiyel) bir büyüme sergilediğini açıkça ortaya koymaktadır.

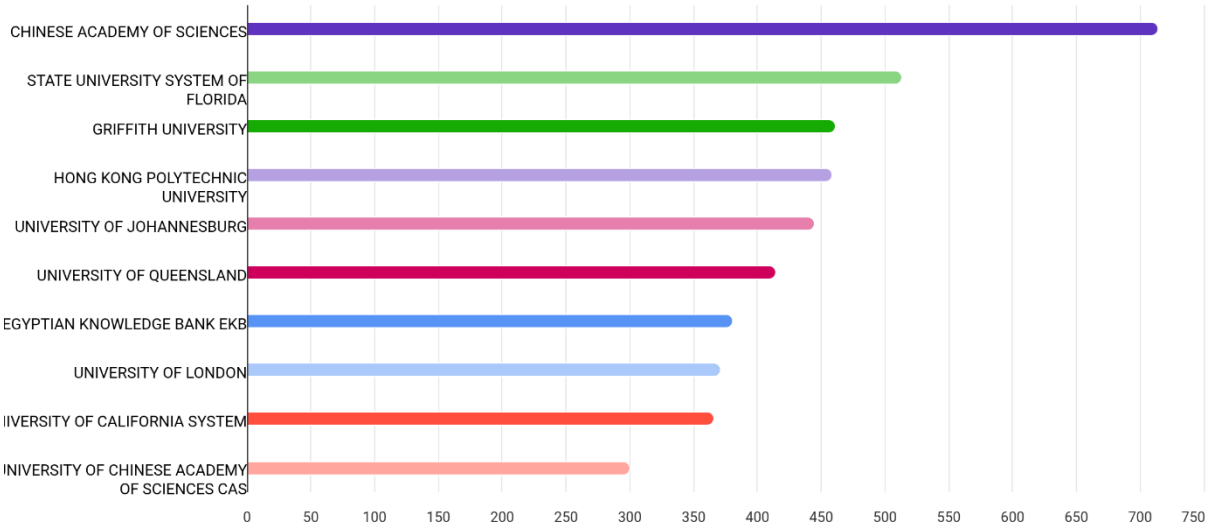
Alanın coğrafi dağılımı incelendiğinde Çin (10.133 yayın), ABD (5.648 yayın) ve Avustralya (3.180 yayın) önderliğinde belirgin bir küresel kümelenme göze çarpmakta; kurumsal ölçekte ise Chinese Academy of Sciences, State University System of Florida ve Griffith University gibi kurumların başı çektiği görülmektedir.

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Görsel 4. Sürdürülebilir Turizm Konulu Yayınların Coğrafi Dağılım Haritası.

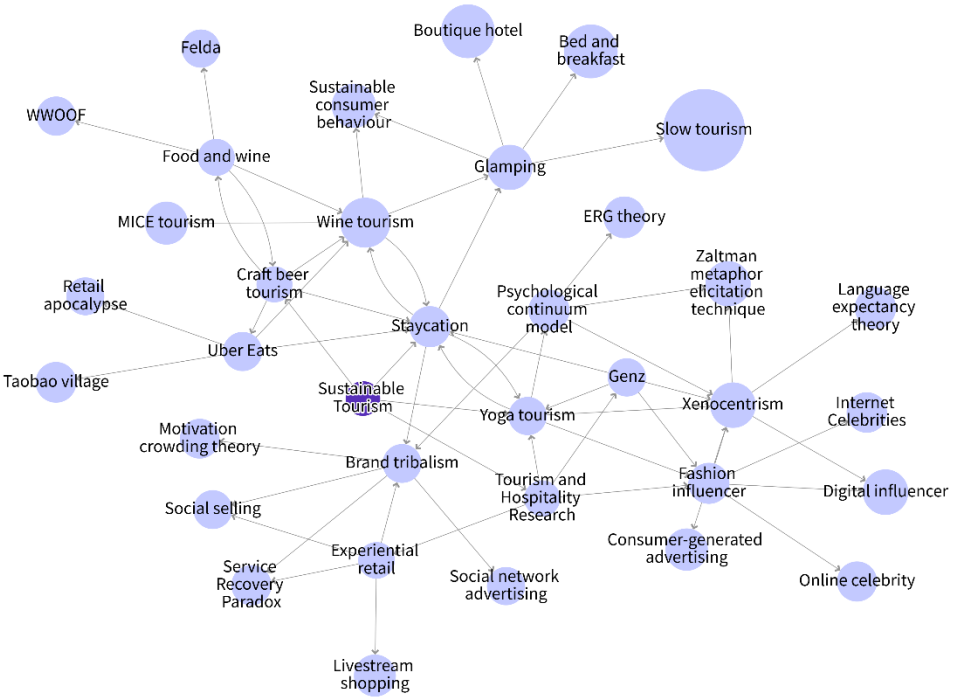
Görsel 4'de verilen harita, Çin, ABD ve Avustralya'nın küresel literatür üretiminde niceliksel bir hegemonyaya sahip olduğunu göstermektedir.



Görsel 5. Literatüre Katkı Sağlayan En Üretken Kurumlar.

Görsel 5'de görülen kurumsal dağılıma göre *Chinese Academy of Sciences* lider konumdayken, onu sırasıyla *State University System of Florida* ve *Griffith University* takip etmektedir.

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Görsel 6. Sürdürülebilir turizm makro literatürünün kelime bulutu (Word Cloud).

Genel literatürün kelime bulutunda (Word Cloud) "iklim değişikliği", "Covid-19", "ekoturizm" ve "kültürel miras" gibi makro çerçevelerin baskınlığı dikkat çekmektedir.

Makro ölçekteki bu çalışmalarda turistlerin çevre dostu davranışları, Değer-İnanç-Norm ve Planlanmış Davranış Teorisi gibi teoriler üzerinden giderek daha fazla anlaşılmakta; çevresel bilgi, eko-destinasyon imajı, dijital etkileşim ve biyosferik değerler gibi faktörler sürdürülebilir tercihleri artırmaktadır (Alashiq & Aljuhmani 2025; Khan, Qayyum, Ali & Jamil 2026). İkna edici iletişimde 'sevimlilik' (cuteness), sosyal ve kişisel normlar, sosyal medya söylentileri ve dijital akran ağlarının, turistlerin sorumlu niyetlerini ve yeşil satın alma davranışlarını etkilediği, ilişkisel ve işlevsel değerlerin ise bu süreçte kritik roller oynadığı gösterilmiştir (Xu vd. 2025; Javed vd. 2025; Khan, Mehmood & Khan 2025).

Ayrıca metaverse deneyimleri, yeşil teknoloji ve nöropazarlama gibi teknolojideki ilerlemeler, sürdürülebilir davranışların daha etkili bir şekilde teşvik edilmesini sağlarken, konaklama işletmelerinde misafir memnuniyetini ve güvenliğini artırmaktadır (Khan, Qayyum, Ali & Jamil 2026; Chaudhary, Singh & Ghosh 2025; Isa & Alsharif 2026). Eko-etiketler, eko-markalar ve sorumlu turizm kampanyaları da dahil olmak üzere pazarlama stratejileri, tüketici güvenini inşa etmek ve eko-turizm paketlerine yönelik satın alma kararlarını etkilemek için yoğun şekilde kullanılmaktadır (Isa & Alsharif 2026; Liberato vd. 2023).

Yönetişim cephesinde ise Çevresel, Sosyal ve Kurumsal Yönetişim (ESG) çerçevelerinin turizm planlaması ve gelişimine entegre edilmesi, destinasyon dayanıklılığı, büyüme ve taşıma kapasitesi yönetimi için bütüncül yaklaşımlar sunmaktadır (Camilleri, 2026; Xu & Li, 2025). Makro çalışmalar yerel halkın, özellikle de kadınlar ve gençlerin yaratıcı sanatlar, eko-turizm ve dijital altyapı yoluyla güçlendirilmesini; yeşil finansman ve yenilenebilir enerjinin sürdürülebilir turizm gelişimi için stratejik itici güçler olarak kullanılmasını vurgulamaktadır (Nthoi, 2025; Chen, 2025; Jiang & Hassan, 2025).

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3. KAVRAMSAL VE METODOLOJİK TARTIŞMA: GÜNCEL YAKLAŞIMLAR VE MİKRO DİNAMİKLER

Makro düzeydeki bu geniş perspektifin ötesinde, filtreleme stratejisi sonucunda elde edilen 2026 yılına ait 9 güncel literatür incelemesi (review), makro sorunların artık çok daha mikro düzeyde; teknolojik arabuluculuk, vatandaşlık davranışları ve yenileyici (regenerative) yaklaşımlarla ele alındığını kanıtlamaktadır.

Güncel literatürde öne çıkan en kritik kırılmalardan biri, dijitalleşme ve yapay zeka (YZ) sistemlerinin sürdürülebilir turizm ekosistemine entegrasyonudur. Üretken Yapay Zeka (GenAI) araçları, turizm ve ağırlama sektöründe hem müşteri deneyimini hem de iş gücü dinamiklerini eşzamanlı olarak yeniden yapılandıran çift yönlü bir aktör konumuna gelmiştir (Ferreira & Kastenholz, 2026). Bu teknolojik dönüşümün tüketici tarafında, algı ve davranışları yönetmek amacıyla YZ tarafından oluşturulan değerlendirme özetlerinin inandırıcılığının şeffaflık ile doğrudan ilişkili olduğu görülmektedir (Shi vd., 2026). Ayrıca dijitalleşme yalnızca ticari kaygılarla değil, kültürel miras turizminde erişilebilirliği artıran Kapsayıcı İnsan-YZ Arabuluculuğu (IHAM) çerçevesiyle etik ve kapsayıcı bir tasarım sorunu olarak da formüle edilmektedir (Wang vd., 2026). Çevre konularının turist zihniyetindeki yansıması ise sosyal medya platformlarının veri altyapısıyla şekillenmekte, çevre dostu turizm anlayışı sosyo-dijital kanallar aracılığıyla yönetilmektedir (Janik & Ryszko, 2026).

Metodolojik ve kavramsal odak noktasındaki ikinci büyük sapma, "sürdürülebilirlik" kavramının yerini yavaş yavaş "rejeneratif (yenileyici) turizm" ve "toplumsal dayanıklılık" (resilience) kavramlarına bırakmasıdır. Kırsal turizm bağlamında arıcılık turizmi (apitourism) gibi faaliyetler; sadece çevreyi koruyan değil, destinasyon altyapısı ile bilinçli seyahat yönelimlerini bir araya getirerek sosyo-ekolojik bir yenilenme sağlayan İkili-Koşullar Çerçevesi üzerinden ele alınmaktadır (Vitale vd., 2026). İklim değişikliğinden etkilenen kış turizmi bağlamında ise salt çevresel müdahalelerin ötesine geçilmesi, sorunun ekonomik çeşitlendirme ve sosyal işgücü çerçeveleriyle çözülmesi gerektiği vurgulanmaktadır (Kiashemshaki vd., 2026). Turizm ekosisteminde bu yenileyici hedeflere ulaşılabilmesi için temel şartın, çalışanlardan yerel halka ve turistlere kadar tüm aktörlerin risk algısını ve psikolojik sahiplenmesini barındıran "vatandaşlık davranışı"nı (citizenship behaviour) benimsemesi olduğu kanıtlanmıştır (Sartika vd., 2026). Topluluk dayanıklılığı üzerine yapılan çalışmalar; ekolojik felaket kurtarma ve disiplinlerarası işbirliklerini merkeze almaktadır (Wu vd., 2026). Ek olarak, mali politikalarda KDV gibi vergilendirme araçları, salt gelir elde etmekten çıkıp talep yönetimi ve yerel altyapıların finanse edilmesi için stratejik bir dayanıklılık enstrümanı olarak konumlandırılmaktadır (Hesami, 2026).

4. GELECEK PROSPEKTİFİ VE SONUÇ

Mevcut bilimsel birikim, sürdürülebilir turizmde bireysel güdüler, teknolojik ilerlemeler ve politika çerçeveleri arasındaki dinamik etkileşimi vurgulamaktadır. WoS üzerinde yapılan makro haritalamalarda öne çıkan kavramlar (Topic Map) ile 2026 yılı inceleme makalelerinin bulguları sentezlendiğinde, alanın geleceği netleşmektedir.

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Görsel 7. Sürdürülebilir Turizmin Kavramsal Konu Haritası (Topic Map).

Ağ analizi, geleneksel sürdürülebilirlik kavramının günümüzde Z kuşağı, moda fenomenleri gibi tüketici algıları ile glamping ve yoga turizmi gibi yeni nesil deneyimsel niş pazarlarla derinden entegre olmaya başladığını işaret etmektedir.

İlk olarak, insan-veri etkileşimi (Wang vd., 2026) ve GenAI araçlarının entegrasyonu (Ferreira & Kastenholz, 2026), niş turizm türlerinin pazarlanmasında bir standart haline gelecektir. İkinci olarak, iklim krizleri geleneksel sürdürülebilirlik anlayışını zorlayacak; bunun yerine sosyo-ekolojik yenilenmeyi merkeze alan (Vitale vd., 2026) ve vatandaşlık davranışıyla desteklenen (Sartika vd., 2026) dayanıklılık modelleri (Wu vd., 2026) ön plana çıkacaktır. Özetle, ekonomik büyüme, çevresel koruma ve sosyal eşitliği dengelemeyi hedefleyen turizm sektörü; bireysel, örgütsel ve politik düzeydeki eylemlerin teknolojik dönüşümle bütünleştirildiği çok daha çok boyutlu ve yenileyici bir geleceğe doğru ilerlemektedir.

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ERKEN CUMHURİYET DÖNEMİ'NDE ANKARA REFİK SAYDAM HIFZISSIHHA YERLEŞKESİ MİMARİSİNDE VİYANA ETKİLEŞİMLERİ

THE INFLUENCE OF VIENNA ON THE ARCHITECTURE OF THE REFIK SAYDAM CENTRAL INSTITUTE OF HYGIENE IN ANKARA DURING THE EARLY REPUBLICAN PERIOD

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ÖZET

Bu çalışma, Refik Saydam Hıfzıssıhha Yerleşkesi'nde bulunan yapıların tarihsel süreçleri üzerinden, Viyana ile olan etkileşim bağlamında Viyana Modernizmi ve Erken Cumhuriyet Dönemi'nde Ankara mimarisi çerçevesinde bir analiz yapılmasını amaçlamaktadır. Literatürde çoğunlukla tekil yapı ölçeğinde ele alınan yerleşke, bu çalışmada bütüncül bir yaklaşımla değerlendirilmiştir. Bu kapsamda, yerleşke sınırları içerisinde yer alan ve Theodor Jost ile Robert Oerley tarafından tasarlanan, modernizme geçişin erken örnekleri arasında sayılan Kimyahane ve Bakteriyoloji binası, Merkez bina, Hıfzıssıhha Mektebi ve İkametgâh Apartmanı incelenmiştir. Söz konusu yapılar, Viyana Modernizmi'nin üç farklı işlevsel yaklaşımına ait etkiler taşımaktadır. Çalışma, literatür ve arşiv taramasıyla elde edilen yazılı ve görsel belgelerin analizi ile yerinde gerçekleştirilen saha araştırmasının bulgularına dayanmaktadır. İnceleme sonucunda, yerleşkedeki yapıların yalın cephe düzenleri, hijyenik mekân kurguları ve etkin doğal ışık kullanımı ile Viyana Modernizmi'nin özellikleri arasında güçlü benzerlikler bulunduğu tespit edilmiştir. Kolay temizlenebilir, aydınlık, beyaz renk ağırlıklı ve yalın malzemeli iç mekânlar, simetrik tasarım anlayışıyla sıklıkla tekrar eden baklava dilimi deseni gibi unsurlar da bu etkileşimin yansımalarıdır. Ayrıca, söz konusu mimari özellikler ve yerleşkedeki yeşil alan tasarımı, Josef Hoffmann tarafından Viyana yakınlarında tasarlanan Purkersdorf Sanatoryumu (1904-05) ile benzerlikler de göstermektedir. İkametgâh Apartmanı'nda görülen sade cephe tasarımı, üçgen formlu balkonlar ve cephe boyunca uzanan denizlikler ise Viyana Modernizmi etkileri taşıyan Viyana sosyal konut mimarisiyle doğrudan biçimsel ilişkiler kurmaktadır. Sonuç olarak bu çalışma, Refik Saydam Hıfzıssıhha Yerleşkesi'nin yalnızca Erken Cumhuriyet Dönemi'nin modernleşme söylemi içinde değil, aynı zamanda Viyana kökenli modern mimarlık yaklaşımlarının Ankara'daki yansımalarını bütüncül biçimde barındıran önemli bir örnek olduğunu ortaya koyarak, erken Cumhuriyet mimarlığının değerlendirilmesine katkı sunmayı hedeflemektedir.

Anahtar Kavramlar: Ankara, Erken Cumhuriyet Dönemi, Refik Saydam Hıfzıssıhha Yerleşkesi, Robert Oerley, Theodor Jost, Viyana.

ABSTRACT

This study analyzes the historical processes of the buildings within the Refik Saydam Central Institute of Hygiene and the influence of Vienna Modernism on Ankara's architecture during the Early Republican Period. While existing literature often evaluates the campus at an individual building scale,

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this study utilizes a holistic approach. Within this scope, the Chemistry and Bacteriology Building, the Central Building, the School of Hygiene, and the Residential Building inside campus boundaries designed by Theodor Jost and Robert Oerley are examined. These structures reflect three distinct functional approaches of Vienna Modernism. The study includes an analysis of written and visual documents obtained through literature and archive searches as well as findings of field research conducted on site. The examination revealed strong similarities between the simple façade arrangements, hygienic spatial designs, and effective use of natural light in the buildings and the characteristics of Vienna Modernism. Interior elements such as easy-to-clean, bright, predominantly white, and simple interior materials along with a symmetrical design and frequently repeated diamond-shaped pattern further reflect this interaction. Notably, the campus' green space and architectural features show similarities to Josef Hoffmann's Purkersdorf Sanatorium (1904-05). Furthermore, the simple façades, triangular balconies, and continuous windowsills of the Residential Building establish direct links to Vienna's social housing architecture which bear the influence of Vienna Modernism. In conclusion, this study aims to contribute to the evaluation of Early Republican architecture by demonstrating that the Refik Saydam Central Institute of Hygiene comprehensively embodies both the modernization discourse and the specific reflections of Vienna modern architectural approaches in Ankara.

Keywords: Ankara, Early Republican Period, Refik Saydam Central Institute of Hygiene, Robert Oerley, Theodor Jost, Vienna.

GİRİŞ

13 Ekim 1923'te Ankara'nın başkent olması ve 29 Ekim 1923'te Cumhuriyet'in ilân edilmesiyle birlikte Türkiye'de ulus-devlet inşa süreci başlamıştır. Kurtuluş Savaşı'nın kazanılmasından ardından 13 milyonluk nüfusunun 1,5 milyonu tüberküloz, frengi ve trahoma gibi hastalıklarla mücadele etmiştir (İlikan-Rasimoğlu, 2014:16). Ankara bu yıllarda, sıtma yuvası bataklıklarına, susuzluğa ve sert iklime sahip, yoksul, 40.000 kadar nüfuslu bir bozkır kasabası görünümündedir (Aslanoğlu, 2010:28). Sağlık sorunları, yeni kurulan Türkiye Cumhuriyeti'nin en önemli meselelerinden biri olarak görülmüş ve bu alandaki iyileştirmeler ise devletin öncelikli hedefleri arasında yer almıştır (Tuğluoğlu, 2008:4, 23).

Erken Cumhuriyet Dönemi'nde sağlık konusunun yanı sıra en önemli sorunlardan bir diğeri ise yeni başkent Ankara'nın inşası olmuş ve Atatürk bu konuya büyük önem vermiştir (Alsaç, 1973:15). Bu dönemde mimarlık pratiğini ve eğitimini modern olana yöneltmek, "muasır medeniyetler seviyesine ulaşma" hedefinin vazgeçilmez bir koşulu olarak değerlendirilmiş ve bu doğrultuda çeşitli kararlar alınmıştır. Atatürk için, insanların refah içinde yaşayabileceği ve yüzyılın taleplerine uygun modern şehirler inşa etmek, modern bir toplum yaratma hayalinin ilk adımı olmuştur (Tuncer Pürselim ve Kurtoğlu, 2023:314).

Erken Cumhuriyet Dönemi'nde mimarlık alanındaki modernleşme faaliyetleri özellikle devlete ait sağlık ve kamu yapılarında yeni ve modern yaşam standartlarına uygun yapıların inşa edilmesine öncü olmuştur (Ateş, 2011). Bu süreçte Ankara'da, Cumhuriyet'in kurucu kadrosunun sağlıklı nesiller yetiştirebilme hedefi doğrultusunda sağlık alanına odaklanılmıştır. Sağlık sektöründeki değişim ve dönüşüm ise dönemin Sağlık Bakanı Dr. Refik Saydam (1881-1942) sayesinde mümkün olmuştur (İlikan-Rasimoğlu, 2014:16, 18). Sağlık alanında büyük yeni adımlar atılmış, Erken Cumhuriyet Dönemi'nde başkent Ankara'da yeni gelen yabancı mimarlar modern sağlık kurumları tasarlamıştır. İlk planlama kriterleri 1924-1925 Lörcher planında da belirlenen, Sağlık Bakanlığı'nın hemen ardından iki sağlık binası daha inşa edilmiştir. Bunlar, Cumhuriyet yapı programının erken Modernist örnekleri olarak Refik Saydam Hıfzıssıhha Yerleşkesi (1928-32, mimarlar Theodor Jost ve Robert Oerley; "Hygieia" kabartmasının tasarımcısı heykeltıraş Wilhelm Frass) ile Numune Hastanesi'dir (1933, Oerley) (Önge, 2007:83). Sunulan bu çalışmada Refik Saydam Hıfzıssıhha Yerleşkesi ve yerleşkedeki yapılar söz konusu bağlamda analiz edilecektir.

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YÖNTEM

Çalışma kapsamında inceleme sahası olarak, Erken Cumhuriyet Dönemi'nde (1923-38), Dr. Refik Saydam'ın öncülüğünde Avusturyalı mimarlar Theodor Jost ve Robert Oerley tarafından tasarlanan Refik Saydam Hıfzıssıhha Yerleşkesi seçilmiştir. Yerleşkede yer alan yapılar, inşa edildikleri dönemde özellikle sağlık alanında hem işlevsel hem de simgesel önem taşımaktadır. Bu bağlamda, seçilen örneklerin Erken Cumhuriyet Dönemi mimarisi açısından oldukça önemli olduğu düşünülmektedir. Yerleşkedeki yapıların mimarlarının ve "Hygieia" kabartmasının tasarımcısı heykeltıraşın Avusturyalı olması, bu dönemde Viyana'da modernizm bağlamında gelişen üslupların Türkiye'de tasarlanan yapılara yansıdığını göstermektedir.

Bu çalışma, Refik Saydam Hıfzıssıhha Yerleşkesi'nde bulunan yapıları tarihsel süreçleri üzerinden, Viyana ile olan etkileşim bağlamında ele alarak Viyana Modernizmi ve Erken Cumhuriyet Dönemi'nin mimari özellikleri çerçevesinde analiz etmeyi amaçlamaktadır. Bu doğrultuda, nitel araştırma yöntemleri kapsamında literatür ve arşiv kaynak taraması gerçekleştirilmiş; Koç Üniversitesi VEKAM Kütüphanesi ve Arşivi, Cumhurbaşkanlığı Devlet Arşivleri Başkanlığı Cumhuriyet Arşivi, Wien Museum-Online Sammlung, Österreichische Nationalbibliothek (Avusturya Milli Kütüphanesi), Ankara Büyükşehir Belediyesi İmar ve Şehircilik Dairesi Başkanlığı Arşivi, Ankara Kültür Varlıklarını Koruma Bölge Kurulu Müdürlüğü Arşivi ve dönemin önemli süreli yayınlarından olan La Turquie Kémaliste ile ikincil kaynaklardan temin edilen belge ve fotoğraflar incelenmiştir. Elde edilen yazılı ve görsel veriler, Ankara ve Viyana'da gerçekleştirilen yerinde saha araştırmalarıyla desteklenmiş ve bulgular aşağıda sunulmuştur.

ERKEN CUMHURİYET DÖNEMİ'NDE ANKARA'DA YABANCI MİMARLAR

Yeni mimari yaklaşımlar, gelişen teknoloji ve modern yapı malzemeleri, Erken Cumhuriyet Dönemi'nde mimarlık alanında önemli değişikliklere yol açmıştır. Bu dönemde devlet tarafından birçok kamu binası inşa edilmiş ve genç Cumhuriyet'in ideallerini temsil eden modern bir mimari şekillenmiştir. Ayrıca sağlık, eğitim ve altyapı gibi alanlarda toplumsal dinamiklerde köklü değişimlere yol açan politikalar uygulanmış ve bu politikalar, söz konusu alanlarda daha modern teknolojilerin kullanılması ve bu dönemde inşa edilen yapılarda farklı mimari yaklaşımların benimsenmesi sağlanmıştır (Şener ve Kishalı, 2020:89-90).

Erken Cumhuriyet Dönemi'nde öncelikle I. Ulusal Mimarlık Akımı'nın (1908-30) etkisiyle mimari yapılar inşa edilmiştir. Bu dönemde eş zamanlı olarak "Modern Mimari" ya da "Yeni Mimari" şeklinde tanımlanan uluslararası üslup örnekleri, dönemin "yenilenme" hedefleri bağlamında yorumlanarak Ankara başta olmak üzere Türkiye'de birçok şehirde uygulanmıştır (Alpagut, 2010:131; Ergut, 2009). Türkiye'de 1927'den II. Dünya Savaşı'nın başlamasına kadar uzanan Modern Mimarlık dönemi, kendi içinde 3 alt döneme ayrılmaktadır. İlk dönem (1927-33), modern düşünce ve işlerle ilk karşılaşma-hazırlık-deneyimleme evresidir ve "yabancı mimarlar dönemi" olarak da adlandırılmaktadır. İkinci dönemde (1933-38), yerel mimarlar farklı pek çok kamu yapısında doğrudan veya yarışma yoluyla görevlendirilmiş ve egemenlikleri artmaya başlamıştır. Günümüzde kullanılmaya devam eden III. Türkiye Büyük Millet Meclisi binası için açılan yarışma ise üçüncü dönemin başlangıcıdır (Batur, 2005:86-88; Karasözen, 2013'ten akt. Uzunboy vd., 2023:267-268). Bu çalışmada incelenen yapılar kronolojik olarak ilk döneme denk geldiği için, analizler söz konusu dönemin özellikleri çerçevesinde yapılacaktır.

Mimarlıkta ilk olarak uygulamada, ardından eğitim alanında yabancı mimarların yer alması Geç Osmanlı Dönemi'nde başlamış ve Erken Cumhuriyet Dönemi'nde de sürdürülmüştür (Alsaç, 1973:13; Aslanoğlu, 2010:55). Cumhuriyet'in ilk yıllarında Ankara'nın başkent olmasıyla, yeni birçok idari binaya ihtiyaç duyulmuş ve inşaat kapasitesi sürekli artış göstermiştir. Ancak teknik kadroların yanı sıra kalifiye işçi ve ustaların sayısının yetersizliğinden dolayı yabancı mimarlar, şehir plancıları ve mühendisler Türkiye'ye davet edilmiştir (Özer, 1964:51; Saygıner ve Suri, 2024:1253). Devletçi ekonomi politikası kapsamında yeni imar programına uygun olarak çıkarılan "Teşvik-i Sanayi Kanunu"nun (1927) sonucunda yabancı mimarlar dönemi 1927'de başlamış ve 1950'lere kadar sürmüştür. Bu kanunla sanayinin ihtiyaç duyduğu teknik işgücünün yanı sıra sanat, şehircilik, mimarlık ve mühendislik alanlarında yabancıların çalışmalarının önü açılmıştır (Batur, 1998:218). Kanunda

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"Türkiye'de bulunmayan uzmanların Avrupa'dan getirilmesi" maddesi ile başta Almanca konuşulan ülkelerden (Almanya, Avusturya, İsviçre) olmak üzere toplam 40 mimar ve şehir plancısı davet edilmiştir. Hem üniversitelerde ders veren hem de kamu yapılarının projelerinde çalışan bu uzmanlar, Avrupa'daki modern mimari yaklaşımları ve teknikleri Türkiye'de uygulama olanağını bulmuşlardır (Saygıner ve Suri, 2024:1266).

Erken Cumhuriyet Dönemi'nde yabancı mimarlara düşen başlıca görev "Ankara'yı Batılı bir başşehir" hâline getirmekti (Özer, 1964:52). Bu doğrultuda başkentin çehresi kamu, sağlık, eğitim ve kültür yapıları, oteller, parklar vb. ile tamamen Avrupa normlarına uygun olarak yeniden şekillenmiştir. Farklı motivasyonlarla gelen yabancı mimarlar, mühendisler ve şehir plancıları eğitim alanında reformlar gerçekleştirerek üniversitelerin uluslararası standartlara ulaşmasına büyük katkı sağlamış, üniversite ve enstitüler kurup yönetmiş, hatta birçoğu eğitim kitaplarını dahi kendileri kaleme almıştır. Bunun yanı sıra, Cumhuriyet'in ihtiyaç duyduğu yapılaşma ve imar planlama faaliyetlerini de aktif bir şekilde yürütmüşlerdir (Saygıner ve Suri, 2024:1278). Cumhuriyetin ilk yıllarından 1950'lere kadar birçok kurumda yabancı uzman ve teknisyenlerden yararlanılmış, yabancı profesörler üniversitelerde 1950'lere dek eğiticilik yapmışlardır (Aslanoğlu, 2010:55).

1926-55 yılları arasında 20'den fazla Alman, Avusturyalı ve İsviçreli mimar Türkiye'de çalışmıştır. O dönem gelen yabancı mimarlar arasında Theodor Jost (1926), Clemens Holzmeister (1927), Ernst Egli (1927), Robert Oerley (1928), Bruno Taut (1936) ve Paul Bonatz (1943) gibi isimler yer almaktadır (Zander, 2007:23).

YABANCI MİMARLARIN TÜRKİYE'DE YENİ MİMARİ YAKLAŞIMLARI

Mimarlıkta ortak bir dil, uluslararası bir tutum oluşturma çabaları 1920'li yıllarda başlamıştır. Sonuçları ise, ülkemize 1930'lu yıllarda ulaşmıştır (Sözen, 1984:171). Erken Cumhuriyet Dönemi'nde reformların ve yönetimin etkisiyle 1930'larda sona eren ve 1970'li yıllarda I. Ulusal Mimarlık Akımı ismini alan üslubun yanı sıra, mimarlıkta modern ve batılı yapım teknikleriyle birlikte yeni yaklaşımlar görülmeye başlanmıştır (Eldem, 1973:6; Pfeiffer-Taş ve Temel, 2020:354-355). Bu süreçte Türkiye'ye gelen yabancı mimarlar, aldıkları eğitim ve edindikleri mesleki birikimin yanı sıra, geldikleri ülkelerde modernizm bağlamında görülen mimarlık yaklaşımlarını da Türkiye'ye yansıtmışlardır. Bu dönemde uluslararası üslup ya da biçimsel neo-klasik üslubuyla tasarlanan yapılar görülmektedir.

Modern mimarlık, kökenlerini 18. yüzyılda Endüstri Devrimi'nin ortaya çıkardığı gelişmelerden alan, 20. yüzyılın ilk yarısında yaygınlık kazanan ve toplumun değişen gereksinimlerine, dönemin sanat anlayışına ve çağdaş yapım tekniklerine uygun doğrudan çözümler üretmeyi amaçlayan bir mimarlık yaklaşımıdır. Terim, 19. yüzyıl sonlarından itibaren geleneksel üsluplardan ve eski yapım tekniklerinden ayrılan, işlevsellik ve rasyonaliteyi esas alan, modern yapım yöntemleriyle tasarlanan farklı mimari anlayışları tanımlamak için kullanılmaktadır (Hasol, 2021:85). II. Dünya Savaşı'na kadar süren bu dönemde etkili olan modern mimarlık hareketi ile anıtsal bir mimari hedeflenmiş ve işlevsel çözümler öne çıkmıştır. Yapılar hangi amaca yönelik kullanılacaksa, ona göre biçimlendirilmiş ve mekân kurgusu yapılmıştır. Cephelerde yoğun bezemelerden uzaklaşılmış ve yalın olarak tasarlanmıştır. Tarihselciliğe yönelmek yerine çağa uygun bir mimari benimsenmiştir. Dönemin modern yapı malzemesi olan betonarmenin kullanımı yaygınlaşmıştır (Sözen, 1984:171-172). Çalışma kapsamında incelenecek olan Refik Saydam Hıfzıssıhha Yerleşkesi'nde yer alan yapılarda bu yaklaşımlardan bazıları görüldüğü için özellikleri aşağıda kısaca ele alınmıştır.

Uluslararası Üslubun yabancı mimarlar tarafından Türkiye'ye getirilmesiyle birlikte özellikle kamu yapılarında kütle ve cephe hareketleri modern bir şekilde ele alınmaya başlanmış, yapısal ve işlevsel özellikler ön plana çıkmıştır. Net geometriye sahip kütleler, konsollar, pahlı duvarlar, asimetrik tasarımlar ve teras çatılar yapılarda kullanılan modern mimari ögeler olarak görülmeye başlanmıştır (Tuncer Pürselim ve Kurtoğlu, 2023:320). Bu yıllarda Türkiye'de yerli mimarlar da Uluslararası Üslubu benimseyerek, uygulama yapabilme olanakları aramışlardır (Sözen, 1984:171). Ankara özelinde bakıldığında önce Lörcher Planı'nda (1924), ardından Jansen Planı'nda (1928) Yenişehir'deki birçok konut ve kamu yapısı bu üslupla tasarlanmıştır (Alpagut, 2010:73, 126). Yavuz (1973:29) Uluslararası üslubu "enternasyonal biçimler" olarak isimlendirmektedir. 1927'den itibaren Türkiye'ye davet edilen Alman ve Avusturyalı mimarların etkisiyle şekillenen enternasyonal üslup, özellikle Ankara

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mimarisinde belirgin biçimde ortaya çıkmaya başlamıştır (Yavuz, 1973:29). Sosyal devlet anlayışının bir sonucu olarak inşa edilen kamu yapıları, genellikle sağlık, kültür ve eğitim yapılarıdır (Alpagut, 2010:129). Ağırlıklı olarak yabancı mimarlar tarafından tasarlanan bu yapılar, mimari özellikleri ve özelleşmiş programları açısından Cumhuriyet'in hem mekânsal hem de toplumsal modernlik projelerinin fiziksel simgeleri olmuştur (Önge, 2007:82).

Ankara'nın inşa edilme hızının dikkat çektiğine ve özellikle konutların büyük ölçüde Alman ve Avusturya (Viyana) üslubunda tasarlandığına dair gazete yazısı bulunmaktadır (Anonim, 1927:6). Bu çalışma kapsamında, Erken Cumhuriyet Dönemi'nde inşa edilen Refik Saydam Hıfzıssıhha Yerleşkesi'nin mimarisi, Viyana Modernizmi ile kurduğu etkileşimler çerçevesinde aşağıda incelenecektir.

REFİK SAYDAM HIFZISSIHHA YERLEŞKESİ (MERKEZ HIFZISSIHHA ENSTİTÜSÜ/ MERKEZ HIFZISSIHHA MÜESSESİ)

Günümüzde Ankara'nın Çankaya İlçesi, Sağlık Mahallesi'nde yer alan Refik Saydam Hıfzıssıhha Yerleşkesi, arşiv belgelerinde ve literatürde "Merkez Hıfzıssıhha Enstitüsü" veya "Merkez Hıfzıssıhha Müessesi" gibi önceki isimleriyle de anılmaktadır. Bu çalışmada ise söz konusu yerleşkeye "Refik Saydam Hıfzıssıhha Yerleşkesi" ismiyle yer verilmiştir. Yerleşkenin ayrıntılı incelemesine geçmeden önce, tarihçesi kısaca aktarılacaktır.

Refik Saydam Hıfzıssıhha Yerleşkesi'nin Tarihçesi

Osmanlı İmparatorluğu'nda uzun süren savaşlar ölüm ve yaralanmalara yol açmış, işgücünü azaltmış, sosyo-ekonomik zorluklar sağlık hizmetlerine ihtiyaç duyan insan sayısını artırmıştır. Savaşa bağlı olarak gelişen yoksulluk sağlık hizmetlerini de olumsuz etkilemiştir. Osmanlı hükümetinin yaptığı düzenlemeler yetersiz kalmıştır (Ögenler vd., 2023:177). Cumhuriyetin ilk yıllarında, sunulan sağlık hizmetleri Osmanlı dönemiyle bir devamlılık gösterse de kendine özgü yenilikçi özellikleri de vardır (Karabulut, 2007:158). Atatürk, Cumhuriyet'i kuran halkın dinamik ve sağlıklı bir yapıya sahip olmasını çok önemsemiştir. Sağlık ve tıp araştırmaları Atatürk'ün önderliğinde ve talimatları doğrultusunda ivme yakalamış ve dönemin Sağlık Bakanı Dr. Refik Saydam (1881-1942) önderliğinde yürütülmüştür (Aksakal, 2017:219). Atatürk'ün kendisine verdiği tam desteği değerlendiren Dr. Saydam, Osmanlı'dan ve öncesinden miras kalan temeller üzerine bir sağlık teşkilatı kurmuştur (Bulut, 2021:149). Dr. Saydam, Erken Cumhuriyet Dönemi'nde uyguladığı politikalar sayesinde Türkiye'de sosyal devlet anlayışının güçlü örneklerini ortaya koymuş ve ilerleyen yıllarda uygulanacak sağlık hizmetlerinin temellerini atmıştır (Karabulut, 2007:158). Dr. Saydam'ın sağlık alanında bulaşıcı hastalıklarla mücadeledeki en önemli icraatlarından biri "Merkez Hıfzıssıhha[1] Enstitüsü" adıyla kurulan Refik Saydam Hıfzıssıhha Yerleşkesi'dir (Bulut, 2021:149).

10 Mayıs 1928'de TBMM'ye sunulan tasarıda, halk sağlığının korunmasının bilimsel gelişmeler doğrultusunda takip edilmesi gerektiği ve bu nedenle uzmanlardan oluşan bir kuruma ihtiyaç duyulduğu belirtilmiştir. Sıhhiye Vekâleti'nin teknik bir birimi olarak bilimsel araştırmalar için Hıfzıssıhha Kurumu'nun oluşturulması uygun görülmüştür. Ankara'da yer alacak olan bu kurumun en modern cihazlarla donatılacağı, böylece hem teknolojik gelişmelere ayak uyduramayan hekim ve hekim adaylarının bu kurumdan faydalanabileceği hem de dışarıdan gelen her türlü ilacın kontrol edilebileceği söylenmiştir. Tasarı, 17 Mayıs 1928 tarihli meclis oturumunda kabul edilmiş (Karabulut, 2007:155-156) ve aynı tarihli 1267 sayılı yasa ile Sağlık ve Sosyal Yardım Bakanlığı'na bağlı Merkez Hıfzıssıhha Müessesesi kurulmuştur (Aslan, 2005:12).

Hıfzıssıhha Yerleşkesi'nin kurulmasında Rockefeller Vakfı'nın önemli bir etkisi olmuştur. New York Eyaleti Yasama Meclisi tarafından 14 Mayıs 1913'te tüzüğü onaylanan Rockefeller Vakfı'nın (ABD) amacı dünya genelinde insanlığın refahını yükseltmektir (The Rockefeller Foundation, 2025). Rockefeller Vakfı, o yıllarda tüm dünyada hıfzıssıhha okullarının açılmasını desteklemiştir. Dr. Saydam, bu gelişmeleri yakından takip ederek, ihtiyaçları değerlendirmiş ve Türkiye için uyum çalışmaları yürütmüştür. Değişen sağlık politikasının bir sonucu olarak Avrupa'da kurulan Hijyen Enstitüleri gibi

[1] Hıfzıssıhha, "hıfz (korumak)" ve "sıhha (sağlık)" sözcüklerinin birleşiminden oluşmakta ve sağlığın korunması anlamına gelmektedir. Genel anlamda halk sağlığıyla ilgili her türlü konu, hıfzıssıhhanın alanına girmektedir (Aslan, 2005:9).

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kurumlar, halk sağlığı için gerekli bazı ilaç, serum ve aşıları üretmekle ve sağlık ekiplerinin eğitim çalışmalarını ve hastalıklar için gerekli laboratuvar tetkiklerini yapmakla sorumludur. Dr. Saydam, benzer bir kurumun Türkiye'de de kurulması için çalışmalara başlamış ve Rockefeller Vakfı'ndan destek istemiştir. Vakıf, Hıfzıssıhha Yerleşkesi için toplam 280.000 ABD doları ödeme yapmıştır (Tunç, 2024:14). Kimyahane ve Bakteriyoloji binasına, ekipmanların kurulumu ve satın alınması için yapılan 80.000 ABD doları tutarındaki ilk bağışı anan bir plaket asılmıştır (Şekil 1).



Şekil 1. Refik Saydam Hıfzıssıhha Yerleşkesi, Kimyahane ve Bakteriyoloji binası, 2025 (Şule Pfeiffer-Taş arşivi, 2025).

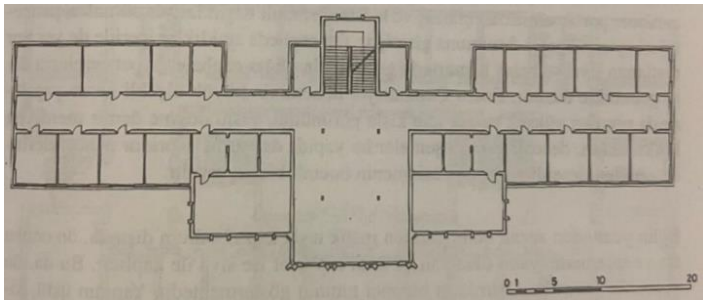
Refik Saydam Hıfzıssıhha Yerleşkesi, koruyucu sağlık hizmeti sunan, sağlıklı kişilerin korunması ve hasta olmamaları için gereken tedbirleri alan bir kurumdur (Dilek, 2021). Cumhuriyet'in ilk yıllarında ülkemizde bazı hastalıklara karşı serum ve aşı üreten kurumlar hariç halk sağlığını her yönüyle kapsayan bir kurum yoktur (Metintaş, 2008:127). Bu nedenle yerleşkenin görevleri arasında ilaç, serum ve aşı üretimi, modern halk sağlığı yöntemlerinin uygulanması, gerekli laboratuvar testlerinin yapılması ve altyapı merkezlerinin koordinasyonu yer almaktadır (Başaran, 2021:175). Program kapsamında, sağlık alanında görev yapacak personelin yetiştirilmesi ve hâlihazırda çalışan personelin eğitimine katkı sağlamak için bir Hıfzıssıhha Mektebi'nin kurulması öngörülmüştür (Aslan, 2005:12). Yerleşkenin plan ve proje işlemlerini, Dr. Saydam'ın davet ettiği Avusturyalı mimarlar Theodor Jost ve Robert Oerley yapmıştır (Metintaş, 2008:128; Yılmaz ve Çügen, 2011). Yerleşkenin ayrıntılı incelemesine geçmeden önce, yapının mimarları Jost ile Oerley'in hayatlarına, mimari üsluplarına ve yapılarına kısaca yer verilmiştir.

Avusturyalı Mimarlar Theodor Jost ve Robert Oerley

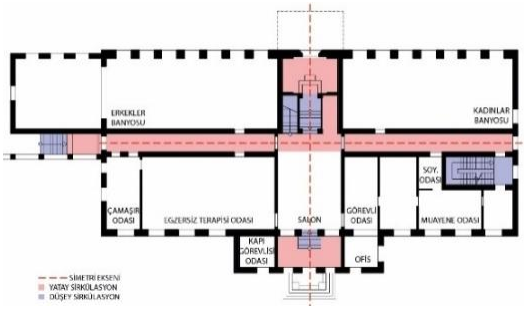
1927 tarihli Teşvik-i Sanayi Kanunu'ndan bir yıl önce ülkeye davet edilen yabancı mimarlardan ilki Avusturyalı mimar Theodor Jost'dur. (Aslanoğlu, 2009:72). Jost, dönemin Sağlık Bakanı Dr. Saydam tarafından birçok Alman doktorla birlikte, Sağlık Bakanlığı'na danışman sıfatıyla tahminen 1926 yılında yeni yapılar inşa etmek ve Cumhuriyet'in gelişmesine katkıda bulunmak üzere Ankara'ya davet edilmiştir. 1928'e kadar Türkiye'de kalan Jost'un hakkında detaylı bilgiye erişilememiştir (Dere, 2021:466; Goethe-Institut Ankara, 2010c; Kılınç, 2002b:103).

Jost'un Ankara'daki ilk yapısı, modern mimarlığın Ankara'daki ilk örneklerinden biri (Tanyer, 2014:111) ve kentin yeni bölgesi Sıhhiye'de inşa edilen ilk hükümet binası olan Sıhhat ve İçtimai Muavenet Vekaleti'dir (1926-27) (Şekil 2). Yapı, 2019 yılından itibaren Ankara Valiliği olarak kullanılmaktadır (Önge, 2007:83). Aslanoğlu (2010:122) binayı "Türkiye'de uluslararası mimarlığın ilk temsilcisi ve dönemine göre Ankara'nın ilk modern görünüşlü mimarlık örneğidir." şeklinde tanımlamaktadır. Bodrum üzerine 3 katlı olan bina (Aslanoğlu, 2010:122) simetrik plan yerleşimi, merkezi koridor, merdiven konumlanışı-formu ve kolonların yerleşimi yönünden Avusturyalı mimar Josef Hoffmann tarafından tasarlanan Purkersdorf Sanatoryumu'yla (1904-05, Viyana) büyük ölçüde benzerlik taşımaktadır (Şekil 2 ve Şekil 3). Yapı, yönetimin yabancı mimarları seçme eğilimini gösteren ilk örnektir (Alpagut, 2012:77).

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Şekil 2. Sıhhat ve İçtimai Muavenet Vekaleti binası, 1. kat planı, 1926-27 (Aslanoğlu, 2010:123).



Şekil 3. Purkersdorf Sanatoryumu, yükseltilmiş zemin kat rekonstrüksiyon planı (Thun-Hohenstein, 2012:152'den şematize edilmiş plan: Köse, 2023:75).

Jost'un Ankara'daki bir diğer önemli eseri ise, aşağıda ayrıntılı olarak incelenecek olan Hıfzıssıhha Yerleşkesi'nin ilk yapısı Kimyahane ve Bakteriyoloji (aşı üretim) binasıdır (1927-32) (Goethe-Institut Ankara, 2010c).

Jost gibi sağlık alanında Ankara'da çalışan bir başka Avusturyalı mimar ise Robert Oerley'dir (1876-1945) (Aslanoğlu, 2009:78-79). Mimar, ressam ve zanaatkâr olan Oerley, 1892-96 yılları arasında Viyana Uygulamalı Sanatlar Okulu'nda (Kunstgewerbeschule) eğitim almıştır (Wien Geschichte Wiki, 2023). Viyana Secession[2] Binası'nın (1897-98) mimarı Joseph Maria Olbrich (1867-1908), binanın tasarım sürecinde Oerley ile iş birliği yapmıştır (Lægring, 2020:100). Kariyeri açısından büyük önem taşıyan ve Viyana Modernizmi'nin örneklerinden biri olan Luithlen Sanatoryumu'nu (Auersperg Sanatoryumu), 1908'de Viyana'da tasarlamıştır (Köse, 2023:153-154). 1907-39 yılları arasında Viyana Secession üyesi olan Oerley (Wien Geschichte Wiki, 2023), 1911-12 yılları arasında Viyana Secession Birliği'nin (The Vienna Secession, 2020) başkanlığını yapmıştır (Blau, 1999:426).

Sağlık yapılarını planlamaya başlayan Jost, Oerley'in gelişinden kısa bir süre sonra Türkiye'den ayrılmış, Oerley ise bu görevi tek başına üstlenmiştir (Ateş, 2011). Cumhuriyet'in erken döneminde Türkiye'ye gelen ilk yabancı mimarlar arasında yer alan (Tanyer, 2014:105) Oerley, 1928'de Ankara'da Sağlık Bakanlığı İnşaat Bürosu'nda çalışmaya başlamıştır (Tankut, 1990:75). Bu sırada "Avusturya Mimarlar Birliği" (*Zentralvereinigung der Architekten Österreichs*) başkan yardımcısıdır (Blau, 1999:273). Oerley, "İmar Müdürlüğü'nün yönetici konumundaki baş danışmanı" olarak Ankara'nın mimari ve şehircilik yapılaşmasına yoğunlaşmıştır (Goethe-Institut Ankara, 2010b). Ankara İmar Müdürlüğü Fen İşleri Bölümü yürütücülüğü yapmış (Tankut, 1990:75), 1929'da "Ankara İmar Müdürlüğü Başmimarı" olmuştur (Ateş, 2011). 1928-32 yılları arasında İstanbul Güzel Sanatlar Akademisi'nde ders vermiştir (Long, 2022:208).

Ankara'da 1928-33 yılları arasında özellikle Sağlık Bakanlığı için yapılar tasarlamış ve bu nedenle "Cumhuriyet döneminin sağlık yapıları mimarı" olarak tanınmıştır (Ateş, 2011). O dönemde başta Ankara olmak üzere Türkiye'de en çok yapıyı Oerley üretmiştir. Mimarın Ankara'daki yapılarından bazıları, Kızılay Meydanı'na adını veren (Tanyer, 2014:125) Kızılay Genel Müdürlüğü binası (Hilal-i Ahmer Müdiriyyeti) (1928-30), Refik Saydam Hıfzıssıhha Yerleşkesi (merkez bina, okul, lojman ve ahırlar) (1928-32), Ankara Ulus Hali (1930), Numune Hastanesi (1933) (Goethe-Institut Ankara, 2010b) ve Şehir Çarşısı'dır (1931-32) (Cengizkan, 2002:82). Çocuk Esirgeme Kurumu'nun Keçiören'deki Umay Pavyonu'na ek yapmıştır (Cengizkan ve Cengizkan, 2019:452). Ankara'nın yanı sıra İstanbul'da Tuzla İçmeleri Kaplıca Oteli'ni (1930-32) de tasarlamıştır (Ateş Can, 2014).

Cengizkan ve Cengizkan (2019:452), Oerley'i erken modernist olarak tanımlamakta ve Oerley'in başlıca ilkelerini "mantık (işlevsellik) ve sadelik (kullanım içi basitlik-sağlamlık)" olarak aktarmaktadır.

[2] 1897'de kurulan Viyana Secession Hareketi'nin üyeleri arasında Gustav Klimt (1862-1918), Josef Hoffmann, Joseph Maria Olbrich, Koloman Moser (1868-1918) ve Otto Wagner (1841-1918) yer almaktadır (Kuleli ve Pfeiffer-Taş, 2022:62; Pfeiffer-Taş ve Köse, 2024:129; Temel ve Pfeiffer-Taş, 2026:34).

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Ateş Can'a (2014:10) göre, Oerley'in I. Dünya Savaşı öncesi tasarımlarına Art Nouveau üslubu hâkimdir. Türkiye'deki tasarımlarının bir kısmı ise, "Kızıl Viyana (1919-1934) dönemi mimarisinin" (Pfeiffer-Taş ve Temel, 2024) etkisini yansıtmaktadır. Ankara'da olduğu süreyi de kapsayacak şekilde toplam 32 yıl Viyana Secession üyesi olan Oerley'in, akımın özelliklerini aşağıda da tartışılacağı üzere Türkiye'deki yapılarına taşıdığı görülmektedir.

Yerleşkedeki yapıların mimarları Oerley ve Jost'un yanı sıra, Kimyahane ve Bakteriyoloji binasının cephesinde yer alan "Hygieia" kabartmasının tasarımcısı da 1919-39 ve 1948-50 yılları arasında Viyana Secession'un üyesi olan Avusturyalı heykeltıraş Wilhelm Frass'tır (1886-1968) (Wien Geschichte Wiki, 2025).

Refik Saydam Hıfzıssıhha Yerleşkesi'nin Konumu

Ankara, yeni kurulan devletin ideolojik yaklaşımını kamu yapıları, kurumları ve kentsel mekânlar arasındaki sağlıklı ilişkiler üzerinden yansıtacak biçimde başkent olarak tasarlanmıştır. Bu süreçte "sağlık" kavramı, kelime anlamının yanı sıra Türk devriminin temellerine referans vermekte ve Kemalist projenin de düşünsel dayanaklarından birini oluşturmaktadır. Dönemin kent planında Sıhhiye Meydanı sağlık kavramıyla ilişkilendirilmiştir. Bu bağlamda Sıhhiye, öncü sağlık kurumlarının belirli bir plan çerçevesinde yoğunlukla yerleştirildiği kentsel bölgelerden biridir. 1920'ler ve 30'lar Ankara'sının çoğu kamu yapısında olduğu gibi, Sıhhiye'de yer alan binalar da genellikle yabancı mimarlar tarafından projelendirilmiştir (Kılınç, 2002a:124-125, 141).

Günümüzde Ankara'nın Çankaya ilçesi, Sağlık Mahallesi'nde yer alan, Jost ve Oerley tarafından tasarlanan Refik Saydam Hıfzıssıhha Yerleşkesi, Erken Cumhuriyet Dönemi'nde Sıhhiye bölgesine yakın bir konumda inşa edilen ilk yapılardan biridir. Yapı "kentsel ölçekte üretilmiş bir ideolojik söylemin en açık temsilcisi ve belki de Sıhhiye üzerinden yürütülebilecek bir Türk modernleşmesi tartışmasının en yalın dayanak noktası" olarak betimlenmektedir (Kılınç, 2002a:141-143). Aynı zamanda yerleşkenin sağlıklı kent ve sağlıklı toplum ilişkisinin en etkin üreticilerinden olduğu aktarılmaktadır. Jansen tarafından hazırlanan Ankara İmar Planı'nda da yer alan (Şekil 4) yerleşkede birçok yapı ve birim bulunmaktadır. Modern cihazların yer aldığı yerleşke, sağlık sektörünün Erken Cumhuriyet Dönemi'ndeki en önemli girişimlerindendir (Yılmaz ve Çügen, 2011).



Şekil 4. Refik Saydam Hıfzıssıhha Yerleşkesi'nin Ankara İmar Planı'nda konumu, 1928 (Architekturmuseum TU Berlin, t.y.)

Yerleşke, Kimya, Bakteriyoloji, İmmunbiyoloji ve Farmakoloji olmak üzere 4 şubeden oluşmaktadır (Gotschlich, 1938:9). Yerleşkede, Kimyahane ve Bakteriyoloji binası (1927-28, Jost), Merkez bina (İmmünobiyoloji (Serumhane) ve Farmakoloji binası) (1932-35, Oerley), Hıfzıssıhha Mektebi (1932-36, Oerley), İkametgâh Apartmanı (lojmanlar) (1930, Oerley), ahırlar (deney hayvanları ve karantina binası) ve idari bina (1932, Oerley) bulunmaktadır (Bulut, 2021:33; Yılmaz ve Çügen, 2011) (Şekil 5 ve Şekil 6). Aynı zamanda yerleşkede meteoroloji istasyonu, kütüphane ve özel konferans salonu da yer almaktadır (Gotschlich, 1938:10). Yerleşkede doğuya bakan L planlı gazino-kulüp ve apartmanlar bloğu ilerleyen yıllarda mimar Tulû Baytın (?-2020) tarafından tasarlanmıştır (Cengizkan, 2002:80) (Şekil 4). Kimyahane ve Bakteriyoloji binası, Merkez bina ve Hıfzıssıhha Mektebi, yerleşkenin merkezindeki

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dairesel avlunun çevresinde, yerleşkenin giriş aksına referans veren simetrik bir düzen içerisinde konumlanmış ve üç yönden "U" biçimli bir mekânsal kurgu oluşturmuştur (Şekil 5).



Şekil 5. Refik Saydam Hıfzıssıhha Yerleşkesi hava fotoğrafı, 1935 (Cangır, 2007:1404'ten yazarlar tarafından işlenmiştir).



Şekil 6A. Refik Saydam Hıfzıssıhha Yerleşkesi, 1938 (Koç Üniversitesi VEKAM Kütüphanesi ve Arşivi, 1938).

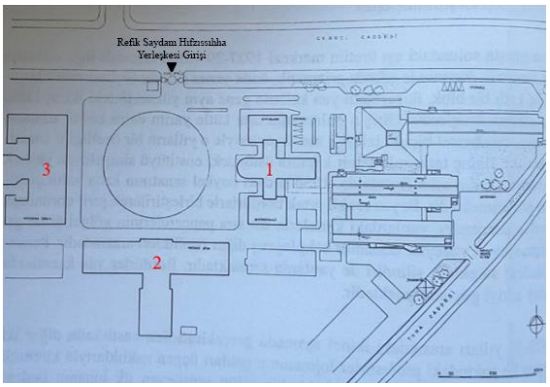


Şekil 6B. Refik Saydam Hıfzıssıhha Yerleşkesi, t.y. (Koç Üniversitesi VEKAM Kütüphanesi ve Arşivi, t.y.).

Refik Saydam Hıfzıssıhha Yerleşkesi Yapılarının Cephe, Plan ve İç Mekân Özellikleri

Kimyahane ve Bakteriyoloji binası hariç yerleşkedeki tüm yapıların planları 40.000 lira karşılığında Oerley'e çizdirilmiştir (Tokgöz, 1938:20). Kimyahane ve Bakteriyoloji binası, yerleşke kurulmadan önce, 1927-28 yılları arasında yerleşke sınırları içerisinde Jost tarafından tasarlanarak (Bulut, 2021:33, 36) "Redlich ve Berger Kardeşler (*Brüder Redlich und Berger*) İnşaat Şirketi (Viyana)" tarafından inşa edilmiştir (Cumhurbaşkanlığı Devlet Arşivleri Başkanlığı Cumhuriyet Arşivi, 1928). Kimyahane'de 1928 yılında, Bakteriyoloji'de ise 1931 yılında faaliyete başlanmıştır (Tokgöz, 1938:21). Ardından Merkez bina ve Hıfzıssıhha Mektebi eklenerek büyük bir orta avlunun üç yanına yerleştirilmiştir. Kimyahane ve Bakteriyoloji binası, yerleşkenin ana girişinin solunda bulunmaktadır (Aslanoğlu, 2010:209) (Şekil 7).

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1.Kimyahane ve Bakteriyoloji Binası

2. Merkez Bina (İmmünobiyoloji (Serumhane) ve Farmakoloji Binası)

3. Hıfzıssıhha Mektebi

Şekil 7. Refik Saydam Hıfzıssıhha Yerleşkesi, 1927-32 yerleşme planı, t.y. (Aslanoğlu, 2010:210'dan işlenmiştir).

Ankara Kültür ve Tabiat Varlıklarını Koruma Kurulu'nun 31.01.1989 tarih ve 656 sayılı karar raporu ekinde yerleşkedeki yapıların ayrıntılı tanımı şu şekilde yapılmıştır: "Yapılar, I. Ulusal Mimarlık Dönemi sonrası anlayışı içinde değerlendirilebilir, I. Ulusal Mimarlık Dönemi'ndeki temel noktalardan kaçınıldığı dikkati çekmektedir. İşleve göre biçimlendirilmiş geniş ve ferah mekânlar, yer yer görülen taş kaplamalar, geniş cam pencereli ve yoğun bezemelerden arınmış yalın cepheler yapılarda dikkati çeken özelliklerdir. Her üç yapıda hizmet binası olarak kullanılmaktadır ve yapılarda laboratuvarlar, çalışma odaları, toplantı salonları yer almaktadır." (Ankara Kültür ve Tabiat Varlıklarını Koruma Kurulu, 1989). Hıfzıssıhha Yerleşkesi'nde 1992 yılı itibarıyla teşkilat yapısında yapılan değişiklikler ve yenilikler sonucunda hizmetlerde bir gelişim yaşanmış ve yeni yapılar eklenmiştir. Bulut (2021:120-124), aynı yılın yerleşim durumunu tez çalışmasında ayrıntılı bir şekilde aktarmaktadır.

1930-40 yılları arasında Orta Avrupa etkisindeki uluslararası mimarlık biçimlerinde plan çözümlerinde cephe düzenleri, bir önceki Milli Mimarlık döneminde de olduğu gibi, genellikle simetrik olarak ele alınmaktadır. Yeni Ankara mimarisine yansıyan anıtsal özellikler sadece simetrik düzenlemelerden ibaret değildir. Anıtsal görünüşü etkileyen diğer özellikleri yatay, düz çatılı veya çatıları gizlenmiş prizmatik kütleler, ritmik, dikdörtgen pencere düzenlemeleri, genellikle ucuz olduğu için kullanılan ve "edelputz" diye adlandırılan çimentolu serpme sıva veya suni taş kullanılmasından ötürü, binaların almış olduğu gri renk, dekorasyondan arınmış mermer, pirinç, krom demir gibi yeni tip endüstriyel malzemelerin ve düz hatlı eşyanın, kare, dikdörtgen, daire veya yarım daire gibi yalın geometrik formlarla birlikte kullanılması olarak özetlenebilir (Yavuz, 1973:30). Hıfzıssıhha Yerleşkesi'nde yer alan yapılarda da bu özelliklerin birçoğuna yer verilmiştir. Yerleşkede yer alan yapıların cephe, plan ve iç mekân özellikleri aşağıda incelenmiştir.

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Kimyahane ve Bakteriyoloji Binası: 1927-28 yılları arasında Jost tarafından tasarlanarak inşa edilmiştir. İki bloktan oluşan binanın kuzey bloğunda Kimyahane, güney bloğunda ise Bakteriyoloji yer almaktadır (Bulut, 2021:46). Kimyahane ve Bakteriyoloji binası, önde yarım silindir ve arkada prizmatik biçimli uzantılara sahip simetrik üç katlı bir bloktan oluşmaktadır. Yerleşkedeki diğer yapılara göre farklı bir üsluba sahip olan binanın ön cephesindeki silindirik bölüm hariç, diğer kütlelerin üzerindeki az eğimli çatı, yükseltilmiş duvarların arkasına gizlenmiştir. Girişi içeren orta kütle dönemin karakteristik yarım silindir şekline ve aynı formdaki merdivene sahiptir. Çift kanatlı binanın ortasında bulunan yarım silindir biçimli çıkmanın ve beyaz renkli bordürlerle çerçevelenen yatay şerit pencerelerin güçlü bir Art Deco etkisi yarattığı aktarılmaktadır. Pencerelerin devamlılığı silindir çıkmayı yanlardan sarmakta, yan kanatlardaki bordürler ise yatay etkiyi kuvvetlendirmektedir (Aslanoğlu, 2010:209; Nicolai, 2011:29) (Şekil 8). Bu bağlamda yapı, yalın cephesi ve yatay şerit pencereleriyle modern mimarinin belirgin özelliklerini taşımaktadır (Aslanoğlu, 2009:73). Yapıda, Erken Cumhuriyet Dönemi'nde Ankara'da inşa edilen birçok örnekte olduğu gibi, gri serpme sıvalı yüzeylerin yanı sıra tuğla ve taş örgü ile betonarmenin beraber kullanımı görülmektedir (Aslanoğlu, 2010:209; Tunç ve Tunç, 2022:11). Oerley, kat planlarının sanayi ve yapı ustası olan Bruno Bauer'e ait olduğuna dair bir not geçmiş ve bu notta Jost hakkında şu sözleri söylemiştir: "Yapının dış görüntüsünden, bina tasarımını moda ve espri olarak görmekte olan Viyanalı genç mimar Theodor Jost sorumludur." (Nicolai, 2011:29).



Şekil 8A. Kimyahane ve Bakteriyoloji binasının batı (ön) cephesi, 1940 (Koç Üniversitesi VEKAM Kütüphanesi ve Arşivi, 1940).



Şekil 8B. Kimyahane ve Bakteriyoloji binası, 2025 (Şule Pfeiffer-Taş arşivi, 2025).

Binanın ön cephesinin orta bölümünde demir giriş kapısı üzerindeki dışbükey duvarda bir kabartma yer almaktadır. Bu kabartma, Avusturyalı heykeltıraş Wilhelm Frass'a ait kireçtaşından yapılmış, 7 metre yüksekliğindeki "Hygieia (Sağlık)" adlı eserdir (Frass ve Frass, 1932:29) (Şekil 9A). Kabartmanın sol alt köşesinde "1927 W. FRASS" yazısı bulunmaktadır (Yılmaz ve Çügen, 2011).

Antik Yunan mitolojisinde tıp tanrısı Asklepios ve kızı tanrıça Hygieia (Şekil 9B), MÖ 5. yüzyılda Asklepios kültünün ortaya çıkışından beri hekimlerle ilişkilendirilen ve koruyucu olarak tapınılan Greko-Romen dünyasının en bilinen tanrıları arasındadır (Beumer, 2016:5). Tanyer (2014:163) ise, kabartmayı "kadın atlet figürü" olarak betimlemektedir. Hygieia kabartması, bu binada olduğu gibi heykel ya da kabartma şeklinde Avrupa'da da kullanılmıştır. Kimyahane ve Bakteriyolojine binasında olduğu gibi Hollanda'da "Groningen Hijyen Laboratuvarı'nın (Laboratorium voor Hygiene 1883)" giriş kapısının üstünde de kabartma olarak yer almaktadır. Aynı zamanda İskoçya Edinburg'da ve Almanya'da Hamburg Borse'de de heykel olarak kullanılmıştır (Yılmaz ve Çügen, 2011). Ankara'nın modern yapılarını yurt dışına tanıtılmasında önemli rol oynayan "La Turquie Kémaliste" dergisinin "Ankara Construit" bölümüne ait iç kapakta yapıdaki Hygieia kabartmasına yer verilmiştir (Şekil 9C). Kabartmanın üzerine daha sonra cam sundurma eklenmiştir (Şekil 9D).

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Şekil 9A. Wilhelm Frass ve Hygieia kabartması (Frass ve Frass, 1932:29).



Şekil 9B. "The Hope Hygieia" heykeli (Strong, 1928:Plate IX).



Şekil 9C. Kimyahane ve Bakteriyoloji binası, Hygieia kabartması, t.y.

(La Turquie Kémaliste, 1936:25).



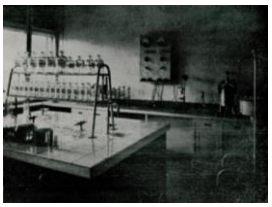
Şekil 9D. Kimyahane ve Bakteriyoloji binası, Hygieia kabartması, 2025 (Şule Pfeiffer-Taş arşivi, 2025).

Bakteriyoloji'nin özgün tasarım özellikleri, 1938 tarihli tanımlamalar aracılığıyla ortaya konulmaktadır: "Bakteriyoloji şubesi büyük kapıdan bahçeye girildiği zaman soldaki binanın yarısını işgal etmektedir. Bu kısım iki kat üzerindedir. Alt katta büyük buzdolabının bulunduğu oda ile Santirifüj odası, Anbar tâkim iki tularami tetkik taharriyat lâburatuarı vardır. […] Üst katta sekiz oda vardır." (Akan, 1938:44).

Kimyahane ve Bakteriyoloji binasının yüksekliği 53,31 metre, genişliği ise 47,80 metredir. Yapıda yer alan büyük koridorlar kuzey-güney doğrultusunda ana giriş eksenine dik olarak yerleştirilmiştir. Giriş holü yaklaşık 7 metre yüksekliğindedir. Yarım silindir şeklindeki çıkmanın üçüncü katındaki laboratuvarların pencereleri, giriş holünün "çatı pencereleri" olarak devam etmektedir. Koridorlar yüksek tavanlı laboratuvarlarla sonlanmaktadır. Laboratuvarlarda yer alan tezgâhlar beyaz seramiklerden ve demirden yapılmıştır (Şekil 10 ve Şekil 11). Büyük laboratuvarın girişinde tek ve çift kanatlı olmak üzere iki tip kapı yer almaktadır (Kılınç, 2002b:127; Yılmaz ve Çügen, 2011). Yarım silindir biçimli çıkma bölümde, alçak tavanlı ofisler bulunmaktadır. Bodrum katın ışık alması için zemin kat döşemesinin bazı bölümlerinde cam tuğla kullanılmıştır. Duvarlar, yerden yükseklikleri 2 metre olan pencerelerin seviyesine kadar beyaz seramikle kaplanmıştır. Çalışma tezgâhları pencerelerin bulunduğu duvarlara (Şekil 11) doğal aydınlatmadan en yüksek seviyede yararlanmak amacıyla yerleştirilmiştir (Avcı ve Memikoğlu, 2017:125-126, 129).



Şekil 10A. Kimyahane, 1936 (Aslan, 2005:72).



Şekil 10B. Kimyahane, t.y.

(Scheller, 1938:31).

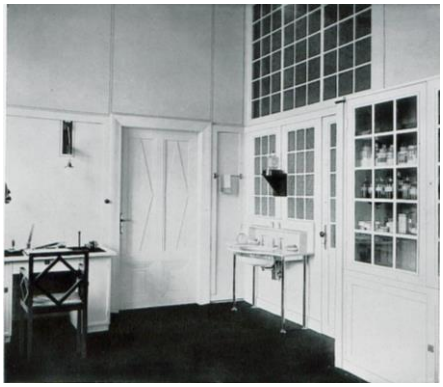


Şekil 11A. Bakteriyoloji, 1936 (Şule Pfeiffer-Taş arşivi).



Şekil 11B. Bakteriyoloji, 1936 (Aslan, 2005:93).

Kimyahane ve Bakteriyoloji binasında, duvarlarda ve kapı doğramalarında yoğun olarak kullanılan beyaz renk ile kare ve baklava dilimi şeklindeki geometrik formların Viyana yakınlarındaki Josef Hoffmann tasarımı olan Purkersdorf Sanatoryumu ile gösterdiği benzerlikler dikkat çekmektedir (Şekil 12 ve Şekil 13).



Şekil 12. Purkersdorf Sanatoryumu, muayene odası, 1906 (Bredt, 1906:430).



Şekil 13. Refik Saydam Hıfzıssıhha Yerleşkesi, t.y. (Aslan, 2005).

Purkersdorf Sanatoryumu'yla yine benzer bir özellik olarak her iki yapının da özgün tasarımında düz çatı kullanıldığı görülmektedir (Köse, 2023:131-132). Benzer bir değişimin Kimyahane ve Bakteriyoloji binasının teraslı çatısında da olduğu ve ilk hâline ilerleyen yıllarda kırma çatı ilave edildiği anlaşılmaktadır (Kılınç, 2002b:132). Çatı örtüsünde görülen bu değişimlerin öncesinde her iki yapının da özgün çatı tasarımında modernizmin özelliklerinden biri olarak karşımıza çıkan düz çatı formunun kullanıldığı gözlemlenmektedir.

Merkez Bina (İmmünobiyoloji (Serumhane) ve Farmakoloji Binası): Merkez bina (Şekil 14), 1932-35 yılları arasında Oerley tarafından tasarlanmış ve inşa edilmiştir. Bina, yerleşkenin giriş aksı boyunca uzanmakta ve merkez avlunun güneyinde yer almaktadır. "T formlu" (Şekil 5 ve Şekil 7) binada, betonarme karkas, tuğla ve taş yığma inşaat sistemi kullanılmıştır (Cengizkan, 2002:80).

Aynı yerleşkede yer almalarına rağmen, Merkez binanın mimarisi Kimyahane ve Bakteriyoloji binasının mimarisine göre hem farklı mimarlar tarafından tasarlanmış olması hem de geç tarihli oluşu nedeniyle farklılıklar göstermektedir. Daha işlevsel ve simetrik bir cephe tasarımına sahip olan Merkez binanın kuzey (ana giriş) cephesi, yerleşkenin merkezinde yer alan avluya yönelmektedir. Kuzey cephesinde her katta sağ kanatta 11 adet ve sol kanatta 11 adet olmak üzere 22 adet pencere yer almaktadır. Cephede bodrum katta kaba yontulu bosajlı kesme taş kullanılırken, zemin ve birinci kat edelputz sıvayla kaplanmıştır (Aslanoğlu, 2010:176). Bodrum katın doğal ışık alması için zemin kat yükseltilmiştir. Yapının ana girişi yapının ortak aksına konumlandırılmış ve iki kat yüksekliği boyunca geriye çekilmiştir. Zemin kata ana girişte yer alan 8 basamaklı merdivenle erişilmektedir. Merdivenlerin üzerinde geniş bir balkon yer almaktadır. Düşey yapısal girintilerle çerçevelenen ve korunaklı bir biçimde tasarlanan zemin ve birinci kat pencereleri, cephede hâkim olan yatay etkiye düşey bir vurgu kazandırmaktadır (Şekil 14). Oerley, Türkiye'de ve Viyana'da yaptığı bina tasarımlarında, modern mimarinin kübik yaklaşımının düz çatısını kullanmamıştır. Yapılarında genellikle çatı oyunlarına yer vermekte ve bu da cepheye hareketlilik kazandırmaktadır. Luithlen Sanatoryumu (Köse, 2023:153-155) hariç, yapıları kiremitli eğimli çatılara ve genellikle çatı pencerelerine sahiptir (Ateş, 2011; Ateş Can, 2014:10). Merkez bina ise kalın saçak kornişiyle sonlandırılmıştır ve üzerinde üçgen ışıklıkların bulunduğu kiremitli eğimli çatı yer almaktadır (Goethe-Institut Ankara, 2010a) (Şekil 14A).

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Şekil 14A. Merkez Bina, t.y. (Gotschlich, 1938:9).



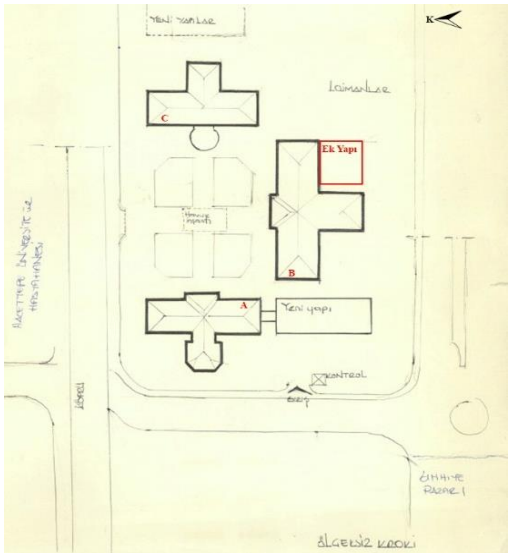
Şekil 14B. Merkez Bina, 2025 (Şule Pfeiffer-Taş arşivi, 2025).

Çatıdaki kademeli parapet duvarı ve bu duvarda yer alan yuvarlak pencere, simetrik cephe tasarımı, orta aksa konumlandırılan ana giriş ve düşey yuvalarda toplanan pencereler Oerley'in Kızılay Genel Müdürlüğü yapısıyla benzerlik göstermektedir (Cengizkan, 2002:77) (Şekil 15). Merkez binanın ve Hıfzıssıhha Mektebi'nin cephe tasarımları büyük ölçüde benzerlik göstermektedir.



Şekil 15. Kızılay Genel Müdürlüğü binası, 1933 (Cangır, 2007:1310).

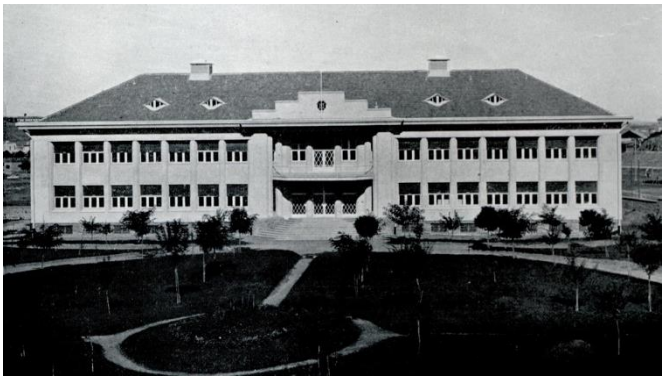
Binanın iç avluya bakan ön kütlesinin zemin katı, laboratuvar ve odalardan oluşmakta; merkezdeki merdiven yanından kütlenin uzantısı olan noktada, birleştirme işlemi olarak tuvaletler yer almaktadır (Cengizkan, 2002:80). Şekil 16'daki ölçeksiz krokide de görüldüğü gibi Merkez binaya (B) sonradan tek katlı bir yapı ilave edilmiştir (Ankara Kültür ve Tabiat Varlıklarını Koruma Kurulu, 1989).



Şekil 16. Yerleşkeye ait ölçeksiz kroki, t.y. (Ankara Kültür ve Tabiat Varlıklarını Koruma Kurulu, 1989'dan kırmızı renkle işaretlenmiştir.)

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Hıfzıssıhha Mektebi: Hıfzıssıhha Mektebi ile ilgili yasa 1928'de çıkmasına rağmen mektep, 1932-36 yılları arasında Oerley tarafından tasarlanıp inşa edilmiş ve Dr. Saydam tarafından 2 Kasım 1936'da açılmıştır (Dedeoğlu, 2001:468; Goethe-Institut Ankara, 2010a) (Şekil 17). Literatürde Aslanoğlu (2010:176) ve Cengizkan (2002:79) da yapının mimarının Oerley olduğunu aktarırken Ankara Kültür Varlıklarını Koruma Bölge Müdürlüğü Arşivi'nde, Hıfzıssıhha Mektebi'nin mimarı olarak V. Hüttig ismi geçmekte olup, Sözen (1984:215) de yapının Hüttig tarafından tasarlandığını belirtmektedir[3]. Yerleşkede en yüksek meblağ mektebin inşasına ayrılmıştır (Tokgöz, 1938:21). Yerleşkenin batısında yer alan mektep, Adnan Saygun Caddesi'ne paralel olarak konumlanmıştır. Bodrum katla birlikte üç katlı olan mektep, büyük bir avlu ile çerçevelenmekte ve "E formu" yapan simetrik bir düzenlemeye sahip kütlelerden oluşmaktadır (Goethe-Institut Ankara, 2010a; Soyşekerci, 2023:3789) (Şekil 5 ve Şekil 7). İki kat boyunca geriye çekilen orta akstaki giriş bölümünün önünde yer alan 8 basamaklı merdiven, sekizgen formun bir parçası gibi dışa doğru uzanmaktadır. Girişin üzerinde geniş bir balkon yer almaktadır. Cephelerde üst ve zemin kat pencereleri yapısal unsurların arasındaki ortak girintiler içine alınmıştır (Şekil 18). Dönemin strüktürel açıdan sağlam yapılarından olan mektebin döşeme ve duvarlarında betonarme kullanılmış, bodrum katı kaba yontulu bosajlı kesme taşla, diğer katlar ise edelputz sıvayla kaplanmıştır (Aslanoğlu, 2010:176; Goethe-Institut Ankara, 2010a). Hıfzıssıhha Mektebi'nde de Merkez binada olduğu gibi kalın bir saçak kornişiyle biten kütlelerin üzerinde kiremitle kaplı çatı, çatıda üçgen ışıklıklar ve ana giriş aksı hizasında çatıda yuvarlak pencereli kademeli parapet duvarı yer almaktadır (Cengizkan, 2002:77, 81; Goethe-Institut Ankara, 2010a) (Şekil 18).



Şekil 17. Hıfzıssıhha Mektebi, t.y. (La Turquie Kémaliste, 1934:3).



Şekil 18. Hıfzıssıhha Mektebi, doğu cephesi, 2025 (Şule Pfeiffer-Taş arşivi, 2025).

Yerleşkede yer alan yapılarda genellikle yalın malzemeler kullanılmıştır. Pencere boyutları mekânın işlevine ve tavan yüksekliğine bağlı olarak farklılık göstermektedir. Pencerelerde demir konstrüksiyonlu ahşap storlar yer almaktadır. Hıfzıssıhha Mektebi'nde de bu storlar kullanılmıştır (Şekil 19A). Ana girişteki demir kapı dışındaki diğer kapı ve pencere doğramaları ahşap malzemeden yapılmıştır. Bazı ahşap kapılara cam eklenmiştir (Yılmaz ve Çügen, 2011). Oerley'in tasarımlarındaki karakteristik özelliklerden biri pencerelerin formu ve yerleşim düzenidir. Benzer özelliklere sahip pencere ve kapı tasarımlarını hem Viyana'daki hem de Türkiye'deki yapılarında kullanmıştır (Ateş Can, 2014:11). Hıfzıssıhha Mektebi'nin girişi, Oerley'in yapılarını simgeleyen ve onları tanınır kılan (Cengizkan, 2002:81) baklava dilimli demir giriş kapılarıyla ve korkuluklarla vurgulanmaktadır. Mektebin giriş kapısında, kapının yanında bulunan pencerelerde ve birinci kat balkon kapısında baklava dilimli demir korkuluklar bulunmaktadır (Şekil 19B ve Şekil 19C). Baklava dilimli kapıları Ateş Can (2014:11), "elmas biçimli"; Aslanoğlu (2010:176) ise "lozanj biçimli" olarak ifade etmektedir. Bu form Oerley'in Numune Hastanesi, Kızılay Genel Müdürlüğü binası (Şekil 15) ve Tuzla İçmeleri Kaplıca Oteli (Şekil 20) yapılarının giriş bölümlerinde de görülmekte ve Oerley'in kapı tasarımlarını tipleştirmektedir (Aslanoğlu, 2010:176; Ateş, 2011; Cengizkan, 2002:81). Aynı zamanda Oerley, Viyana'da bulunan

[3] Aslanoğlu (2010:176), Ankara Kültür Varlıklarını Koruma Bölge Müdürlüğü Arşivi raporu ve Sözen (1984:215) tarafından yapının mimarına ilişkin bir kaynak verilmediği için teyit edilememiştir.

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George Washington-Hof konut kompleksindeki (1927-30) Akazienhof (Şekil 32) yapısının cephesinde de baklava dilimine yer vermiştir.

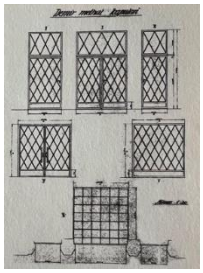


Şekil 19A. Hıfzıssıhha Mektebi, batı cephesi, t.y.

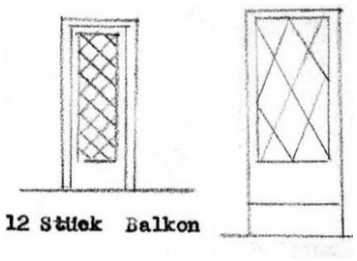
(Goethe-Institut Ankara, 2010a).



Şekil 19B. Hıfzıssıhha Mektebi kapı detayı, 2025 (Şule Pfeiffer-Taş arşivi, 2025).



Şekil 19C. Hıfzıssıhha Yerleşkesi metal kapı detayları (Cengizkan, 2002:83).



Şekil 20. Tuzla İçmeleri Kaplıca Oteli kapı detayları (Ateş Can, 2014:11).

Oerley'in bu kapı detayları, Avusturyalı mimar Hubert J. Gessner (1871-1943) tarafından Viyana'da tasarlanıp inşa edilen Reumannhof Belediye Sosyal Konutları'nda (1924-26) (Pfeiffer-Taş ve Temel, 2024) (Şekil 21) ve Hoffmann'ın Purkersdorf Sanatoryumu'nda (Köse, 2023) (Şekil 22) da görülmektedir.



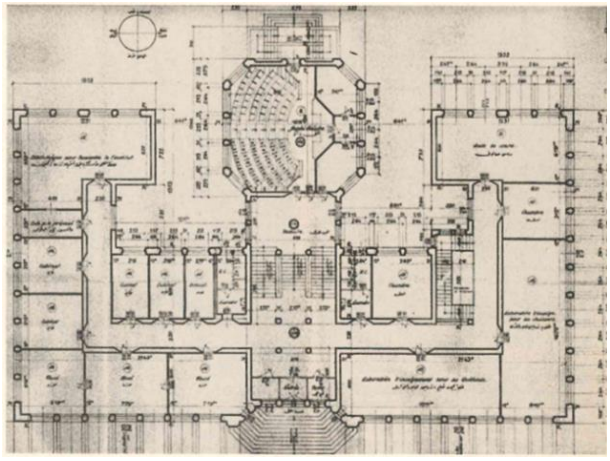
Şekil 21. Reumannhof Belediye Sosyal Konutları kapı detayları, 2022 (Şule Pfeiffer-Taş arşivi, 2022).



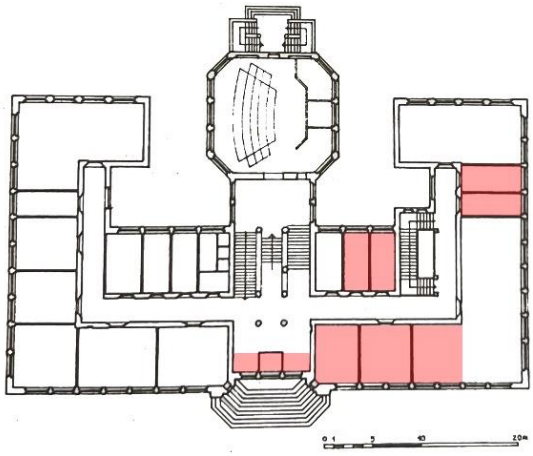
Şekil 22. Purkersdorf Sanatoryumu, yemek odası kapısı, 2022 (Şule Pfeiffer-Taş arşivi, 2022).

Hıfzıssıhha Mektebi'nde zemin katta laboratuvarlar ve derslikler koridorların etrafında düzenlenmiştir (Aslanoğlu, 2010:176) (Şekil 23). Şekil 23A ve Şekil 23B'deki zemin kat planlarına bakıldığında, kuzey kanattaki mekân sayısı ve mekân büyüklükleri farklılık göstermektedir. Şekil 23B'de yer alan zemin kat planının kesin tarihine ulaşılamadığından, Şekil 23A ile kronolojik bir sıralama yapılamamıştır. Bu nedenle planlar arasındaki farklılıkların yapının kullanım sürecinde gerçekleştirilen olası mekânsal düzenlemelerden kaynaklanmış olabileceği düşünülmektedir.

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Şekil 23A. Hıfzıssıhha Mektebi, zemin kat planı, 1929 (Cengizkan, 2002:87).



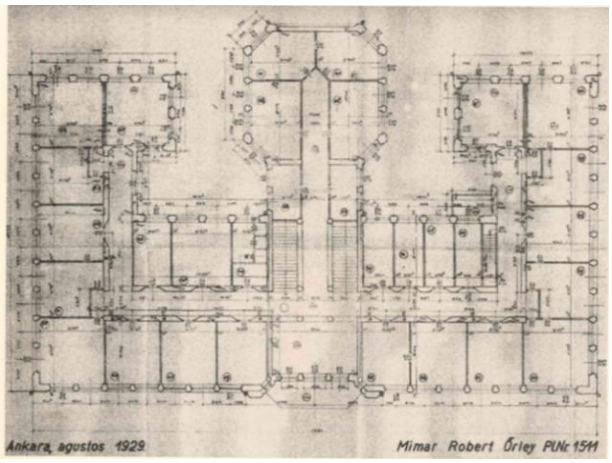
Şekil 23B. Hıfzıssıhha Mektebi, zemin kat planı, t.y.

(Merkez Hıfzıssıhha Enstitüsü Sağlık Okulu Arşivi'nden akt. Aslanoğlu, 2010:177'den kırmızı renkle işaretlenmiştir).

Zemin kattaki sekizgen planlı kanatta yer alan amfinin plan içindeki konumu, yapının mekânsal kurgusu açısından önem taşımaktadır. Amfi, Refik Saydam Hıfzıssıhha Yerleşkesi'nin iç avlusuna yönelmek yerine dış cepheye (günümüzde Ahmet Adnan Saygun Caddesi'ne) bakacak şekilde konumlandırılmıştır (Şekil 23 ve Şekil 24). Amfinin sağ ve sol kanatlara göre daha öne çekilmesi, doğal ışık ve havalandırma koşullarını iyileştirirken aynı zamanda yapının görüş mesafesini artırarak kentle görsel ve mekânsal ilişki kurmasına olanak tanımaktadır. Bunun yanı sıra doğrudan bağlantılı merdivenlerle dış mekâna erişim imkânı sağlamaktadır (Şekil 23). Birinci kat planında simetrik bir yerleşim gözlemlenmektedir (Şekil 25). Mektep, 1936-1983 ve 2003-2011 yılları arasında işlevini sürdürmüştür (Yıldırım, 2024:64).



Şekil 24. Refik Saydam Hıfzıssıhha Yerleşkesi, 2025 (Ankara Büyükşehir Belediyesi, İmar ve Şehircilik Dairesi Başkanlığı Arşivi, 2025).



Şekil 25. Hıfzıssıhha Mektebi, birinci kat planı, 1929 (Cengizkan, 2002:86).

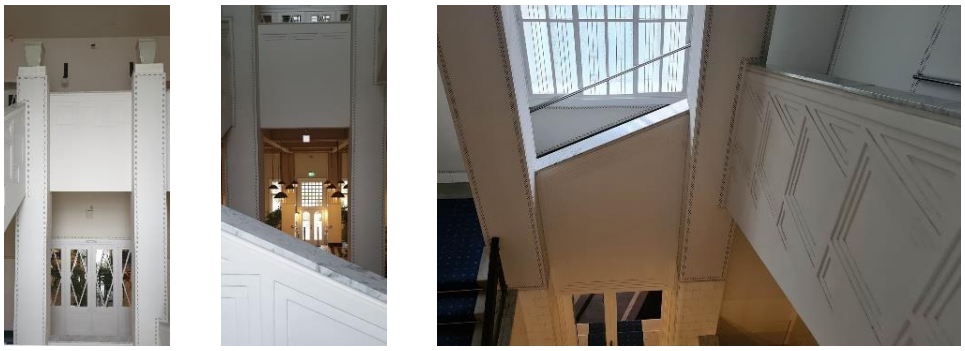
Bulaşıcı hastalıklar, karanlıkla, düzensizlikle, tozla, kirle, tarihsel ve geleneksel olanla eşleştirilmiştir. 1930'lu yılların modernist söyleminde yer alan sağlık, hijyen, aydınlık ve temizlik gibi dönemin gözde kavramlarına ve bu kavramların ortaya çıktığı mimarlık ürünlerine bakmak önemlidir (Yılmaz, 2016:503, 513). Erken Cumhuriyet Dönemi'nde ulusal üslup, işlevsellikten uzak bulunduğu için eleştirilmiş, mimaride sıklıkla tercih edilen süsleme ve oymalarda toz birikmesi, temizlik ve hijyen

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açısından uygun görülmeyerek olumsuz değerlendirilmiştir (Alpagut, 2010:129). Dolayısıyla yerleşke genelinde yer alan şubelerin iç mekân fotoğraflarına bakıldığında beyaz renk kullanımı, hijyenik, aydınlık, temiz ve yalın olma gibi unsurlar ön plana çıkmaktadır. Koridorlara hâkim olan beyaz renk ve yalınlık modern bir yapı izlenimi sunmaktadır (Şekil 26). Mektebin iç mekânında beyaz renk tercihi, modern tasarım anlayışı ve geometrik formların kullanımı, yapının Purkersdorf Sanatoryumu'nun iç mekân tasarımıyla gösterdiği benzerlikler arasında yer almaktadır (Şekil 27).



Şekil 26. Hıfzıssıhha Mektebi, t.y. (Aslan, 2005).



Şekil 27. Purkersdorf Sanatoryumu, 2022 (Şule Pfeiffer-Taş arşivi, 2022).

İkametgâh Apartmanı (Profesör Lojmanları/Kimya Apartmanı): İkametgâh Apartmanı (Şekil 5 ve Şekil 6), 1930'da Oerley tarafından tasarlanıp inşa edilmiştir. Erken Cumhuriyet Dönemi'nin ilk yıllarında düşük nüfus yoğunluğu nedeniyle apartman inşası sayısı azdır. Hıfzıssıhha Yerleşkesi çevresinin profesörlere ait evlere ayrıldığı aktarılmaktadır (Aslanoğlu, 2010:43-44). İkametgâh Apartmanı, Hıfzıssıhha Yerleşkesi içerisinde Ankara Sağlık Memurları Okulu'nun (günümüzde Hekimevi ve Türkiye Halk Sağlığı Kurumu Başkanlığı binası) arkasında ve Sıhhiye Çok Katlı Otopark binasının karşısında yer almaktadır. Günümüzde lojman olarak kullanılan No:39'daki bu yapı Kimya Apartmanı ismini almıştır (Ankara I Numaralı Kültür Varlıklarını Koruma Bölge Kurulu, 2013).

Ankara 1 Numaralı Kültür Varlıklarını Koruma Bölge Kurulu'nun 14.03.2013 gün ve 545 sayılı karar raporu ekinde yapının ayrıntılı tanımına yer verilmiştir. Burada yer alan tanıma göre İkametgâh Apartmanı, araları belli bir yükseklik üzeri demir parmaklıklı duvarlarla örülmüş bir bahçeyle çevrilidir. Apartmanın bahçesinde yeşil alanlar, otopark alanı ve bir kamelya bulunmaktadır. Bina, bodrum kat üzerine zemin+3 kat olacak şekilde inşa edilmiştir ve her katta 4 daire bulunmaktadır. İç avlulu bir yapıya sahip olan ve betonarme olarak inşa edilen yapının dış cephesinde dışa taşkın geniş saçaklar vardır. Cephede orta kısımlardaki ve köşelerdeki çıkıntılar yapıya hareketlilik kazandırmaktadır. Yapıda denizlikler cephe boyunca devam etmektedir (Ankara I Numaralı Kültür Varlıklarını Koruma Bölge Kurulu, 2013) (Şekil 28). Oerley'in Ankara'da bulunan Urgancı Abidin Bey Apartmanı'nda (1932) da aynı şekilde denizliklerin cephe boyunca devam ettiği görülmektedir (Şekil 29).

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Şekil 28A. İkametgâh Apartmanı, t.y. (Ankara I Numaralı Kültür Varlıklarını Koruma Bölge Kurulu, 2013).



Şekil 28B. İkametgâh Apartmanı (günümüzde Kimya Apartmanı), 2025 (Merve Köse arşivi, 2025).



Şekil 29. Urgancı Abidin Bey Apartmanı, 2025 (Merve Köse arşivi, 2025).

Ankara 1 Numaralı Kültür Varlıklarını Koruma Bölge Kurulu'nun 2013 tarihli raporunda yer alan bilgilere göre İkametgâh Apartmanı'nda biri diğerinden bağımsız iki ayrı giriş yer almakta olup, bu girişler düzgün kesme taş sövelerle çerçevelenmiş ve üçgen alınlıklı lentolarla vurgulanmıştır. Bodrum kat pencereleri demir parmaklıklıdır. Günümüzde tüm pencere doğramaları PVC malzeme ile yenilenmiş ve bir kısmı yine PVC jaluzi ile kapatılmıştır. Giriş cephesinde, zeminde kapının iki yanında dikdörtgen pencereler, yanlarda balkonlar, köşelerde ise üçgen formlu balkonlar bulunmaktadır. Üst katlarda da pencere ve balkon düzeni aynı hatta simetrik olarak devam etmektedir (Şekil 28). Binada katlar arası geçiş demir tırabzanlı beton merdivenlerle sağlanmaktadır. Daire giriş kapıları çift kanatlı ve ahşap malzemeden yapılmıştır. Evlerin içinde, uzun bir antre ve buraya açılan odalarla ıslak hacimler yer almaktadır. Tavan yükseklikleri yaklaşık 3,5 metre olan dairelerde özel bir dolap ya da mobilya benzeri düzenleme bulunmamaktadır (Ankara I Numaralı Kültür Varlıklarını Koruma Bölge Kurulu, 2013).

İkametgâh Apartmanı'nın (Şekil 30) yanı sıra, Oerley'in tasarladığı Avusturya'daki Hanusch-Hof (1923-25) (Şekil 31) (Cengizkan ve Cengizkan, 2019:453) ve George Washington-Hof konut kompleksinde yer alan (1927-30) Akazienhof (Şekil 32) yapılarında da yalın cephe tasarımı ve üçgen çıkma görülmektedir. Ayrıca Oerley ilerleyen yıllarda tasarladığı İstanbul'daki Tuzla İçmeleri Kaplıca Oteli (1930-32) yapısında da üçgen formlu balkonlara yer vermiştir (Şekil 33).



Şekil 30. İkametgâh Apartmanı (Günümüzde Kimya Apartmanı), 2025 (Merve Köse arşivi, 2025).



Şekil 31. Hanusch-Hof Konutları, Viyana, 1926 civarı (Wien Museum-Online Sammlung, t.y.).



Şekil 32. George Washington-Hof Akazienhof, t.y. (Das Rote Wien, t.y.).



Şekil 33. Tuzla İçmeleri Kaplıca Oteli, 1930'lar (Ateş Can, 2014:6).

İkametgâh Apartmanı'nın cephe tasarımında, 1919-34 yılları arasında inşa edilen Viyana konut tipolojilerinden etkilenildiği aktarılmaktadır (Cengizkan, 2002:81). O dönemde Viyana'da oldukça yaygın olan üçgen form kullanımı İkametgâh Apartmanı'nın güneybatı cephesinde de görülmektedir (Şekil 30). Benzer üçgen form kullanımı, Kızıl Viyana Dönemi'nde Avusturyalı mimarlar Gessner, Karl Ehn (1884-1957), Jaksch (1879-1970), Siegfried Theiss (1882-1963), Hans Clemens Holzmeister

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(1886-1983), Hermann Aichinger (1885-1962), Heinrich Schmid (1885-1949) ve Karl Krist (1883-1941)'in sosyal konut yapılarında da yer almaktadır. Gessner'in Metzleinstalerhof (1923-24) (Şekil 34A) ve Reumannhof Belediye Sosyal Konutları (Şekil 34B) ile Ehn'in Szidzinahof (1925) (Şekil 34C) yapılarında hem üçgen formlu pencereli çıkma hem de üçgen balkon kullanımına yer verilmiştir. Buna karşılık Holzmeister'in Blathof (1924) (Şekil 34D) yapısında yalnızca üçgen formlu pencereli çıkma görülmektedir. Reumannhof Belediye Sosyal Konutları'ndaki üçgen formlu pencereli çıkmalar, konutların doğu ve batı yönlerinden gün ışığından daha etkin bir şekilde yararlanması amacıyla tasarlanmıştır (Pfeiffer-Taş ve Temel, 2024:58).



Şekil 34A. Metzleinstalerhof, 1924 (Gessner, 1924:10).



Şekil 34B. Reumannhof Belediye Sosyal Konutları, 2022 (Şule Pfeiffer-Taş arşivi, 2022).



Şekil 34C. Szidzinahof, t.y. (Austria Sites, 2025).

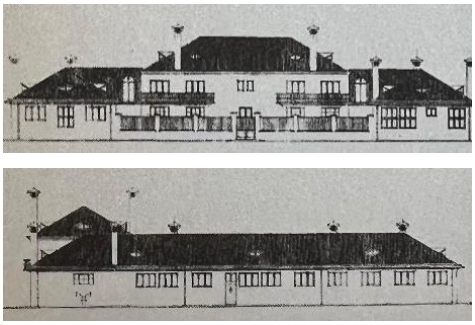


Şekil 34D. Blathof, 1925 (Blau, 1999:385).

Merkez bina ve Hıfzıssıhha Mektebi'nin yanı sıra İkametgâh Apartmanı ve ahırlar (deney hayvanları ve karantina binası) da üçgen ışıklıklı kiremit kaplı eğimli çatıya sahiptir. Dik çatılı, üç kollu, ortası avlu, yan cepheleri tek katlı ve orta cephesi iki katlı olan ahırlar (Şekil 6B ve Şekil 35), 1932'de Oerley tarafından tasarlanıp inşa edilmiş (Aslanoğlu, 2010:209; Cengizkan, 2002:81-82) ve 1968'de Esenboğa Serum Çiftliği'nin faaliyete geçmesinin ardından yıkılmıştır (Bulut, 2021:120).



Şekil 35A. Ahır ve idari binası, t.y. (Baecher, 1938:73).

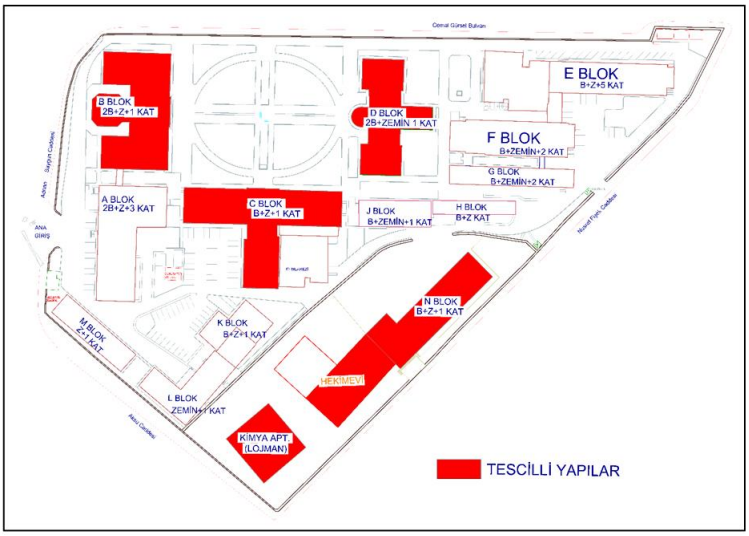


Şekil 35B. Ahırlar, 1932 (Cengizkan, 2002:89).

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Günümüzde Refik Saydam Hıfzıssıhha Yerleşkesi: Görevde bulunduğu süre boyunca sağlık alanına önemli katkılar sunan Dr. Saydam'ın 1942'de vefatının ardından, TBMM, "10 Ağustos 1942 gün ve 4288 sayılı yasa ile Merkez Hıfzıssıhha Müessesesi'ne T.C. Refik Saydam Merkez Hıfzıssıhha Müessesesi" adını vermiştir (Aksakal, 2017:227). 14 Aralık 1983 tarihli ve 181 sayılı Kanun'un Geçici Madde 6'sına göre "Refik Saydam Merkez Hıfzıssıhha Müessesesi'nin adı Refik Saydam Hıfzıssıhha Merkezi Başkanlığı" olarak değiştirilmiştir (Sağlık Bakanlığı, 2025a). Aynı yıl Hıfzıssıhha Mektebi'ndeki personel ve uzmanlar farklı illere gönderilerek mektep kapatılmıştır (Dedeoğlu, 2001:469). 1999'da yerleşkenin temel işlevi olan aşı üretim tesisleri kapatılmış, Bakanlığa bağlı olan "Türkiye Halk Sağlığı Kurumu'nun" alt kurumu hâline getirilmiş ve 2017'de adı "T.C. Halk Sağlığı Genel Müdürlüğü" olarak değiştirilmiştir. Böylece 89 yıldır faaliyet gösteren "Refik Saydam Hıfzıssıhha Merkezi Başkanlığı" kapatılmıştır (Bulut, 2021:150).

Hıfzıssıhha Mektebi (B Blok) ve Kimyahane ve Bakteriyoloji binası (D Blok), Erken Cumhuriyet Dönemi yapılarından olması nedeniyle, Ankara Kültür ve Tabiat Varlıklarını Koruma Kurulu'nun 31.01.1989 tarih ve 656 sayılı kararıyla tescillenmiş ve 1. grup korunması gereken kültür varlığı olarak belirlenmiştir. Eski adı Merkez Bina (İmmünobiyoloji (Serumhane) ve Farmakoloji binası) olan Türkiye Halk Sağlığı Kurum Başkanlığı binası (C Blok), Ankara 1 Numaralı Kültür Varlıklarını Koruma Bölge Kurulu'nun 01.10.2015 tarih ve 2696 sayılı kararıyla tescillenmiş ve 1. grup koruma statüsü kapsamına alınmıştır. Eski adı Ankara Sağlık Memurları Okulu olan Hekimevi ve Türkiye Halk Sağlığı Kurumu Başkanlığı binası (N Blok), sonradan eklenen bölümler hariç olmak üzere, Ankara 1 Numaralı Kültür Varlıklarını Koruma Bölge Kurulu'nun 01.10.2015 tarih ve 2696 sayılı kararıyla tescillenmiştir ve 1. grup koruma statüsündedir. Son olarak, Kimya Apartmanı (İkametgâh Apartmanı), Ankara 1 Numaralı Kültür Varlıklarını Koruma Bölge Kurulu'nun 14.03.2013 tarih ve 545 sayılı kararıyla tescil edilmiş ve 2. grup koruma statüsüne alınmıştır (Ankara Büyükşehir Belediyesi, İmar ve Şehircilik Dairesi Başkanlığı Arşivi, 2025:12) (Şekil 36). T.C. Sağlık Bakanlığı Sağlığın Geliştirilmesi Genel Müdürlüğü tarafından, 22 Mayıs 2025'te Ankara'da Kimyahane ve Bakteriyoloji binasının Sağlık Mirası Müzesi'ne dönüştürülmesi için "Bilgi ve Deneyimin Işığında Sağlık Mirası Müzesi Çalıştayı" yapılmıştır (Sağlık Bakanlığı, 2025b).



Şekil 36. Yerleşkedeki tescilli yapılar (Ankara Büyükşehir Belediyesi, İmar ve Şehircilik Dairesi Başkanlığı Arşivi, 2025:13).

DEĞERLENDİRME VE SONUÇ

Erken Cumhuriyet Dönemi'nde Türkiye'nin modern ve çağdaş bir ulus-devlet olarak konumlandırılması, Cumhuriyet ideolojisinin topluma yayılması ve uluslararası ölçekte modern ve sağlıklı bir ülke algısı oluşturulması temel hedefler arasında yer almıştır. Bu bağlamda, başkent Ankara'da Avusturyalı mimarlar Theodor Jost ve Robert Oerley tarafından tasarlanan Refik Saydam Hıfzıssıhha Yerleşkesi hem dönemin sağlık politikalarının hem de modern mimarlık anlayışının simgesel bir temsilini sunmaktadır. Yerleşke, dönemin bulaşıcı hastalıklarıyla mücadelede ve aşı ile

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serum konusunda yurt dışına bağımlılığı azaltmada önemli bir rol oynayarak ülkenin kendi kendine yetebilen bir yapıya kavuşmasına hizmet etmiştir. Bu yönüyle yerleşke, mimarlık, sağlık ve ideoloji üçgeninin somutlaştığı önemli bir Erken Cumhuriyet Dönemi yapısı olarak değerlendirilebilir.

Refik Saydam Hıfzıssıhha Yerleşkesi, literatürde genellikle tekil yapı ölçeğinde ele alınmıştır. Bu nedenle, yerleşkenin bütüncül bir yaklaşımla incelenmesi bu çalışmanın temel katkılarından birini oluşturmaktadır. Yerleşke sınırları içerisinde yer almalarına karşın, Jost tarafından tasarlanan Kimyahane ve Bakteriyoloji binası, Oerley'in tasarladığı Merkez bina, Hıfzıssıhha Mektebi ve İkametgâh Apartmanı ile karşılaştırıldığında belirgin mimari farklılıklar sergilemektedir. Bu farklılıklar, yapıların farklı mimarlar tarafından tasarlanmış olmasının yanı sıra, Kimyahane ve Bakteriyoloji binasının daha erken bir tarihte inşa edilmiş olmasıyla da ilişkilendirilebilir. Oerley'in tasarladığı yapılarda ortak olarak gözlemlenen çatıdaki kademeli parapet duvarı, parapet üzerinde yer alan yuvarlak pencere açıklığı, simetrik cephe kurgusu, orta aksa yerleştirilen vurgulu ana giriş, düşey yuvalar içerisinde gruplanmış pencere düzeni ve cephe boyunca süreklilik gösteren denizlikler, mimarın benimsediği tutarlı ve tekrarlayan bir tasarım anlayışına işaret etmektedir. Bu ortak mimari ögeler, Oerley'in Viyana Modernizmi'nin yalın, işlevsel ve simetriye dayalı mimari yaklaşımını Ankara bağlamında yeniden yorumladığını göstermektedir.

Yerleşkede yer alan Kimyahane ve Bakteriyoloji binası, Merkez bina, Hıfzıssıhha Mektebi ve İkametgâh Apartmanı'nda gözlemlenen yalın cephe düzeni, doğal ışığın etkin kullanımı, hijyen odaklı mekân kurgusu, kolay temizlenebilir, beyaz renk ağırlıklı ve yalın malzemelerle tasarlanan iç mekânlar ve sıklıkla tekrar eden baklava dilimi deseni, Viyana Modernizmi'nin özellikleriyle benzerlikler göstermektedir. Söz konusu yapılar, Viyana Modernizmi'nin üç farklı işlevsel yaklaşımına ait etkileri aynı yerleşke sınırlarında bir arada barındırmaları bakımından önem taşımaktadır. Hıfzıssıhha Mektebi'nin iç mekânlarında beyaz renk tercihi, modern tasarım anlayışı ve geometrik formların kullanımı, Josef Hoffmann tarafından Viyana yakınlarında tasarlanan Purkersdorf Sanatoryumu'nun (1904-05) iç mekân tasarımıyla doğrudan benzerlikler göstermektedir. Kimyahane ve Bakteriyoloji binası ile Purkersdorf Sanatoryumu'nun özgün tasarımlarında düz çatı formunun tercih edilmiş olması, her iki yapının da modern mimarlığın temel ilkeleri doğrultusunda ele alındığını göstermektedir. Ayrıca, yerleşkenin yeşil alan tasarımının da Purkersdorf Sanatoryumu'yla benzerlikler taşıdığı tespit edilmiştir. İkametgâh Apartmanı'nda görülen sade cephe tasarımı, üçgen formlu balkonlar ve cephe boyunca uzanan denizlikler ise Viyana Modernizmi dönemi sosyal konut mimarisiyle doğrudan biçimsel ilişkiler kurmaktadır.

Bu çalışma, Erken Cumhuriyet Dönemi'nde Refik Saydam Hıfzıssıhha Yerleşkesi yapılarında Viyana etkisini ve Avusturyalı mimarların Ankara'ya taşıdığı tasarım yaklaşımlarını ortaya koymaktadır. Çalışmanın söz konusu dönemde Ankara mimarisinde Viyana ile kurulan mimari etkileşimlerin okunabilmesine yönelik önemli bir örnek olduğu düşünülmektedir.

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ETHICAL ISSUES IN TECHNOLOGY AND NEW BEST PRACTICES

A Lifecycle Governance Framework for Responsible Innovation

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ABSTRACT

The rapid diffusion of digital technologies, artificial intelligence (AI), and data-driven systems is reshaping social, political, educational, and professional life. Alongside gains in efficiency, personalization, and productivity, these technologies create ethical risks involving discrimination, opacity, weakened accountability, privacy loss, surveillance, manipulation, environmental burden, and unequal access. This conceptual paper develops an interdisciplinary analysis grounded in applied ethics, political theory, professional ethics, data protection, and responsible-innovation scholarship. It asks how technically embedded design choices shape fairness, transparency, human agency, accountability, dignity, and ecological sustainability, and how institutions can convert high-level ethical principles into operational controls. The study uses an integrative narrative review and normative synthesis of academic literature, international standards, and major governance instruments, including UNESCO's Recommendation on the Ethics of Artificial Intelligence, the OECD AI Principles, the NIST AI Risk Management Framework, and the European Union Artificial Intelligence Act. The analysis identifies a recurring implementation gap: organizations often publish ethical commitments without assigning decision rights, documenting evidence, auditing outcomes, or creating accessible routes for challenge and remedy. To address this gap, the paper proposes a lifecycle governance framework organized around seven practices: risk classification, stakeholder participation, data and model governance, ethical impact assessment, independent review, continuous monitoring, and incident response with remedy. A university implementation model is presented because higher education institutions simultaneously develop, procure, teach, research, and deploy AI. The paper concludes that responsible innovation requires ethics to function as an auditable institutional capability rather than as a late-stage compliance statement. Human rights, social equity, and planetary well-being should be treated as design constraints throughout the technology lifecycle.

Keywords: artificial intelligence ethics; algorithmic bias; data privacy; digital governance; professional ethics; human-centered design; environmental ethics; responsible innovation

1. Introduction

Digital systems increasingly mediate access to education, employment, finance, health care, public services, information, and political participation. Decisions once made through visible organizational procedures may now be influenced or executed by predictive models, ranking systems, recommendation engines, biometric tools, and generative AI. These systems can expand capability and reduce administrative burdens, but they can also distribute opportunities and harms at scale. Because the relevant choices are embedded in datasets, objectives, interfaces, thresholds, and procurement contracts, technological systems are not ethically neutral instruments. They embody assumptions about what should be measured, optimized, tolerated, and ignored.

The central problem is therefore not whether technology is beneficial or harmful in the abstract. The problem is how benefits, risks, power, and responsibility are distributed across a system's lifecycle. An accurate model can still be unjust if the decision context is illegitimate; a transparent system can still be coercive; and a privacy notice can be formally valid while meaningful consent is absent. Ethical

evaluation must connect technical performance with institutional purpose, social context, fundamental rights, professional duties, and environmental consequences.

Recent governance initiatives reflect this socio-technical understanding. UNESCO (2021) places human dignity, rights, well-being, environmental protection, transparency, fairness, and human oversight at the center of AI ethics. The OECD AI Principles, updated in 2024, connect trustworthy AI with human rights, democratic values, robustness, transparency, and accountability (OECD, 2024). NIST's AI Risk Management Framework organizes institutional practice through the functions Govern, Map, Measure, and Manage (Tabassi, 2023). The European Union Artificial Intelligence Act adopts a risk-based legal framework and establishes obligations for specified high-risk uses (European Union, 2024). Together, these instruments move the debate from voluntary aspiration toward structured governance, yet implementation remains uneven.

This paper contributes by integrating the principal ethical problem areas and translating them into a practical lifecycle framework, with specific attention to universities. It addresses three questions: (1) Which ethical risks recur across contemporary data-driven technologies? (2) Why do principle-based ethics programs frequently fail to prevent harm? (3) Which institutional practices can make responsible innovation concrete, reviewable, and capable of learning? The argument is that ethics must be built into organizational routines, technical documentation, decision rights, and mechanisms for remedy—not added as an isolated approval at the end of development.

2. Method and Scope

The study adopts an integrative narrative review and normative policy-analysis approach. This method is appropriate because the research problem spans empirical computer science, philosophy, law, public policy, organizational governance, information studies, and environmental research. Rather than estimating a pooled effect, the paper synthesizes recurring concepts, documented harms, and governance responses across heterogeneous sources.

Sources were selected purposively according to four criteria: foundational relevance to technology ethics; empirical or conceptual influence in debates on bias, privacy, accountability, surveillance, labor, or environmental impact; institutional authority; and practical usefulness for lifecycle governance. The corpus includes peer-reviewed research, scholarly books, and primary governance instruments from UNESCO, the OECD, NIST, and the European Union. The synthesis proceeded in three stages: ethical risks were grouped into thematic domains; cross-cutting governance failures were identified; and the resulting findings were translated into operational practices for institutions.

This is a conceptual paper and does not claim systematic-review completeness or present new empirical data. Its recommendations are reasoned propositions grounded in the reviewed evidence and standards. The approach also recognizes that legal obligations differ by jurisdiction. Accordingly, the proposed framework is not a substitute for legal advice; it is an organizational architecture that should be mapped to applicable data protection, consumer protection, labor, intellectual property, sectoral, and AI regulation.

3. Ethical Foundations for Technology Governance

3.1 Consequences, duties, and justice

Consequential reasoning asks whether a system's benefits justify its foreseeable harms and whether less harmful alternatives exist. Deontological approaches emphasize duties and rights that cannot be traded away merely because an intervention is efficient. Justice-oriented theories examine how benefits, burdens, and opportunities are distributed, with special attention to groups that have historically had less power. These perspectives are complementary: aggregate utility cannot excuse discrimination, while formal equality may be insufficient where existing structural disadvantage shapes data and outcomes.

3.2 Human dignity, autonomy, and capability

Human dignity requires people to be treated as persons rather than as data points or targets of optimization. Autonomy involves meaningful opportunities to understand, choose, refuse, and contest. In digital environments, formal consent often fails because services are indispensable, interfaces are

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manipulative, or data practices are too complex to evaluate. A capability perspective broadens analysis from nominal access to whether people can actually use technology to pursue valued goals. Accessibility, digital literacy, language, affordability, and institutional support therefore become ethical design requirements.

3.3 Relational and professional responsibility

Responsibility is distributed across designers, data scientists, managers, vendors, deployers, regulators, and users. Distributed responsibility must not become diluted responsibility. Professional ethics requires actors to anticipate foreseeable misuse, disclose limitations, preserve competence, protect confidentiality, and escalate serious risks. Institutions must specify who has authority to approve, pause, modify, or retire a system and must protect employees and students who report concerns.

3.4 The socio-technical perspective

Fairness and safety are properties of systems-in-context, not merely of models. Selbst et al. (2019) warn that abstracting a technical artifact from its social setting can produce solutions that appear mathematically fair while preserving institutional injustice. Ethical review must therefore include the organizational process, human decision-makers, incentives, affected populations, feedback loops, and alternatives—including the option not to automate.

4. Core Ethical Issues

4.1 Algorithmic bias and discrimination

Algorithmic bias can arise from historical inequality, unrepresentative samples, measurement choices, labels that act as biased proxies, optimization objectives, and differences between development and deployment contexts. Barocas and Selbst (2016) demonstrate how apparently neutral data practices may generate disparate impact. Buolamwini and Gebru (2018) empirically found substantial intersectional performance disparities in commercial gender-classification systems, illustrating why aggregate accuracy can conceal unequal error rates.

Fairness cannot be reduced to a single universal metric. Statistical definitions may conflict, and the appropriate standard depends on the decision, affected rights, baseline inequality, and consequences of errors. A robust process begins by defining the relevant harm; examining subgroup performance and data provenance; involving affected stakeholders; testing alternative designs; and documenting why a selected criterion is appropriate. Monitoring is necessary because models, populations, and institutional practices change after deployment.

4.2 Opacity, explainability, and contestability

Complex models and fragmented supply chains can make it difficult to know how a decision was produced or who is accountable. Opacity may be technical, organizational, or strategic. Explainability should therefore be matched to audience and purpose: developers need diagnostic information; operators need limitations and escalation rules; affected persons need an intelligible account of the decision and a meaningful route to challenge it; auditors need evidence and access sufficient to test claims.

Transparency alone is not accountability. Publishing a model card or general description is useful only if responsible actors can be identified and outcomes can be corrected. Contestability is the bridge between explanation and justice. High-impact decisions should include notice of automation, accessible review by a competent person, protection from retaliation, and timely correction or remedy.

4.3 Privacy, surveillance, and civil liberties

Data-intensive systems encourage collection beyond the original purpose and create incentives for secondary use. Nissenbaum's (2010) theory of contextual integrity shows that privacy depends on appropriate information flows, not merely secrecy. Solove (2006) similarly describes privacy as a family of problems including collection, processing, dissemination, and invasion. Ethical data governance should apply purpose limitation, minimization, proportionality, security, retention controls, and meaningful participation.

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Surveillance can chill expression and association even when no adverse decision is recorded (Richards, 2013). Biometric monitoring, remote proctoring, workplace analytics, and location tracking deserve heightened scrutiny because power is unequal and opting out may be unrealistic. Institutions must ask whether monitoring is necessary, whether a less intrusive alternative exists, who can access the data, how long they are retained, and whether individuals can obtain review and redress.

4.4 Manipulation and the monetization of attention

Digital platforms frequently optimize for engagement because attention can be converted into advertising revenue, behavioral data, or market power. Recommendation and interface systems may exploit cognitive vulnerabilities through endless feeds, variable rewards, dark patterns, and hyper-personalized persuasion. Zuboff (2019) situates these practices within surveillance capitalism, while broader digital-ethics research highlights threats to autonomy and democratic deliberation.

The ethical response is not limited to disclosure. Product teams should prohibit deceptive design, assess risks to children and vulnerable users, provide meaningful controls, limit sensitive targeting, and measure well-being and informational quality alongside engagement. Governance must align incentives so that teams are not rewarded exclusively for time-on-platform or conversion.

4.5 Accountability gaps and automated decision-making

Automation can create a moral crumple zone in which front-line staff or users bear blame for failures generated by system design and organizational policy. Conversely, nominal human oversight may be ineffective when reviewers lack time, expertise, authority, or access to contrary evidence. Meaningful human control requires defined decision rights, training, workload, documentation, and the practical ability to override the system.

Accountability should attach to functions rather than vague collective responsibility. The system owner is accountable for purpose and resources; data stewards for provenance and access; developers for documented testing; domain experts for contextual validity; independent reviewers for challenge; senior leadership for risk acceptance; and incident teams for response and remedy. Vendors should not be permitted to use trade secrecy to block essential audit and due-process requirements.

4.6 Labor, professional judgment, and inequality

AI can augment professional work, but it can also deskill workers, intensify monitoring, shift risk to contractors, and obscure unpaid data labor. Automated scheduling and performance systems may treat efficiency as the sole objective while ignoring health, care obligations, and professional discretion. Responsible deployment requires worker participation, assessment of job quality and workload, training, and explicit rules preventing punitive use of unreliable inferences.

The digital divide is not simply a lack of connectivity. It includes affordability, device quality, accessibility, language, skills, institutional support, and the ability to influence system design. Systems that assume stable broadband, high literacy, or a specific language can exclude people even when nominal access exists. Equity assessment should therefore examine both access and outcomes.

4.7 Environmental and ecosystem ethics

Large-scale computing consumes energy, water, minerals, and hardware, and generates electronic waste. Training is only one component; repeated inference, data-center construction, cooling, network use, and device replacement also matter. Strubell et al. (2019) and Henderson et al. (2020) helped establish the need to report computational and carbon costs. Environmental claims should be based on lifecycle evidence rather than isolated efficiency improvements.

Planetary well-being should be a design constraint. Teams should compare smaller or task-specific models, reuse existing models where appropriate, optimize inference, schedule workloads around lower-carbon energy, measure water and energy use, extend hardware life, and include rebound effects. Environmental burdens must also be assessed distributively because extraction, data centers, and waste often affect communities that receive fewer benefits.

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5. Why Ethics Programs Fail

Many organizations have adopted principle statements, yet principles can remain too abstract to guide contested decisions. Terms such as fairness, transparency, and human oversight are interpreted differently, and teams facing delivery pressure may lack methods, authority, or evidence requirements. Ethics washing occurs when public commitments are disconnected from budgets, incentives, procurement, and accountability.

A second failure is the checklist mentality. A one-time assessment cannot capture changes in data, users, models, vendors, or social context. Documentation may become a ritual if it records compliance without testing outcomes. A third failure is organizational fragmentation: privacy, security, legal, procurement, accessibility, sustainability, and academic governance may review the same system independently, leaving cross-cutting risks unowned.

Finally, organizations often focus on model performance while neglecting purpose. A system can be accurate and still unnecessary, disproportionate, or incompatible with rights. Good governance begins with legitimacy: What problem is being solved? Who defined it? Who benefits? Who bears risk? What non-technical alternatives exist? What evidence would justify stopping the project?

6. A Lifecycle Framework for Responsible Innovation

The proposed Ethical Technology Lifecycle Framework (ETLF) translates values into seven linked governance practices. It is compatible with the NIST functions Govern, Map, Measure, and Manage, and can be aligned with legal duties under the EU AI Act and data-protection law. Its distinctive emphasis is on participation, decision rights, and remedy.

Practice	Core question	Required evidence	Decision gate
1. Classify	How serious and reversible are the potential harms?	Use case, affected groups, rights, risk tier, alternatives	Proceed, redesign, or prohibit
2. Participate	Whose knowledge and interests are missing?	Stakeholder map, consultation record, disagreements	Purpose and requirements approved
3. Govern data/model	Are inputs, objectives, and limitations defensible?	Data provenance, quality, access, model/system cards	Build or procurement approval
4. Assess impact	What harms may occur and how will they be controlled?	Ethical/fundamental-rights, privacy, security, accessibility, environmental assessments	Pre-deployment authorization
5. Review independently	Can claims withstand informed challenge?	Audit tests, red-team results, conflict disclosures	Conditional or final approval
6. Monitor	Are real outcomes acceptable across groups and time?	Logs, subgroup metrics, drift, complaints, resource use	Continue, modify, pause, or retire
7. Respond/remedy	Can harm be reported, corrected, and learned from?	Incident register, notification, appeal, correction, lessons	Closure and governance update

6.1 Risk classification and legitimate purpose

Classify systems before procurement or development using severity, scale, reversibility, vulnerability, rights affected, degree of automation, and dependency on the service. Some uses should be prohibited because their purpose or power imbalance is incompatible with dignity or rights. Classification determines the depth of documentation, testing, approval, and monitoring.

6.2 Stakeholder participation

Participation should occur before requirements are fixed and continue through monitoring. Include affected persons, domain professionals, technical staff, accessibility specialists, privacy and security experts, environmental expertise, and representatives able to identify structural inequality. Record disagreements and explain how input changed the system.

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6.3 Data, model, and procurement governance

Maintain inventories of data sources, lawful and ethical bases, provenance, quality limitations, access rights, retention, and deletion. Document model purpose, training or adaptation, evaluation, subgroup performance, security, known limitations, and prohibited uses. Procurement contracts should secure audit rights, incident notification, change control, data-return/deletion, accessibility, portability, and exit options.

6.4 Integrated ethical impact assessment

For high-impact systems, combine ethical, fundamental-rights, privacy, security, accessibility, and environmental analysis in a coordinated process. Assess normal use, foreseeable misuse, failure, and cumulative effects. Each risk must have an owner, mitigation, evidence, residual-risk decision, and review date. Publication should be the default for a proportionate summary, subject to legitimate security and privacy limits.

6.5 Independent assurance

Independence is a matter of incentives and authority, not only organizational distance. Reviewers need access to documentation and testing resources, freedom from delivery targets, and authority to require remediation or escalation. External audit may be necessary when harms are severe, internal expertise is limited, or public trust requires additional assurance.

6.6 Monitoring and change management

Approval is conditional on continued evidence. Monitor technical performance, subgroup impacts, complaints, overrides, appeals, security events, data drift, user behavior, and resource consumption. Material changes in purpose, model, data, vendor, population, or context should trigger reassessment. Define quantitative and qualitative stop thresholds before deployment.

6.7 Incident response and remedy

Incident processes should be accessible to affected people, not only technical staff. Organizations need channels for reporting, rapid triage, containment, preservation of evidence, notification, correction, appeal, compensation or other remedy where appropriate, and public learning. Root-cause analysis must examine incentives, governance, staffing, and procurement—not merely individual error.

7. Implementing Ethical Technology Governance in Universities

Universities are a critical setting because they occupy multiple roles: educator, employer, researcher, public-interest institution, technology developer, data controller, and purchaser. AI may be used in admissions, learning analytics, assessment, plagiarism detection, student support, research, human resources, surveillance, and administrative decision-making. These uses affect people who may have limited ability to opt out and can influence educational opportunity and academic freedom.

A university should establish an Ethical Technology Governance Committee that complements—rather than replaces—research ethics boards, data-protection functions, information security, procurement, and academic governance. Membership should include academic staff, professional services, students, IT, legal/privacy, accessibility, sustainability, and external expertise where required. Conflicts of interest must be declared. The committee should approve policy, risk tiers, high-impact deployments, exemptions, and public reporting.

A central register should record each significant system's owner, purpose, vendor, data categories, affected groups, risk tier, legal basis, assessment status, model/version, approval conditions, monitoring indicators, incidents, and retirement date. High-impact educational decisions should never rely on an unreviewable automated output. Students and staff should receive clear notice, understandable explanations, accessible alternatives where feasible, and human review with authority to correct outcomes.

Education is itself a control. Computing, business, design, law, health, and social-science curricula should integrate ethics into technical assignments, not confine it to a single lecture. Students should

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practice stakeholder analysis, documentation, bias testing, privacy-enhancing design, threat modeling, environmental measurement, and incident response. Staff procuring or using AI need role-specific training, while senior leaders need training on risk acceptance and accountability.

8. Discussion

The synthesis shows that the main ethical risks of emerging technology are connected by a common structure: data and computational capacity are concentrated, while people affected by decisions often lack information, bargaining power, and remedy. Bias, surveillance, manipulation, labor harms, and environmental burden should not be governed as unrelated issues. They arise from choices about purpose, optimization, scale, and accountability.

The framework also clarifies the relationship between ethics and law. Law establishes binding minimums and institutional powers; ethics asks whether conduct is justified when rules are incomplete, lagging, or permissive. Ethical governance should not be used to evade legal compliance, but compliance alone cannot determine whether a technically lawful system is necessary, proportionate, or socially legitimate. Conversely, ethics must be disciplined by evidence and decision processes if it is to avoid becoming symbolic.

A practical tension remains between transparency and other legitimate interests, including privacy, security, and intellectual property. The solution is not maximum disclosure of every technical detail. It is layered transparency: meaningful notice and reasons for affected persons; sufficient operational information for users; deeper access for qualified auditors and regulators; and public reporting about purposes, risks, incidents, and performance. The burden should rest on the institution to justify secrecy where secrecy blocks accountability.

Environmental ethics further expands responsible innovation beyond immediate users. Efficiency gains do not automatically reduce total resource use because scale and rebound effects may increase consumption. Institutions should require environmental reporting proportionate to computational intensity and should include energy, water, hardware, and supply-chain considerations in procurement and architecture decisions.

9. Recommendations

1. Treat ethical governance as a funded institutional function with authority, expertise, and executive accountability.

2. Create and maintain an inventory of significant automated and AI-enabled systems, including procured tools.

3. Use risk tiers to determine assessment depth, approval level, independent assurance, and monitoring frequency.

4. Require integrated ethical and fundamental-rights impact assessments before high-impact deployment and after material change.

5. Build participation, accessibility, and worker/student voice into problem definition and evaluation.

6. Contract for auditability, incident notification, change control, data deletion, portability, and viable exit.

7. Publish proportionate information about system purposes, limitations, risk controls, and performance.

8. Provide understandable notice, human review, appeal, correction, and remedy for consequential decisions.

9. Measure environmental impacts and compare lower-resource technical and non-technical alternatives.

10. Connect incidents and complaints to organizational learning, policy revision, and system retirement decisions.

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10. Limitations and Future Research

The paper's integrative method supports breadth but does not provide the replicability of a systematic review or the causal evidence of an empirical study. The proposed framework should be tested through comparative case studies, interviews, and implementation research across institutions of different size, resources, and regulatory environments. Future work should develop validated indicators for contestability, meaningful human oversight, participation quality, and environmental proportionality. Research is also needed on governance for general-purpose and agentic AI, cross-border vendor accountability, and the long-term effects of AI-mediated education on learning, professional formation, and academic freedom.

11. Conclusion

Technology ethics is not an obstacle to innovation; it is a discipline for ensuring that innovation remains worthy of public trust. Digital systems encode choices about people, institutions, and the planet. When those choices are hidden, fragmented, or driven solely by profit and efficiency, harm becomes easier to produce and harder to contest.

The paper has argued for a lifecycle approach that connects legitimate purpose, participation, risk classification, documentation, impact assessment, independent review, monitoring, and remedy. The proposed framework gives universities and other organizations a practical route from values to evidence and decision rights. Its central principle is simple: systems with greater capacity to affect rights and life chances require stronger justification, stronger oversight, and stronger routes for challenge.

Responsible innovation ultimately requires institutions to accept that some technically feasible uses should be redesigned, limited, delayed, or rejected. By treating human dignity, democratic values, social equity, professional responsibility, and planetary well-being as design constraints, organizations can pursue technological progress without separating capability from responsibility.

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EVALUATING THE REDUCED CREW CONCEPT IN THE TRANSITION TO FUTURE FLIGHT DECK OPERATIONS: A HUMAN FACTORS AND PILOT TRAINING PERSPECTIVE

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ABSTRACT

The rapid advancement of automation, artificial intelligence, and digital flight technologies is reshaping the future of commercial aviation. Within this transformation, the Reduced Crew Operations (RCO) concept has emerged as a promising approach to improving operational efficiency while introducing new challenges related to human performance and flight safety. As cockpit roles continue to evolve, understanding the implications of RCO from both human factors and pilot training perspectives has become increasingly important. This study provides a conceptual evaluation of the Reduced Crew Operations concept within the broader transition toward Future Flight Deck Operations. Drawing on recent literature and publications from international aviation organizations, the paper discusses how RCO may influence pilot responsibilities, workload, situational awareness, decision-making, and human-automation interaction. In addition, the potential implications of RCO for competency-based pilot training are examined in light of emerging technological and operational requirements. Rather than proposing a definitive solution, the study highlights key challenges and identifies research areas that require further investigation. The findings suggest that technological advancements alone will not ensure the successful implementation of future flight deck concepts, and that equal attention should be given to human factors and the continuous evolution of pilot training systems.

Keywords: Reduced Crew Operations; Future Flight Deck Operations; Human Factors; Pilot Training; Flight Deck Automation;

INTRODUCTION

Automation in aviation refers to the strategic allocation of operational functions to machines that would otherwise be performed by human operators (Antonovich, 2008). Over the past decades, each new generation of transport aircraft has incorporated increasingly sophisticated automation systems, enabling capabilities such as precision landings in low visibility conditions, optimized fuel management, and enhanced operational efficiency. These technological advancements have contributed significantly to improving flight safety while transforming the pilot's role from direct manual control to the supervision and management of complex human-automation interactions. Recent research further shows that higher levels of cockpit automation can improve performance and reduce workload while simultaneously creating challenges for visual monitoring, vigilance, situational awareness, and appropriate trust in automated systems (Bliss & Wise, 2023; Lounis et al., 2025). Consequently, maintaining effective collaboration between pilots and automated systems has become a critical requirement for safe and efficient flight operations. As automation continues to assume a greater range of operational functions, understanding how pilots interact with these systems becomes increasingly important for maintaining situational awareness, appropriate levels of trust, and effective human oversight.

Building on this evolution, the aviation industry is undergoing a rapid digital transformation driven by advances in Artificial Intelligence (AI). AI technologies enhance operational performance by processing large volumes of operational data, including real-time weather information, flight plans, and aircraft system data, to support route optimization, risk prediction, and operational decision-making (International Civil Aviation Organization [ICAO], 2025). This transformation has accelerated the

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development of the Future Flight Deck (FFD), also referred to as the Smart Cockpit, which integrates intelligent technologies to support safer and more efficient flight operations (European Union Aviation Safety Agency [EASA], n.d.). Within this environment, AI is increasingly viewed as a collaborative partner that provides real time decision support, enhances situational awareness, and reduces pilot workload. As intelligent automation assumes a greater share of routine cockpit tasks, pilots are expected to focus increasingly on strategic decision making, mission management, and the supervision of automated systems (ICAO, 2025). This shift in the distribution of responsibilities between pilots and intelligent systems raises important questions regarding how cockpit roles, human oversight, and operational responsibility should be structured in increasingly automated flight environments.

The transition toward highly automated flight operations has also stimulated growing interest in Reduced Crew Operations (RCO) and Single Pilot Operations (SPO). These concepts are associated with potential efficiency gains and changing workforce pressures, while advances in AI and cockpit automation continue to expand the technical feasibility of crew reduction. Recent industry forecasts also indicate sustained long-term demand for newly qualified aviation personnel, including pilots, reinforcing the importance of workforce planning and training capacity as the commercial aviation system continues to grow (Boeing, 2026). Nevertheless, the implementation of reduced-crew concepts remains limited by significant safety and regulatory concerns. Current regulatory frameworks in Europe continue to require no fewer than two flight crew members for relevant commercial air transport operations, while EASA's recent research has concluded that, with the current cockpit design and within the limits of the research, an equivalent level of safety between eMCO and current two-pilot operations cannot yet be sufficiently demonstrated (EASA, n.d.). These limitations indicate that the transition toward reduced-crew operations cannot be considered solely from a technological perspective, as the role of human operators remains fundamental to maintaining safe flight operations.

Despite the continuous advancement of cockpit automation, the human element remains central to aviation safety. Human factors continue to contribute to a substantial proportion of aviation accidents, while experienced pilots play a vital role in managing unexpected situations and mitigating system failures (Bailey et al., 2017). Consequently, the aviation industry is increasingly adopting Competency-Based Training and Assessment (CBTA) and Evidence-Based Training (EBT), which focus on developing both technical and non-technical competencies, including situational awareness, workload management, decision making, and problem-solving, to prepare pilots for highly automated flight environments (Boeing Global Services, 2025; Bailey et al., 2017). These developments highlight the importance of adapting pilot training to ensure that pilots remain capable of effectively managing both automated systems and unexpected operational conditions.

Against this background, the primary objective of this study is to provide a conceptual evaluation of Reduced Crew Operations (RCO) within the broader transition toward Future Flight Deck (FFD) operations. Drawing on recent literature and publications from international aviation organizations, this paper examines the implications of crew reduction from the perspectives of human performance and future pilot training. Furthermore, it identifies the key challenges associated with these emerging operational concepts and highlights research areas requiring further investigation. Ultimately, the study argues that technological advancement alone cannot ensure aviation safety without maintaining a strong emphasis on the human element.

Future Flight Deck Operations and Reduced Crew Operations

Future Flight Deck Operations

The concept of the Future Flight Deck (FFD), frequently referred to in regulatory literature as the Smart Cockpit, represents a fundamental transformation in cockpit design, shifting from conventional flight decks toward highly integrated, intelligent, and data-driven operational environments (European Union Aviation Safety Agency [EASA], n.d.). Unlike traditional automation, which has often been described as “strong but brittle” due to its limited adaptability to unexpected situations, future flight deck concepts are increasingly based on Increasingly Autonomous Systems (IAS) that operate as collaborative partners rather than passive tools. In this paradigm, automation functions as a “curious partner” capable of

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continuously interacting with pilots, learning from operational data, and supporting complex decision-making processes (Bailey et al., 2017).

The convergence of several emerging technologies enables this transformation. Artificial Intelligence (AI) plays a central role by processing large volumes of operational data including weather information, aircraft performance parameters, air traffic conditions, and flight plans to support real-time decision-making. According to ICAO (2025), AI-enabled systems are expected to allow aircraft to sense, decide, and act autonomously for routine operational tasks while keeping human operators responsible for strategic oversight.

In parallel, advanced automation extends beyond rule-based programming by incorporating machine learning algorithms that adapt system behavior to operational conditions. Rather than simply executing predefined commands, these adaptive systems continuously optimize their responses based on environmental changes and operational feedback (Bailey et al., 2017). Furthermore, Decision Support Systems (DSS) are becoming an essential component of future flight deck architectures. These systems assist pilots by predicting traffic congestion, optimizing flight trajectories, identifying operational risks before they develop, and recommending appropriate mitigation strategies. Consequently, the pilot's role is gradually evolving from direct aircraft manipulation toward supervisory control, strategic decision-making, and effective management of intelligent automated systems (ICAO, 2025). This technological evolution provides the foundation for new operational concepts that aim to further optimize airline efficiency, including Reduced Crew Operations (RCO).

Reduced Crew Operations

Reduced Crew Operations (RCO) represent one of the most significant operational changes proposed for future commercial aviation. The concept involves reducing the number of pilots required on the flight deck while maintaining an equivalent level of operational safety. The concept is being explored in response to potential efficiency gains, evolving operational needs, sustained demand for qualified aviation personnel, and advances in cockpit automation that may enable new forms of operational support (Boeing, 2026; EASA, n.d.). This operational shift has led to the development of different crew-reduction concepts, each involving different levels of automation, pilot responsibility, and operational support.

According to the EASA eMCO-SiPO framework (EASA, n.d.), RCO consists of two primary operational concepts. The first is Extended Minimum Crew Operations (eMCO), in which two pilots remain onboard during critical flight phases such as takeoff and landing, while only one pilot actively monitors the aircraft during the cruise phase as the other pilot takes a controlled rest period. This approach seeks to reduce crew workload and fatigue while maintaining operational continuity during long-haul flights (EASA, n.d.; Bailey et al., 2017). The eMCO concept therefore represents a relatively gradual approach to crew reduction, as it retains two pilots onboard while introducing a temporary reduction in active flight deck staffing during less critical phases of flight.

The second concept, Single-Pilot Operations (SiPO), proposes a more extensive reduction by allowing a single pilot to manage the entire flight. Under this concept, the onboard pilot would receive support from advanced cockpit automation, a virtual co-pilot, and, when necessary, remote ground-based operators capable of providing decision support, monitoring aircraft systems, and assisting with abnormal or emergency procedures (Bailey et al., 2017; EASA, n.d.). Compared with eMCO, SiPO therefore represents a more fundamental transformation of the traditional flight crew structure and places greater reliance on automation, remote support, and the capabilities of the remaining onboard pilot.

To clarify the relationship between these terms, RCO functions as the overarching concept, of which eMCO and SiPO represent the two primary operational forms, as summarized in Table 2 below:

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Table 2. Overview of Reduced Crew Operations Concepts. Source: Author's synthesis based on EASA (n.d.) and Bailey et al. (2017).

	Description
eMCO	Extended Minimum Crew Operations - two pilots remain onboard; one pilot actively monitors the aircraft during cruise while the other takes a controlled rest period.
SiPO	Single-Pilot Operations - one onboard pilot manages the flight with support from advanced automation, a virtual co-pilot, and remote ground-based operators.

Despite the potential economic benefits of RCO including lower operating costs, increased scheduling flexibility, and more efficient utilization of flight crews the concept presents substantial challenges regarding operational safety. The most critical concern is achieving safety equivalence with conventional two-pilot operations. EASA's eMCO-SiPO research concluded that, with the current cockpit design and within the limits of the research, an equivalent level of safety between eMCO and current two-pilot operations cannot yet be sufficiently demonstrated. The main areas requiring further consideration include pilot incapacitation monitoring, fatigue and drowsiness, sleep inertia, cross-checks, and physiological needs (EASA, n.d.). These concerns demonstrate that reducing the number of pilots requires not only technological compensation for the loss of human redundancy but also a reassessment of how safety-critical tasks are distributed between humans and automated systems.

Finally, the transition toward Future Flight Deck operations and Reduced Crew Operations is not solely a technological transformation but also a human factors challenge. As pilots increasingly shift from manual aircraft control to supervisory management of intelligent automation, maintaining situational awareness, trust calibration, workload management, and effective human-automation collaboration becomes essential for preserving flight safety. These human-centered issues have therefore become one of the primary research priorities for future commercial aviation.

HUMAN FACTORS AND PILOT TRAINING PERSPECTIVE

Human Factors

Situational Awareness (SA): Situational awareness remains one of the most important human factors challenges associated with increasing flight deck automation (Antonovich, 2008). As cockpit systems become more advanced, display designs may reduce the perceptual salience of important information, making critical changes more difficult for pilots to detect unless supported by clear alerts (Antonovich, 2008). Automation has also gradually shifted the pilot's role from directly controlling the aircraft to supervising automated systems, increasing the risk of becoming “out of the loop” (Antonovich, 2008; International Civil Aviation Organization [ICAO], 2025). This issue becomes particularly evident during prolonged “heads-down” activities, where pilots focus on programming the Flight Management System (FMS) instead of monitoring the external environment, potentially reducing overall situational awareness (Antonovich, 2008). These challenges suggest that future cockpit technologies should actively support pilots in maintaining situational awareness rather than relying solely on conventional warning systems. This concern becomes particularly critical in reduced-crew environments, where the loss of a second pilot's independent monitoring increases the risk that reduced situational awareness may go undetected.

Workload: High-fidelity simulations conducted by NASA indicate that single-pilot operations (SPO) significantly increase pilot workload throughout all phases of flight compared with conventional two-

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pilot operations (Bailey et al., 2017). Without another pilot to share operational responsibilities, pilots are more likely to prioritize aircraft control while postponing or omitting secondary tasks such as checklist completion or communication during demanding situations (Bailey et al., 2017; Air Line Pilots Association [ALPA], 2019). Consequently, effective workload management becomes increasingly important, requiring pilots to anticipate future operational demands and allocate available resources before workload reaches critical levels (McDonald et al., 2017). This highlights the importance of cockpit systems capable of recognizing excessive workload and providing adaptive support when necessary. Therefore, this issue becomes particularly significant when the second pilot is no longer continuously available to share operational demands.

Decision Making: In future flight deck concepts, decision-making is expected to become a collaborative process between pilots and intelligent automated systems. Artificial intelligence can rapidly analyze operational information, including weather conditions, aircraft performance, and traffic data, to provide decision support recommendations (ICAO, 2025). However, this capability also introduces the possibility of automation bias, where pilots may accept system recommendations without sufficient critical evaluation. Bailey et al. (2017) therefore proposed the concept of a "curious partner," in which the autonomous system actively engages with the pilot by questioning decisions and encouraging critical thinking instead of simply providing solutions. Furthermore, effective decision-making depends not only on available information but also on the pilot's cognitive readiness, workload, stress, and fatigue. This dynamic becomes especially significant in RCO, where the absence of a second pilot removes an important source of independent cross-checking during high-stakes decisions.

Trust in Automation and Human-Automation Interaction: As automation continues to demonstrate high levels of reliability, pilots may gradually develop excessive confidence in automated systems, increasing the risk of automation complacency (Antonovich, 2008). Such overreliance can weaken active monitoring and encourage pilots to transfer responsibility to automation instead of maintaining active supervision (Antonovich, 2008). Modern automated systems also provide limited feedback regarding their internal decision-making processes, making it more difficult for pilots to understand system behavior during abnormal situations. Future flight deck concepts should therefore promote transparent and collaborative human-automation interaction, allowing both the pilot and the autonomous system to exchange information through intuitive communication while maintaining a shared understanding of the operational situation (Bailey et al., 2017; ICAO, 2025). Accordingly, the effectiveness of future human-automation collaboration will depend not only on system reliability but also on pilots' ability to maintain appropriate levels of trust, monitor automation effectively, and intervene when necessary. In a reduced-crew context, this challenge is amplified, as the remaining pilot must calibrate trust in automation without the benefit of a colleague's independent judgment.

Pilot Training

Current Understanding and the Need for Change: Traditional pilot training has largely emphasized procedural knowledge, checklist discipline, and technical proficiency. However, advances in aircraft technology have shifted the focus of aviation safety from mechanical failures toward human performance, with human error remaining a major contributing factor in aviation accidents (Bailey et al., 2017; Boeing Global Services, 2025). As cockpit automation continues to evolve, pilot training must also evolve to prepare flight crews for increasingly complex and technology-driven operational environments.

CBTA and EBT Frameworks: Competency-Based Training and Assessment (CBTA) together with Evidence-Based Training (EBT) represent the current direction of pilot training. Rather than concentrating solely on technical flying skills, CBTA develops a broader set of competencies, including situational awareness, workload management, communication, and problem-solving (Boeing Global Services, 2025). EBT complements this approach by using operational data to identify the most relevant safety risks and designing training scenarios accordingly (Boeing Global Services, 2025). Together, these approaches encourage continuous performance improvement through observable behaviors, structured feedback, and competency development instead of simple pass-or-fail evaluations (Boeing Global Services, 2025; EASA, n.d.). This competency-focused approach provides an important

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foundation for preparing pilots to operate effectively in increasingly automated and potentially reduced-crew flight environments.

Future Competencies: Future pilots operating in reduced-crew or highly automated environments will require competencies that extend beyond traditional flying skills. Single-Pilot Resource Management (SRM), which focuses on the effective management of all available onboard and external resources, including AI-based decision-support systems and remote operators, will become increasingly important (Federal Aviation Administration [FAA], n.d.). In addition, pilots must develop strong human-machine collaboration skills and apply Threat and Error Management (TEM) principles while supervising automated systems (Boeing Global Services, 2025; ICAO, 2025). Future training should also introduce adaptive learning methods, AI literacy, and familiarity with cognitive monitoring technologies, enabling pilots to work effectively alongside intelligent cockpit systems. Leadership, communication, and critical thinking will remain essential competencies, particularly when pilots are required to intervene during situations where automation reaches its operational limitations (Boeing Global Services, 2025; Antonovich, 2008). Taken together, these competencies suggest that future pilot training must evolve from traditional aircraft-centered instruction toward a more human-centered model that emphasizes effective interaction with intelligent systems, adaptive decision-making, and continuous monitoring of pilot performance.

Overall, the continuing evolution of cockpit automation requires a parallel evolution in both human factors research and pilot training. As pilots transition from manual aircraft operators to strategic supervisors of increasingly intelligent systems, future flight deck concepts should integrate adaptive technologies that support situational awareness, workload management, decision-making, and effective human-automation collaboration. This alignment between technological development, human factors, and pilot training will be essential for ensuring that future aviation systems remain both technologically capable and human centered.

DISCUSSION

The transition toward Reduced Crew Operations (RCO) and the Future Flight Deck (FFD) represents a complex intersection of technological ambition, economic considerations, and regulatory caution. Although significant advances have been achieved in aircraft automation, artificial intelligence, and decision support technologies, the discussion surrounding RCO reveals a fundamental challenge for the future of commercial aviation: achieving operational efficiency without compromising the level of safety currently provided by two-pilot operations. Therefore, the feasibility of RCO should not be evaluated solely according to technological capability, but rather according to whether the overall operational system can demonstrate an equivalent or higher level of safety (Bailey et al., 2017; EASA, n.d.). This perspective highlights the need to consider not only the capabilities of emerging technologies but also their interaction with human operators, operational procedures, and safety management frameworks.

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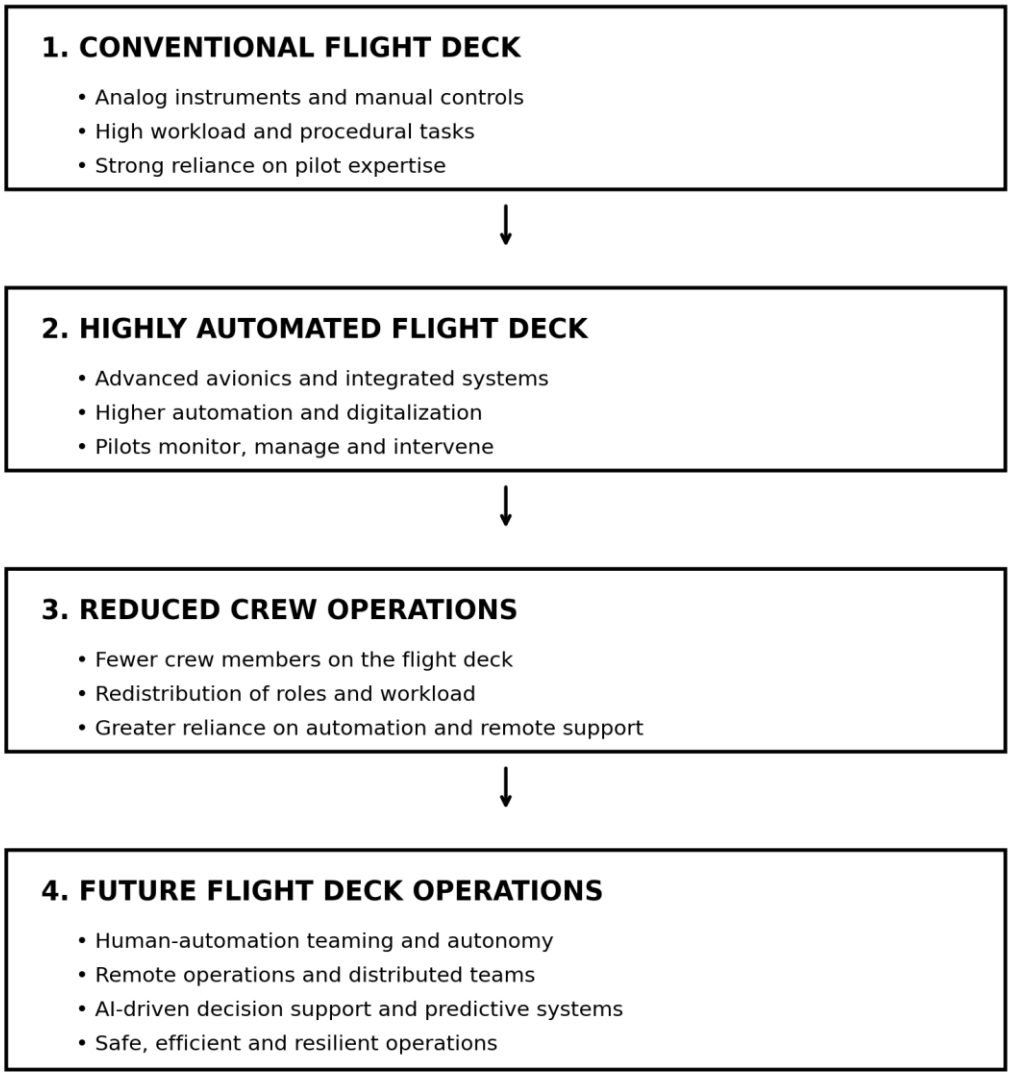


Figure 1. Transition Toward Future Flight Deck Operations. Source: Author's synthesis based on Bailey et al. (2017), EASA (n.d.), and ICAO (2025).

As illustrated in Figure 1, the transition toward Future Flight Deck Operations can be understood as a gradual movement from conventional automation toward increasingly integrated human-automation cooperation, with RCO representing a potential future operational application rather than an isolated technological change. Within this transition, changes in crew structure create direct implications for human performance and pilot training, which are summarized in Table 2 below.

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Table 2. Potential Human Factors and Pilot Training Implications of Reduced Crew Operations. Source: Author's synthesis based on Bailey et al. (2017), Boeing Global Services (2025), and EASA (n.d.).

Theme	Possible Implications
Situational Awareness	Increased monitoring demands and greater reliance on system-generated information
Workload	Redistribution of pilot tasks from manual flying toward monitoring and supervision
Decision Making	Greater reliance on automation and decision-support systems
Human-Automation Interaction	Increased need for effective automation monitoring, mode awareness, and intervention
Communication & Coordination	Changes in crew coordination and increased reliance on remote support
Pilot Training	Need for new competency requirements, including automation management, system monitoring, and decision-making skills

As summarized in Table 2, the implications of RCO extend across situational awareness, workload distribution, decision making, human-automation interaction, communication and coordination, and pilot training requirements. Taken together, these implications indicate that increasing reliance on automated systems is likely to shift pilots from direct manual control toward greater monitoring, supervision, and system-management responsibilities, requiring additional competencies in automation management, decision-making, and continuous system monitoring (Bailey et al., 2017; Boeing Global Services, 2025; EASA, n.d.). From a pilot-training perspective, this implies that competency frameworks must be evaluated not only against the demands of current multi-crew operations, but against the specific requirements that Table 2 identifies for reduced-crew environments.

Sufficiency of Current Training Frameworks

One of the critical questions emerging from the transition toward RCO is whether existing pilot training frameworks, particularly Competency-Based Training and Assessment (CBTA) and Evidence-Based Training (EBT), are sufficient for future reduced-crew environments. These approaches represent a significant development from traditional task-based training because they emphasize competencies, resilience, decision-making, and non-technical skills. However, they have largely evolved within the context of multi-crew operations, where pilots continuously provide mutual monitoring, cross-checking, workload sharing, and immediate intervention (Boeing Global Services, 2025; McDonald et al., 2017). This dependence on crew-based safety mechanisms raises questions about whether existing competency frameworks can fully address the demands of operations in which such human redundancy is reduced or removed.

The removal or reduction of this human redundancy introduces new training requirements. In a reduced-crew or single-pilot environment, the pilot may be required to manage prolonged periods of isolation, increased responsibility, and a substantially greater individual cognitive workload. In addition, the nature of the pilot's interaction with automation may change from predominantly monitoring automated

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systems to actively intervening when automation reaches its operational limitations. Consequently, CBTA and EBT can provide an important foundation for RCO training, but they should be further adapted to address the psychological, cognitive, and operational characteristics of reduced-crew environments (Bailey et al., 2017; EASA, n.d.; FAA, n.d.). Taken together, these findings suggest that competency-based frameworks are necessary but not sufficient for reduced-crew environments unless they explicitly address the loss of crew-based redundancy-that is, training frameworks must address not only individual pilot competencies but also the pilot's ability to maintain safe performance when conventional crew-based support is no longer continuously available.

Future training frameworks should therefore incorporate scenarios specifically designed around pilot incapacitation, prolonged single-pilot operation, automation degradation, unexpected system behavior, and high-workload decision-making without immediate crew support. This would allow training to move beyond the assessment of individual competencies toward the assessment of the pilot's ability to maintain operational resilience within a highly automated system (EASA, n.d.; FAA, n.d.). By incorporating these scenarios, future training could provide a more comprehensive assessment of operational resilience and help determine whether pilots are adequately prepared to manage the unique risks associated with reduced-crew operations.

Human Factors and Operational Resilience

Human factors remain one of the most significant challenges associated with RCO. Among the primary concerns are pilot incapacitation, fatigue, sleep inertia, workload management, and the potential loss of continuous human cross-monitoring. In current two-pilot operations, the second pilot represents an important layer of operational resilience by providing independent monitoring, detecting errors, challenging decisions, and intervening when the other pilot becomes incapacitated or overloaded (Bailey et al., 2017; McDonald et al., 2017; EASA, n.d.). This distinction is particularly important because it reframes redundancy not merely as an extra pair of hands, but as a distinct cognitive function that any RCO system must replicate or compensate for.

In an RCO environment, this redundancy cannot simply be assumed to disappear without consequence. Technological systems may provide monitoring and decision support, but their ability to reproduce the adaptive and context-sensitive characteristics of human monitoring remains a critical research question. In particular, the resting-pilot concept introduces additional concerns regarding sleep inertia and the time required for the pilot to regain an adequate level of situational awareness following a period of rest (Bailey et al., 2017; EASA, n.d.).

Another important human-factors concern is automation bias. As decision-support systems become increasingly capable, pilots may become progressively more dependent on automated recommendations and less inclined to challenge system outputs. This creates a potential shift from active supervision toward passive acceptance. The future pilot must therefore retain a critical and questioning role, continuously evaluating whether the system's recommendations are consistent with the operational context. In this sense, effective human-machine cooperation should not eliminate human judgment but should strengthen the pilot's ability to identify situations in which automation may become unreliable or reach its operational limits (Antonovich, 2008; ICAO, 2025). This balance between automation support and human judgment is central to the future role of the pilot.

Evolution of the Pilot's Role

The transition toward the FFD is also expected to transform the professional role of the pilot. Rather than functioning primarily as a tactical operator who directly controls the aircraft and manages individual systems, the future pilot may increasingly assume the role of a manager and supervisor of the overall operation (ICAO, 2025; EASA, n.d.). This shift places greater emphasis on supervisory, cognitive, and decision-making competencies.

This transformation does not necessarily imply a reduction in pilot expertise. Instead, it represents a shift in the nature of that expertise. The pilot will increasingly be required to understand system behavior, evaluate automated decisions, manage multiple interacting systems, and intervene when automated processes encounter unexpected or ambiguous situations. Consequently, future pilot

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competence will depend not only on traditional flying skills but also on advanced capabilities in human-machine teaming, system supervision, decision-making, and automation management (Boeing Global Services, 2025; ICAO, 2025). These changing competency requirements also have direct implications for the design of future pilot training.

A central requirement will be the ability to recognize the boundaries of automation. Highly automated systems may perform effectively under expected conditions while becoming less reliable in situations outside their design assumptions. These "brittle" limits represent critical points at which human intervention becomes essential. The future pilot must therefore remain sufficiently engaged with the operation to detect these boundaries before an automated system failure develops into a safety-critical event (Antonovich, 2008; ICAO, 2025).

Implications for Future Research

The findings of the reviewed literature suggest that future research should move beyond the assumption that increased automation alone will resolve the challenges associated with RCO. Instead, greater attention should be directed toward System Design for Operations, in which technology, human performance, training, procedures, and regulatory requirements are considered as interconnected components of a single operational system (Bailey et al., 2017; EASA, n.d.; ICAO, 2025). This systems-based perspective provides a basis for identifying the areas in which further research is most needed.

Several areas require further investigation. First, highly reliable and non-intrusive pilot-state monitoring systems should be developed to support the early detection of incapacitation, excessive fatigue, and degraded cognitive performance. Second, research should examine how bidirectional communication between pilots and artificial intelligence can be optimized so that AI systems function as transparent and explainable decision support partners rather than opaque sources of recommendations. Third, future studies should investigate how training and operational procedures can maintain an appropriate level of pilot engagement without creating excessive workload or undermining the benefits of automation (EASA, n.d.; ICAO, 2025). These research priorities are closely linked to the broader challenge of maintaining operational resilience in reduced-crew environments.

Taken together, these findings suggest that the transition toward RCO is best understood as a human-system integration challenge rather than a purely technological one: the central question is not whether automation can perform an increasing share of flight-deck tasks, but whether the complete operational system can match or exceed the resilience currently provided by two human pilots (Bailey et al., 2017; EASA, n.d.). The literature indicates that RCO and the FFD are technically plausible but remain constrained by unresolved human-factors, training, certification, and operational-resilience challenges, and that the principal barrier is the ability of the aviation system as a whole not automation alone to provide an equivalent level of safety once an element of human redundancy is removed. Accordingly, the most viable pathway toward the future flight deck is unlikely to be a direct replacement of the second pilot, but a gradual evolution in which automation, pilot-state monitoring, adaptive training, and decision-support technologies are integrated within a human-centered framework that expands human capability while preserving meaningful human oversight, intervention, and accountability (EASA, n.d.; ICAO, 2025).

CONCLUSION

This study has provided a conceptual evaluation of Reduced Crew Operations within the broader transition toward the Future Flight Deck, examining recent literature from the perspectives of human factors and pilot training. The reviewed evidence indicates that although artificial intelligence, advanced automation, and increasingly autonomous systems can improve operational efficiency, human factors remain a fundamental determinant of flight safety: pilots continue to provide monitoring, decision-making, and adaptive capabilities that current automated systems cannot fully reproduce (Antonovich, 2008; Bailey et al., 2017; ICAO, 2025).

The main implication is that the viability of RCO should not be judged by the level of automation achieved, but by whether the resulting operational system can demonstrate safety and resilience equivalent to, or greater than, conventional two pilot operations. As the pilot's role evolves from direct

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tactical operation toward supervision, decision-making, and human-machine collaboration, training frameworks such as CBTA and EBT provide a useful foundation but will require further adaptation to the distinctive demands of reduced-crew environments, including automation supervision, incapacitation management, and independent decision making under reduced redundancy (Boeing Global Services, 2025; Bailey et al., 2017; EASA, n.d.). Future research should therefore prioritize reliable pilot-state monitoring, transparent human-AI communication, and training and procedures capable of sustaining pilot engagement without introducing excessive workload so that the future flight deck evolves not as a replacement of the human pilot, but as a more integrated form of human-machine operation.

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EFFECT OF AQUEOUS EXTRACT OF *COMBRETUM SERICEUM* STEM BARK ON RELATIVE ORGAN WEIGHT IN HIGH-FAT DIET FED RATS

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ABSTRACT

Hyperlipidemia is a metabolic condition characterized by elevated blood lipids. Relative organ weight is a sensitive parameter used to evaluate potential toxicological effects of therapeutic agents. *Combretum sericeum*, a traditional African medicinal plant locally known as "Taru" in Hausa, has significant pharmacological activity. This study investigated the effect of aqueous *Combretum sericeum* stem-bark extract on relative organ weight in high-fat diet-fed rats. Thirty-five Wister albino rats weighing between 40g to 100g were grouped into seven consisting of five rats each based on body weight and gender. Groups of rats maintained on a high fat diet, containing 33% fat, were given daily oral doses of 200mg/kg, 400mg/kg and 800mg/kg of the aqueous extract of *Combretum sericeum* stem bark prepared by maceration, for three weeks. At the end of treatment, the spleen, kidney, and liver were harvested, weighed, and their relative organ weights determined. Data was analyzed using one-way ANOVA followed by Tukey's post-hoc test, with significance set at $p < 0.05$. The high-fat diet and extract treatment produced no significant changes in the relative weights of the spleen, kidney, or liver across the treatment groups. This suggests that the extract did not cause major organ-weight alterations in high-fat diet-fed rats during the experimental period. However, the extract-control group showed increased spleen and kidney relative weights, suggesting that the effect of the extract may differ in the absence of the high-fat diet. Overall, aqueous *Comberetum sericeum* stem-bark extract at 200–800 mg/kg did not significantly affect relative organ weights in high-fat diet-fed rats.

Keywords: Hyperlipidemia, *Combretum sericeum,* High-fat diet, Relative organ weight, Extract

INTRODUCTION

Hyperlipidemia is a prevalent metabolic disorder characterized by elevated levels of plasma lipids, including cholesterol, triglycerides, and various lipoproteins such as low-density lipoprotein (LDL) and very low-density lipoprotein (VLDL), with or without decreased high-density lipoprotein (HDL) (Anbarasi and Brindha 2021). The pathophysiology centers on excessive VLDL and LDL concentrations, which can lead to altered, oxidized LDL uptake by macrophages, vascular inflammation, and plaque growth. It is a critical risk factor in the development of atherosclerosis, a pathological process involving the accumulation of lipids and formation of fibrous plaques within large and medium arteries. This progression narrows arterial lumen, reducing blood supply and increasing the risk of ischemic cardiovascular events including coronary artery disease, stroke, and peripheral vascular disease (Jadhav *et al.,* 2025). Hyperlipidemia may result from inherited genetic abnormalities, referred to as primary hyperlipidemia, or develop secondary to conditions such as diabetes mellitus, obesity, hypothyroidism, and chronic kidney disease. Certain medications and unhealthy lifestyle practices may also contribute to its development or worsen the condition. When hypercholesterolemia is poorly controlled, it can increase the risk of complications, including carotid artery disease, stroke, peripheral vascular disease, hypertension, and type 2 diabetes mellitus (Nalla et al., 2023). Hyperlipidemia is considered one of the major risk factors causing cardiovascular diseases (CVDs) and CVDs accounts for one-third of total deaths around the total world (Mumthaj et al., 2021). It remains a significant public health challenge, contributing substantially to the global burden of cardiovascular disease. Comprehensive management, encompassing both lifestyle modifications and pharmacological therapies, is crucial for preventing its devastating complications (Jadhav et al., 2025). According to a recent report, approximately 1 in 3 adults worldwide presents with hypercholesterolemia, contributing to a considerable proportion of coronary events and cerebrovascular accidents (Ballena-Caicedo *et al.,* 2025). Dyslipidemia is a significant health

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concern among adults in rural Nigerian communities, with women appearing to bear a greater burden (Asogun et al., 2026). The findings highlight the need for targeted interventions to address hypercholesterolemia and reduce the associated risk of atherosclerotic cardiovascular disease (CVD) within these populations.

Various drugs are used to treat hyperlipidemia and to reduce Cholesterol levels in the plasma which includes Statins and fibrates. There predominantly rely on lipid-lowering medications like statins, fibrates, and cholesterol absorption inhibitors to mitigate LDL levels and enhance lipid profiles (Tiwari 2024). Despite their proven efficacy in cholesterol reduction and CVD risk minimization, there exists a compelling need for further drug innovations to tackle the constraints of existing therapies and optimize outcomes for hyperlipidemia patients particularly among populations grappling with genetic lipid disorders or statin intolerance (Dey et al., 2024)

The Combretaceae family is a vast group of plants that is distributed tropically throughout the world, with centers of diversity in Africa and Asia. In traditional medicine, certain species of Combretum are widely used as diuretics and to treat bleeding, diarrhea, infections, diabetes, malaria, and inflammation. Species of the Combretaceae have an impressive history of traditional use for the treatment of microbial infections, and ethnopharmacological studies have shown that both crude extracts and isolated compounds possess antimicrobial properties (Anokwuru et al. 2025). Different species of combretum contain flavonoids, terpenoid, steroids, saponins, tannins, and alkaloids which are responsible for the antioxidant and anti-inflammatory potentials of combretum genus. There are several species in this genus which their biological activities and bioactive constituents are yet to explore for therapeutic applications. (Ali et al.; 2024).

Combretum sericeum locally called “taru” in Hausa is a shrub that is abundant in the savanna region of west Africa. The plant is used for treatment of various ailments such as stomach disorder, conjuvtivities and fever (Mann *et al.,* 2003). It has been proven to have anti-inflammatory activity (Sini *et al.,* 2010), and antioxidant activity (Zongo *et al.,* 2011). *Combretum sericeum* leaves and root bark have been traditionally used in the treatment of stomach disorders, wounds, bone fractures, and conjunctivitis (Toafode et al., 2022). In addition, it demonstrated significant antioxidant activity, supporting its potential medicinal value (Coulidiati et al., 2011). However, to the best of our knowledge, there is little scientific research or proof that shows the hypolipidemic effect of the plant has been evaluated. Therefore, the study aimed to determine the effect of aqueous extract of *Combretum sericeum* stem bark on relative organ weight in high-fat diet fed rats.

MATERIALS AND METHOD

Plant Collection and Extraction

The plant was harvested from Funtua Local Government, Katsina State, in July. It was identified at the herbarium section of the Department of Botany, Faculty of Life Science, Ahmadu Bello University Zaria, and a voucher sample number 0900151 was deposited. Preparation of plant extract was done by shade drying for one week, then dried at 40°C in an oven for three hours. The dried sample were pulverized and 100 g of the powdered stem bark, hundred grams of the powdered form was soaked in 1.5L of distilled water for 12 hours with intermittent mixing. The suspension was filtered through muslin cloth then Whatman’s No.1 filter paper. The filtrate was evaporated to dryness and the extract reconstituted in distilled water when required.

Feed Formulation

The normal feed formulation was formulated using 200g of commercial grower’s mash, 100ml of boiled water, 6g of cassava flour, while the high fat diet was formulated as reported by (Umar *et al.*,2012) with little modification. Baker’s fat (Pt Salim Ivomas Pratama Tbk, Indonesia.) of 81g was added into the commercial grower’s mash (Vital Feeds, Jos) of 219g, and mixed thoroughly. The cooled solution of boiled water and cassava flour were poured into the mixture of feed and bakers fat, then mixed and molded and allowed to dry for 2 hours before weighing and giving it to each group.

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Animal Treatment

Thirty-five Wister albino rats of both sexes weighing between 40g to 100g were acclimatized to the environmental conditions for one week and fed with standard feed and water *ad libitum* before starting the experiment. The animals were grouped into seven groups consisting of five rats each based on body weight and gender. The experiment was carried out in two phases which lasted for three weeks each. In the first phase, the rats were fed with the high fat diet for three weeks in order to induce hyperlipidemia. In the second phase, the rats were given various treatment as follows: Group 1: Normal control (Rats fed with normal diet and no treatment). Group 2: High fat diet fed rats treated orally with daily low dose (200mg/kg body weight) of aqueous extract of *combretum sericeum* stem bark, for three weeks. Group 3: High fat diet fed rats treated orally with daily medium dose (400mg/kg body weight) of aqueous extract of *combretum sericeum* stem bark, for three weeks. Group 4: High fat diet fed rats treated orally with daily high dose (800mg/kg body weight) of aqueous extract of *combretum sericeum* stem bark, for three weeks. Group 5: High fat diet fed rats treated orally with daily standard drug (Lipitor 167µg/kg body weight), for three weeks. Group 6: High fat diet fed rats but not treated (high fat diet control). Group 7: Rats fed with normal diet but treated with high dose (800mg/kg body weight) of aqueous extract of *combretum sericeum* stem bark (extract control). All animals were humanely sacrificed in fasted state after termination of experiment post treatment, and organ which were the spleen, kidney and liver samples were collected.

Sample Preparation and Analysis

The organs were harvested and organ weight of each animal and their body weight was measured using a weighing balance. Data presented as Means ± SD and analyzed using ANOVA and tukey post hoc test and significance was determined at $p < 0.05$.

RESULT AND DISCUSSION

From the result in Table 1 shows that the high-fat diet and the plant extract had no effect on the organ weight of rats fed normal and high-fat diet because there was no significant difference between the relative organ weight of all the groups.

TABLE 1: Effect of Aqueous Extract of *Combretum sericium* Stem Bark on Relative Organ Weight (%) in High-Fat Diet Fed Rats.

GROUPS	SPLEEN	KIDNEY	LIVER
NORMAL CONTROL	0.40±0.04[a]	0.70±0.12[a]	3.86±0.63[a]
HFD + 200mg/kg Cs.sb	0.47±0.13[a]	0.76±0.05[a]	4.33±0.36[a]
HFD + 400mg/kg Cs.sb	0.43±0.07[a]	0.68±0.02[a]	4.03±0.46[a]
HFD + 800mg/kg Cs.sb	0.52±0.15[a]	0.73±0.07[a]	4.62±0.66[a]
STANDARD CONTROL	0.36±0.03[a]	0.66±0.10[a]	3.85±0.21[a]
HFD CONTROL	0.39±0.08[a]	0.76±0.10[a]	3.94±0.22[a]
EXTRACT CONTROL	0.79±0.10[b]	0.88±0.08[b]	4.82±0.29[a, b]

All values are means ± SD of five replicates. Values with different superscripts down a column are statistically different. HFD= High-fat diet, Cs.sb= *Combretum sericeum* stem bark.

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The experiment shows that the aqueous extract of *Combretum sericeum* stem bark does not have any significant difference on the relative organ weight of the rats fed normal and high-fat diet similar to the study by (Kabir et al., 2021). The significantly elevated relative spleen and kidney weights observed in the extract control group suggest that administration of the extract alone may have induced organ specific physiological or adaptive responses

CONCLUSION

This study showed that administration of aqueous extract of *Combretum sericium* stem bark has no effect on relative organ weight in high-fat diet fed rats

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THE EFFECT OF FISCAL GOVERNANCE ON THE FISCAL SUSTAINABILITY DURING SHOCKS: CASE OF ALBANIA

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ABSTRACT

The paper investigates the behavior of the fiscal deficit, as a variable of the fiscal sustainability, related to the indicators of fiscal governance (such as the government effectiveness, corruption, public accountability) in Albania during 1993 – 2024. The analysis focuses on the dynamics of this behavior associated with the core macroeconomic indicators mostly during the diverse shocks. The empirical results demonstrate through the linear modeling that the foremost macroeconomic variables are not significant to determine the behavior of fiscal deficit. Meanwhile, the fiscal deficit represents a counter-reactive behavior to the public debt accumulated in the previous periods and throughout the several shocks in order to undertake the rational protective measures through the tightening fiscal policy. Meanwhile, the institutional variables play mostly more important role towards explaining the behavior of fiscal deficit compared to the macroeconomic variables taking into consideration in this analysis. This concluding remark reveals the significance that the institutional variables should take into the analysis of fiscal consolidation forecasts by the fiscal policymakers in the future in Albania, despite of the inevitability of comprehensive examination on the fiscal deficit behavior.

Keywords: Fiscal sustainability, Fiscal governance, Fiscal rules

JEL Codes: H61; H62; E62

1. Introduction

Referring to theoretical and empirical examinations, it was confirmed that the sensitivity of government behavior towards the diverse types of shocks has received a detailed priority by the fiscal policymakers through the control instruments to neutralize the various shocks. The fiscal governance should converge towards the fiscal sustainability through the efficacy of government spending, enhancing the accountability and transparency of public finances in order to contribute to the institutional consolidation, particularly in developing countries. Moreover, Le et al. (2025) examined the fluctuations amongst the government spending, institutional quality, and the sustainable development considering the developing countries during 1990 - 2022. The authors' findings emphasized that the public spending affected positively the sustainable development within a strong institutional framework, taking into consideration the policy consistency. Furthermore, the authors advocated that the developing countries would achieve the effective sustainable development through the integrated fiscal and institutional strategies.

Meanwhile, Bergam et al. (2016) stressed that the fiscal rules have been more effective towards shrinking the structural primary deficits in order to converge the fiscal sustainability referring to the European Union countries during 1990 – 2012. Otherwise, the authors provided that the efficacy of fiscal rules enhanced due to the policy transparency and the obligation to execute the fiscal programs. Nevertheless, Brady and Magazzino (2018) examined the long-term linkage amongst the government

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revenues and spending, also amongst the primary fiscal deficit and public debt. Meanwhile the authors confirmed the lack of fiscal sustainability related to the specific groups of European Union countries.

According to Organic Budget Law of Albania strongminded the core standard of non-negative primary balance. Also, the Albanian government has implemented the fiscal rule to achieve the robust budgetary discipline. The several fiscal rules including the budget balance rules, debt rules, expenditure rules, and revenue rules are amassed to avoid the fiscal pressures and to provide the fiscal foresight and sustainability throughout the good and bad times. The discretionary budgetary arrangements controlled by the appropriate fiscal instruments continuously. However, the volatility of fiscal behavior in Albania has affected certainly during the shocks of pyramid scheme crisis, the global financial crisis of 2008 and the global pandemic, Covid-19.

The paper follows to investigate the appropriate literature related to the fiscal sustainability and fiscal governance. Additionally, the succeeding section demonstrates the methodological approach and empirical results. The final section demonstrates the concluding remarks of paper.

2. Literature review

The following theoretical and empirical examinations reveal a wide range of results regarding the dynamics of fiscal sustainability into the comprehensive circumstances, particularly during shocks.

Efeoğlu (2025) investigated the effect of good governance indicators on the sustainable development in several Balkan countries, including five Balkan countries which are part of the European Union, during 2006 – 2022. The author emphasized through the empirical results that the indicators of good governance, such as the accountability, political stability, government effectiveness and the rule of law, contributed positively to the sustainable development, meanwhile the control of corruption affected negatively the sustainable development of selected countries. The findings of author highlighted the significance of the solid institutional structures in Balkan countries in order to contribute to long-term sustainable development.

Franek and Postula (2021) analyzed the impact of government fiscal instruments, such as fiscal rules, medium-term budgetary frameworks, independent fiscal institutions, related to the fiscal results of European Union countries during 2004 – 2016. The authors' empirical assessments emphasized that the use of fiscal instruments demonstrated a positive and statistically significant effect against the overall government balance to GDP ratio. Furthermore, the authors' findings presented that multi-year budgetary frameworks demonstrated the large effect on the fiscal balance, meanwhile the linking amongst the fiscal rules and autonomous fiscal institutions provided a slighter effect on the fiscal outcomes. It concluded according to the empirical results of authors that the integrated implementation of fiscal instruments supports the convergence of solid fiscal frameworks in European Union countries based on complementarity.

Afonso et al. (2023) investigated the impact of fiscal sustainability, taking into consideration the reactions of the primary government balance and the global government balance towards the ratio of debt-to-GDP, but also the reaction of government revenues to the government spending, in several OECD countries during 1950 – 2019. The empirical results of authors demonstrated that the output gap affected positively the fiscal sustainability through considering the reaction of the primary and global government balances, and the reaction of government revenues to government spending, but authors highlighted the conditional reaction due to the ratio of debt.

Ndiaye et al. (2026) examined the impact of institutional quality related to the public spending and tax revenues taking into consideration the panel of developed and developing countries during 2000 – 2023. The authors' empirical results demonstrated that the developing countries were more responsiveness against the implemented fiscal policies. Also, the authors emphasized that public spending instigates the tax revenues in the short – run and long - run, depending on the institutional quality. Referring to the authors' empirical findings, it was concluded that the institutional structure had a significant impact on the sustainability in the long - run. Meanwhile, the authors highlighted that the institutional reforms and fiscal rules should be implemented depending on the level of economic development of the countries.

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Onofrei et al. (2021) examined the impact of fiscal rules on the governments' fiscal behavior converging towards the fiscal sustainability related to the several developing EU countries during 2000–2014. Considering the empirical results, the authors underscored an active and solid interaction amongst the legal and institutional frameworks in order to increase the effectiveness of independent fiscal institutions converging to the comprehensive fiscal policy and sustainable public finances. Furthermore, the authors supported the sight of the significance of fiscal risk management and control mechanisms to improve the public sector performance and fiscal sustainability in developing countries.

Wright et al. (2017) emphasized the importance of rules related to the strengthening fiscal discipline, shortening fiscal procyclicality, and enhancing the budget transparency and reliability to manage the problems of fiscal deficit and public debt taking into consideration the Caribbean countries. The empirical results of authors demonstrated that the fiscal rules related to the government spending attained the positive results in terms of shrinking macroeconomic instability and increasing welfare.

3. Methodology and results

In order to achieve the sustainable results, it used the appropriate methodological aspects for the considered period and were associated with the dynamic contexts of fiscal indicators converging towards the fiscal sustainability.

3.1 Methodological background

This paper uses the quantitative approaches to estimate the effect of fiscal rules, government effectiveness and government accountability, as variables of fiscal governance, towards the fiscal sustainability in Albania. It examined the dynamics of fiscal sustainability, under the fiscal rules or without them, particularly during the times of shocks.

To analyze the fiscal sustainability, exclusively during the various shocks, the paper is based on the approach of fiscal response function, which it demonstrates how the budget deficit as a percentage of GDP is affected by the variables of public debt, macroeconomic and institutional indicators. Referring to the approaches according to the literature on the fiscal sustainability, it argued that the fiscal policy considered sustainable if the deficit responded to the changes of public debt. To assess the fiscal sustainability, it used the regression models of Ordinary Least Squares (OLS) in the following general form referring to Albania's data throughout 1993–2024, according to access data by the Albanian Ministry of Finance and the World Bank.

Due to the possibility of multicollinearity between the governance indicators, it estimated four different models, where each model included only one institutional variable (the government effectiveness, corruption control, and public accountability). Considering the empirical evaluations through time series data, in order to address the common problems arising possibly in this context, such as the heteroscedasticity and autocorrelation of errors, it applied the standard errors corrected according to the approach of Newey–West. This approach allows more consistent and reliable estimations of coefficients according to the statistical significance, improving the empirical interpretation of results. Referring to the context of literature review (Afonso et al. (2017); Efeoğlu, R. (2025)), the estimation of results is specified according to the following model:

$$Def_t = \beta_0 + \beta_1 Debt_{t-1} + \beta_2 Z_{it} + \beta_3 FR_t + \beta_4 Shock_t + \beta_5 IVar_t + \beta_4 Shock * FR + \varepsilon_{it}$$

where Def_t demonstrates the depended variable related to the fiscal deficit, $Debt_{t-1}$ notes the lag public debt, Z_{it} is a vector of control variables including the macroeconomic determinants (economic growth ratio, unemployment ration, inflation ratio), the variable FR_t demonstrates the fiscal rules, $Shock_t$ denotes the diverse shock in the economy (where it equals 1 for the year of shock and 0 otherwise) and variable $IVar_t$ includes the institutional indicators (Government effectiveness, corruption control and public accountability).

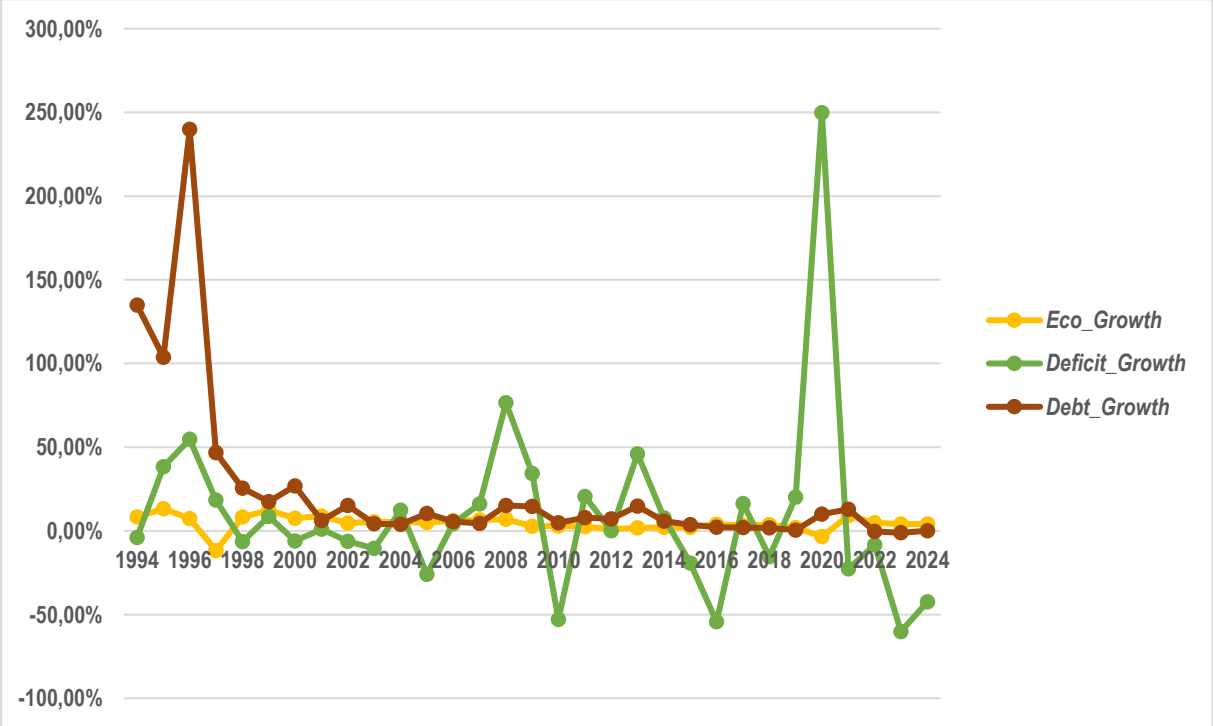
3.2 Contextual background

The following Graph 1 demonstrates the economic growth ratio, the fiscal deficit growth ratio and the public debt growth ratio during 1994 – 2024. It reveals the greatest volatility according to the fiscal deficit growth ratio. These trends related to the fiscal deficit growth rate are explained by the internal

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and external determinants. The graph 1 confirms the highest growth rate of fiscal deficit in 2020, due to the global pandemic, Covid-19, and the subsequent effects of earthquake in 2019, meanwhile it turns out the second highest ratio in 2008, as a result of the global financial crisis of 2008. Likewise, the high fiscal deficit growth rate proves in the electoral years, such as in 2013 and 1996, evidencing the effect of political budget cycles during this period. Nevertheless, the behavior of public debt growth rate demonstrates a moderate stability, except of 1996, where the greatest public debt growth rate evidencing in the graph 1. According to the graph 1, it verifies the downward propensity of public debt growth ratio after 1996, but maintaining the same convergent behavior with the economic growth ratio after 2000 and reducing the gap amongst the economic growth rate and the public debt growth rate. Despite of the steady propensity of public debt growth ratio, also it evidences the high public debt growth rates during 2008 and 2020, due to the external shocks, but throughout 2005, 2009, 2013 and 2021 due to they were designated as the electoral years.

Graph 1 Trends of economic growth, fiscal deficit growth and debt growth during 1994 – 2024



Source: Authors' Computation (2026)

3.2 Empirical results

Table 1 demonstrates the empirical results of the effects of fiscal governance towards the fiscal sustainability, particularly during the diverse shocks, according to four linear model.

The empirical results in Table 1 reveals that all estimated models are statistically significant overall and have the good explanatory power, but the good fit model turns out to model (3). In terms of coefficients, the institutional variables evidence as the most significant: the governance effectiveness is positive and significant in several models, while the public accountability is so significant in model (3). Referring to the empirical results of model (3), it is demonstrated that the public debt with a time lag denotes a negative, but significant effect, suggesting a corrective response of fiscal policy to the increase of public debt. Meanwhile, the macroeconomic variables such as economic growth, inflation and unemployment do not result as statistically significant, except of model (4), where the inflation ration exposes a negative effect and statistically significant. According to the institutional variables, explicitly the government effectiveness and the public accountability, it turns out that the effect of government effectiveness is negative, but insignificant, meanwhile the effect of public accountability is positive and significant. However, it should be noted that the effect of government effectiveness is positive and statistically significant in the results of models (1) and (4).

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The empirical results of model (3) demonstrate that the shocks have a negative effect and are statistically significant, but the fiscal rules and the interaction variable of fiscal rules and shocks are statistically insignificant. Also, the fiscal rules are statistically insignificant, but they expose a positive effect on the fiscal deficit. Otherwise, it should be noted that fiscal rules were not applied for the entire period taking into consideration, but they were applied from 2016 to 2024. Analyzing the empirical results demonstrated in Table 1, it is proven that the responsiveness of the fiscal deficit is influenced by the behavior of public debt and institutional variables. These empirical results do not support the completely convergence according to the theoretical and empirical reviewed literature, but also with the expected results of these variables, where one of the main reasons remains the short time series taken into consideration in the analysis.

Table 1 Empirical results

Variables	Dependent variable: Fiscal Deficit (%GDP)			
	(1)	*(2)*	*(3)*	*(4)*
Debt (lag)	0.023 (0.033)	0.023 (0.034)	-0.088** (0.038)	0.009 (0.029)
Economic Growth	0.010 (0.107)	0.004 (0.110)	0.041 (0.083)	-0.003 (0.105)
Unemployment ratio	-0.174 (0.212)	-0.164 (0.218)	0.006 (0.170)	
Inflation ratio	-0.108 (0.081)	-0.098 (0.086)	0.020 (0.070)	-0.134* (0.074)
Government Effectiveness	4.608** (1.807)	3.548 (3.219)	-0.106 (1.821)	4.958*** (1.744)
Corruption Control		2.328 (5.796)		
Public Accountability			13.070*** (3.257)	
Shock	-1.499 (1.661)	-1.700 (1.766)	-2.916** (1.327)	-1.108 (1.580)
Fiscal Rule	-0.120 (1.449)	-0.158 (1.481)	2.001 (1.235)	0.414 (1.286)
Shock × Fiscal Rule	0.214 (2.000)	0.356 (2.069)	1.540 (1.575)	-0.047 (1.960)
Constant	-1.686 (2.956)	-0.607 (4.038)	-0.454 (2.297)	-3.282 (2.210)
Observations	31	31	31	31
R^2	0.739	0.741	0.853	0.731
Adjusted R^2	0.645	0.631	0.789	0.650
Residual Std. Error	1.776 (df=22)	1.811 (df=21)	1.367 (df=21)	1.763 (df=23)
F Statistic p-value	7.805*** (df=8;22)	6.691*** (df=9;21)	13.490*** (df=9;21)	8.951*** (df=7;23)
Note:	**p<0.1;*	***p<0.05;*	****p<0.01*	

Source: Authors' Computation Using R Studio (2025)

Following to the empirical results in Table 1, the above models are tested through the series of diagnostic tests to verify the validity of their empirical specification. Overall, the diagnostic results accessible in Table 2 support the validity of estimated model (3). Model (3) demonstrated in Table 1 provides a solid basis for empirical interpretation.

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Table 2 Results of validity

Test	Statistics	p-value	Results
Breusch–Pagan (Heteroscedasticity)	6.4265	0.6966	There is no heteroscedasticity.
Breusch-Godfrey (Autocorrelation)	0.0012103	0.9722	There is no autocorrelation.
Ramsey RESET (Model Specification)	0.013729	0.9864	The model is specified correctly.
VIF (Multicollinearity)	1.158	—	There is no multicollinearity.
Jarque Bera Test (Normality)	0.40238	0.8178	The statistical residuals have a normal distribution.

Source: Authors' Computation Using R Studio (2025)

4. Concluding remarks

Referring to the demonstrated empirical results, the measure of fiscal deficit responsiveness contributes to the fiscal sustainability regardless of the presence or absence of shocks in the economy. The empirical results do not demonstrate a procyclicality of fiscal policy through the behavior of fiscal deficit taking into the consideration of the statistical significance of core macroeconomic indicators (such as economic growth, inflation, unemployment). However, it should be noted in this analysis that these macroeconomic indicators contribute in the position of consequence and not cause, orienting for other research areas through longer time series in order to ensure the long-term fiscal sustainability. Furthermore, the behavior of fiscal deficit is counter-reactive linking to the various shocks, indicating a tightening fiscal policy during the considered shocks. Moreover, the similar behavior of fiscal deficit is confirmed towards the public debt accumulated in previous periods.

Meanwhile, the interaction of fiscal rules with shocks does not turn out to be significant, indicating that the fiscal sustainability is a priority regardless of the conditionality of fiscal rules during shocks or the lack of them. However, it is mostly proven related to the empirical results that the institutional variables have a more influential role in the performance of fiscal deficit compared to the macroeconomic variables. This conclusion provides a signal for fiscal policymakers in Albania to pay more attention towards the institutional determinants into the fiscal sustainability, although it needs the additional comprehensive research related to the role of fiscal governance in the long-term fiscal sustainability.

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FULL TEXTS BOOK

FISCAL SUSTAINABILITY IN AN ERA OF GLOBAL UNCERTAINTY: LESSONS FOR PUBLIC FINANCE

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ABSTRACT

The objective of this study was to provide a conceptual and analytical framework for public finance based on recent studies, publications issued by major international organisations, and current issues facing the world's financial markets. The approach used in this research is a description and comparison using the IMF's (International Monetary Fund) fiscal balance data for both the general government and gross debt across various country classifications for the years of 2019 – 2025, as well as a conceptual analysis of recent institutional reports. The study contributes by demonstrating that fiscal sustainability cannot be inferred from common deficit and debt thresholds because financing conditions, monetary backstops and shock-transmission mechanisms differ systematically across country groups. It involves the ability to continue delivering public services, maintain a stable macroeconomic environment, generate sufficient fiscal resources to absorb future economic shocks and similar concepts. In addition, the study identifies many of the most important "lessons learned" by decision-makers in developing countries based upon previous international experience, which could help inform those currently making decisions about their own country's options. The overall results demonstrate that these factors — including high levels of public debt, increasing servicing costs due to higher interest rates, ongoing or recurring budget deficits, demographic challenges and the resulting structural constraints — are all important barriers to achieving sustainable levels of spending through tax revenues and/or borrowing. Therefore, it can be concluded that the ability to support sustainable funding for governmental functions is an essential component of public policy design that supports long-term economic resilience, promotes social welfare programming, and establishes the foundation for sustainable economic development.

Key Words: Economic Resilience, Fiscal Policy, Fiscal Space, Fiscal Sustainability, Global Uncertainty.

JEL Classification: E62; F44; H30; H60; H63.

INTRODUCTION

Fiscal sustainability in times of global uncertainty refers to a state's capacity to sustainably finance its public sector over time by controlling debt levels, ensuring the continuous delivery of public goods and services, and maintaining economic stability. While a sustainable fiscal position is often associated with lower public debt levels, it also encompasses a robust and flexible fiscal framework that is able to meet both the revenue and expenditure requirements of the state in the future. In addition to protecting the stability of public finance, a robust fiscal framework will provide the resilience to withstand shocks from fluctuating economic circumstances. Since the onset of the COVID-19 Pandemic, the global economy has experienced unprecedented uncertainty. It is no longer possible to evaluate the performance of public finances using traditional metrics, such as economic growth and budget balance alone. Public finances are operating in an increasingly complex world. The COVID-19 pandemic, wars, international conflicts, volatile commodity markets (food, energy), inflation, changing interest rates, banking crises, climate change, and changes in global trade all place pressure on the financing structure of states. Thus, an assessment is needed of how well the global environment can withstand financial shocks in terms of public finance resilience and the appropriateness of the fiscal policy response (IMF, 2025a).

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Recent evidence indicates that the global fiscal outlook has deteriorated further since April 2025, as persistently high public debt, rising debt-service burdens, geopolitical tensions and heightened policy uncertainty have intensified risks to fiscal sustainability (IMF, 2026). Perhaps the most significant challenge facing public finances in times of global uncertainty is the rapid and uncontrolled increase in government spending. Governments typically spend large amounts of money during extraordinary events (i.e., economic crises, natural disasters, etc.) to stimulate the economy, protect people who have experienced income loss due to the event, and to continue delivering essential services. At the same time, tax collections decline during periods of economic downturn resulting in rising budget deficits and greater reliance on borrowing.

Consequently, during times of crisis, fiscal policy must address two competing goals: supporting the economy and ensuring long-run fiscal sustainability. Fiscal space represents the capacity of a country's government to implement additional expenditure programs in response to an unforeseen economic crisis or other types of unexpected shocks (IMF, 2020). Countries with excessive debt burdens and persistent deficit budgets and little flexibility to borrow funds, will have less room to manoeuvre when they need to support the economy when a crisis arises. On the other hand, countries with prudent levels of public debt relative to their GDP, robust revenue bases and efficient institutional arrangements for implementing fiscal policy, will be better equipped to deal with economic crises than countries without these attributes.

Establishing fiscal discipline in "normal" times not only improves a nation's budget balance but prepares it for potential future crises (Heller, 2005). Another important lesson from experience with global uncertainty is that public finances should not focus solely on budget deficits and total public debt. With increased global uncertainty come increased fiscal risks for governments. Potential obligations under public-private partnerships agreements, financial difficulties associated with state owned enterprises, unfunded liabilities associated with pension plans, damage from natural disasters and bail outs of financially distressed sectors could all impose significant financial burdens upon the state. Identifying, quantifying, and proactively managing risk is becoming increasingly important in modern public finance.

In addition to establishing fiscal space, another lesson for public finance from experiences with global uncertainty is that the effectiveness of how governments use their fiscal resources is as important as the number of resources available. While spending increases may be required during times of crisis there must also be consideration given to whether these expenditures will produce positive economic and social returns. Public investment in education, health care, infrastructure, digitalization, research and development and innovation can improve human capital over time which can lead to improved productive capacity and enhanced public revenues (Barbiero & Cournède, 2013). In contrast, ineffectively allocating public funds over extended periods results in ongoing burdens on the budget. Therefore, rather than focusing solely on reducing spending, the primary objective of public finance should be to allocate scarce public resources to maximise their positive effects on the economy and society.

FISCAL SPACE AND EXPENDITURE EFFICIENCY UNDER GLOBAL UNCERTAINTY

Under conditions of heightened global uncertainty, framing fiscal policy as a binary choice between increasing and reducing public expenditure provides an excessively narrow representation of the available policy options. Governments may find it beneficial to consider timely, targeted and temporary fiscal interventions that have clearly identifiable cost implications for the general fund. The four main components of medium-term fiscal frameworks (the design of the framework) include (World Bank, (2021):

1) A spending assessment

2) Performance-based budgeting

3) Financial risk reporting

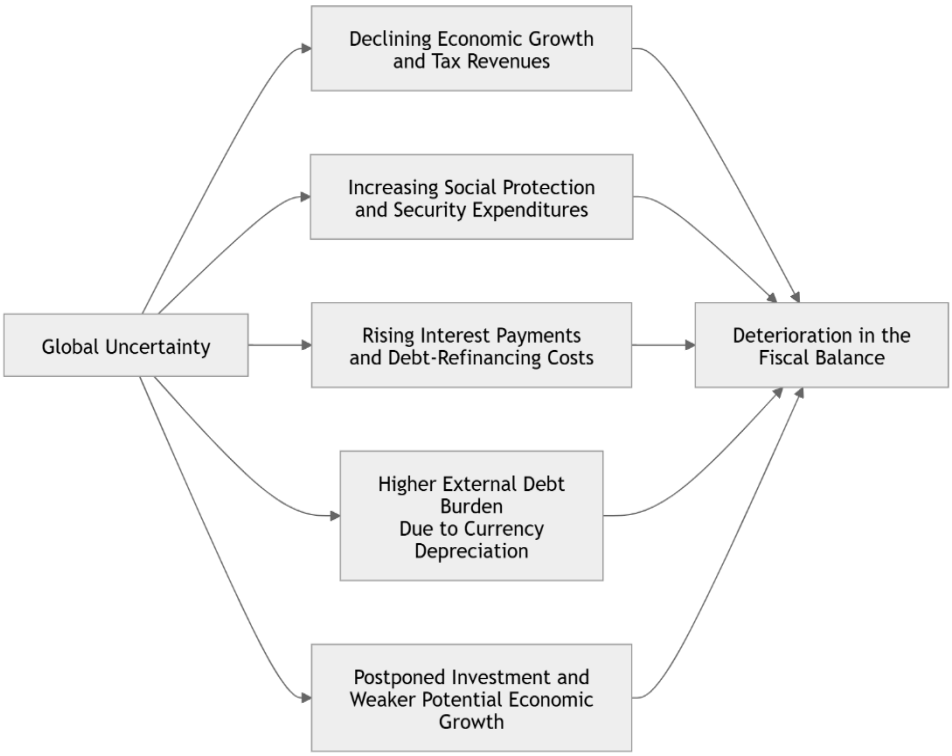
4) An independent audit system

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The ability of a country's budget to withstand shocks and maintain its level of public services is based on both the size of the country's financial resources as well as their effective use in supporting economic progress, social welfare programs, and institutional buffers against economic shocks. Therefore, assessing fiscal space requires an integrated approach that incorporates several factors such as: (i) Maturity and Currency Composition of Debt; (ii) Interest Costs; (iii) Revenue Quality and Tax-Collection Capacity; (iv) Proportion of Non-Discretionary Expenditure; and (v) Institutional Credibility.

A country's fiscal space is neither an immediately available source of funds nor is it automatically equal to its present-day debt-to-GDP. As such, the size of a country's fiscal space is determined by two factors; the amount of current public debt and the ability of the government to produce new primary surpluses, the interest rate charged on its outstanding public debt, its economic growth rates, its perceived sovereign creditworthiness and the degree of confidence that investors have in the fiscal institution of the government (Ostry et al., 2010).

When the effective nominal interest rate on government debt exceeds nominal GDP growth, stabilising the debt-to-GDP ratio requires a stronger primary balance, thereby constraining fiscal flexibility. Conversely, when the effective nominal interest rate remains below nominal GDP growth, debt-rollover pressures are reduced, and policymakers have greater fiscal space. However, this favourable interest–growth differential does not eliminate welfare losses, refinancing risks, or equilibrium multiplicity associated with high levels of government debt (Blanchard, 2019). Therefore, determining the size of a country's fiscal space cannot solely rely on the size of the debt-to-GDP ratio. Fiscal space must also consider the interest-growth gap, the composition and denomination of a country's debt, market confidence and institutional credibility. This integrated assessment is illustrated in Figure 1, with global uncertainty tightening fiscal conditions by increasing the number of transmission channels.



Source: Author's conceptualisation based on IMF (2025a), OECD (2025).

Figure 1. The Transmission Channels of Global Fiscal Uncertainty to the Fiscal Balance

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The major trade-off for policymakers is how to best meet the short-term demands of a crisis (meeting current needs) versus how to maintain fiscal sustainability over time. In addition to creating new demand pressures (e.g., through increased expenditures on health care, disaster relief, etc.), all crises described above simultaneously reduce the availability of funds needed to finance such expenditures.

Efficiency in public spending can be defined as the social and economic value generated by each unit of public expenditure. This implies that governments should attempt to allocate their limited funding into programs that have greater social benefits (healthcare, education, social welfare programs, "green" initiatives and productive infrastructure). Therefore, expenditure efficiency cannot be confused with overall reductions in government spending (across-the-board cuts): poorly planned consolidation may lead to improved headline balances over the near term at the expense of future economic growth or exacerbate sensitivity to future exogenous shocks (OECD, 2017).

THE EVOLUTION OF FISCAL BALANCES ACROSS COUNTRY GROUPS UNDER GLOBAL UNCERTAINTY

Global fiscal positions did not follow a linear path of post-crisis normalisation between 2019 and 2025. The COVID-19 pandemic caused a substantial deterioration in government revenues and fiscal balances in 2020. Fiscal balances partially recovered during 2021–2022 as temporary support measures expired and nominal GDP rebounded. However, starting in early 2023, the increasing levels of geopolitical tensions, rising interest rates, food and energy subsidies and increased defence spending have resulted in very slow economic expansion. Additionally, the current outlook for fiscal balance has deteriorated.

Fiscal Capacity, Policy Space and Uneven Responses to Global Uncertainty

The level of fiscal response to uncertainty varies among countries based on their respective financing capabilities, maturities of their outstanding debt and compositions of their currencies, credibility within institutions, and their specific economic structures. Advanced economies tend to have a greater capability to provide large-scale responses to crises relative to emerging economies, which cannot implement stimulus measures without diminishing market confidence. Developing economies classified as low-income tend to have limited financial capacity to run deficits because of binding financing constraints and limited policy space, rather than fiscal responsibility (Johansson, 2016).

As demonstrated in the years 2019-2025, fiscal space does not exist as a readily available resource for governments to draw upon during periods of post crisis recovery. A clear lesson of the past few years is that having a long-term strategic capability to develop strong public finance practices is essential and should be cultivated during "normal" times. The overall general government fiscal balance includes the budget of the federal government as well as the budgets of all state, local and regional (sub)national governments, social security funds and other entities that are part of the general government. It therefore measures the difference between the sum of revenues from the central and sub-national governments and social security institutions on one hand, and the sum of their expenditure on the other.

When the fiscal balance has a positive value, then there will be a fiscal surplus; when it has a negative value, the entity in question will need to borrow, i.e. it will have a fiscal deficit (De Clerck & Wickens, 2015). Thus, the indicator gives an overview of how financially robust or weak a whole branch of government is by looking at its financial performance across different levels of government. Hence, prior to the emergence of the pandemic-induced economic collapse in 2020, there existed significant heterogeneity in the global economy with respect to fiscal capacity. Particularly, many developing countries entered the 2020 crisis with extremely limited fiscal space resulting from narrower tax bases, higher borrowing costs, reliance upon external funding sources, and vulnerability to exchange-rate risks (Kose et al, 2022). Table 1 below presents the financial dynamics of the General Government Fiscal Balances under Global Uncertainty between 2019 and 2025:

Table 1. General Government Fiscal Balances under Global Uncertainty, 2019–2025

Country Group	2019	2020	2024	2025
World	−3.5	−9.5	−5.0	−5.1
Advanced economies	−3.0	−10.3	−4.7	−4.3
Emerging market and developing economies	−4.4	−8.4	−5.5	−6.1
Low-income developing countries	−4.1	−5.4	−3.4	−3.5

Source: International Monetary Fund (IMF, 2025a), *Fiscal Monitor: Fiscal Policy under Uncertainty*, Washington, DC: International Monetary Fund (IMF) p. 2.

For comparison purposes, 2019 was selected as the benchmark year prior to the onset of the COVID-19 Pandemic. At that time, the combined deficit of governments worldwide was approximately 3.5 percent of Gross Domestic Product (GDP) In developed countries, the deficit ratio was less than that of the world average -- 3.0 percent -- whereas in Emerging Market & Developing Economies (EMDEs), it had risen to 4.4 percent. Likewise, in Low-Income Developing Countries (LIDCs), the deficit ratio had increased to 4.1 percent.

Governments around the world responded to the economic collapse caused by COVID-19 in 2020 through unprecedented increases in governmental spending. As such, there resulted a major decline in fiscal balances across virtually all country groups. The general government deficit worldwide rose by six percentage points over the course of one calendar year, i.e., from 3.5 percent in 2019 to 9.5 percent of GDP in 2020. This is primarily attributable to decreases in taxation revenues, increases in health-related expenditures, increased provision of unemployment compensation and business subsidies, and the use of automatic stabilization devices. Advanced economies were among those experiencing the largest declines in their fiscal balances (Loayza & Pennings, 2020). Specifically, the general government deficit for advanced economies rose from 3.0 percent in 2019 to 10.3 percent in 2020. However, this does not imply that advanced economies possess more fragile fiscal structures than other country groups. Rather, advanced economies typically enjoy lower interest rates, well-developed financial systems, robust support from their Central Banks, and reserves denominated in currencies used as international mediums-of-exchange. Consequently, the large deficits experienced by advanced economies in 2020 reflect not merely deteriorations in their fiscal positions; rather, they reflect both the degree of available fiscal space and their capacity to intervene publicly during times of crisis (OECD, 2025).

Fiscal Sustainability under Global Uncertainty: Cross-Country Heterogeneity in Fiscal Capacity and Policy Adjustment

The current state of increased global instability has moved beyond the definition of fiscal sustainability as simply keeping budget deficits and/or total public debt levels below some threshold (Ghosh et al., 2013). Fiscal sustainability cannot be evaluated with a single universal debt threshold. The fiscal fatigue model argues that initial responses to growing public debt are usually an improvement in a government's primary surplus. However, as debt continues to grow, it becomes increasingly hard for the government to generate the large primary surpluses needed to stabilise the debt. Sovereign risk and default possibilities continue to grow. Thus, we consider a nation's "fiscal space" to be the difference between the current debt ratio and a nation's estimated maximum sustainable level of debt, not simply whether it meets some arbitrary number established by someone outside of the nation (Ghosh et al., 2013).

The main challenge is that although countries are exposed to the same global risks and therefore should be able to respond to those risks with similar fiscal instruments, for the same length of time, they do not.

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Thus, in a world of growing global uncertainty, differences in each country's fiscal capacity; their access to funding sources; the level of trust that investors place in their governments and their institutions; and the range of fiscal policy options available will play significant roles in determining the degree to which a country's fiscal sustainability is affected. This distinction is clear when comparing the pre- versus post-pandemic economic performance across different regions of the world.

Most of the large declines in public revenue experienced during the pandemic were accompanied by very sharp increases in both health-related expenditures and social protection expenditures, as well as expansive policies implemented to stimulate economic recovery. Budget balances declined across nearly all regional groups. However, the rates at which fiscal balances recovered after the pandemic differed dramatically across countries (World Bank, 2020). Countries whose financial systems have been more stable, who have better developed capital markets, and who have higher levels of domestic borrowing capacity were able to continue financing larger budget deficits and accumulating larger amounts of public debt over a longer period than countries whose financial system was less stable; whose capital market was less developed; and/or whose foreign exchange denominated borrowing burden increased faster than other factors (Bank for International Settlements, 2012).

Emerging-market and developing-economy governments faced a smaller space for policy action, due to the effect on their ability to expand fiscal support through exchange rate devaluation, increasing interest rates on government borrowings (higher borrowing costs), decreasing levels of foreign investment into local markets (capital outflows) and increased spread between domestic- and international-interest-rates on government debt obligations (sovereign risk premia). Therefore, improvements in fiscal balances, seen in some countries from 2021 through 2022, should not be taken as an indication that previously identified fiscal vulnerabilities were completely addressed. The reduction of emergency funding, the normalisation of cyclically recovering revenues, the inflation-driven expansion of nominal tax bases, reduced transfer payments associated with unemployment rates, and an increase in nominal GDP have each been factors contributing to what appears to be a correction in fiscal ratios (IMF, 2024; IMF, 2025a). Therefore, post-pandemic fiscal improvement has had some cyclical and accounting factors as opposed to being due to fundamental structural adjustments. Table 2 below presents government fiscal balances across country groups:

Table 2. General Government Fiscal Balances across Country Groups, 2019–2025

Country Group	2019	2020	2021	2022	2023	2024	2025*
World	−3.5	−9.5	−6.3	−3.7	−4.9	−5.0	−5.1
Advanced Economies	−3.0	−10.3	−7.2	−2.9	−4.6	−4.7	−4.3
Advanced Economies excluding the United States	−1.0	−7.6	−4.3	−2.3	−2.5	−2.6	−2.5
Emerging Market and Developing Economies	−4.4	−8.4	−5.0	−4.8	−5.2	−5.5	−6.1
Emerging Markets excluding China	−3.1	−7.8	−4.2	−2.9	−4.2	−4.3	−4.5
Low-Income Developing Countries	−4.1	−5.4	−4.6	−4.5	−3.9	−3.4	−3.5
Oil-Producing Economies	−0.1	−7.3	−0.6	3.0	0.5	−0.9	−1.2

*Figures for 2025 are IMF staff projections

Source: IMF (2025a). *Fiscal Monitor: Fiscal Policy under Uncertainty*, April 2025, Washington, D.C.: International Monetary Fund (IMF).

Table 2 reveals a significant variation among countries in terms of the total budget balance for national governments (central/federal and provincial/state) versus Gross Domestic Product (GDP) during the COVID-19 crisis. Additionally, this table illustrates the non-linear nature of governments' fiscal policy normalization in response to the COVID-19 pandemic. Thus, these countries have not recovered equally from the effects of the pandemic, nor have they done so at equal rates. It is also important to note that

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the global fiscal balance deteriorated from −3.5% of GDP in 2019 to −9.5% in 2020; equivalently, the fiscal deficit widened by 6 percentage points. Furthermore, since 2021 and especially 2022, when all extraordinary government fiscal stimulus programs ended, the deficit fell to -6.3% and then to -3.7%, largely as a direct result of an improvement in economic activity. However, it is interesting to note renewed deterioration/widening in deficits beginning in 2023. The global fiscal balance subsequently deteriorated to −4.9% of GDP in 2023 and −5.0% in 2024, and is projected at −5.1% in 2025, indicating a renewed widening of the global fiscal deficit.

It should be noted that the deterioration in headline fiscal balances was substantially larger in advanced economies, primarily reflecting their greater capacity to finance large-scale countercyclical support. Developed country deficits were -3.0% in 2019 but had dramatically deteriorated to -10.3% in 2020. In addition, the dramatic deterioration in developed country deficits indicates the availability of sufficient resources for extended fiscal support programs in developed countries during periods of crisis. However, the fiscal deficit narrowed to -2.9% of GDP in 2022— extremely close to the levels experienced prior to the pandemic — with a return to a deficit of -4.6% and -4.7% for 2023 and 2024, respectively. While an estimated -4.3% deficit in 2025 would indicate a partial return to normalcy, the fiscal deficit is not projected to return fully to its pre-pandemic level over the forecast horizon. In other words, the most significant obstacle that faces advanced economies is no longer how to substantially decrease the large deficits generated by the crisis; rather, it is how to eliminate much larger structural deficits that emerge subsequent to the crisis (IMF, 2025a; IMF, 2026).

This change illustrates that deficits of developed countries are primarily driven by the fiscal performance of the U.S. In effect, developed countries do not share an identical fiscal adjustment capacity or persistent deficits. However, developing and emerging market economies present a different scenario post-pandemic. In developing/emerging markets, the total government deficit increased from -4.4% in 2019 to -8.4% in 2020. Developing/emerging markets also experienced additional decreases in deficit ratios — i.e., from -8.4% to -5.0% and -4.8% — in 2021 and 2022, respectively. Nonetheless, developing/emerging markets experienced another decrease in fiscal balance post-2023. Furthermore, increasing deficit ratios — i.e., -5.2% in 2023, -5.5% in 2024 and -6.1% in 2025 — illustrate that developing/emerging market fiscal recoveries post-pandemic are unsustainable. Hence, deficit ratios for developing/emerging markets are projected to be roughly 1.7 percentage points higher than in 2019 by 2025. These results demonstrate that developing/emerging market fiscal situations were impacted by both the pandemic and by the continuing financial problems that emerged during the post-pandemic time frame.

Although there was an important fiscal improvement from 2021 to 2022 as a result of the 2020 global economic crisis, we have again seen since 2023 a sharp increase in general government fiscal imbalances. The magnitude and duration of this worsening differ significantly depending on whether it is developing or emerging economies. Advanced economies can generally sustain larger fiscal deficits for longer periods because they have deeper capital markets, lower risk premia and greater monetary and financial capacity than emerging market and developing economies (Blanchard, 2019). Therefore, a given budget deficit in an emerging market economy may pose a greater fiscal sustainability risk than a similarly sized deficit in an advanced economy because of higher borrowing costs, narrower financing options and greater exchange-rate exposure (Reinhart et al., 2003). Therefore, Table 3 points out that when the world is uncertain with regards to what will happen economically, the concept of fiscal sustainability has to take into consideration the gap in the fiscal deficit, but also each country's ability to raise funds (financing capacity), its fiscal resources and the flexibility of its fiscal policy to react to unexpected economic shock. Table 3 presents the evolution of general government gross debt and the resulting pressures on fiscal space across country groups during 2019–2025:

Table 3. General Government Gross Debt and Increasing Pressures on Fiscal Space across Country Groups, 2019–2025*

Country Group / Indicator	2019	2020	2021	2022	2023	2024	2025	Δ 2019–2025 (pp)	Δ 2020–2025 (pp)
World	83.8	98.9	94.0	89.9	91.3	92.3	**95.1**	**+11.3**	−3.8

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Table 3. General Government Gross Debt and Increasing Pressures on Fiscal Space across Country Groups, 2019–2025*

Country Group / Indicator	2019	2020	2021	2022	2023	2024	2025	Δ 2019–2025 (pp)	Δ 2020–2025 (pp)
Advanced Economies	103.6	122.0	115.5	109.3	108.2	108.5	**110.1**	**+6.5**	−11.9
Advanced economies excl. United States	100.4	114.8	109.1	101.7	99.5	98.4	**99.7**	−0.7	−15.1
G7 economies	117.9	139.4	132.3	124.5	122.7	123.2	**124.9**	**+7.0**	−14.5
Euro area	83.6	96.5	93.9	89.5	87.4	87.7	**88.7**	**+5.1**	−7.8
Emerging market and developing economies	54.5	64.1	63.2	63.4	67.4	69.5	**73.6**	**+19.1**	**+9.5**
Emerging market and middle-income economies	55.2	65.0	64.0	64.2	68.2	70.3	**74.8**	**+19.6**	**+9.8**
Emerging markets excl. China	52.0	61.4	58.4	55.0	57.5	56.7	**58.4**	**+6.4**	−3.0
EM & middle-income economies: **Asia**	58.8	68.9	69.6	73.1	77.8	82.3	**87.9**	**+29.1**	**+19.0**
EM & middle-income economies: **Europe**	28.4	36.9	34.4	31.8	33.6	34.9	**37.9**	**+9.5**	+1.0
EM & middle-income economies: **Latin America**	67.5	76.6	70.8	68.3	74.0	70.4	**71.6**	**+4.1**	−5.0
EM & middle-income economies: **MENA**	43.1	54.2	51.3	43.4	44.0	44.6	**47.4**	**+4.3**	−6.8
Low-income developing countries	43.1	50.1	49.4	50.2	53.7	52.7	**52.0**	**+8.9**	**+1.9**
Low-income developing countries: **Sub-Saharan Africa**	43.6	50.1	51.3	53.0	56.3	56.1	**55.4**	**+11.8**	**+5.3**

*General government gross debt is expressed as a percentage of GDP. Figures for 2025 are IMF staff projections based on information available through April 14, 2025. Changes (Δ) are calculated by the author and expressed in percentage points.
Source: IMF (2025a). *Fiscal Monitor: Fiscal Policy under Uncertainty*, April 2025, Washington, D.C.: International Monetary Fund (IMF); IMF (2025b). World economic outlook database: April 2025. Washington, DC: International Monetary Fund (IMF). Retrieved from IMF World Economic Outlook Database.

Table 3 shows that global general government gross debt increased by 15.1 percentage points between 2019 and 2020, rising from 83.8% to 98.9% of GDP. Although the global debt-to-GDP ratio declined somewhat in both 2021 and 2022, the trend reversed itself in 2023. The global debt-to-GDP ratio was projected to reach 95.1 percent in 2025. The global ratio was 11.3 percentage points above its pre-pandemic ratio. Therefore, the post-pandemic decline in debt was a partial reversal of the very large increase in debt caused by the pandemic, not a full reversal of the large increase in debt. Developed countries' government-debt-to-GDP ratio rose from 103.6 percent in 2019 to 122 percent in 2020 before declining to 110.1 percent in 2025. Developed countries were able to provide significant amounts of fiscal assistance during the pandemic and recover enough economically to reduce their debt ratios.

Despite this reduction, developed countries' governments had a higher debt ratio in 2025 than they did in 2019. Specifically, developed countries' governments had a debt ratio that was 6.5 percentage points higher in 2025 than it was in 2019. As such, developed countries have not yet recovered to their pre-pandemic levels of government debt. Another interesting aspect of advanced economies is how much of the aggregate numbers are being affected by one economy: the U.S. Excluding the U.S., the ratio of

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government debt to GDP for advanced economies declines from 100.4 percent in 2019 to 99.7 percent in 2025. At the same time, the ratio of government debt to GDP for all advanced economies increases by 6.5 percentage points from 2019 through 2025. This difference illustrates that the group's averages are weighted by the financial conditions of the largest member economies (IMF, 2025b).

For G7 countries, which represent many of the wealthiest nations in the world including Canada, France, Germany, Italy, Japan, the UK and the U.S., the ratio of government debt to GDP was 139.4 percent in 2020 and reflected how hard these countries hit their economies during the pandemic. While G7 countries saw their ratios fall to 124.9 percent in 2025, these ratios remained 7 percentage points above where they stood prior to the pandemic. Similarly, in the euro area, the government-debt-to-GDP ratio declined from 96.5% in 2020 to 88.7% in 2025, remaining 5.1 percentage points above its 2019 level. These findings illustrate that wealthy countries may be able to reverse some of the damage done by the pandemic to their budgets; nevertheless, high interest rates, aging populations, defence spending, energy transitions, and climate policy may continue to limit fiscal room for manoeuvre.

A final finding of note from Table 3 is that the amount of government debt as a share of GDP rose for emerging market and developing country economies after the pandemic and did so throughout the post-pandemic period (Aligishiev et al., 2023). Although emerging countries typically have lower debt ratios than wealthier nations and therefore often appear to have more fiscal room to manoeuvre, they tend to finance themselves at higher-risk premia than richer countries. Moreover, emerging countries rely far more heavily on short-term financing than do rich countries; consequently, emerging-country governments have a larger component of foreign-currency-denominated government obligations (liabilities). Finally, poor institutions, small tax bases, informal sectors, income volatility, and limited crisis-management capacity can create long-term challenges to maintaining public solvency (IMF, 2024).

DISCUSSION

The results demonstrate that while the improved budget balances since the pandemic do not indicate a restoration of fiscal sustainability, the reduction in budget deficits from 2021-2022 was due to ending emergency funding programs, resumption of economic activity, expansion of the tax base and increased nominal GDP. While these improvements alone are insufficient to show that the government has established more sustainable sources of income and/or more efficiently spends its funds, the growth in deficits subsequent to 2023 and the public debt ratios rising to above the pre-pandemic levels by 2025 suggest that the fiscal adjustments were largely short-term and cyclically driven. As noted previously, the risk associated with a given level of budget deficit or debt stock (i.e., fiscal vulnerability) is determined by factors other than the size of the deficit or stock, including: the cost of issuing new debt; the maturity profile of outstanding debt; the proportion of debt denominated in foreign currencies; the breadth and depth of local capital markets; the ability of governments to collect taxes; institutional credibility; and whether they have access to extraordinary forms of financing.

Therefore, measuring fiscal sustainability through universally applicable numerical thresholds ignores differences in financing conditions and shock-transmission mechanisms across country groupings (Ghosh et al., 2013). In contrast, the sudden and severe decline in fiscal positions experienced by many advanced economies in 2020 represented a manifestation of their ability to fund large-scale expenditure for healthcare, income support and business assistance. Their deep domestic capital markets, low-risk premia, long maturities on their debt and substantial liquidity support provided by their central banks allowed them to continue to fund very large fiscal deficits without losing access to financial markets. Thus, the emergence of large fiscal deficits during the initial stages of the pandemic indicated not only the fiscal fragility of these economies but also their availability of fiscal space (OECD, 2020).

Nevertheless, the ongoing pressures resulting from high interest rates, aging populations, defence spending, energy transitions and the costs of climate-related policies will severely limit fiscal space in these countries going forward. On the other hand, there exists a fundamentally different transmission mechanism at work in emerging market and developing economies. While emerging market and developing economies typically exhibit lower public debt-to-GDP ratios compared to those found in advanced economies, this difference in itself is not sufficient to indicate a larger fiscal space. Emerging

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market and developing economies experience higher borrowing costs, rely on short-term funding arrangements, face capital outflow pressures, are subject to currency fluctuations that affect both their exchange rate values and their terms-of-trade position vis-a-vis foreign creditors, and have a greater percentage of their external obligations denominated in foreign currencies. All of these factors can generate significant fiscal risks -- even if a country exhibits a low debt-to-GDP ratio -- because if the local currency depreciates, the domestic-currency value of foreign-currency-denominated liabilities increases, thereby worsening debt-service burdens and fiscal vulnerability. Additionally, any tightening in global financial conditions raises both the costs faced by these countries in refinancing their existing debts and the costs associated with purchasing additional credit-risk insurance.

Additionally, while inflation may temporarily improve fiscal ratios by boosting tax revenues and nominal GDP, inflation-indexed entitlements would increase the need for countries to make future social transfer payments and borrow to cover their costs. Consequently, the observed declines in fiscal ratios beginning in 2023 reflect that the post-pandemic recoveries have yet to alleviate structurally based vulnerabilities related to financing and exchange rates within these economies. Low-income developing countries' relatively small deficits do not necessarily represent stronger fiscal performance. These countries possess narrow tax bases; underdeveloped domestic financial systems; limited access to international capital markets; and high debt service burdens which prohibit them from implementing comprehensive countercyclical fiscal policies during times of crises (OECD, 2021). Thus, small deficits exhibited by these countries are often indicative of restrictions in their ability to finance activities rather than evidence of prudent fiscal practices. Limited spending on health care, education, social protection programs and infrastructure may reduce budget deficits over time but reduces a country's long-run capacity for growth; depletes human capital development; undermines tax revenues; and ultimately threatens a country's overall fiscal sustainability. For oil-producing countries, fiscal balance largely depends upon commodity prices and hydrocarbon production/revenues. Increases in commodity prices provide additional cash flow during periods where energy prices are high -- although much of this appears as "temporary" as opposed to "permanent." When energy prices drop -- this cash flow disappears rapidly. Thus, these countries must avoid converting temporary commodity price gains into long-term commitments. While advanced countries face long-term spending pressures stemming from managing a high but still manageable level of debt, emerging market economies focus on interest expense and exchange rate risk concerns. Low-income countries concern themselves with access to financing options and generating adequate income streams. Oil-producing countries concern themselves with price volatility as it relates to commodity production.

CONCLUSION

A key takeaway from this study is that the international fiscal outlook for the 2019–2025 period is not just a "crisis normalisation" type of scenario. Although the massive fiscal imbalances resulting from the COVID-19 pandemic were smaller in 2021-2022, it does not necessarily follow that the basic issues with government finances are resolved. A number of factors contributed to an initial reduction in budget imbalance indicators, including the disappearance of emergency support programs, economic recovery, increased tax collection (wider tax base), and a decrease in the demand for social assistance. Nevertheless, a host of challenges to maintaining fiscal balances emerged after 2023 stemming from rising defence spending, high interest rates, price volatility for energy and food products, and costs associated with implementing climate-related policies. Additionally, there are concerns about slowing worldwide economic activity.

These different characteristics among country groups indicate that identical-sized reductions in budget deficits or increases in public sector debt ratios do not pose equivalent levels of fiscal risk. Central banks in advanced economies generally offer strong support to governments when credit spreads are unfavourable. Emerging markets and low-income economies have limited fiscal flexibility even when their public sector debt ratios are significantly below those of advanced economies. From a public finance perspective, one major finding is that governments do not have an easily accessible reservoir of fiscal space to draw on when a crisis arises. Rather, fiscal space needs to be established through setting credible medium-term fiscal frameworks during normal times. Governments should use the opportunity of non-crisis periods to broaden their tax bases, review tax expenditures, issue regular reports on fiscal

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risks and redistribute public resources to sectors with high potential economic and social returns (health, education, social security, productive infrastructure, digitalisation, green transition). Reducing public expenditure is not sufficient to achieve efficient expenditure.

On the contrary, while preserving public spending in socially beneficial sectors, governments should reform inefficient public programs. Otherwise, short-run budget balancing could reduce long-run growth capacities and destabilise debt dynamics in both the medium and long run. Therefore, fiscal support measures should be timely, targeted, temporary and transparently communicated with respect to expected budgetary costs. Finally, under global uncertainty, achieving fiscal sustainability involves much more than satisfying a given threshold for either a country's public debt stock or budget deficit. What counts is whether a government supplies basic public goods and services, maintains its fiscal credibility, and does not use up future options for policymaking during times of crisis. As such, instead of simply focusing on achieving the goal of fiscal restraint (e.g., avoiding excessive borrowing or unsustainable budgets), the central goal of contemporary public finance is to achieve four complementary goals: maintaining fiscal flexibility; improving the efficiency of how government spends money; building credibility into all public institutions, and making the public sector more resilient to economic shocks.

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ASSESSING THE IMPACT OF MANAGERIAL FACTORS ON TOURISM BUSINESS PERFORMANCE IN RELATION TO COST STRUCTURE: THE CASE OF VLORA REGION

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ABSTRACT

This study investigation explores the impact of managerial determinants on the operational efficiency of tourism enterprises, with a particular focus on cost structure dynamics in the Vlora region of southern Albania. Given the region's pronounced dependence on seasonal tourism and its increasingly vital contribution to the national economy, understanding the managerial factors that drive business success holds considerable strategic importance. The research employs a mixed-methods approach, integrating quantitative data from financial statements with qualitative evidence gathered through semi-structured interviews with business managers. The key managerial variables examined include cost planning and control, decision-making processes, strategic orientation, human resource management practices, and the capacity to effectively balance fixed and variable costs. The findings indicate that enterprises operating under high fixed-cost structures are more vulnerable to market volatility, particularly in the absence of effective managerial practices. In contrast, firms that implement flexible cost strategies and exhibit adaptive leadership demonstrate greater financial resilience and enhanced performance. These results underscore the critical role of managerial efficiency and strategic planning in optimizing resource allocation, especially within tourism markets marked by high levels of uncertainty and seasonality. This research contributes meaningfully to the literature on tourism management by offering evidence-based recommendations aimed at improving enterprise performance through cost structure optimization and the development of capacity-building initiatives tailored to tourism managers in emerging regional markets.

Keywords: Tourism business performance, cost structure, strategic management, resource allocation, seasonal tourism, managerial efficiency.

Introduction

Tourism has become a major engine of economic activity, employment creation and regional development for Albania. Coastal destinations have been expanding especially fast, driven by the increase in domestic and international demand, investment in accommodation infrastructure and the growth of tourism-related services. Within this context, Vlora represents one of the most significant tourism destinations in southern Albania. The development of tourism creates substantial opportunities for local enterprises, but it also generates managerial challenges. Tourism businesses operate in an environment characterised by demand uncertainty, strong competition, changing consumer preferences, labour-market constraints and significant seasonal fluctuations. These characteristics make managerial efficiency an important determinant of enterprise performance. One of the most important structural characteristics of tourism in Vlora is its seasonality. Much of the tourism demand is concentrated in the summer months, with many enterprises experiencing a large fall in demand for the rest of the year. There is an inherent imbalance between revenues and expenses. Revenue fluctuates according to occupancy and customer demand, whereas many costs remain relatively stable. This problem becomes particularly important for enterprises with high fixed costs. Rent, depreciation, permanent salaries, financing costs, maintenance, insurance and administrative expenditures may continue even when the number of customers decreases.

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The relationship can therefore be expressed as:

Total Cost = Fixed Cost + Variable Cost

While variable costs generally respond to changes in activity, fixed costs create a continuing financial obligation. Consequently, a decline in occupancy may produce a disproportionate decline in profitability. At the same time, the existence of fixed costs creates the potential for economies of scale. When a tourism enterprise increases its volume of activity without a proportional increase in total costs, fixed costs are distributed across more customers or service units. Average cost consequently decreases. The central issue is therefore not simply whether tourism enterprises should grow, but whether they can operate at an economically efficient scale while maintaining sufficient capacity utilisation throughout seasonal fluctuations. The objective of this study is to examine the interaction between managerial efficiency, cost structure, economies of scale and seasonality and to identify managerial practices that can improve operational and financial performance among tourism enterprises in Vlora.

Conceptual Framework

➢ Structure of Cost and Performance The financial performance of a business is a key indicator of its sustainability.

In simple terms, profitability is**: Profit = Revenue − Total Costs.**

This relation indicates that, in case of higher revenues, higher profits are not guarantyd if costs rise in the same proportion or faster.Effective management must therefore seek an appropriate balance between revenue generation, expenditure and service quality. Tourism businesses normally operate with a combination of fixed and variable costs. Fixed costs include rent, depreciation, permanent salaries, insurance, maintenance and administrative expenditure, whereas variable costs may include food and beverage inputs, temporary labour, cleaning materials, commissions and other consumables. During low-demand periods, fixed costs can become a major source of financial pressure. Managers consequently need mechanisms for forecasting demand, adjusting variable costs and improving resource utilization. Cost management should not be interpreted simply as cost minimization. Overly aggressive cuts in staffing, maintenance, product quality or customer services can hurt customer satisfaction and revenues in the future. The strategic objective is cost optimization: achieving efficiency while preserving the quality and competitiveness of the tourism product.

➢ Management Capabilities

Management capabilities include strategic planning, financial management, decision-making, human-resource management, market analysis, problem-solving and resource allocation. In tourism, these capabilities are especially important because managers must make decisions under changing demand conditions. Effective planning can help businesses anticipate seasonal fluctuations, organize staff, control procurement and allocate resources to the most profitable activities.Strong managerial capabilities may therefore affect financial performance through several mechanisms. Better budgeting can reduce unnecessary expenditure; improved workforce planning can reduce labour inefficiency; stronger procurement practices can control input costs; and better market analysis can support pricing and service decisions. The expected relationship is consequently positive: as management capabilities improve, the probability of achieving a higher financial-performance category should increase.

➢ Management Innovation

Management innovation extends beyond technological innovation. It includes new or substantially improved organizational procedures, financial-control systems, employee-management practices, customer-management methods, decision-making systems and approaches to resource allocation. Digital reservation systems, data-supported pricing, digital accounting and integrated customer-management systems are examples of practices that can improve managerial efficiency. Innovation can be particularly valuable for tourism businesses because it allows managers to respond more rapidly to changes in demand. Innovative practices can reduce transaction costs, improve information availability, increase operational efficiency and strengthen customer relationships. The expected relationship between management innovation and Profit is therefore also positive.

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Methodology

➢ **Research Design and Data**

The empirical analysis follows a quantitative econometric design. The models presented are Ordered Logit specifications, appropriate for an ordered dependent variable representing financial-performance outcomes. The reported estimations use 210 valid observations, with one missing or incomplete observation excluded.

➢ **Econometric Model**

The ordered-logit framework estimates the probability that an observation belongs to a particular ordered category of the dependent variable. Conceptually, the model can be represented as $P(Y_i \leq j) = 1/[1 + \exp(-(\alpha_j - X_i\beta))]$, where Y represents the ordered financial-performance outcome, X represents the managerial explanatory variable, β is its estimated coefficient and α represents the threshold parameters. A positive coefficient indicates that higher values of the explanatory variable are associated with a greater tendency toward higher categories of the ordered outcome, assuming the model conditions are satisfied.

Two separate specifications are considered in order to identify the contribution of management capabilities and management innovation. This approach provides a direct empirical test of the two managerial components included in Hypothesis.

Results and Discussion

The study tests the following hypothesis exactly as formulated in the research framework:

Hypothesis: There is significant positive relationship between Financial performance and management capacities as well as management innovation.

For empirical interpretation, hypothesis is examined through two related relationships: management capabilities with financial performance and management innovation with Profit. The statistical decision is based primarily on the sign and significance of the estimated coefficients.

➢ Management Capabilities and Financial Performance

Model estimates the relationship between management capabilities and financial performance. The reported coefficient is 0.775078, with a standard error of 0.223156 and a z-statistic of 3.473. The corresponding p-value is 0.0005

Model 8: Ordered Logit, using observations 1-211 (n = 210)
Missing or incomplete observations dropped: 1
Dependent variable: Fitim
Standard errors based on Hessian

	Coefficient	*Std. Error*	*z*	*p-value*	
Management capacities	0.775078	0.223156	3.473	0.0005	***
cut1	−1.37632	0.521768	−2.638	0.0083	***
cut2	1.96163	0.496569	3.950	<0.0001	***
cut3	4.35487	0.581570	7.488	<0.0001	***
cut4	7.09831	1.13301	6.265	<0.0001	***

Mean dependent var	1.438095		S.D. dependent var	0.711139
Log-likelihood	−215.6422		Akaike criterion	441.2844
Schwarz criterion	458.0199		Hannan-Quinn	448.0499

Number of cases 'correctly predicted' = 108 (51.4%)
Likelihood ratio test: Chi-square(1) = 77.3209 [0.0000]

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The positive coefficient demonstrates that management capabilities are positively associated with the financial-performance outcome. The p-value of 0.0005 is considerably below 0.05, indicating strong statistical significance. The likelihood-ratio test provides additional evidence of model significance, with LR Chi-square(1) = 77.3209 and p < 0.0001. The model correctly predicts 108 observations, or 51.4% of cases.The evidence therefore supports the first component of H3. The magnitude and sign of the coefficient indicate that management capabilities are an important managerial factor associated with stronger financial performance. In practical terms, businesses with stronger planning, control, coordination and decision-making capacities are more likely to achieve better financial outcomes.

➢ *Management Innovation and Profit*

Model estimates the relationship between management innovation and Profit. The coefficient for management innovation is 0.531561, with a standard error of 0.215076 and a z-statistic of 2.472. The p-value is 0.0135.

Model 9: Ordered Logit, using observations 1-211 (n = 210)
Missing or incomplete observations dropped: 1
Dependent variable: ***Profit***
Standard errors based on Hessian

	Coefficient	*Std. Error*	*z*	*p-value*	
Management innovation	0.531561	0.215076	2.472	0.0135	**
cut1	−1.80181	0.529489	−3.403	0.0007	***
cut2	1.47804	0.489637	3.019	0.0025	***
cut3	3.81952	0.561773	6.799	<0.0001	***
cut4	6.54410	1.12111	5.837	<0.0001	***

Mean dependent var	1.438095		S.D. dependent var	0.711139
Log-likelihood	−218.8204		Akaike criterion	447.6407
Schwarz criterion	464.3762		Hannan-Quinn	454.4063

Number of cases 'correctly predicted' = 110 (52.4%)
Likelihood ratio test: Chi-square(1) = 70.9645 [0.0000]

The coefficient is positive and statistically significant at the 5% level. Thus, higher management innovation is associated with movement toward higher Profit categories. The likelihood-ratio test is also statistically significant: LR Chi-square(1) = 70.9645, p < 0.0001. The model correctly predicts 110 observations, equivalent to 52.4% of cases.

These results support the second component of H3. Management innovation appears to contribute to financial performance by improving organizational efficiency, information use, adaptability and the ability to respond to market conditions.

Hypothesis Testing

Component	Variable	Coefficient	p-value	Decision
Ha	Management capabilities	0.775078	0.0005	Supported
Hb	Management innovation	0.531561	0.0135	Supported

Both estimated coefficients are positive and statistically significant. Therefore, the empirical evidence supports Hypothesis: there is a significant positive relationship between financial performance and management capabilities as well as management innovation. The statistical evidence is consistent across the two models and is reinforced by the highly significant likelihood-ratio tests.

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It is important, however, to distinguish statistical association from a definitive causal effect. The coefficients establish a statistically significant relationship within the estimated models; stronger causal conclusions would require an appropriate longitudinal or experimental design and additional controls.

Discussion and Conclusion

Discussion

The findings demonstrate that managerial quality is a meaningful component of tourism-business performance. Management capabilities have the stronger estimated coefficient of the two focal variables (0.775078 versus 0.531561), suggesting a particularly important association with the ordered financial-performance outcome in the present specifications. This does not imply that management innovation is unimportant; rather, both dimensions contribute statistically significant information about financial performance.

The results can be interpreted through the characteristics of tourism enterprises. Managers must continuously coordinate labour, supplies, accommodation or service capacity, customer relations and financial resources. In a seasonal destination, these decisions become more complex because demand changes considerably across the year. A manager with strong planning and control capabilities can adjust operations to these changes, while an innovative manager can introduce new procedures and tools that make such adjustment more efficient.

The cost structure plays a central role in this account. It may be that the business is still active but the profitability is decreasing if demand decreases, and the fixed costs are relatively constant. Good managerial practices can help to minimize avoidable variable costs, increase capacity utilization and support diversification during low season. At the same time, innovation can improve information flow and enable more timely responses to demand changes.

The findings are also consistent with the broader view that innovation in tourism is not restricted to new products. Organizational and managerial innovation may be equally important because it changes the way resources are coordinated and decisions are implemented. Consequently, investment in managerial knowledge and organizational improvement can represent an indirect investment in financial sustainability.

Conclusion

This study examined the relationship between management capabilities, management innovation and financial performance in tourism businesses in the Vlora Region. The proposed hypothesis is supported by empirical evidence obtained from two Ordered Logit models. Model showing that management capabilities have a positive and significant relationship with financial performance ($\beta = 0.775078$; $p = 0.0005$). Model shows positive and significant relationship between management innovation and Profit ($\beta = 0.531561$; $p = 0.0135$). Both likelihood-ratio tests are highly significant, which further supports the idea that the estimated relationships are meaningful within the models. The general conclusion states that better financial performance is related to better managerial capabilities and better management innovation. Managerial competence is very important for tourism enterprises working in a seasonal environment like that of Vlora, since profitability relies on the capacity to coordinate resources, control costs, keep service quality and adjust operations to changing demand. Management innovation strengthens this capacity by introducing more efficient organizational and decision-making practices.Accordingly, Hypothesis is supported by the reported econometric evidence. The findings underline the need for tourism enterprises and destination stakeholders to treat

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ASSOCIATION BETWEEN BASELINE CAIT SCORE AND CHANGES IN JUMP PERFORMANCE AND ANKLE STRENGTH IN ATHLETES WITH CHRONIC ANKLE INSTABILITY

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Background: Chronic ankle instability (CAI) is characterized by recurrent episodes of ankle instability and persistent performance deficits following lateral ankle sprain. The Cumberland Ankle Instability Tool (CAIT) is a validated patient-reported measure of ankle instability severity; however, whether baseline CAIT severity is associated with subsequent changes in objective performance remains unclear.

Objective: To examine the association between baseline CAIT scores and changes in jump performance, reactive strength, and ankle muscle strength following rehabilitation in athletes with CAI.

Methods: Seventy-eight athletes with CAI were allocated to a control group (CG), exercise group (EG), or exercise plus kinesio taping group (EG+KT; n=26 each). EG and EG+KT completed a six-week balance and resistance training program, with EG+KT additionally receiving kinesio taping. Countermovement jump (CMJ) performance and 40-cm drop-jump contact time and reactive strength ratio (RSR) were assessed using a ground reaction force platform, while ankle inversion and eversion strength were measured using an EasyForce® dynamometer. Pearson correlations examined associations between baseline CAIT scores and pre-to-post changes in each outcome.

Results: Baseline CAIT scores were not significantly associated with changes in CMJ performance (r=.088, p=.442), RSR (r=.003, p=.980), drop-jump contact time (r=.057, p=.618), inversion strength (r=.038, p=.741), or eversion strength (r=−.003, p=.983). All associations were negligible ($|r|\leq.088$).

Conclusion: Baseline CAIT scores were not associated with changes in jump performance, reactive strength, or ankle muscle strength, indicating that athletes with greater initial ankle instability did not systematically improve more or less than those with milder instability. Baseline CAIT severity therefore showed limited association with rehabilitation-related changes in the objective outcomes assessed.

Keywords: chronic ankle instability; Cumberland Ankle Instability Tool; countermovement jump; reactive strength; ankle strength; rehabilitation**.**

Introduction

Lateral ankle sprain (LAS) is one of the most common musculoskeletal injuries encountered in sport and physical activity, and a substantial proportion of affected individuals develop persistent symptoms and recurrent instability after the initial injury. Chronic ankle instability (CAI) is characterized by recurrent ankle sprains, repeated episodes or perceptions of "giving way," and persistent symptoms such as pain, weakness, restricted motion, and reduced self-reported function. Rather than representing a single impairment, CAI is currently understood as a heterogeneous and multifactorial condition involving interacting mechanical, sensorimotor, and motor-behavioral deficits [1,2].

The assessment of perceived ankle instability is therefore an important component of both CAI identification and clinical evaluation. The Cumberland Ankle Instability Tool (CAIT) is a nine-item, 30-point patient-reported questionnaire developed to quantify the severity of functional ankle instability, with lower scores reflecting greater perceived instability[3]. The instrument has demonstrated good validity, internal consistency, and excellent test–retest reliability[3]. Condition-specific self-reported measures such as the CAIT are recommended for identifying individuals with CAI in research settings[4].

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More recent evidence has also supported the applicability and internal consistency of the CAIT in athletic populations, including elite volleyball players[5]. However, as a patient-reported measure, the CAIT primarily captures perceived ankle instability and related functional limitations rather than directly measuring objective physical performance.

Individuals with CAI may exhibit sensorimotor impairments across several domains, including balance, functional performance, muscle function, and proprioception[6]. Alterations in neuromuscular control and lower-extremity biomechanics have also been identified during dynamic jump-landing tasks in individuals with CAI[7]. Specifically, individuals with CAI demonstrate altered ankle kinematics during the drop-vertical jump compared with healthy controls[8]. These findings highlight the presence of objective sensorimotor and movement-related alterations in CAI that may not be fully captured by patient-reported measures of ankle instability.

Despite the established role of the CAIT in identifying and quantifying perceived ankle instability, it remains unclear whether baseline CAIT severity is associated with the magnitude of subsequent changes in objective physical performance following rehabilitation. Clarifying this relationship is clinically relevant, as baseline CAIT scores are readily available and could potentially provide information about rehabilitation-related changes beyond their established role in characterizing perceived ankle instability.

Therefore, the purpose of this study was to examine the association between baseline CAIT scores and pre-to-post changes in countermovement jump performance, drop-jump contact time, reactive strength ratio, and ankle inversion and eversion strength in athletes with CAI following a six-week rehabilitation period.

Materials and Methods

Study Design

This study used data from a randomized controlled trial evaluating a six-week balance and strength rehabilitation program, performed with or without kinesio taping, in athletes with chronic ankle instability (CAI). Participant recruitment, assessments, intervention, and follow-up were conducted between November 2024 and May 2025 at the Biomechanics Laboratory of the Sports University of Tirana. The study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Ethics Committee of the Sports University of Tirana (Protocol No. 3109/2, November 6, 2024). Written informed consent was obtained from all participants before enrolment. The trial was retrospectively registered at ClinicalTrials.gov (NCT07427290).

Participants

Seventy-eight collegiate athletes aged 18–25 years from volleyball, basketball, and football completed the study. Participants had at least three years of regular sports training experience and trained 2–3 times per week for approximately 1–2 hours per session. Eligibility was determined according to the International Ankle Consortium criteria[4]. Inclusion criteria comprised a history of at least one lateral ankle sprain ≥12 months before enrolment, the most recent ankle sprain ≥3 months before inclusion, more than two episodes of "giving way," and a Cumberland Ankle Instability Tool (CAIT) score ≤25[4]. Exclusion criteria included previous lower-extremity musculoskeletal surgery, lower-limb fractures or other orthopedic conditions, musculoskeletal injury within the previous three months[4], and neurological or vestibular disorders that could affect neuromuscular function or functional performance.

Participants were randomly allocated in a 1:1:1 ratio to an Exercise Group (EG), Exercise plus Kinesio Taping Group (EG+KT), or Control Group (CG), with 26 participants in each group. Outcome assessors and the statistician were blinded to group allocation.

Rehabilitation Protocol

Participants in the EG and EG+KT completed a supervised six-week rehabilitation program performed three times per week, with each session lasting approximately 35–40 minutes. The program combined progressive balance exercises on a wobble board[9] with ankle resistance exercises using elastic bands

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(TheraBand)[10]. Exercises were performed using the limb affected by CAI. The EG+KT received kinesio taping approximately 20 minutes before each rehabilitation session[11], whereas the CG continued their usual sports activities without receiving the structured rehabilitation program.

Outcome Assessments

All measurements were performed before and after the six-week intervention under standardized laboratory conditions. CAI severity was assessed using the Cumberland Ankle Instability Tool (CAIT), a nine-item patient-reported questionnaire scored from 0 to 30, with lower scores indicating greater perceived ankle instability[3,12].

Countermovement jump (CMJ) performance was assessed using the Leonardo Mechanograph GRFP STD force plate system (Novotec Medical GmbH, Pforzheim, Germany). Participants performed three bilateral CMJs with maximal effort, separated by one-minute recovery periods. The highest jump height (m) was retained for analysis[13,14].

Drop-jump performance was assessed using the same force plate system from a 40-cm platform. Participants were instructed to land bilaterally and immediately jump vertically while minimizing ground-contact time. Three valid trials were performed with approximately 60 seconds of recovery between trials, and the mean value was used for analysis[15,16]. Contact time (tc) and the flight time-to-contact time ratio (ta/tc), referred to as the reactive strength ratio (RSR), were automatically calculated by the manufacturer's software.

Isometric ankle inversion and eversion strength were assessed on the affected limb using the EasyForce® Digital Dynamometer (Meloq Devices, Stockholm, Sweden). Participants performed three maximal voluntary isometric contractions for each movement direction, each lasting 3–5 seconds, with 10 seconds of rest between trials. The mean of the three trials was used for analysis and expressed in Newtons (N)[17,18].

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, version 26.0 (IBM Corp., Armonk, NY, USA). Data normality was assessed using the Shapiro–Wilk test.

Pearson correlation coefficients (r) were calculated to examine the associations between baseline CAIT scores and pre-to-post changes in CMJ height, drop-jump contact time, RSR, ankle inversion strength, and ankle eversion strength across the study sample. Statistical significance was set at $p < 0.05$.

Results

Baseline Characteristics

Seventy-eight athletes with CAI were included in the analysis, with 26 participants in each group. Baseline characteristics were comparable across the three groups, with no statistically significant differences in age, body weight, height, BMI, or CAIT score (all $p > 0.05$). Mean baseline CAIT scores were 19.35 ± 2.51 in the CG, 19.04 ± 3.32 in the EG, and 19.92 ± 2.51 in the EG+KT group ($p = 0.517$) (Table 1).

Table 1. Baseline Characteristics by Group

Variable	CG (Mean ± SD)	EG (Mean ± SD)	EG+KT (Mean ± SD)	F	p-value
Age	19.42 ± 2.35	20.12 ± 1.68	19.88 ± 0.99	1.037	0.36
Weight (kg)	77.53 ± 11.86	76.29 ± 14.49	73.36 ± 12.95	0.69	0.505
Height (m)	1.8 ± 0.06	1.77 ± 0.07	1.78 ± 0.06	2.089	0.131
BMI	23.8 ± 3.25	24.34 ± 3.72	23.19 ± 3.57	0.693	0.503
CAIT score	19.35 ± 2.51	19.04 ± 3.32	19.92 ± 2.51	0.666	0.517

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Association Between Baseline CAIT and Changes in Performance Outcomes

Pearson correlation analysis was performed to examine the association between baseline CAIT scores and pre-to-post changes in objective performance and ankle strength outcomes (Table 2). No statistically significant associations were observed for any of the assessed outcomes. Baseline CAIT scores showed negligible correlations with changes in countermovement jump height ($r = 0.088$, $p = 0.442$), reactive strength ratio ($r = 0.003$, $p = 0.980$), drop-jump contact time ($r = 0.057$, $p = 0.618$), ankle inversion strength ($r = 0.038$, $p = 0.741$), and ankle eversion strength ($r = -0.003$, $p = 0.983$).

Table 2. Pearson Correlation between Baseline CAIT Score and Change Scores

Outcome	Pearson r	p-value
Countermovement Jump performance Change	0.088	0.442
Reactive Strength Ratio	0.003	0.980
Drop jump (contact time) Change	0.057	0.618
Ankle inversion strength Change	0.038	0.741
Ankle Eversion Strength Change	-0.003	0.983

Discussion

The main finding of the present study was that baseline CAIT scores were not significantly associated with changes in countermovement jump height, reactive strength ratio, drop-jump contact time, or ankle inversion and eversion strength following the six-week rehabilitation period. All correlations were negligible ($r = -0.003$ to 0.088), indicating that, within the range of CAIT scores represented in this cohort, greater perceived ankle instability at baseline was not associated with either greater or smaller subsequent changes in objective performance and strength outcomes.

Previous studies have shown that the relationship between CAIT scores and objective neuromuscular function is not uniform across different outcomes. Significant associations have been reported between CAIT scores and selected measures of ankle strength and dynamic balance, whereas other measures, including eversion strength, were not significantly associated with CAIT[19]. Associations between CAIT scores, hip abductor strength, and functional performance have also been observed in women with CAI, but not in men, further suggesting variability in the relationship between perceived instability and objective function[21]. Importantly, these studies examined CAIT and objective function concurrently, whereas the present study investigated whether baseline CAIT was associated with the magnitude of subsequent change following rehabilitation. Thus, an association between CAIT and physical function at a given time point does not necessarily imply that CAIT is associated with the extent of subsequent functional change.

This distinction may reflect the multifactorial nature of CAI and the difference between perceived instability and objectively measured physical impairment. Objective ankle strength deficits are well documented in CAI, with evidence of deficits in ankle invertor and evertor strength compared with uninjured controls[20]. However, the presence of these deficits does not establish that their subsequent change during rehabilitation will correspond to baseline perceived instability. CAIT scores have also been shown to be more strongly associated with global perception of ankle instability ($\rho = 0.76$) than with the broader Lower Extremity Functional Scale ($\rho = 0.50$)[3]. Together, these findings support the view that patient-reported instability and objective physical function capture related but distinct aspects of CAI.

From a clinical perspective, the present findings suggest that baseline CAIT score alone may have limited value for anticipating changes in jump-related performance or ankle strength following rehabilitation. The CAIT remains a valid and reliable measure for quantifying perceived functional ankle instability[3], but objective performance and strength assessments may provide complementary information when evaluating rehabilitation-related changes. Accordingly, assessment of athletes with CAI may benefit from combining patient-reported instability with objective measures rather than relying on CAIT severity alone.

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Several limitations should be considered. The restricted range of baseline CAIT scores resulting from the eligibility criteria may have attenuated the observed correlations, and the analysis across the entire cohort did not account for potential differences in rehabilitation exposure among the three study groups. Future studies with larger samples and broader CAIT severity ranges are warranted.

Conclusion

Baseline CAIT severity was not associated with changes in jump performance, reactive strength, or ankle inversion and eversion strength following rehabilitation in athletes with CAI. These findings suggest that perceived ankle instability at baseline and changes in objective neuromuscular performance represent distinct aspects of rehabilitation assessment. Combining patient-reported and objective measures may therefore provide a more comprehensive evaluation of athletes with CAI.

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PROMOTING TOURISM THROUGH MAPS AND CATALOGUES: CASE STUDY - MUNICIPALITY OF SUHAREKA (KOSOVA)

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ABSTRACT

The Municipality of Suhareka (ancient Theranda) occupies a strategic position in Kosovo, serving as a historical and modern transit corridor. Despite its rich prehistoric archaeology, unique viticulture landscape, its regional tourism potential remains underutilized due to the lack of synthesized spatial and visual frameworks. This study systematic inventories and analyzes the municipality's spatial, historical, and socio-economic assets to develop dedicated thematic maps and tourism catalogs for sustainable regional development. The methodology utilizes a four-tiered interdisciplinary approach: a comprehensive literature and institutional document review, Geographic Information Systems (GIS) for spatial mapping and tourist route optimization, high-resolution drone for aerial heritage site documentation, and digital frameworks for online promotional dissemination. The results establish a digitized, dual-component tourism framework that successfully bridges and visualizes localized assets, which in the municipality are ranging from the prehistoric Hisar site to active agrotourism zones, cultural festivals (Festari, Golden Eagle Carnival), and modern sporting landmarks (KF Ballkani). The study concludes that integrating Suhareka's historical, industrial, and spatial data into formalized maps and catalogs provides a vital tool for local governance. This framework effectively counters chaotic high-density urban development, preserves historical memory, and transitions Suhareka from a mere transit node into a digitally visible, distinct regional tourism destination.

Keywords: Kosovo, catalogs, GIS, archeological and historical facts, promote tourism.

INTRODUCTION

Some of the main concepts related to tourism are leisure, entertainment, hospitality and recreation However, tourism is the most difficult to define and researchers have not yet come to a consensus about it. Authors like Fuster (1971), LeiPer (1979), Sessa (1985), Molina (1991) Palomo (1991), Ascânio (1992), Jafari (1995), Beni (1988), and Boullón (2002), didn't graduate in tourism, but in other fields like administration, architecture, biology, communication among others. (A. P. Netto 2009).

Wahab (1977: 26) defined tourism as: A human intentional activity that serves as a mean of communication and as a link of interaction between the peoples, inside a country or even beyond its geographical demarcations. It involves the temporary displacement of people from one region to another, country or even continent, with the objective of satisfying necessities and not the realization of remunerated activity. For the visited country, tourism is an industry whose products are consumed in loco, producing invisible exports.

Tourism is defined by UNWTO a social, cultural and economic phenomenon which entails the movement of people to countries or places outside their usual environment for personal or business/professional purposes. These people are called visitors (which may be either tourists or excursionists; residents or non-residents) and tourism has to do with their activities, some of which involve tourism expenditure. The tourism, as a phenomenon of local to global impact, and complex

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activity with complex effects, from the economic to the social ones and, not least with influence on the environment, determined a new way of cohabitation between the natural and anthropic and anthropogenic environment through tourism. Its bipolar character phenomenon and business - has given it a particular position among other categories of activities, such as generating flows of tourism product consumers, from the area of origin, or the tourist market, to the tourist's destination area, including touristic attractions belonging to the natural and man-made environment, or primary touristic offers, which includes the tourism infrastructure with different size and complexity. (N. Ciangă, V. Sorocovschi 2017)

The map is defined as 'a representation or abstraction of geographical reality: a tool for presenting geographical information in a way that is visual, digital, or tactile' (Board 1990). Clearly, the map in the 90's was seen as a communication tool (technology) that includes multimodal ways of representation (art), without any explicit references to science or use. Going further back in time, ICA's Commission II, then responsible for the Multilingual Dictionary of Technical Terms in Cartography proposed the following map definition: 'A representation, normally to scale and on a flat medium, of as election of material or abstract features on, or in relation to, the surface of the earth or of a celestial body' (ICA, 1973). Maps are "neatly drawn, bird's-eye views of the earth's surface. They show where places and things are located and help us find our way from one place to another" (Campbell, 1998).

Touristic catalogues, in academic research papers, often analyzed interchangeably with tourist brochures, leaflets, or booklets, are defined as multimodal promotional texts that combine verbal and visual elements to construct a desired destination image, inform consumers, and influence holiday choices.

The Municipality of Suhareka is located in the southern part of Kosovo. It borders the municipalities of Prizren, Mamusha, Rahovec, Malisheva, Lipjan, Shtime, Ferizaj, and Shtërpce (Osmani, J.2008). It extends across the following latitudes: 42°15'to 42°30' (N). Its longitudinal range extends from 20°45' to 21°00' (E). (PZHK 2018). Comprising 42 cadastral zones, the municipality has a boundary perimeter of 103 km and an area of 361 km², covering 3.3% of Kosovo's territory and 25.22% of the Prizren region. It enjoys a favorable geographical location that has historically served as a crossroads for regional and wider transport routes, connecting major centers across Albanian lands. Notable among these is the Lissus–Naissus (Lezhë-Niš) route, which linked the Adriatic to the interior of the Illyrian Peninsula and connected important centers such as Singidunum (Belgrade), Naissus, Vendenis (Gllamnik-Podujevë), Vellanis (Prishtina), and Vicianum, continuing on to Therandë, Prizren, Gabuleum (Kukës), and Lissus (Lezhë) (Leksikoni 2018). In the vicinity of the town, one encounters the toponyms Hisar, Dubiçak, and Shirokë; traces found there indicate the settlement's development since prehistoric times (8th7th centuries BCE) - archaeological evidence testifying to trade links between the area's inhabitants and other locations along the Adriatic Sea. It is first mentioned by this name in 1348. The renowned travel writer Ami Boué, passing through the settlement in 1836, noted the presence of only Albanian inhabitants. (Encyclopedic Dictionary of Kosovo, 2018) According to the 2024 General Population Census, the Municipality of Suhareka has a population of 45,749 (KSA, 2024).

The aim of this study is to promote the tourism potential of the Municipality of Suhareka through the development of thematic maps and tourism catalogues that integrate its historical, cultural, natural, and socio-economic assets. The study aims to enhance their visibility and accessibility, support sustainable tourism planning, and provide a practical framework for local governance and regional tourism development.

MATERIALS AND METHODS

This study used an interdisciplinary approach combining documentary research, GIS, drone, field survey, and cooperation with a local NGO. The goal was to identify, map and visually present the tourism resources of Suhareka Municipality for use in thematic maps and tourism catalogues.

1. **Literature and document review**- We reviewed scientific literature and institutional documents to build a database on the municipality's historical, cultural, natural and tourism assets. Particular attention was given to Decision 5304/2025/02 and the official lists of the Ministry of Culture, and Tourism on protected cultural monuments (MCT -Cultural Heritage List for Temporary Protection 2025 – 2026), as

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well as Municipal Assembly Decision 016/27355 on protected natural monuments under the Ministry of Environment and Spatial Planning.

Existing cartographic materials were also examined. Apart from a tourism-map by Gollopeni 2011, available maps mainly related to urban and municipal development plans by private companies. These materials helped us assess existing spatial information and the need for a more integrated tourism mapping framework.

2. GIS analysis and map production - ArcGIS was used to organize, analyze and visualize the spatial data. All identified tourism resources were georeferenced and stored in a spatial database, enabling analysis of their distribution and production of thematic maps. GIS also supported the design of tourist routes and the preparation of cartographic outputs for promotion. This approach follows established practice in heritage documentation, where spatial data and visual records are combined to improve interpretation and management of cultural landscapes (Lynch et al. 2020).

3**. Drone photography** - Drone imagery was collected to document selected tourism and heritage sites from above. The photographs provided high-resolution visual material for the catalogues and supported the spatial representation of key sites.

4. Field survey - Fieldwork verified the location, accessibility, physical characteristics and tourism relevance of sites identified through documents and GIS. Observations and photographs collected during the visits helped assess each site's suitability for inclusion in the maps and catalogues. Combining field survey with remote sensing, GIS is a recognized method for producing more detailed interpretations of archaeological landscapes (Lynch et al. 2020).

5. **NGO cooperation** - The tourism maps were produced and disseminated with the NGO GIS & Software Solution (GSS). This partnership supported the preparation of the cartographic materials and their installation at high-traffic locations in the city, improving public access to tourism information and strengthening the practical use of the research in local tourism promotion.

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RESULTS AND DISCUSSION

Map of Natural and Cultural-Historical Monuments under Protection in the Municipality of Suhareka



Fig. 1. Map of Natural and Cultural-Historical Monuments under Protection in the Municipality of Suhareka

One of the main outcomes of the study was the "Map of Natural and Cultural-Historical Monuments under Protection in the Municipality of Suhareka." The map shows more than 70 legally protected natural, cultural and historical monuments. Only officially protected sites were included, giving a focused spatial overview of recognized heritage in the municipality.

The map was created using GIS-based spatial analysis and cartographic visualization, based on institutional data on protected heritage. By bringing all sites into a single spatial framework, it provides a clearer picture of their distribution across Suhareka and makes them easier to locate in relation to the wider municipal territory.

To support public use, the map was printed in several formats. More than 1,000 copies were distributed in high-traffic locations with the support of municipal representatives. A large-format version (6 × 3 metres) was permanently installed on an interior wall of the City Museum of Suhareka, offering visitors a comprehensive visual overview of the municipality's protected heritage.

Beyond being a cartographic product, the map serves as a tool for heritage interpretation, public awareness and tourism promotion. Integrating more than 70 protected sites creates a basis for linking individual heritage locations with potential tourism routes and for including them in broader tourism planning and promotional activities.

Tourism Catalogues of the Municipality and City of Suhareka

Building on the protected heritage map, two complementary promotional products were developed: The Tourism Catalogue of the Municipality of Suhareka and the Tourism Catalogue of the City of Suhareka.

Instead of conventional brochures, the catalogues were designed as compact spatial and visual tools that connect tourism resources with their location and current appearance. The municipal catalogue was based mainly on the map of protected natural and cultural-historical monuments. To provide a more detailed visual representation, 20 photographs were selected and included: 10 cultural-historical sites, 4 archaeological sites, and 6 natural assets such as vineyards, valuable individual trees, high mountain peaks and other features. All photos reflect actual field conditions, and about 80% were taken with drones, offering an aerial perspective and a clearer view of the sites and their surroundings.

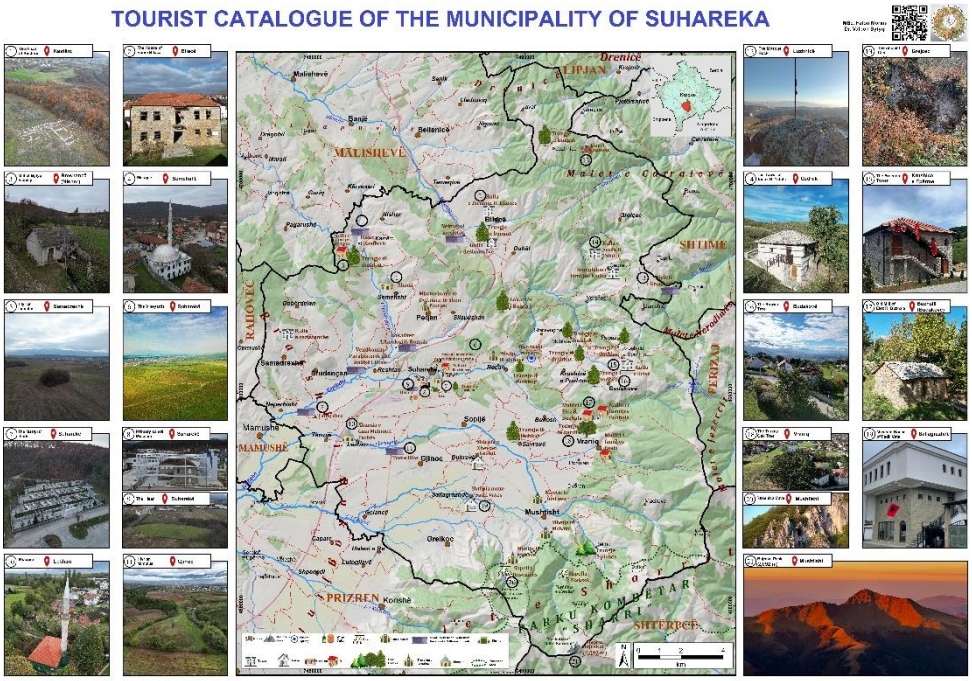


Fig. 2. Tourism Catalogues in the Municipality of Suhareka

The Tourism Catalogue of the City of Suhareka

The City of Suhareka Tourism Catalogue used a satellite image as its spatial base. Each of the 18 selected photographs was assigned a number and a precise location on the image, allowing users to identify exactly where each attraction is situated within the urban area. The catalogue presents 8 cultural, historical and religious sites; 2 natural features, including landscapes and walking trails; 3 images on local sports achievements in football, basketball and motorcycling; 2 cultural festivals (Festari and the Golden Eagle Carnival); and 1 image of locally produced agricultural products. This mix broadens the idea of tourism beyond traditional heritage by including sport, cultural events, local production and contemporary aspects of the city's identity. A key feature of both catalogues is the integration of visual

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documentation with spatial information. The photos do more than illustrate attractions; their connection with maps and spatial references helps users understand both the appearance and location of each resource. This is especially useful in destinations where tourism sites are dispersed and visitors lack clear information on how to find and connect them.

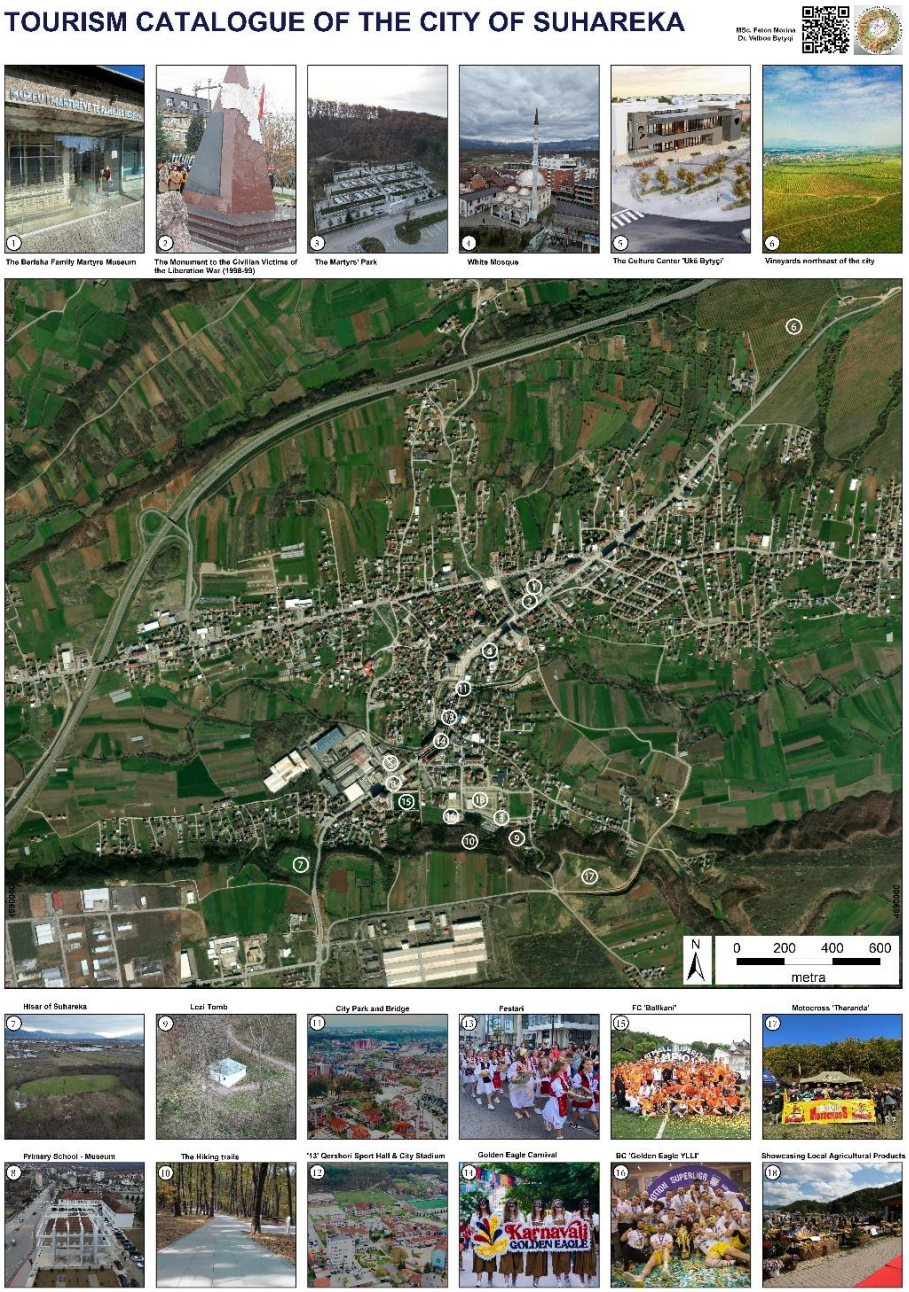


Fig. 3. Tourism Catalogues in the City of Suhareka

The results show that combining GIS-based spatial data, satellite imagery, field photography and drone documentation can create a concise and accessible tourism communication tool. The catalogues also broaden Suhareka's tourism identity by linking protected heritage, archaeological resources, natural landscapes, vineyards, urban landmarks, sport, cultural festivals and agricultural production within a single promotional framework. In this way, they complement the protected heritage map by turning spatial information into a more visitor-oriented format and providing a practical instrument for increasing the visibility and accessibility of local tourism resources.

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A key characteristic of both catalogues is the integration of visual documentation with spatial information. The photographs do not merely illustrate the attractions; their connection with maps and spatial references enables users to understand both the appearance and location of the respective resources. This approach is particularly relevant for destinations where tourism resources are spatially dispersed and where visitors may lack sufficient information for identifying and connecting individual attractions.

The two catalogues were produced as a single double-sided printed sheet, with the municipal tourism catalogue presented on one side and the city tourism catalogue on the reverse side.



Fig. 4. Tourism Catalogues of the Municipality & City of Suhareka in leaflet format

This format enabled information concerning the wider municipality and the urban area to be communicated through a single, easily distributable product. More than 1,500 copies were printed and distributed to visitors, residents, institutions, and other interested users.

The results demonstrate that combining GIS-based spatial information, satellite imagery, field photography, and drone-based visual documentation can produce a concise and accessible tourism communication tool. The catalogues also broaden the representation of Suhareka's tourism identity by connecting protected heritage, archaeological resources, natural landscapes, vineyards, urban landmarks, sport, cultural festivals, and agricultural production within a single promotional framework. Consequently, the catalogues complement the protected heritage map by transforming spatial information into a more visitor-oriented format and providing a practical instrument for increasing the visibility and accessibility of local tourism resources.

City Orientation Map and Improvement of Urban Accessibility

As a complementary component, an Orientation Map of Suhareka City was developed to improve the identification and accessibility of key landmarks, public institutions, cultural sites and visitor-related facilities. The map identifies 24 important locations across different functional categories, including cultural, archaeological, religious, educational, administrative, service, recreational and healthcare facilities.

These 24 locations were selected to give visitors and residents a simplified spatial overview of the city’s main points of interest. Unlike the protected heritage map, which focuses only on legally protected monuments, the orientation map takes a broader urban perspective by including places that shape everyday life and the visitor experience.

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he first copies were installed on two wooden display structures in prominent public spaces near the Municipal Building and the City Museum, chosen for their visibility and potential to serve both residents and visitors in the central area. Additional A0-format maps were then produced and placed in key public institutions and locations across the city, including the Police Station, Post Office, Hospital, Library, bus stations, cultural institutions and municipal facilities. This created a network of publicly accessible orientation points, allowing users to consult spatial information at different stages of their movement through the city.

The orientation map extends the role of cartography from tourism promotion to urban wayfinding and spatial accessibility. By showing important destinations within a single visual framework, it helps visitors understand the city's structure, identify relevant services and attractions, and connect cultural and tourism sites with the wider urban environment.

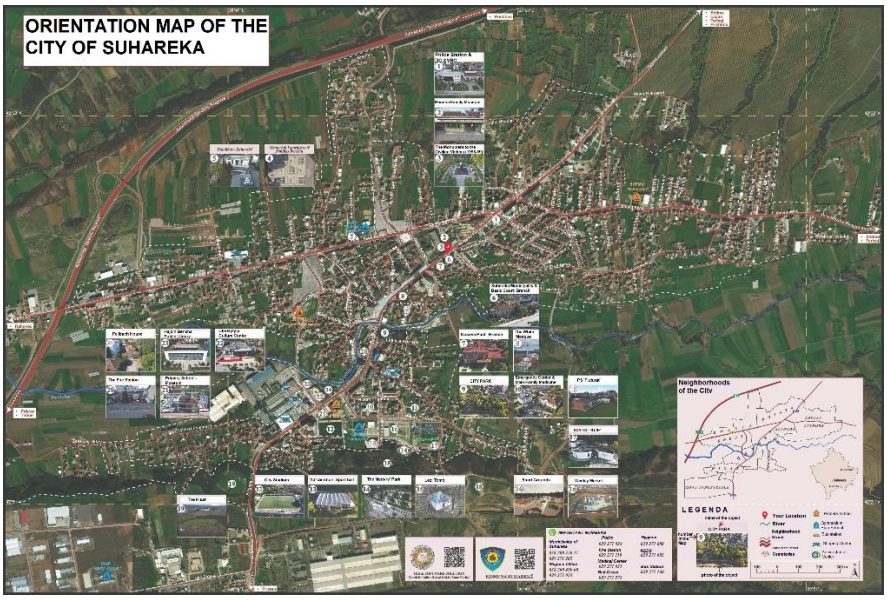


Fig. 5. Orientation Map of the City of Suhareka

Together with the protected heritage map and the two tourism catalogues, the orientation map forms the third component of an integrated tourism information system developed in this study.



Fig. 6. Orintation Map of the City of Suhareka on a wooden stand near the Municipality building and the city museum

The protected heritage map provides information on legally protected assets at municipal scale; the catalogues offer visual and spatial information on selected attractions and activities; and the orientation

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map provides a practical tool for navigating the urban environment. Combined, these three products create a multi-level communication framework linking heritage identification, tourism promotion and urban orientation.

From a local development perspective, the results show how relatively accessible GIS and cartographic tools can be transformed into practical public information infrastructure. Instead of remaining only digital or research outputs, the maps were physically integrated into public spaces and institutions, increasing the potential for continued use by residents, visitors and local authorities.

CONCLUSION

This study shows that maps and tourism catalogues can be practical tools for promoting and increasing the visibility of tourism resources in Suhareka Municipality. By combining GIS, field research, drone photography and spatial documentation, more than 70 legally protected natural, cultural and historical monuments were identified and presented within a single cartographic framework. The tourism catalogues and the city orientation map extended this framework by linking heritage with natural landscapes, archaeological sites, cultural and religious attractions, sport, festivals, agricultural products and key urban facilities.

Distributing these materials in museums, public institutions and high-traffic locations, in printed form, created a simple and publicly accessible tourism information system. The study concludes that integrating spatial and visual information can support heritage interpretation, public awareness, tourism promotion and local planning. At the same time, the maps and catalogues provide a basis for future digital initiatives such as interactive WebGIS platforms, QR-based interpretation, digital tourist routes and regularly updated spatial databases.

For Suhareka, this approach can help strengthen territorial identity and reduce the perception of the municipality mainly as a transit destination. By connecting historical heritage with natural, cultural, agricultural, sporting and contemporary assets, Suhareka has the potential to build a more diverse and recognizable regional tourism profile. Future work should focus on continuously updating the cartographic and visual database, expanding digital dissemination, improving visitor infrastructure, and evaluating how these tools influence tourist behaviour and support sustainable local development.

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IMPLEMENTATION OF THE ALBANIAN DYSPHAGIA TREATMENT PROTOCOL IN NEUROLOGY WARD; TWO-CASE REPORT

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ABSTRACT

Dysphagia is the medical term for difficulty in swallowing. Clinically it is divided in two main categories: oropharyngeal dysphagia and esophageal dysphagia or commonly called high and low dysphagia. We have developed an Albanian Dysphagia Treatment Protocol based on exercises that have currently a scientific importance, and then we have applied it to the patients with oropharyngeal dysphagia in neurology ward. The protocol includes chin positioning exercises (CTAR), oral neuromuscular exercises (buco-linguo-facial exercises), isometric neck exercises, tongue and jaw resistance exercises, and breathing exercises that have a positive impact on swallowing rehabilitation in post-stroke patients.

Objective: Improvement of oral intake

Methodology: Descriptive study

We have included in this study two cases, one male and one female, that are post stroke with difficulty in swallowing, respectively H. H. 81 years old male and Dh. L. 72 years old female. Both patients were tested for cough reflex, gag reflex and pain sensitivity. To both patients we administered the Water Swallowing Test.

Results: Both patients showed improvement in oral intake

Conclusions: These exercises have a positive impact on swallowing rehabilitation in post-stroke patients.

Key words: Stroke, Dysphagia, Rehabilitation, Neurology, Post stroke

Introduction

The swallowing apparatus begins with the mouth and includes the lips, the tongue, the oral cavity, the pharynx, the airway, and the esophagus and its sphincters, both upper and lower.

Dysphagia is the medical term for difficulty in swallowing.

Clinically it is divided in two main categories: oropharyngeal dysphagia and esophageal dysphagia or commonly called high and low dysphagia.

Oropharyngeal dysphagia is at term that describes swallowing problems occurring in the mouth and/or the throat. These swallowing problems most commonly result from impaired muscle function, sensory changes, or growths and obstructions in the mouth or throat.

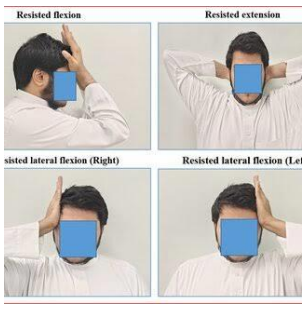
Esophageal dysphagia, which is when the swallowing abnormality arises from the esophagus, typically results from a motility disorder or a physical obstruction that prevents food and drink from passing easily through the esophagus.

We have developed an Albanian Dysphagia Treatment Protocol based on exercises that have currently a scientific importance, and then we have applied it to the patients with oropharyngeal dysphagia in neurology ward.

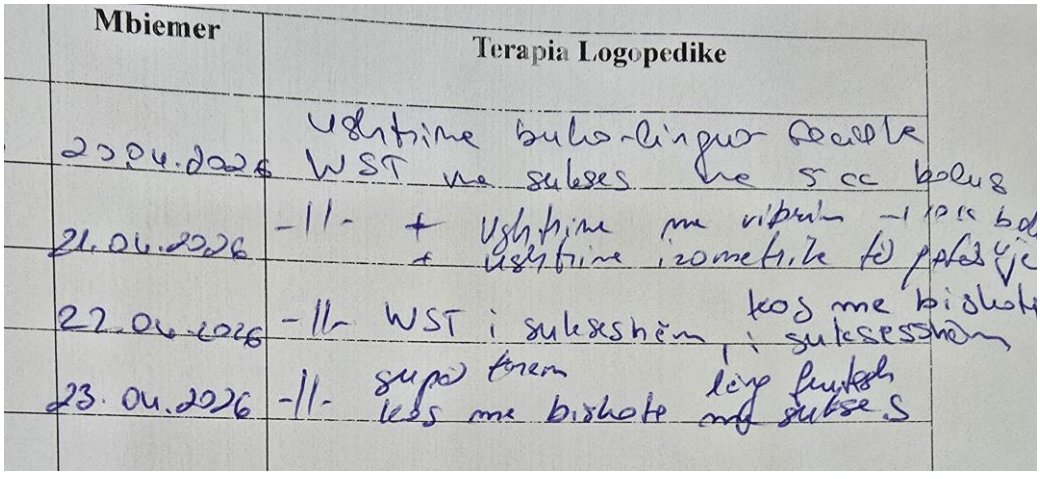
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The protocol includes chin positioning exercises (CTAR), oral neuromuscular exercises (buco-linguo-facial exercises), isometric neck exercises, tongue and jaw resistance exercises, and breathing exercises that have a positive impact on swallowing rehabilitation in post-stroke patients.



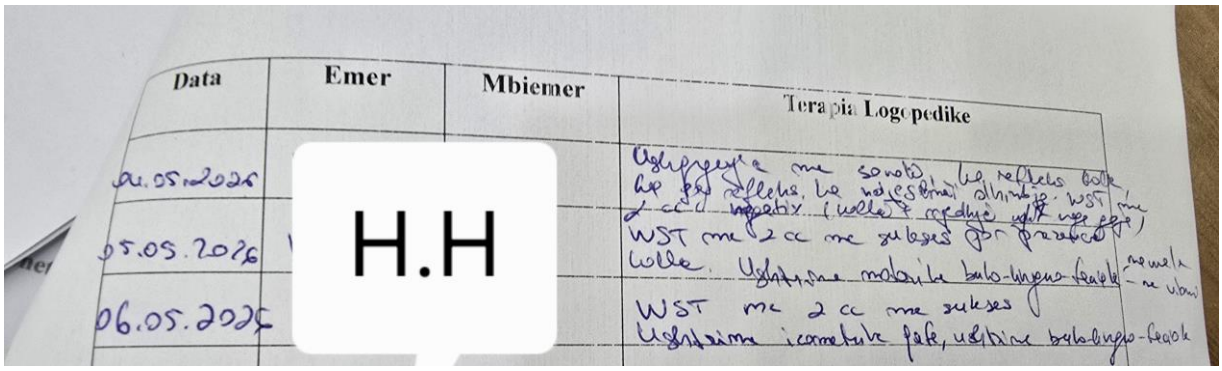


- **Objective:** Improvement of oral intake
- **Methodology:** Descriptive study
- We have included in this study two cases, one male and one female, that are post stroke with difficulty in swallowing, respectively H. H. 81 years old male and Dh. L. 72 years old female.
- Both patients were tested for cough reflex, gag reflex and pain sensitivity.
- To both patients we administered the **Water Swallowing Test**. This test requires swallowing 3 tablespoons of water in a sitting position, with the head flexed and the torso 80º.The path of the water bolus is monitored with the fingers (index finger under the mandible, middle finger at the beginning of the trachea and last finger at the end of the trachea).The test evaluates the presence of deglutition, the presence of cough, the flow of water from the mouth, as well as the alteration of the quality of the voice (ask the patient to say "A") .The presence of coughing during or for at least 1 minute after the test is completed or the presence of a wet voice is considered abnormal.
- **Case 1: Dh. L. 72 years old female**
- Post stroke
- Successful WST
- Had difficulties in swallowing
- Was in therapy for 4 days during the hospital stay
- When she left, she could eat a semi liquid and creamy diet like puree, pudding, creamy soup, milkshakes



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- **Case 2: H. H. 81 years old male**
- Post stroke
- Was tube fed
- WST not successful
- The protocol was implemented for 3 days during hospital stay
- Was recommended a creamy diet when he left with yoghurt, creamy homogenous soup, pudding, jellified water.



Results: Both patients showed improvement in oral intake

Conclusions: These exercises have a positive impact on swallowing rehabilitation in post-stroke patients.

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INVESTIGATING CHARGE ASYMMETRY IN LEPTONICALLY DECAYING Wγ PRODUCTION AT NNLO QCD FOR FUTURE HADRON COLLIDERS

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ABSTRACT

This study presents a novel phenomenological analysis of the charge asymmetry phenomenon for the Wγ production channel, focusing specifically on the subsequent leptonic decay modes ($W^+\gamma \rightarrow l^+\nu_l\gamma$ and $W^-\gamma \rightarrow l^-\nu_l\gamma$) in proton-proton (pp) particle collisions. The phenomenological assessments of the study feature that the precision of the predictions for the leptonically decaying Wγ is significantly enhanced by incorporating genuine next-to-next-to-leading order (NNLO) corrections via QCD perturbation theory calculations. The study systematically evaluates asymmetry distributions across critical observables, namely the photon and decay lepton pseudorapidities (η_γ and η_l) along with their corresponding spatial correlation $\Delta\eta(l, \gamma)$. These higher-order evaluations are carried out utilizing realistic, fiducial phase-space constraints modeled at center-of-mass collision energies of 13 TeV, 14 TeV, and 100 TeV. Furthermore, the investigation highlights the sensitivity of these distributions to the radiation amplitude zero (RAZ) effect inherent to the Wγ channel, proving that $\Delta\eta(l,\gamma)$ plays an important role in identifying the RAZ structure when high-transverse-momentum photons in the final state are present. Additionally, the consequences of executing a jet veto constraint are explored across prospective pp collider energies. To counteract the degradation of asymmetry distributions caused by increasing collision energies, advanced phase-space optimization methods involving tighter jet-veto limits and stiffer photon recoil thresholds are proposed. Ultimately, these charge asymmetry signatures serve as highly sensitive observables, presenting an independent and robust framework for performing stringent standard model particle physics consistency checks and searching indirectly for beyond-the-standard-model physics.

Keywords: High energy particle physics, Hadron collider phenomenology, Gauge boson pair production, Charge asymmetry, NNLO QCD corrections, Radiation amplitude zero, Vector boson leptonic decay.

INTRODUCTION

The associated production of a W boson and a photon (Wγ) in high-energy proton-proton (pp) collisions represents one of the most vital vector-boson pair production processes in electroweak (EW) physics of high-energy particle physics (Weinberg, 1979). The process with subsequent leptonic decay of the W boson, expressed as $pp \rightarrow W\gamma \rightarrow l\nu_l\gamma$ (where l denotes electrons, muons, or taus and their respective antiparticles), provides a clean experimental signature characterized by a high production cross section and manageable background levels at hadron colliders such as the CERN Large Hadron Collider (LHC).

A primary motivation for studying the Wγ process is its direct sensitivity to triple gauge boson couplings (TGC), specifically the WWγ vertex arising from the non-Abelian SU(2)L × U(1)Y gauge structure of the Standard Model (SM). At energy scales substantially higher than the electroweak scale defined by the W-boson mass ($\Lambda \gg m_W$), measurements of the WWγ TGC allow for stringent constraints on higher-dimensional operators within an Effective Field Theory (EFT) framework (Hagiwara et al., 1993; Grzadkowski et al., 2010; Degrande et al., 2013). In this approach, the effective Lagrangian L_{EFT} is expanded as a power series added to the SM Lagrangian L_{SM}:

$$L_{EFT} = L_{SM} + \sum_i (c_i / \Lambda^2) O_i^{(6)} + \sum_j (b_j / \Lambda^4) O_j^{(8)} + ...$$

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Among the dimension-6 operators, $O_{WWW} = \varepsilon^{ijk} W_\mu^{iv} W_v^{j\rho} W_\rho^{k\mu}$ and its CP-violating counterpart $O_{\tilde{W}WW}$ directly modify the WWγ vertex. Any observed anomalous coupling strength would indicate an unambiguous signal for BSM physics emerging at high energy scales. Furthermore, the Wγ channel constitutes a critical irreducible background in searches for heavy charged resonances decaying into gauge boson pairs and in dark matter searches involving energetic photons associated with large missing transverse energy (p_T^{miss}).

In pp collisions, W^+ bosons are produced more abundantly than W^- bosons (via $u\,\bar{d} \rightarrow W^+$ versus $d\,\bar{u} \rightarrow W^-$) due to the excess of the presence of two valence u quarks and one valence d quark in the proton. Traditionally, this phenomenon is captured via the W-boson lepton charge asymmetry, defined as a function of the decay lepton pseudorapidity η_l:

$A_{W(\eta l)} = [\, R_{W(\eta l)} - 1 \,] / [\, R_{W(\eta l)} + 1 \,]$, where $R_{W(\eta l)} = [\, d\sigma(W^+ \rightarrow l^+\nu_l) / d\eta_l \,] / [\, d\sigma(W^- \rightarrow l^-\bar{\nu}_l) / d\eta_l \,]$

In this paper, this concept is extended to the Wγ process by proposing a novel set of observables termed as the Wγ charge asymmetry and denoted as $A_{W\gamma(\lambda)}$, constructed using kinematic variables of the lepton-photon system:

$A_{W\gamma(\lambda)} = [\, R_{W\gamma(\lambda)} - 1 \,] / [\, R_{W\gamma(\lambda)} + 1 \,]$, where $R_{W\gamma(\lambda)} = [\, d\sigma(W^+\gamma \rightarrow l^+\nu_l\gamma) / d\lambda \,] / [\, d\sigma(W^-\gamma \rightarrow l^-\bar{\nu}_l\gamma) / d\lambda \,]$

Here, the variable λ represents key angular and correlation observables: $|\eta_l|$, $|\eta_\gamma|$, $\Delta\eta(l,\gamma) = \eta_l - \eta_\gamma$, and $\Delta R(l,\gamma) = \sqrt{[(\Delta\eta)^2 + (\Delta\varphi)^2]}$. This paper presents the first systematic study of $A_{W\gamma(\lambda)}$ at NNLO Quantum Chromodynamics (QCD) accuracy across present and future pp collider energies.

METHODOLOGY AND COMPUTATIONAL SETUP

Higher-order perturbative QCD calculations are performed for off-shell $W^+\gamma \rightarrow l^+\nu_l\gamma$ and $W^-\gamma \rightarrow l^-\bar{\nu}_l\gamma$ processes using the computational framework MATRIX (version 2.1.0.beta2) (Grazzini, Kallweit, and Rathlev, 2015; Grazzini, Kallweit, and Wiesemann, 2018). The framework utilizes the Catani-Seymour dipole subtraction method for NLO QCD calculations and the q_T-subtraction slicing method for NNLO QCD calculations (Catani and Grazzini, 2007). A slicing cut-off parameter $r_{cut} = 0.0015$ (0.15%) is applied to regularize soft and collinear infrared divergences. Scattering amplitudes at tree-level, one-loop, and two-loop orders are generated automatically via the OpenLoops 2 program (Buccioni et al., 2019). Parton distribution functions (PDFs) are evaluated using the NNPDF4.0 sets (specifically NNPDF40_nnlo_as_01180) (Ball, 2022) accessed through the LHAPDF (v6.4.0) interface, with a strong coupling constant value of $\alpha_s(m_Z) = 0.118$. The electroweak parameters are specified within the G_μ scheme, using complex mass definitions for the gauge bosons:

- W-boson mass & width: $M_W = 80.3850$ GeV, $\Gamma_W = 2.0854$ GeV
- Z-boson mass & width: $M_Z = 91.1876$ GeV, $\Gamma_Z = 2.4952$ GeV
- Fermi constant: $G_F = 1.16639 \times 10^{-5}$ GeV^{-2}

The central renormalization (μ_R) and factorization (μ_F) scales are dynamically set to the quadratic sum of the W-boson mass and photon transverse momentum:

$\mu_0 = \sqrt{[\, M_W^2 + (p_{T\gamma})^2 \,]}$

To ensure direct alignment with experimental capabilities, calculations are performed within realistic fiducial acceptance requirements in line with the CMS 13 TeV measurement (Tumasyan et al., 2022). Leptons are dressed by combining four-momenta of collinear photons within $\Delta R(l,\gamma) < 0.1$. Photons from QCD parton fragmentation are suppressed using the Frixione smooth-cone isolation criterion. Table 1 summarizes the fiducial phase-space baseline selection (BS) requirements.

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Table 1. Summary of the baseline selection (BS) cuts.

Particle / Object	Fiducial Kinematic Requirements (BS)
Charged Lepton ($l \in \{e, \mu\}$)	$p_T^l > 30$ GeV, $\lvert\eta^l\rvert < 2.5$
Neutrino / Missing Energy	$p_T^{miss} > 40$ GeV (no pseudorapidity cut)
Isolated Photon (γ)	$p_T^\gamma > 30$ GeV, $\lvert\eta^\gamma\rvert < 2.5$
Clustered Jets (j)	anti-k_T (R=0.4), $p_T^j > 30$ GeV, $\lvert\eta^j\rvert < 2.5$
Angular Separations	$\Delta R(l,\gamma) > 0.7$, $\Delta R(l,j) > 0.4$, $\Delta R(\gamma,j) > 0.4$
Frixione Isolation Parameters	$n = 1$, $\varepsilon_\gamma = 1.0$, $R_{max} = 0.4$

Theoretical uncertainties originating from missing higher-order QCD terms are estimated by independently varying the renormalization and factorization scales around μ_0 by a factor of 2, utilizing the standard 7-point variation scheme:

$(\mu R / \mu 0, \mu F / \mu 0) \in \{ (2,2), (2,1), (1,2), (1,1), (1,1/2), (1/2,1), (1/2,1/2) \}$

The maximum deviations from central values are treated as scale uncertainties and propagated conservatively (treating scale variations in numerator and denominator as uncorrelated) to the asymmetry ratios. In contrast, PDF and α_s uncertainties are evaluated using NNPDF4.0 replicas and found to yield residual uncertainties below 1% in the ratio quantities; hence, scale variations dominate the total theoretical error bands in the main differential asymmetry results of this report.

PHENOMENOLOGICAL RESULTS

The predicted differential cross sections at NLO and NNLO QCD accuracy are compared with published CMS experimental data at $\sqrt{s}$ = 13 TeV to establish the validity of the computational setup. As demonstrated in Figure 1, NLO QCD calculations systematically underestimate the measured cross sections across the entire photon transverse momentum spectrum ($p_{T\gamma}$) and pseudorapidity range ($|\eta_\gamma|$). Inclusion of NNLO QCD corrections leads to an increase of 25% to 33% in cross-section magnitudes, restoring excellent agreement with CMS data (Tumasyan et al., 2022) within experimental and theoretical scale uncertainties.

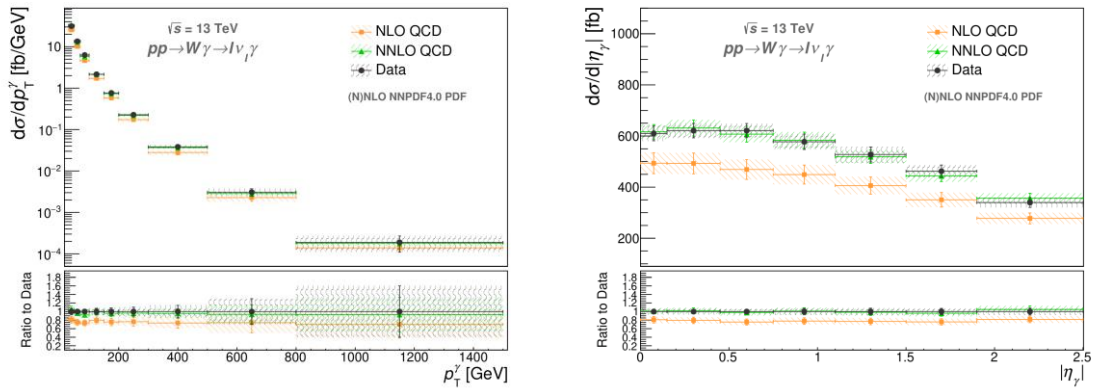


Figure 1. Differential cross sections as functions of $p_{T\gamma}$ (left) and $|\eta_\gamma|$ (right) at (N)NLO QCD in comparison with the data points (Tumasyan et al., 2022).

The predicted NNLO charge asymmetry distributions $A_{W\gamma}(|\eta_l|)$ and $A_{W\gamma}(|\eta_\gamma|)$ are systematically compared across center-of-mass energies of 13 TeV (LHC), 14 TeV (HL-LHC), and 100 TeV (FCC-hh) (Abada et al., 2019), as shown in Figure 2. The corresponding numerical predictions $A_{W\gamma}(|\eta_l|)$ and $A_{W\gamma}(|\eta_\gamma|)$ at various collision energies are provided in Table 2 and Table 3, respectively. The following key observations are obtained based on the predicted results:

- Lepton Pseudorapidity Asymmetry $A_{W\gamma}(|\eta l|)$: Shows a declining trend towards higher central pseudorapidities. When increasing the collision energy from 13 TeV to 100 TeV, the magnitude of $A_{W\gamma}(|\eta_l|)$ drops significantly—by an average factor of ~4.7 within the central region $|\eta l| < 1.9$, becoming nearly flat around 0.03.

- Photon Pseudorapidity Asymmetry $A_{W\gamma}(|\eta_\gamma|)$: Displays an increasing behavior towards forward regions (higher $|\eta_\gamma|$). At 100 TeV, the asymmetry is reduced by an average factor of ~5.7 compared to 13 TeV.

This systematic reduction of asymmetry at higher collision energies is driven by the increasing dominance of sea-quark interactions over valence-quark asymmetries at lower Bjorken-x values. Consequently, any experimental deviation from this falling asymmetry trend at future colliders would serve as a clear indirect signature of new physics.

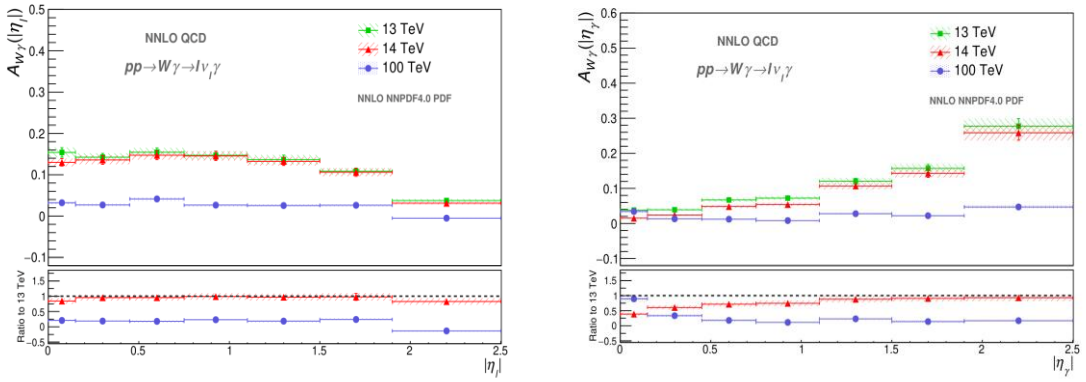


Figure 2. The predicted charge asymmetry distributions $A_{W\gamma}(|\eta_l|)$ (left) and $A_{W\gamma}(|\eta_\gamma|)$ (right) at various center-of-mass energies of pp collisions.

Table 2. Predicted numerical values of $A_{W\gamma}(|\eta_l|)$ at NNLO in bins of lepton pseudorapidity

$\|\eta_l\|$ Bin	13 TeV	14 TeV	100 TeV
0 – 0.15	0.180 ± 3.5% ± 7.2%	0.130 ± 3.6% ± 7.0%	0.032 ± 4.0% ± 8.2%
0.15 – 0.45	0.142 ± 3.1% ± 6.4%	0.136 ± 2.7% ± 7.8%	0.027 ± 2.9% ± 8.9%
0.45 – 0.75	0.154 ± 2.8% ± 6.8%	0.147 ± 2.7% ± 7.1%	0.042 ± 3.0% ± 8.6%
0.75 – 1.1	0.114 ± 2.5% ± 6.8%	0.145 ± 2.4% ± 7.6%	0.027 ± 2.7% ± 9.1%
1.1 – 1.5	0.137 ± 2.6% ± 7.9%	0.088 ± 2.7% ± 7.7%	0.026 ± 2.8% ± 8.7%
1.5 – 1.9	0.109 ± 3.2% ± 7.0%	0.113 ± 2.7% ± 8.5%	0.026 ± 2.9% ± 9.9%
1.9 – 2.5	0.038 ± 2.8% ± 8.5%	0.031 ± 2.8% ± 8.5%	-0.005 ± 3.1% ± 9.7%

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Table 3. Predicted numerical values of $A_{W\gamma}(|\eta_\gamma|)$ at NNLO in bins of photon pseudorapidity

$\|\eta_\gamma\|$ Bin	13 TeV	14 TeV	100 TeV
0 – 0.15	0.038 ± 3.8% ± 6.5%	0.015 ± 3.9% ± 9.3%	0.034 ± 3.5% ± 9.1%
0.15 – 0.45	0.013 ± 2.6% ± 9.3%	0.039 ± 2.7% ± 7.0%	0.024 ± 2.6% ± 7.3%
0.45 – 0.75	0.077 ± 2.5% ± 7.2%	0.048 ± 2.7% ± 7.4%	0.012 ± 3.2% ± 9.1%
0.75 – 1.1	0.072 ± 2.6% ± 7.7%	0.054 ± 2.6% ± 7.8%	0.008 ± 2.7% ± 8.8%
1.1 – 1.5	0.120 ± 2.7% ± 7.1%	0.122 ± 2.5% ± 7.4%	0.028 ± 2.9% ± 8.8%
1.5 – 1.9	0.022 ± 2.9% ± 9.3%	0.157 ± 3.1% ± 7.3%	0.177 ± 2.8% ± 8.2%
1.9 – 2.5	0.278 ± 3.1% ± 7.7%	0.259 ± 2.6% ± 8.2%	0.047 ± 3.2% ± 9.4%

The Wγ process exhibits a fundamental quantum mechanical interference effect known as Radiation Amplitude Zero (RAZ), where tree-level scattering amplitudes completely vanish at a center-of-mass scattering angle corresponding to cos θ* = ±1/3 (Mikaelian, Samuel, and Sahdev, 1979; Baur, Errede, and Landsberg, 1994). In pp collisions, this effect produces a characteristic dip around Δη(l,γ) = 0 in differential cross sections. However, real parton emissions at higher order in QCD and requirements of hard recoiling photons (e.g., $p_{T\gamma}$ > 100 GeV) fill in this dip in cross-section distributions, destroying the visibility of the RAZ. This paper demonstrates a breakthrough finding: while cross-section dips are erased by hard photon cuts, the charge asymmetry distribution $A_{W\gamma}(\Delta\eta(l,\gamma))$ retains extreme sensitivity to the RAZ effect in hard-scattering regimes. When imposing a hard photon cut ($p_{T\gamma}$ > 100 GeV) alongside a jet veto (BS_JV_$p_{T\gamma}$>100 GeV), the $A_{W\gamma}(\Delta\eta(l,\gamma))$ distribution develops a sharp, pronounced drop right at Δη(l,γ) = 0 at 14 TeV, which remains distinguishable even up to 100 TeV as shown in Figure 3. This makes charge asymmetry a far superior probe for studying electroweak radiation zeros under energetic kinematic selections.

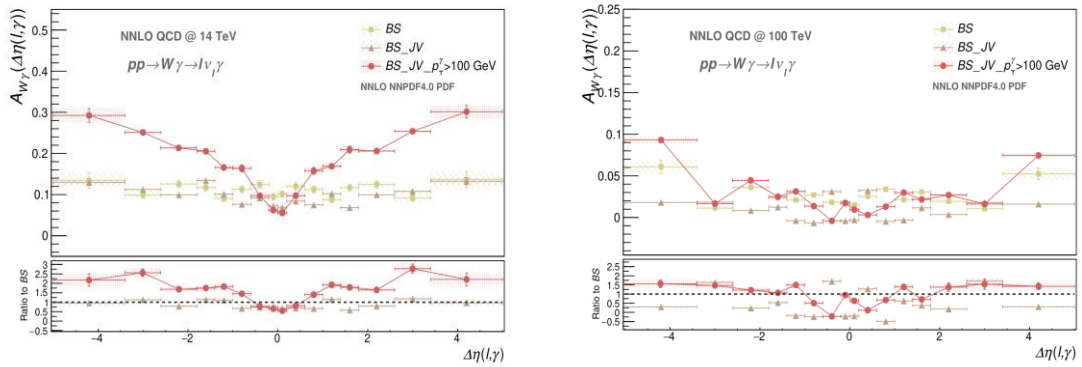


Figure 3. The NNLO predictions of charge asymmetry distributions $A_{W\gamma}(\Delta\eta(l,\gamma))$ at 14 TeV (left) and 100 TeV (right) of pp collisions

Moreover, the constrained phase-space regions combining jet vetoes with elevated photon transverse momentum thresholds ($p_{T\gamma}$ > 100 GeV and $p_{T\gamma}$ > 200 GeV) are evaluated at 14 TeV and 100 TeV to account for the dilution of asymmetry at higher collision energies. The results reveal that requiring $p_{T\gamma}$ > 200 GeV significantly enhances asymmetry magnitudes in central lepton regions as shown in Figure 4, compensating for the energy-driven reduction and providing optimized sensitivity for dark matter and high-mass resonance searches.

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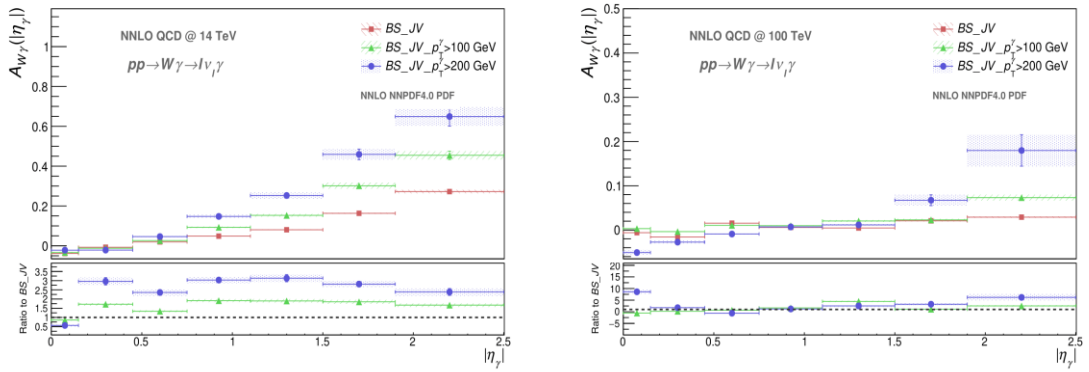


Figure 4. The NNLO predictions of charge asymmetry distributions $A_{W\gamma}(|\eta_\gamma|)$ with increasing $p_{T\gamma}$ requirements compared at 14 TeV (left) and 100 TeV (right) of pp collisions

CONCLUSIONS

In this paper, the charge asymmetry phenomenon in the leptonically decaying Wγ process ($A_{W\gamma}(\lambda)$) has been introduced and systematically analyzed for the first time at NNLO QCD accuracy. It has been observed that inclusion of NNLO QCD corrections increases predicted cross sections by 25–33% over NLO, achieving permille-level theoretical precision and excellent agreement with 13 TeV CMS data. Furthermore, the AWγ(λ) distributions are assessed to exhibit a clear energy dependence, decreasing by factors of 4.7–5.7 when advancing from 13 TeV to 100 TeV due to sea-quark PDF dominance. Moreover, unlike cross-section distributions where hard photon recoil obscures radiation amplitude zeros, the asymmetry observable $A_{W\gamma}(\Delta\eta(l,\gamma))$ maintains a sharp dip at $\Delta\eta(l,\gamma) = 0$ under high-$p_{T\gamma}$ cuts, establishing a novel technique for probing radiation interference phenomena. The results are also assessed for BSM searches potential. It has been observed that imposing hard photon cuts ($p_{T\gamma} > 200$ GeV) with jet vetoes recovers large asymmetry magnitudes at future colliders, offering strong diagnostic power for dark matter and BSM effective operator searches.

Conclusively, the $A_{W\gamma}(\lambda)$ distributions are found to be robust, sensitive observables for both SM tests and new-physics searches at current and future colliders (LHC, HL-LHC, FCC-hh). The methodology and findings provide a framework for future experimental measurements and theoretical studies of charge asymmetry in Wγ production. From an experimental point of view, the $A_{W\gamma}(\lambda)$ definitions and phase-space selections from this study can be used to design analyses at the LHC or future colliders. In theoretical studies, the provided $A_{W\gamma}(\lambda)$ NNLO predictions and uncertainty estimates can be exploited as benchmarks for further studies or for constraining new physics models. The results summarized in this proceeding report are derived from the original paper (Saygin, 2025) which includes full results that can be used as benchmark in the context of the phenomenology of the Wγ production in pp collisions. Preceding this, the charge asymmetry phenomenon is also extensively investigated for the Zγ pair-production process as a probe for SM precision studies and BSM searches in the respective literature (Saygin, 2024).

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FULL TEXTS BOOK

THE EFFECTS OF A PERMANENT PACEMAKER ON WOMEN'S SEXUAL HEALTH

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ABSTRACT

Cardiovascular diseases are among the major chronic, progressive and life-threatening health problems. Permanent pacemakers and implantable cardioverter-defibrillators (ICDs) are widely used in the treatment of arrhythmias. Pacemakers prolong life by regulating the heart rhythm in cases of bradycardia and conduction disorders; ICDs, on the other hand, prevent sudden cardiac death by delivering a shock in the event of life-threatening arrhythmias. However, various complications may occur following implantation, such as haematoma, infection, pneumothorax and electrode problems.

Permanent pacemaker and ICD implantations affect not only an individual's physiological well-being but also their psychosocial life. In particular, issues such as depression, anxiety, sleep problems, impaired body image and a reduced quality of life are reported more frequently in female patients. In individuals with an ICD, fears of receiving a shock, anxiety about facing death and concerns regarding device malfunction may be observed; this situation can also have a negative impact on their sex life. Sexual dysfunction is observed in a significant proportion of individuals with cardiovascular disease, with women experiencing more sexual problems than men. In particular, avoidance of sexual activity is a notable behaviour among women with an ICD.

The literature indicates that psychosocial support and patient education increase device acceptance, reduce anxiety about shocks and improve sexual function. However, it is noted that sexual health is the least addressed area within the educational requirements following the implantation of a permanent pacemaker. It is therefore important for nurses to provide psychosocial support by adopting a patient-centred and holistic approach to care, and to incorporate sexual health into their educational programmes.

Keywords: Pacemakers, women's health, sexuality

WHAT IS A PACEMAKER?

Cardiovascular diseases are common, chronic, progressive and life-threatening conditions (Aliakbari et al., 2022; DSÖ, 2025). One of the methods used to treat cardiovascular diseases and arrhythmias is the implantation of a permanent pacemaker (Puette et al., 2024).

The true origins of the concept of the pacemaker date back to the late 1700s, when Luigi Galvani discovered that he could induce a frog's heart to contract simply by passing an electric current through it (Puette et al., 2024). Cardiac pacing, which involves using electrical stimuli to generate or modify the heart's mechanical activity, began in the 1930s with Hyman's term 'artificial pacemaker' (Pavia et al., 2001). A pacemaker may be implanted as a result of degeneration of the cardiac conduction system and changes in intercellular conduction, or as a result of symptoms of cardiac pathology or non-cardiac diseases (Glikson et al., 2021). The first permanent pacemaker was implanted in 1958 in Arne Larsson, a 43-year-old Swedish man who had suffered severe Stokes-Adams episodes and required frequent resuscitation (Deforge et al., 2019).

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Pacemakers are medical devices that send electrical impulses to stimulate the heart muscles and regulate the heart's rhythm; they are used in cases of bradycardia, syncope or arrhythmias (Mlynarski et al., 2020; Dalia et al., 2023). Pacemakers can be either temporary or permanent, depending on the patient's needs (Puette JA et al., 2024). Temporary pacemakers provide life-saving benefits by controlling the heart rate to ensure effective myocardial contractility and adequate cardiac output until a permanent pacemaker is implanted (Harrigan et a., 2007). Permanent pacemakers, on the other hand, help to regulate irregular heartbeats and ensure that the heart contracts when the sinoatrial node is not functioning properly (İbrahim NM et al., 2024). Permanent pacemakers are most commonly implanted in our country to treat atrioventricular block, sick sinus syndrome and slow-rate atrial fibrillation (Kılıçarslan., 2010). Permanent pacemakers are categorised into two main groups in the Turkish Society of Cardiology guidelines: pacemakers and implantable cardioverter-defibrillators (ICDs) (TKD., 2025; Breitenstein A. et al., 2019). Pacemaker batteries, which regulate the heart rhythm using electrical impulses, are the preferred treatment for severe and symptomatic bradycardia (Brunner M. Et al., 2004). ICD devices with defibrillation capabilities, on the other hand, help the heart to return to its normal rhythm in the event of arrhythmias by delivering shocks of varying intensities (Colquitt et al., 2014). An implantable cardioverter-defibrillator (ICD) provides a survival benefit by reducing mortality and morbidity in patients at risk of sudden cardiac arrest (Lee KS. Et al., 2020; Cutitta KE. Et al., 2014; Sears et al., 2005; Sears et al., 2009). A study on pacemakers and ICDs (implantable cardioverter defibrillators), which covered 50 countries worldwide, noted that the US had the highest number of pacemaker implantations, whilst Germany had the highest number of new implantations per million people (Mond et al., 2004).

The European Society of Cardiology; the incidence of post-implantation complications in pacemaker and cardiac resynchronisation therapy; haematoma (2.1–5.3), 5–15 per cent tricuspid regurgitation, and that major complications requiring reintervention—such as pacemaker electrode dislodgement, insulation defects, electrode fractures, and sensing or threshold issues—occur at a rate of 1–5.9 per cent; it states that complications such as infections (0.7–1.7 per cent), pneumothorax (0.5–2.2 per cent), haemothorax (0.1 per cent), brachial plexus injury (<0.1 per cent), pacemaker syndrome (1–20 per cent), and death within thirty days (0.8–1.4 per cent) may also occur (WHF., 2025). The incidence of infection in pacemakers and implantable cardiac devices ranges from 0.6 per cent to 3.4 per cent (Blomström-Lundqvist et al., 2020). A study found that 2,233 (2.6 per cent) of 85,276 primary ICD implantations resulted in a haematoma complication (Sridhar et al., 2016).

THE EFFECTS OF PACEMAKERS ON WOMEN'S HEALTH

The implantation of pacemakers and implantable cardioverter-defibrillators has a negative impact on quality of life from a social, psychological and emotional perspective, primarily due to issues relating to device compatibility (Burns et al., 2005, Bulantekin ve ark., 2010). Permanent pacemakers, which are used in the treatment of cardiovascular diseases, whilst effective in prolonging life, can increase depression and anxiety in women, cause sleep problems, and have a negative impact on body image and quality of life (Gonçalo et al., 2020; Polikandrioti et al., 2021; Özmen et al.2025Although an ICD is far more effective than other treatments in managing arrhythmias and heart disease, it also brings with it many challenges, such as living in fear of receiving a shock, concerns about the future, anxiety about device malfunction, sexual health, lifestyle restrictions, the prospect of death at the moment of a shock, and pain caused by the shock (Abbasi et al., 2016). The appearance of the implanted device and/or the resulting scar may be a greater cause for concern for women than for men (Suleman et al., 2022). In individuals with heart disease, psychological distress and, consequently, sexual functioning may be adversely affected (Friedman et al., 2000). Changes in sexual function and sexual desire may occur as a result of the use of medication or the fitting of a pacemaker to treat arrhythmias (Adalet ve ark., 2002). A study has indicated that women report higher levels of general and shock-related anxiety and greater concerns about body image than men, yet women show greater improvement in physical function (Starrenburg et al., 2014). A qualitative study on the focused life stories of women with pacemakers has indicated that the experiences of women with permanent pacemakers revolve around various themes, such as disengagement from care, experiencing fear and/or resistance associated with having the device, body imagery, normalisation, positioning themselves as carers, finding resilience, and feelings of being able to cope with anything (Beery et al., 2002). It is reported that pacemakers increase depression and

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anxiety in women, affect body image and sexuality, and negatively impact quality of life by causing sleep problems and a loss of social roles (Yarnoz et al., 2006). The literature indicates that women with permanent pacemakers experience a reduced quality of life as a result of impaired body image perception due to scarring, the large size of the device, the pacemaker being conspicuous under clothing, increased levels of depression and anxiety, the impact on body image, sleep problems, the loss of social roles, and the negative impact on physical roles and functions (Pycha et al., 1990; Passman et al., 2007; Davis et al., 2004; Gonçalo et al., 2020; Polikandrioti et al., 2021).

THE EFFECTS OF A PACEMAKER ON WOMEN'S SEXUAL HEALTH

According to the WHO, sexuality is not merely the absence of disease, dysfunction or disability, but a state of physical, emotional, mental and social well-being in relation to sexuality (WHO., 2025). Sexual health encompasses the somatic, cognitive, intellectual, social and emotional aspects of general health (Şalvarcı ve ark.,2020). It is noted that there is a link between sexual activity and cardiac death, and that individuals with heart disease often avoid sexual activity (Chen et al., 2009). The literature suggests that there is a link between cardiovascular diseases and sexual function, depressive symptoms and quality of life (Şalvarcı ve ark.,2020). Sexual function in both women and men may be adversely affected by anxiety arising from cardiovascular diseases (Şalvarcı ve ark., 2020; Virani et al., 2023). The fact that sexual dysfunction, vaginal atrophy, avoidance of sexual intercourse and fears regarding sexual activity are more common in women with cardiovascular disease suggests that this group is more vulnerable in terms of sexual health (Armeni et al., 2025). 75 per cent of people with cardiovascular disease experience problems with sexual function, whilst women are twice as likely to experience sexual health problems (Ziapour et al., 2024). Female patients report experiencing more ICD shocks, anxiety and depression than male patients (Andersen et al., 2023). In particular, women with an ICD implanted to deliver shocks in the event of a sudden arrhythmia may experience a fear of death at the moment of the shock and may adopt behaviours that involve avoiding sexual activity (Abbasi et al., 2016; Maroto-Montero,2018; Ziapour et al., 2024).

It has been reported that 79.5 per cent of nurses have insufficient knowledge of pacemakers (Tiryag., 2024). Nurses should adopt a patient-centred and holistic model of care for women with pacemakers; as part of their educational role, they should provide psychosocial and emotional support to help individuals with permanent pacemakers successfully adapt to their new way of life. Providing psychosocial education and social support helps to reduce anxiety about shocks, increases acceptance of the device, and can lead to improved adaptation to sexual life (Angelidou., 2009; Kostis et al., 2005; Polikandrioti et al., 2021). It has been reported in the literature that sexual activity is the area in which the lowest learning requirements following the implantation of a permanent pacemaker have been reported; it has also been reported that the desire for sexual intercourse decreases due to the fear of receiving a shock during sexual intercourse (Moradi et al., 2022; Mlynarski et al., 2020; Cook et al., 2013). The European Society of Cardiology emphasises that sexuality should be included among the topics covered in the education provided to individuals with permanent pacemakers (Glikson et al., 2022).

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INVESTIGATING THE TRADE-OFF BETWEEN RECONSTRUCTION FIDELITY AND IDENTITY PRESERVATION IN DDIM INVERSION FOR FACE IMAGES

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ABSTRACT

Latent Diffusion Models (LDM) are deep learning based generative models that represent high-dimensional image data in a low-dimensional latent space and achieve high quality image synthesis by applying iterative noise reduction within this space. In LDM based image editing and transformation steps, a real image must first be inverted into the model's noise space before it can be processed. DDIM inversion is a deterministic method that reverses the standard DDIM sampling step, moving the image step-by-step into a noise domain without randomness, and aiming to approximately reconstruct the original image using the same timescale. This study investigates the behavior of the fidelity level of the DDIM inversion-reconstruction process as a function of the number of steps used. The motivation for this study is that the choice of the number of inversion steps in LDM-based face editing and frontalization studies is a critical design decision in terms of both computational cost and identity preservation. Experiments were conducted on the Honda face dataset using a pretrained LDM model on the CelebA-HQ dataset. Each image was encoded into the latent space via a VAE encoder, then transferred to the noise space using deterministic DDIM inversion at a specified number of steps and reconstructed using reverse DDIM reconstruction at the same number of steps. Reconstruction performance was evaluated using four metrics, LPIPS, SSIM, PSNR, and ArcFace cosine similarity. The findings reveal a consistent improvement across all criteria as the number of steps increases. At low steps, identity preservation is more fragile compared to image quality metrics, indicating that structural integrity is preserved earlier while identity information continues to degrade disproportionately. As the step count increases, this trend reverses where identity preservation gradually catches up with and eventually surpasses general quality metrics. At high step numbers, a clear saturation is observed across all metrics, while the corresponding gain in computation time no longer yields a proportional improvement in quality. These findings demonstrate that identity protection should be considered as a separate criterion when selecting the number of inversion steps in studies involving LDM-based face images. A configuration considered sufficient for ensuring structural quality at low step numbers may prove inadequate when it comes to identity protection. This study presents an analysis aimed at determining the ideal number of inverse steps that optimizes computational cost in identity critical applications.

Keywords: Latent diffusion models, DDIM inversion, Face images

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INTRODUCTION

Advances in image synthesis have opened up new possibilities in numerous fields, including creative content production, image restoration, super-resolution, missing region completion, medical imaging, virtual reality, digital human modeling, and biometric applications. At the heart of this development are deep generative models capable of learning high dimensional image distributions and generating new examples from those learned distributions. Variational autoencoders have provided a systematic approach to generative modeling by mapping observed data to a probabilistic latent representation, generative adversarial networks have enabled the synthesis of highly realistic images through a adversarial learning mechanism established between a generator and discriminator. More recently, diffusion models have emerged as a new paradigm in generative modeling by formulating image generation as the removal of iteratively injected noise through a learned reverse process (Ho et al., 2020; Kingma & Welling, 2022).

Denoising Diffusion Probabilistic Models (DDPMs) represent the underlying architecture of this paradigm. The fundamental mechanism of diffusion models is based on two processes: forward and reverse process. In the forward process, Gaussian noise is iteratively added to an image, transforming it into pure noise. In the reverse process, a neural network is trained to estimate the noise present in the corrupted sample at a specific time step during sampling, starting from random noise, these predictions are utilized to synthesize a novel image from the data distribution. Although this training objective is relatively simple and stable, two distinct computational bottlenecks limit the practical applicability of DDPM, the diffusion process operates directly in the high dimensional pixel space, and the reverse process requires thousands of sequential network evaluations. In the literature, these two challenges have been addressed through two independent approaches. The high memory and computational cost of pixel space has been solved with Latent Diffusion Models (LDM) proposed by (Rombach et al., 2022). LDM performs the diffusion process in a low dimensional latent space learned by a pretrained autoencoder, instead of the original pixel space of the image. However, LDM changes the space in which the diffusion process operates, but it does not change the sequential time step of the process. Therefore, sampling cost remains a problem that needs to be addressed separately.

To overcome this second limitation, Denoising Diffusion Implicit Models (DDIMs) were introduced. (Song et al., 2022) introduced a class of models that share the DDPM training objective but rely on non-Markovian forward processes. By allowing sampling over a reduced subsequence of time steps rather than the full training schedule, DDIM achieves generation quality comparable to DDPMs in significantly fewer steps. DDIM is highly compatible with Latent Diffusion Models (LDMs), the diffusion process is performed in the latent space, while DDIM handles sampling, thereby reducing the computational cost of both pixel-space processing and high step counts. Moreover, the deterministic nature of DDIM not only accelerates sampling but also facilitates advanced image editing and inversion applications the primary focus of this study. In diffusion models, standard image generation begins with a random noise sample. In contrast, editing a real image poses a distinct challenge. Specific features must be modified while strictly preserving the image's original content, geometry, and identity information. The real image must first be projected onto the model's generative trajectory that is, transformed into a corresponding noisy state. Diffusion inversion is enabled by the deterministic nature of DDIM. Recent studies, DiffusionCLIP (Kim et al., 2022), Prompt-to-Prompt (Hertz et al., 2022) and Imagic (Kawar et al., 2023) have demonstrated that the success of image editing relies heavily on how accurately the source image is represented within the model's latent trajectory.

However, standard DDIM inversion does not yield an exact and lossless reconstruction, the assumption of local approximation weakens when the number of steps is low, leading to accumulated errors that cause the inversion and reconstruction trajectories to diverge. EDICT (Wallace et al., 2022), AIDI (Pan et al., 2023), and ReNoise (Garibi et al., 2024) have sought to mitigate this issue by employing exactly invertible architectures or iterative correction mechanisms. A similar trend is observed in the real-image editing literature, frameworks like SDEdit (Meng et al., 2022), DiffusionCLIP, Prompt-to-Prompt, and Imagic have addressed the trade-off between preserving the source image and achieving the target edit through various strategies. The consensus among these studies is that inversion success depends not only on the generative capacity of the model but also on the number and distribution of the time steps.

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In the context of facial images, the inversion problem highlights that reconstruction fidelity encompasses more than just overall image quality. Face frontalization is an ill-posed problem, generating a frontal view from a profile requires hallucinating unseen regions, meaning multiple frontal outputs can match a single profile, but few preserve the original identity.

This study investigates the effect of the number of steps used in DDIM inversion on reconstruction fidelity and computational cost for facial images. The experiments employ images from the Honda/UCSD Video Database (Kuang-Chih Lee et al., 2003). Each image is mapped into the latent space using the autoencoder of the LDM pretrained on the CelebA-HQ dataset (Liu et al., 2015). The latent representations are processed with deterministic DDIM inversion across ten different step configurations N=5,10,15,20,30,50,75,100,150,200 and reconstructed using the corresponding number of steps. Performance is evaluated using PSNR, SSIM, LPIPS, and ArcFace cosine similaritya and processing time is measured for each *N* value.

METHODOLOGY

This section briefly summarizes the theoretical basis of the diffusion model used in the experiments, as well as the DDIM sampling and inversion procedures. In this study, the DDIM inversion-reconstruction pair is used without any added correction mechanism.

Latent Diffusion Models (LDM)

DDPM converts an image into pure noise by iteratively adding Gaussian noise in the forward process, while in the reverse process, a trained neural network predicts the noise at each step (Ho et al., 2020). Since this process is carried out directly in pixel space, it creates a significant computational cost in high resolution images. LDM performs the diffusion process in a lower-dimensional latent space learned by an autoencoder instead of the pixel space (Rombach et al., 2022). The input image x is transferred to the latent space in the form $z_0 = E(x)$ via an encoder, the diffusion process is performed on this z_0, and the resulting image is converted back to the image space by a decoder. The model used in this study also has an LDM architecture, and all inversion and reconstruction operations are performed in the latent space.

DDIM Sampling

DDIM is a sampling method that shares the same training objective as DDPM but defines a deterministic regression process (Song et al., 2022). The transition from the latent representation z_t in time step t to the previous step is calculated as follows:

$$z_{t-1} = \sqrt{\alpha_{t-1}} \left(\frac{z_t - \sqrt{1-\alpha_t}\,\epsilon_\theta^{(t)}(z_t)}{\sqrt{\alpha_t}} \right) + \sqrt{1-\alpha_{t-1}}\,.\,\epsilon_\theta^{(t)}(z_t) \quad (1)$$

Here, α_t represents the cumulative effect of the noise schedule, and $\epsilon_\theta^{(t)}$ represents the network's noise estimate**.**

DDIM Inversion

The DDIM inversion is based on applying the Equation 1 in the reverse direction. The same formula is rearranged to transition from z_t to z_{t+1}:

$$z_{t+1} = \sqrt{\alpha_{t+1}} \left(\frac{z_t - \sqrt{1-\alpha_t}\,\epsilon_\theta^{(t)}(z_t)}{\sqrt{\alpha_t}} \right) + \sqrt{1-\alpha_{t-1}}\,.\,\epsilon_\theta^{(t)}(z_t) \quad (2)$$

This procedure is a first-order local approximation based on the assumption that the noise estimate calculated for z_t is also valid for z_{t+1}. As the interval between time steps increases (as the number of steps N decreases), the accuracy of this approximation decreases and accumulated deviation can occur between the inversion-reconstruction pair. This study experimentally investigates the step dependent behavior of this deviation without adding any correction mechanism.

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EXPERIMENTS

Dataset and Pretrained Model

Experiments were conducted on the Honda/UCSD (Kuang-Chih Lee et al., 2003) facial dataset, which consists of 640 images collected from 20 individuals, with approximately 32 images from each individual. Because the dataset includes facial images captured under varying exposure and lighting conditions, it is suitable for evaluating the identity protecting properties of hidden representations across intraclass variation. Some images from the dataset are shown in Figure 1.



Figure 1. Sample images from the dataset.

As a diffusion model, a pretrained LDM on the CelebA-HQ face dataset was used. The model's first-stage autoencoder has a VQ-regularized structure and reduces the input to a 64×64×3 latent representation. The diffusion process was trained with a linear noise chart over a time step of T=1000. In this study, the model was not retrained, it was used for direct inference with pretrained weights.

Evaluation Metrics

Each image in the Honda dataset is encoded into the latent space using the VAE encoder of the pre-trained model to obtain z_0. This latent representation is transferred to a noisy state z_t by subjecting it to deterministic DDIM inversion at a specified number of steps N. Then, reconstructed $\hat{z_0}$ by applying DDIM sampling at the same number of steps N. The resulting $\hat{z_0}$ is transferred to the image space by decoder to generate the $\hat{x}$ reconstruction. Finally, $\hat{x}$ is compared with the original image x via LPIPS, SSIM, PSNR and ArcFace cosine similarity, and this process is repeated for N=5,10,15,20,30,50,75,100,150,200.

Learned Perceptual Image Patch Similarity (LPIPS) (Zhang et al., 2018) quantifies perceptual similarity between pairs of images using feature representations derived from a pre-trained deep network, and has been shown to have higher agreement with human perceptual judgments compared to pixel-level measures. Lower values indicate higher perceptual similarity. The Structural Similarity Index Measure (SSIM) (Zhou Wang et al., 2004) evaluates local structural patterns, brightness, and contrast between images and provides a measure of structural accuracy that is particularly sensitive to the preservation of facial regions such as eyes, nose, and mouth. A higher SSIM value indicates higher similarity. The Peak Signal-to-Noise Ratio (PSNR) measures the ratio between the maximum possible pixel value expressed in decibels and the mean squared reconstruction error, and higher values indicate lower pixel-level degradation. To assess the preservation of biometric identity in facial images, a metric specific to the identity is needed in addition to general purpose metrics. ArcFace, trained with additive angular margin loss to increase the angular separation between classes in the embedding space of the face recognition network, aims to produce feature vectors where faces belonging to the same identity are close together, and faces belonging to different identities are far apart (Deng et al., 2022). Cosine similarity was calculated between normalized ArcFace embeddings obtained from original and reconstructed images.

Results and Analysis

The LPIPS, SSIM, PSNR, ArcFace cosine similarity and processing time values obtained for different step numbers are presented in Table 1. A consistent improvement is observed in all metrics from N=5

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to N=200, LPIPS decreases from 0.6119 to 0.0591, while SSIM increases from 0.6958 to 0.9549, PSNR from 18.35 to 36.76 and ArcFace cosine similarity increases from 0.0473 to 0.9680. Processing time increases with the number of steps, reaching an average of 10.36 seconds at N=200 , compared to 0.771 seconds at N=5 . The rate of improvement varies according to the step intervals. For example, when going from N=5 to N=20, the ArcFace value increases from 0.0473 to 0.5029, a nearly tenfold increase, while when going from N=100 to N=200, the same metric changes by a relatively limited amount, from 0.9297 to 0.9680.

Table 1. Evaluation metrics results based on sampling step.

Step (N)	LPIPS ↓	SSIM ↑	PSNR ↑	ArcFace ↑	Time (s)
5	0.6119	0.6958	18.35	0.0473	0.77
10	0.5058	0.7522	20.46	0.1425	0.52
15	0.4018	0.8003	22.49	0.3371	0.79
20	0.3256	0.8345	24.08	0.5029	1.05
30	0.2250	0.8827	26.87	0.7071	1.53
50	0.1469	0.9191	30.10	0.8400	2.53
75	0.1021	0.9387	32.93	0.9086	3.85
100	0.0869	0.9447	34.16	0.9297	5.11
150	0.0602	0.9547	36.52	0.9682	8.68
200	0.0591	0.9549	36.76	0.9680	10.36

Figure 2 compares the normalized values of four metrics according to the number of steps. A different pattern is observed between the metrics at low number of steps (N=5-20). At N=10, the normalized SSIM value is 0.22 while ArcFace remains at 0.10; at N=15 , SSIM is 0.40, LPIPS is 0.38, and ArcFace is 0.32 . Around N=30, all four metrics cluster at similar values (in the 0.70-0.72 range) and from this point onwards, the ArcFace curve begins to coincide with the other three metrics.

After N=50, the ArcFace curve moves above the LPIPS and PSNR curves. This difference persists at N=100, with ArcFace at 0.96 and PSNR at 0.86 . Between N=150 and N=200, the change in all four metrics remains limited: ArcFace changes from 0.9682 to 0.9680, SSIM from 0.9547 to 0.9549, LPIPS from 0.0602 to 0.0591, and PSNR from 36.52 to 36.76. In this range, processing time increases by approximately 19%, from 8.68 seconds to 10.36 seconds.

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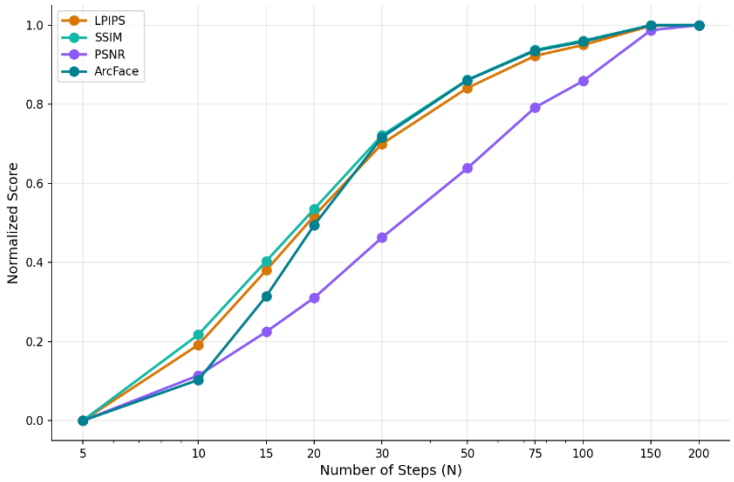


Figure 2. Normalized values of four metrics according to the number of steps

Figure 3 shows the reconstruction outputs obtained at N=5,10,15,20,30,50,75,100,150, and 200 steps for three different images, along with the original images. At N=5 and N=10, the outputs are significantly blurred, the boundaries of facial regions are not clearly distinguishable, and most of the images give the impression of a monochromatic area. At N=15 and N=20, the head position and the general contour of the face begin to become clearer, but inner facial regions such as the eyes, nose, and mouth are still not clearly separated. At N=30 and N=50, the hairline, facial contour, and general expression become recognizable, however, some blurring in the inner facial regions persists.



Figure 3. Reconstruction outputs obtained at sampling steps

At N=75 and N=100, facial regions are clearly distinguishable and the outlines of the eyes and mouth are clearly visible. No visually noticeable difference is observed between the outputs for N=150 and N=200, the images obtained at both step numbers exhibit a visually close appearance to the original image.

CONCLUSION

This study investigates the behavior of standard deterministic DDIM inversion, used within the LDM framework, on reconstruction fidelity of face images, depending on the number of steps used. Experiments were implemented the Honda face dataset over a wide range of step numbers using a pretrained LDM on CelebA-HQ. Performance was evaluated using PSNR, SSIM, LPIPS, and ArcFace cosine similarity.

The findings showed a consistent improvement across all metrics as the number of steps increased, but different metrics did not respond to this improvement at the same rate. In the low steps, the ArcFace score is more fragile behavior compared to metrics reflecting overall image quality, while structural integrity was preserved relatively early, identity information continued to change significantly up to higher step numbers. This trend reversed at intermediate step numbers, with identity preservation surpassing overall quality metrics in later steps. While a significant saturation was observed across all

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metrics towards higher step numbers, the increase in processing time did not continue at the same rate, indicating the existence of a suitable working point in terms of quality cost balance.

This study characterized the step number, a hyperparameter of standard DDIM inversion often overlooked in the literature, through a systematic and controlled experimental design, demonstrating that identity preservation reaches saturation at a threshold different from the overall image quality. It should be noted that the determined saturation point is not a universal constant but may vary depending on the model architecture used, the type of autoencoder, and the hardware conditions. These findings can be further extended by comparing them with corrected inversion methods such as EDICT and AIDI, and testing them within a face frontalization pipeline.

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MULTISCALE COMPUTATIONAL MECHANOPHENOTYPING OF TUBULINOPATHY-ASSOCIATED CYTOSKELETAL DYSFUNCTION IN MICRO-TENN MODELS

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ABSTRACT

Micro-tissue engineered neural networks (micro-TENNs) constitute a controlled three-dimensional platform for longitudinal interrogation of aligned axonal architecture and tract-level biomechanics. Given the central contribution of microtubules to axonal structural integrity, intracellular force transmission and cytoskeletal remodelling, tract-scale mechanical phenotyping provides a plausible analytical bridge between tubulin dysfunction and emergent neural-network behaviour. Here, we developed a MATLAB R2023a computational proof-of-concept to evaluate whether multivariate micro-TENN-like time-series data can be transformed into reproducible construct-level mechanophenotypes and discriminated using donor-grouped machine learning. A deterministic synthetic dataset comprising 120 constructs was generated across three pre-specified scenarios labelled Control, TUBA1A and TUBB3, with four simulated donors per scenario, ten constructs per donor and daily measurements over 21 days. Nine features were derived from longitudinal trajectories of tract length, axial force, calcium synchrony, bundle straightness and viability. A 300-tree random forest classifier was trained on 90 constructs from nine simulated donors and evaluated on 30 constructs from three completely held-out simulated donors. The held-out analysis yielded an accuracy of 0.933, macro-F1 of 0.933 and balanced accuracy of 0.933; two TUBB3-labelled constructs were assigned to the Control class, whereas all TUBA1A-labelled constructs were correctly classified. Out-of-bag permutation analysis identified final shortening percentage as the dominant predictor within the programmed simulation space. These findings verify the computational capacity of the implemented workflow to recover structured multivariate states encoded in the synthetic generator and establish an auditable analytical framework for subsequent biological validation in human induced pluripotent stem cell-derived micro-TENNs with direct mechanical measurements, isogenic controls and independent biological replication.

Keywords: micro-TENN; tubulinopathy; TUBA1A; TUBB3; axonal biomechanics; mechanophenotyping; random forest; synthetic data

INTRODUCTION

Tubulinopathies comprise a genetically and phenotypically heterogeneous spectrum of neurodevelopmental and neurological disorders arising from pathogenic variation in genes encoding α- and β-tubulin isotypes and associated microtubule machinery. Their phenotypic architecture spans cortical malformations, disrupted neuronal migration, aberrant axon guidance, altered neuronal morphology and perturbation of microtubule-dependent interactions with molecular motors and microtubule-associated proteins (Maillard et al., 2023; Puri et al., 2023). Importantly, genotype-phenotype relationships are neither uniform across tubulin genes nor invariant across variants within a single gene. Recent clinical and functional evidence demonstrates substantial heterogeneity in

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TUBA1A-associated disease, with individual variants producing distinct molecular, cellular and developmental consequences (Ren et al., 2024; Hoff et al., 2022).

TUBA1A was selected as a principal mechanistic scenario because it encodes a neuronally enriched α-tubulin isotype that participates directly in microtubule assembly and neuronal morphogenesis. Experimental studies have shown that disease-associated TUBA1A variants can perturb microtubule polymerisation dynamics, acetylation, neuronal branching, migration and cellular morphology. Hoff et al. (2022), for example, demonstrated that TUBA1A-V409I/A variants alter microtubule polymerisation and neuronal morphogenesis, with variant-dependent molecular phenotypes paralleling differences in disease severity. Reduced TUBA1A function has additionally been associated with impaired axonal extension and defective commissural development (Buscaglia et al., 2022), whereas a TUBA1A loss-of-function variant has been shown to compromise tubulin stability and proteostasis (Zocchi et al., 2023). Collectively, these observations position TUBA1A dysfunction as a multiscale perturbation of microtubule homeostasis rather than a lesion confined to a single developmental pathway.

TUBB3 provides a complementary β-tubulin context with distinct implications for neuronal microtubule organisation. As a neuron-specific β-tubulin isotype, TUBB3 contributes to axonal growth, guidance and microtubule architecture. Pathogenic TUBB3 variants are associated with abnormalities of cranial and central axon development, neuronal migration and cortical organisation, while functional studies indicate variant-dependent effects on microtubule dynamics and kinesin interactions (Puri et al., 2023). TUBA1A and TUBB3 therefore provide biologically relevant, mechanistically non-equivalent tubulinopathy-associated scenarios for evaluating whether a common computational framework can resolve distinct patterns of tract-scale behaviour.

A mechanophenotyping strategy is particularly relevant because the microtubule cytoskeleton functions as both a structural scaffold and a dynamic determinant of axonal mechanics. Microtubule organisation, polymerisation state, post-translational modification and interactions with microtubule-associated proteins influence axonal transport, growth, guidance and remodelling (Atkins et al., 2023). These molecular processes are coupled to cellular force transmission and morphological stability, thereby providing a mechanistic route through which tubulin perturbation could propagate from the molecular scale to tract-level structural and mechanical phenotypes. Consistent with this framework, experimental mechanical loading has been shown to remodel the axonal cytoskeleton and alter microtubule organisation (Falconieri et al., 2023; Falconieri et al., 2024).

Micro-TENNs are engineered neural constructs in which spatially discrete neuronal populations are interconnected by aligned, long-range axonal tracts within a defined three-dimensional biomaterial geometry (Harris et al., 2016). Human organoid-derived implementations further demonstrate the feasibility of generating constrained three-dimensional human axonal tracts within this platform (Cullen et al., 2019). Of particular relevance to mechanophenotyping, Chouhan et al. (2024) demonstrated that bundled three-dimensional axonal tracts in micro-TENNs generate intrinsic contractile forces in a manner dependent on microtubule stability. This observation provides a direct experimental basis for integrating longitudinal tract morphology with mechanical readouts when interrogating tubulin-associated cytoskeletal dysfunction.

Axonal mechanics emerge from coordinated interactions among microtubules, actin, membrane-associated structures, molecular motors and additional cytoskeletal components (Ghose and Pullarkat, 2023). Mechanical force is therefore not simply an external perturbation but an active regulator of cytoskeletal state. Falconieri et al. (2023) demonstrated that externally applied mechanical forces increase axonal microtubule density and induce cytoskeletal remodelling, while Falconieri et al. (2024) identified microtubules as a mechanistically relevant signalling hub linking tensile cues to axonal growth and transport. Emerging preprint evidence further implicates RhoA, talin, actomyosin and the spectrin-based membrane-associated skeleton in axonal responses to physiological mechanical forces (Swaim et al., 2025).

Taken together, these observations support a testable multiscale hypothesis in which tubulin-associated molecular perturbations alter microtubule organisation and dynamics, which in turn modify axonal structure, force generation and tract-level behaviour.

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Accordingly, the present study evaluates a defined computational question: whether a reproducible MATLAB workflow can extract structurally and functionally interpretable features from micro-TENN-like longitudinal data and discriminate pre-specified mechanical states under donor-grouped evaluation. The objective is to establish an auditable analytical architecture for future biological experiments, with explicit separation between computational verification in synthetic data and subsequent genotype-specific validation in experimentally measured human micro-TENNs.

RESEARCH AND FINDINGS

Study design and synthetic data generation

All analyses were implemented in MATLAB R2023a using the Statistics and Machine Learning Toolbox. A deterministic synthetic dataset was generated after fixing the random-number seed at 2026. Three pre-specified parameter regimes were defined and labelled Control, TUBA1A and TUBB3. Each scenario comprised four simulated donors and ten micro-TENN constructs per donor. Daily measurements were generated over a 21-day culture interval, producing 120 constructs and 2,520 construct-day observations in total.

The scenario labels denote parameterised computational regimes used to test analytical behaviour; they are not derived from patient cells, experimentally engineered pathogenic variants or measured disease phenotypes.

For each construct, the generator produced longitudinal trajectories for tract length, axial force, calcium synchrony, bundle straightness and viability. Scenario-specific parameterisation was applied to shortening amplitude, temporal contraction midpoint, force amplitude, late-stage synchrony, terminal bundle straightness and viability-loss rate. Simulated donor effects, construct-level variation and observation noise were superimposed on these trajectories to introduce hierarchical variability while retaining controlled between-scenario structure. Consequently, the simulation was designed to contain discriminative multivariate information at the construct level.

Two batch labels were retained for each simulated donor as organisational metadata. The benchmark partition itself was performed exclusively at the donor level; batches were not independently held out. Model performance therefore quantifies generalisation across the specific simulated donor effect encoded by the generator rather than independent batch-level robustness.

Table 1. Synthetic study design and evaluation structure.

Item	Specification
Data status	Synthetic proof-of-concept; not biological or clinical data
Scenario labels	Control, TUBA1A and TUBB3
Observation window	Days 1-21
Simulated cohort	120 constructs; 12 simulated donors; 10 constructs per donor
Time-series variables	Length, axial force, calcium synchrony, bundle straightness and viability
Training and test split	90 / 30 constructs; donors D1-D3 used for training and D4 held out in each scenario
Classifier	300-tree Random Forest (TreeBagger), MinLeafSize = 3, all nine predictors sampled at each split
Primary evaluation metric	Macro-F1 on the held-out simulated donor set

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Feature engineering and classifier evaluation

Nine construct-level descriptors were extracted from the 21-day longitudinal profiles: initial length, final shortening percentage, peak contraction rate, peak force, force-time area under the curve, day of peak force, mean calcium synchrony from day 10 onward, terminal bundle straightness averaged from day 18 onward and minimum viability. These variables were selected to represent complementary structural, mechanical, temporal and functional dimensions of the simulated micro-TENN phenotype.

Relaxation kinetics and bundle thickness were not computed by the implemented workflow and were therefore excluded from the feature matrix. Axial force values were generated synthetically in micro-Newtons and should be interpreted as model variables rather than calibrated experimental force measurements.

A 300-tree TreeBagger random forest classifier was fitted using all nine construct-level predictors, with MinLeafSize set to 3 and all nine predictors available for sampling at each split. To preserve hierarchical independence, the fourth simulated donor from each scenario was completely withheld from model training; no construct from a held-out donor entered the training partition. The resulting split contained 90 training constructs from nine simulated donors and 30 test constructs from three held-out simulated donors.

The supplied computational workflow was intentionally restricted to a single pre-specified classifier configuration. No hyperparameter optimisation, alternative-model comparison, feature-selection procedure, confidence-interval estimation or repeated resampling analysis was performed. Out-of-bag prediction and permutation-based predictor importance were calculated within the training partition to provide internal model diagnostics and interpretable ranking of the encoded feature structure.

Results

The generated longitudinal trajectories reproduced the scenario-specific temporal structure defined by the simulation parameters. Control constructs exhibited the greatest mean tract shortening together with the highest early axial-force profile. TUBA1A-labelled constructs showed attenuated shortening, lower force magnitude, a later force trajectory and reduced late functional measures, whereas TUBB3-labelled constructs occupied an intermediate multivariate regime. These temporal differences were subsequently condensed into construct-level mechanophenotypic descriptors for classification.

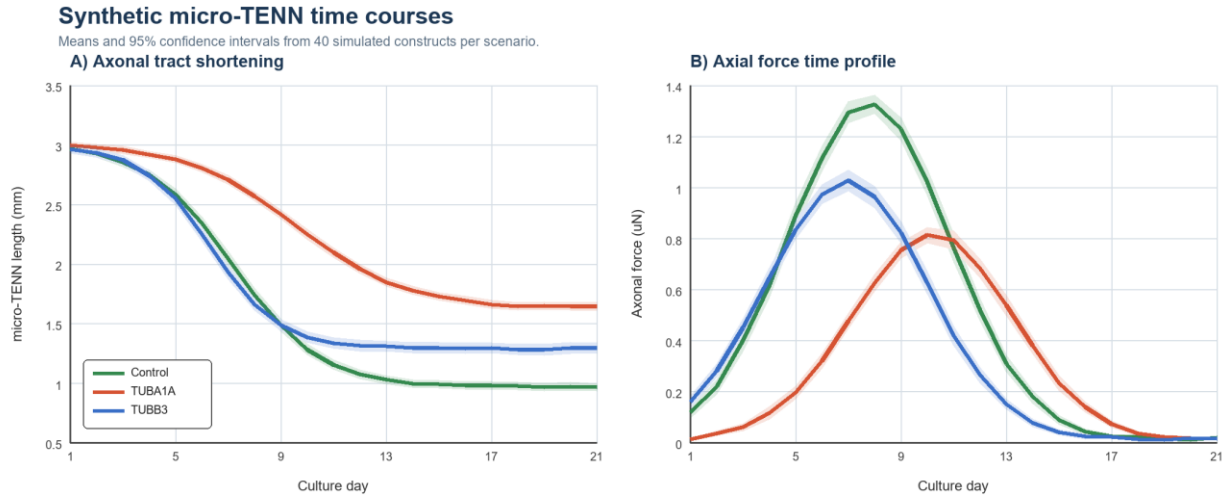


Figure 1. Synthetic 21-day micro-TENN trajectories. (A) Mean tract length and (B) mean axial-force profiles. Shaded regions represent 95% confidence intervals across simulated constructs (n = 40 per scenario). All trajectories were generated computationally and represent the parameterised synthetic model. Source: Authors' analysis of the MATLAB R2023a synthetic time-series dataset.

On the donor-held-out synthetic test set, the classifier correctly assigned 28 of 30 constructs, corresponding to an overall accuracy of 0.933, macro-F1 of 0.933 and balanced accuracy of 0.933. All Control and TUBA1A-labelled constructs were correctly classified; two TUBB3-labelled constructs were assigned to the Control class. One-versus-rest AUC values were 1.000 for all three labels. This combination of perfect rank-based AUC and non-perfect hard-label classification is mathematically consistent because AUC quantifies score ordering across thresholds, whereas the confusion matrix reflects the final class assignment at the implemented decision rule. Within the controlled simulation, the results indicate strong recovery of the encoded class structure under donor-grouped evaluation.

Table 2. *Held-out performance for the synthetic donor-level split.*

Class / metric	Precision	Recall	Specificity	F1	One-vs-rest AUC
Control	0.833	1.000	0.900	0.909	1.000
TUBA1A	1.000	1.000	1.000	1.000	1.000
TUBB3	1.000	0.800	1.000	0.889	1.000
Overall accuracy	0.933	-	-	-	-
Macro-F1	0.933	-	-	-	-
Balanced accuracy	0.933	-	-	-	-

Note. All performance estimates derive from the 30-construct synthetic test partition and therefore quantify computational discrimination within the parameterised simulation.

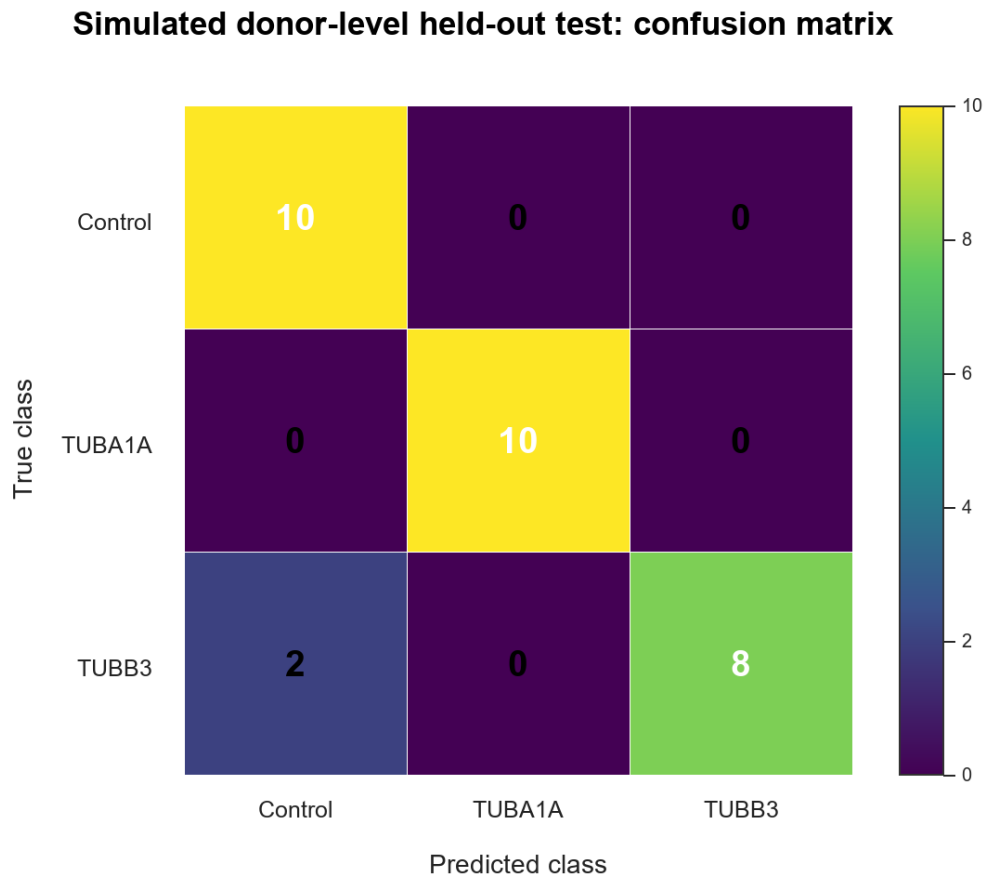


Figure 2. Confusion matrix for the donor-held-out synthetic test set (n = 30 constructs). Rows denote

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true scenario labels and columns denote predicted labels. Two TUBB3-labelled constructs were classified as Control; all Control and TUBA1A-labelled constructs were correctly assigned. Source: Authors' MATLAB R2023a classification output.

Out-of-bag permutation analysis ranked final shortening percentage as the most influential predictor, followed by terminal bundle straightness, minimum viability and late mean calcium synchrony. Because predictor distributions were generated from scenario-specific parameterisation, this ranking identifies the variables that carried the greatest discriminative information within the implemented simulation. It therefore functions as an internal interpretability diagnostic of the computational model and defines explicit candidate readouts for subsequent experimental testing.

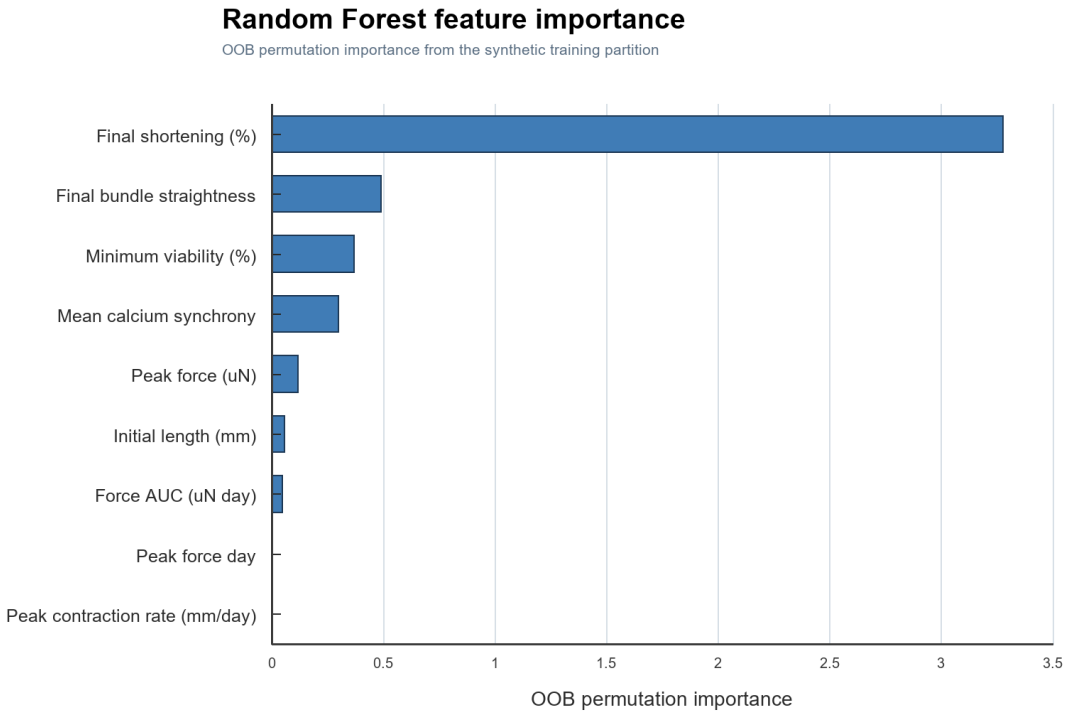


Figure 3. Random forest out-of-bag permutation importance estimated from the synthetic training partition. Final shortening percentage produced the highest permutation-importance signal, followed by terminal bundle straightness, minimum viability and late mean calcium synchrony. Source: Authors' MATLAB R2023a out-of-bag permutation-importance output.

Projection of constructs into the two-dimensional space defined by final shortening and peak force further illustrated the programmed mechanophenotypic geometry. TUBA1A-labelled constructs occupied the lower-shortening, lower-force region, whereas Control constructs were concentrated at higher values of both features. TUBB3-labelled constructs showed partial overlap with the Control distribution, concordant with the two TUBB3-to-Control misclassifications observed in the held-out test set.

Accordingly, the two-feature projection should be interpreted as a visual representation of the multivariate geometry encoded by the synthetic generator and as a template for future experimentally derived mechanophenotype maps.

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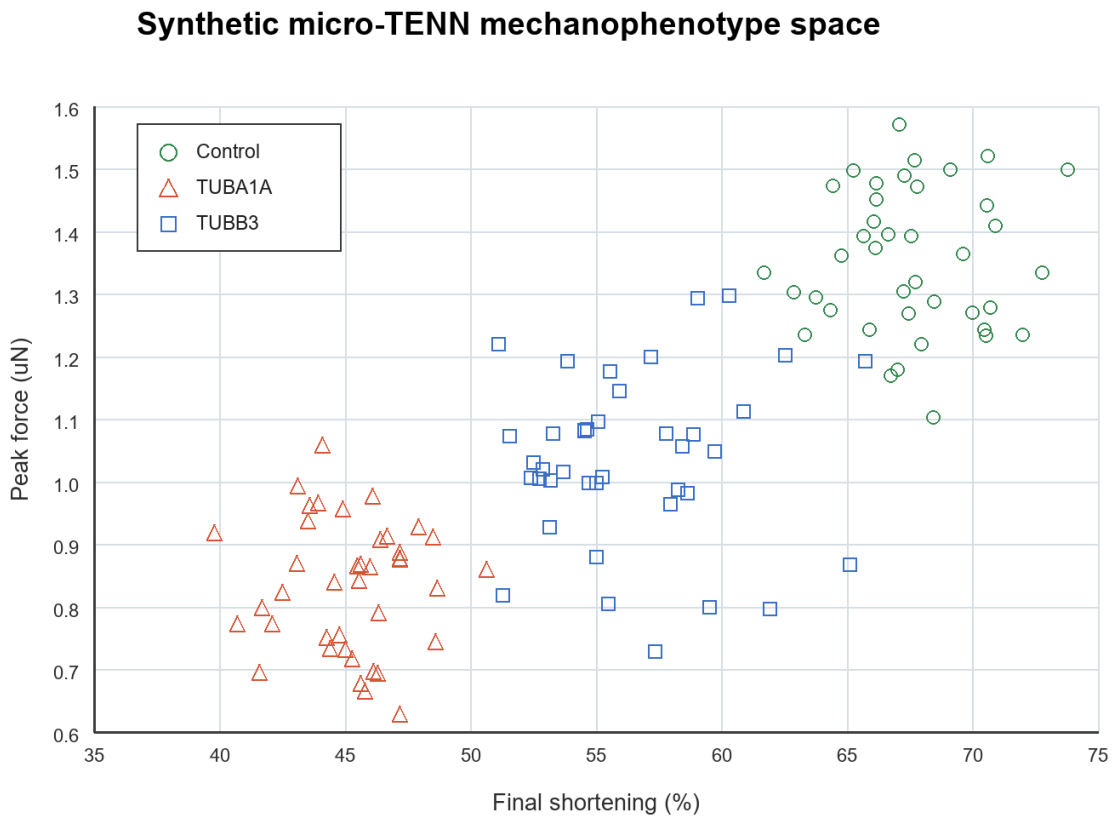


Figure 4. Synthetic mechanophenotype space defined by final shortening percentage and peak force for 120 simulated constructs. Scenario separation and overlap reflect the pre-specified data-generating parameters. Source: Authors' analysis of the MATLAB R2023a synthetic feature dataset.

Mechanistic interpretation and experimental translation

The computational analysis establishes technical separability among pre-defined multivariate mechanical states and verifies the complete analytical sequence from longitudinal signal generation to construct-level feature extraction, donor-grouped classification, performance estimation and predictor-importance analysis. The principal value of the current model is therefore methodological: it provides a reproducible computational scaffold in which assumptions, feature definitions, grouping structure and classifier outputs can be audited before biological data are introduced.

Within this framework, the TUBA1A and TUBB3 labels function as mechanistically motivated parameter regimes rather than experimentally measured genotypes. The reported classification performance consequently quantifies recovery of programmed multivariate structure and should be interpreted as a verification of pipeline sensitivity under controlled synthetic conditions.

The biological rationale for prospective validation is supported by convergent evidence across molecular, cellular and tissue scales. Disease-associated TUBA1A variants can alter microtubule polymerisation and neuronal morphogenesis (Hoff et al., 2022), while TUBA1A loss-of-function can impair tubulin stability and proteostasis (Zocchi et al., 2023). TUBB3-associated variants can perturb microtubule dynamics, axon development and motor-protein interactions (Puri et al., 2023). At the cellular scale, microtubule remodelling contributes directly to axon guidance and pruning (Atkins et al., 2023), and axonal mechanics is increasingly recognised as a determinant of neuronal development and structural stability (Ghose and Pullarkat, 2023). At the engineered tissue scale, micro-TENN axonal tracts generate intrinsic contractile forces whose magnitude depends on microtubule stability (Chouhan et al., 2024).

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These observations define a biologically coherent multiscale model linking genotype-associated molecular perturbation to emergent tract mechanics:

tubulin variant → altered microtubule properties → cytoskeletal reorganisation → altered axonal mechanics → tract-level mechanophenotype.

In the present work, this sequence serves as the mechanistic architecture for prospective experimental testing. The computational model operationalises the terminal structural and mechanical components of this pathway by converting longitudinal tract behaviour into quantitative features that can be evaluated at the construct and donor levels.

Several design features should be considered when translating this framework to biological data. The present dataset is fully synthetic, the scenario-specific differences are encoded a priori, and the held-out evaluation contains one simulated donor per label from a single seeded realisation. Batch identifiers are retained but are not used as an independent validation factor, and no patient-derived or engineered iPSC lines, isogenic controls, microscopy-derived structural measurements or calibrated force measurements are incorporated. These characteristics define the current analysis as a computational verification stage rather than a completed biological mechanophenotyping experiment.

The magnitude and coherence of simulated between-class differences are determined by the data-generating process and may exceed the effect structure observed in biological systems. Consequently, the present feature-importance ranking should be interpreted as a sensitivity map of the programmed model. Its translational value lies in identifying candidate measurements—particularly tract shortening, bundle straightness, viability and calcium synchrony—that can be prospectively quantified and tested for reproducibility in independent biological material.

A biologically validated implementation should include multiple independent patient-derived or genome-engineered iPSC lines per genotype, matched isogenic controls and repeated neuronal differentiations across independent experimental batches. Donor or cell line, rather than image, field of view or technical construct replicate, should constitute the principal biological unit for statistical partitioning and inference.

Mechanical phenotyping should incorporate calibrated direct force measurement using a validated platform, such as known-stiffness microposts or an equivalent force-sensing system with experimentally determined calibration parameters. Longitudinal imaging should be standardised with respect to acquisition geometry, temporal sampling and image-processing procedures, accompanied by blinded quality control and predefined exclusion criteria.

For inferential modelling, grouped nested cross-validation should preserve donor or iPSC-line membership within folds, with a fully independent external or temporally separated test set reserved for final model evaluation. Random forest performance should be benchmarked against appropriately selected baseline classifiers, and uncertainty should be quantified using donor-level resampling or an equivalent hierarchical procedure. Such a design would permit discrimination performance to be interpreted at the biological-unit level rather than at the level of correlated technical observations.

The mechanophenotyping framework can be strengthened further by integrating orthogonal molecular and structural measurements, including microtubule abundance, acetylation state, polymerisation dynamics, axonal transport, tract alignment and calibrated force generation. Multimodal integration of these variables would permit direct assessment of whether molecular disruption of tubulin homeostasis is accompanied by coordinated alterations in cytoskeletal organisation and tract mechanics.

The emerging work of Swaim et al. (2025) provides an additional mechanotransduction context by indicating that physiological mechanical forces can reorganise axonal microtubules through pathways involving RhoA, talin, actomyosin and the spectrin-associated membrane skeleton. As a preprint, this study represents emerging rather than definitive evidence; nevertheless, it reinforces the rationale for integrating mechanical and cytoskeletal measurements within the same experimental architecture.

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CONCLUSION

This study establishes a reproducible MATLAB R2023a framework for transforming longitudinal micro-TENN-like signals into nine construct-level mechanophenotypic features and evaluating pre-specified multivariate states using donor-grouped machine learning.

In the controlled synthetic benchmark, the random forest classifier achieved an accuracy of 0.933, macro-F1 of 0.933 and balanced accuracy of 0.933 on constructs from completely held-out simulated donors. Final shortening percentage carried the strongest out-of-bag permutation-importance signal, and the two observed classification errors were confined to TUBB3-labelled constructs assigned to the Control class. These results quantitatively verify recovery of the structured mechanical differences encoded in the simulation.

The computational architecture is biologically motivated by convergent evidence linking TUBA1A and TUBB3 dysfunction to altered microtubule dynamics, neuronal morphogenesis, axon guidance and cytoskeletal organisation, together with experimental evidence that bundled micro-TENN axonal tracts generate microtubule-stability-dependent contractile forces.

The resulting framework therefore provides a mechanistically informed and analytically auditable foundation for prospective tubulinopathy mechanophenotyping. Its decisive next stage is experimental implementation in directly measured human iPSC-derived micro-TENNs incorporating isogenic controls, independent biological donors, repeated differentiation batches, calibrated mechanical measurements and donor-level statistical validation. This transition will enable the synthetic feature architecture developed here to be tested against genotype-resolved molecular, structural and mechanical phenotypes.

ETHICS STATEMENT

This study used exclusively synthetic computational data and did not involve human participants, animal procedures, patient-derived biological material or identifiable information. Ethical approval was therefore not required.

DATA AND CODE AVAILABILITY

The MATLAB R2023a proof-of-concept package comprises the synthetic longitudinal dataset, feature-extraction functions, random forest classification code and generated result tables described in this manuscript. The materials are available for inspection and reuse upon request from the corresponding author.

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EFFECTS OF PROJECT METHOD ON SENIOR SECONDARY STUDENTS' INTEREST IN PHYSICAL GEOGRAPHY IN JOS NORTH LOCAL GOVERNMENT AREA, PLATEAU STATE, NIGERIA

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ABSTRACT

This study specifically sought the effects of project method on students' interest in Physical Geography in Jos North Local Government Area, Plateau State, Nigeria. The study stated three objectives, answered three research questions and tested three hypotheses. Pre-test, post-test non-equivalent control group design, a type of quasi-experimental design was adopted. A sample of 65 Geography students (28 males and 37 females) from two intact classes of two selected secondary schools in the study area was used for the experiment. The schools were selected and assigned to experimental and control groups through simple random sampling techniques. The experimental group was taught using the project method, while the control group was taught using the conventional lecture method. Students' Interest in Physical Geography Questionnaire (SIPGQ) was used for data collection and was the instrument was validated by three experts from the field of Geography education, test and measurement and Psychology of education. The reliability was tested using Cronbach's Alpha methods with a reliability index of 0.75. Data collected were analyzed using mean, standard deviation and Analysis of Covariance (ANCOVA). The findings revealed that students taught Physical Geography using the project method had significantly higher mean interest scores than those taught using the lecture method. There was no statistical difference between the interest mean score of the male and female students in physical geography, implying that gender has no significant effect on the interest of students towards physical geography. However, there was no statistically significant interaction effect of treatment and gender on students' interest indicating that the project method was effective for both genders. The study concluded that the project method is an effective instructional strategy for improving students' interest towards Physical Geography. It was therefore, recommended that Geography teachers should adopt the project method in teaching Physical Geography concepts and that educational stakeholders should organize training workshops to equip teachers with the necessary skills for effective implementation of project-based learning approaches.

Key words: Project Method, Students' Interest, Geography, Physical Geography and Gender

INTRODUCTION

Geography is the scientific study of the Earth's surface, encompassing its physical features, human societies and the interactions between them. It bridges a gap between natural and social sciences, enabling a comprehensive understanding of global challenges such as climate change, urbanization, and resource distribution (Royal Geographical Society, 2024). Geography is an interdisciplinary subject that enlightens students about the Earth in its totality. It seeks to develop students' appropriate and comprehensive competence which would enable them enhance their personal development and become a contributor to the society. However for an individual to be competent in Geography knowledge, such individual needs quality knowledge of Geography which is obtained in the various branches. According to National Education Research and Development Council 2023 the branches of Geography in secondary schools are: Local Geography, human Geography, regional Geography, practical Geography and physical Geography,

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Physical Geography is a major branch of Geography which focuses on the understanding of natural features and processes of the earth surface. It examines the pattern distribution and dynamics of the physical environment, including the atmosphere, hydrosphere, lithosphere and biosphere. According to Omesimi, Oben and Mbah, (2019) Physical Geography consists of the study of the environment, weather and climate, vegetation, erosion, soil, environmental resources, environmental problems, environmental conservation, and climate change. Gregory (2023) states that Physical Geography is essential for understanding environmental process and challenges such as climate change, natural hazard, degradation, and biodiversity lost. The knowledge of physical Geography provides the opportunity for academic pursuits and professional development. It helps to be enrolled in areas such as cartography, remote sensing, weather forecasting, and climatology among others. However, some students consider Physical Geography difficult and abstract, especially when it is taught mainly through verbal explanations and memorization. This may limit students' active participation in classroom activities and in turn decrease their interest in the subject.

Interest plays a critical role in determining students' motivation, engagement and achievement in Geography. When learners are genuinely interested in a topic, they are more likely to participate actively and retain knowledge for longer periods, leading to better learning outcomes (Schneider and Preckel, 2017). Students' interest in Physical Geography has been consistently linked to their level of achievement in the subject. A study in West Bengal (India) by Samanta and Banerjee (2025) found out that students with higher interest in Geography tend to perform better academically. The study revealed a significant correlation between interest in Geography and achievement. Specifically, students who expressed moderate to high interest in geographical topics achieved higher scores than those with lower interest. Interest has been shown to be a strong predictor of students' achievement irrespective of gender but the relationship is often affected by how the method employed, students' backgrounds (such as cognitive style or gender), and the resources available. This may be as a result of the methods used by Geography teachers, most of them use teaching methods that are not usually effective for classroom delivery of the contents and as such, the students do not usually acquire much. This means that some methods are not appropriate for teaching some contents.

For a particular teaching method to be appropriate and efficient, it has to take into account the nature of the topic, subject, class size, nature of environment, students' age, available resources and the type of learning it supposed to bring about (Brown, 2020). However, many Geography teachers predominantly rely on conventional method (Klein, Henschke, & Clarke, 2023). Despite its popularity, conventional method has been criticized for minimizing students engagement compared to more interactive approaches such as project method. In recent years, educators have emphasized the use of learner-centered teaching strategies that encourage active participation and meaningful learning. One of such strategies is the project method, which involves students in practical activities, investigation, and problem solving. The method allows students to learn by doing and to apply theoretical knowledge to real-life situations.

Project method is a student-centered method in which learners actively engage in real-world task or investigation to gain knowledge and develop skills by promoting inquiry, hands-on explorations and real-world application. The essence of this method is to carry out a useful task in a group in which all the students work cooperatively. Project method fosters critical thinking, problem-solving, and engagement making it an effective teaching strategy (Brown, 2020). This method improves students' interest and the more interested a student is, the more likely he/she is to perform well in that subject.

Several studies has confirmed the effectiveness of project method, Wangmo (2024) on assessing the impact of project-based learning approach on students' academic achievement and attitudes find out that, the use of project -based learning enhances the students' learning compared to the conventional teaching method. Augustine (2024) investigates the effect of project method and concept mapping on the achievement and interest of students in some environmental concepts in Geography in San Juan city. The study revealed that there was significant interaction effect of teaching strategies and gender on student's interest. Ibrahim (2018) found out that field trip significantly improved students interest. Al-Khayat and Al-Barbari (2023), who examined the effect of project-based learning on students' outcomes in Geography reported that gender did not significantly moderate students' interest when learner-

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centered instructional strategies were employed. Saad, Umar, and Musa (2025) investigates the impact of gender differences on academic achievement and interest in Regional Geography among secondary students and reported that the interaction and visual nature of concept mapping enhance students learning output and students interest in regional Geography. The project method is believed to enhance students' understanding of geographical concepts and stimulate their interest in learning irrespective of gender. However, studies have shown that male and female students may differ in how they participate in and benefit from project-based activities (Subba, 2023 & Kidman 2017). This raises the question of whether the project method enhances students' interest equally across gender.

Gender is a social construct that defines the expectations, roles and responsibilities associated with being male, female, or other identities in a given society. It differs from biological sex and is influenced by social, cultural, political and economic factors. Gender roles affect how individuals participate in education, work, and social life, thereby shaping their opportunities and experiences (Subba, 2023). Gender has been recognized as an important factor influencing students' learning experiences. In Nigeria today it is believed that science subjects are for boys while arts subjects are for girls, this believes is inadequate and unproven. Review of literature has showed that girls can equally study Geography and perform better. Abubakar (2024) and Al-Khayat and Al-Barbari (2023) found out that, there was no significant gender difference in the performance and attitudes of students in Geography. Hence, it was against this background that the study investigated the effects of project method on senior secondary students' interest in physical Geography in Jos North Plateau State, Nigeria.

STATEMENT OF THE PROBLEM

Despite the importance of physical Geography, some students demonstrate low interest in the subject. This may be due to the continued use of conventional teaching method which provides limited opportunities for students' to participate actively in the learning process. When Physical Geography is taught mainly through conventional method, students may perceive some topics as abstract and difficult. This may reduce their interest in the subject. It may also result to the subject losing its popularity in the secondary school curriculum. This means losing cartographers, climatologist, weather forecasters, and astronomers among others. Learner-centered methods such as the project method provide opportunities for students' to investigate Geographical problems work collaboratively and relate classroom learning to their environment. It was on this background that this study investigated the effects of project method on senior secondary students' interest in physical Geography in Jos North Plateau State, Nigeria.

OBJECTIVES OF THE STUDY

The objectives of the study were to:

1. determine the interest of secondary students' towards physical Geography in the experimental and control groups before and after the experiment in Jos North Plateau State, Nigeria.

2. find out the male and female secondary students' interest in physical Geography in the experimental and control groups after the experiment in Jos North Plateau State, Nigeria.

3. determine the interaction effect of treatment and gender on the interest of SS ii students using project method in Physical Geography in Jos North Plateau State, Nigeria.

RESEARCH QUESTIONS

The following research questions guided the study

1. What are the interest mean scores of secondary students' towards physical Geography in the experimental and control groups before and after the experiment in Jos North Plateau state Nigeria?

2. What are the interest mean scores of male and female secondary Students in the experimental and control groups in physical Geography after the experiment In Jos North Plateau state Nigeria?

3. What is the interaction effect of treatment and gender on the interest of SS II students using project method in Physical Geography in Jos North Plateau State, Nigeria?

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HYPOTHESES

The following null hypothesis were formulated

1. There is no significant difference between the interest mean scores of experimental and control groups of secondary students in physical Geography before and after the experiment in Jos North plateau state Nigeria.

2. There is no significant difference between the interest mean scores of male and female secondary students' in the experimental and control groups in physical Geography after the experiment in Jos North plateau state, Nigeria.

3. There is no significant difference in the interaction effect of treatment and gender on the interest of SS II students using project method in Physical Geography in Jos North Plateau State, Nigeria.

METHODOLOGY

The study adopted a quasi-experimental design (pre-test, post-test without randomization). This is because the design allowed intact classes to be used where the population differed. The population of the study is made up of all Senior Secondary School II (SS II) students offering Geography in public secondary schools in Jos North Plateau State with a total of 1,152. Samples of 65 SS II students offering Geography (28 males and 37 females) from two selected secondary schools based on their intact classes were used. The two schools were selected using simple random sampling techniques and were assigned to experimental and control groups. 25 items structured questionnaire, known as Students' Interest in Physical Geography (SIPG) was used for data collection. The instrument was adapted from existing standardized instruments available online by Rahma, Suati, & Earnawati (2022). The instrument was structured using the Likert model, in which the responses of the respondents were guided by five scales: Strongly Agree (SA), Agree (A), Undecided (U), Disagree (D), and Strongly Disagree (SD). The instrument was validated by experts from Geography Education, Test and Measurement, and Psychology Education all from University of Jos. The reliability was tested using Cronbach's Alpha method with a reliability index of 0.75. The data collected were analyzed using mean and standard deviation to answer research questions and Analysis of Covariance (ANCOVA) for testing the hypotheses.

RESULTS

Research Question One: What is the interest mean scores of secondary school students' towards physical Geography in the experimental and control groups before and after the experiment in Jos North Local Government Area, Plateau state Nigeria?

Table `1

Pretest and Posttest interest mean score of experimental and control group of students in physical geography.

Group	N	Pretest Mean	SD	Posttest Mean	SD	Mean gain	Mean diff.
Experimental	43	72.00	7.31	104.84	5.16	32.84	13.75
Control	22	74.09	5.74	91.09	5.84	17.00	

The result in Table one revealed the pretest mean score yielded mean of 72.00 and standard deviation (SD) of 7.31 for the experimental group while that of the control group yielded mean of 74.09 and SD of 5.74. This indicated the control group had a better interest towards physical geography than the experimental group before the experiment. Furthermore, the posttest mean score yielded mean of 104.84 and SD of 5.16 for the experimental group while mean of 91.09 and SD of 5.84 for the control group with a mean difference of 13.75 in favor of the experimental group. The Table also indicated a mean gain of 32.84 and 17.00 for the experimental and control groups respectively. This further revealed that

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students in the experimental group developed a higher interest towards physical geography than their counterparts in the control group after being exposed to the knowledge of physical Geography.

Hypothesis One: There is no significant difference between the interest mean scores of experimental and control groups of secondary school students in physical Geography before and after the experiment in Jos North Local Government Area, plate state, Nigeria.

Table 2

Summary of ANCOVA Result Showing Difference between Pretest and Posttest interest Scores of Experimental and Control Groups in physical geography

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	2804.111[a]	2	1402.055	48.845	.000	.612
Interce//pt	6342.606	1	6342.606	220.963	.000	.781
Pretestinterest	54.005	1	54.005	1.881	.175	.029
Group	2581.850	1	2581.850	89.946	.000	.592
Error	1779.674	62	28.704			
Total	656986.000	65				
Corrected Total	4583.785	64				

a. R Squared = .612 (Adjusted R Squared = .599).

The pretest interest yielded F(1,62) = 1.881, P-value = 0.175, indicating that P > 0.05. Since P-value is greater than the 0.05 level of significance, the null hypothesis is retained implying that there is no significant difference between the interest mean scores of experimental and control groups of secondary school students in physical Geography before the experiment. The posttest yielded F(1,62) = 89.946, P < 0.05, partial η2 = 0.592, since the P-value of 0.000 is less than 0.05 level of significance with an effect size of 59.2%, the null hypothesis was rejected, indicating that there is a significant difference between the interest mean scores of experimental and control groups of secondary school students in physical Geography after the experiment. The result further reveals an adjusted R squared value of 0.599 which means that 59.9 percent of the variation in the dependent variable which is students' interest is explained by variation in the treatment, while the remaining is due to other factors not included in this study. Hence, we can say that project method does increase students' interest mean score in physical geography.

Research Question Two: What are the interest mean scores of male and female secondary school Students in the experimental and control groups in physical Geography after the experiment In Jos North Local Government Area Plateau state Nigeria?

Table 3

Pre-Test and Post-Test Interest Mean score of Male and Female Students toward Physical Geography in the Experimental Group

Group	N	Pretest Mean	SD	Posttest Mean	SD	Mean gain	Mean diff.
Male	18	72.56	7.69	103.89	5.35	31.33	1.63
Female	25	71.60	7.16	105.52	5.02	33.92	

Table three contained the pretest and posttest interest mean score of male and female students in the experimental and control groups in physical geography. The pretest mean score of male students yielded mean of 72.56 and SD of 7.69, while that of the female students yielded mean of 71.60 and SD of 7.16 with a difference of 0.96 in favor of the male students. This implies that both groups were at the same level in their interest towards physical geography. The posttest mean score of the male students yielded

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mean of 103.89 and SD of5.35 while the mean score of the female yielded mean of 105.52 and SD of 5.02 with mean gain of 31.33 and 33.92 for male and female students respectively. The posttest mean difference between them is 1.63 in favour of the female students. The mean gain by the two groups revealed that there is great improvement in the students' interest in physical geography after receiving the treatment. This implies that project method improves students' interest towards physical geography regardless of gender.

Hypothesis Two: There is no significant difference between the interest mean scores of male and female secondary school students' in the experimental and control groups in physical Geography after the experiment in Jos North Local Government Area plateau state Nigeria.

Table 4

Summary of ANCOVA Result on Posttest Interest of Experimental and Control Groups in Physical Geography based on Gender

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	54.419[a]	2	27.210	1.023	.369	.049
Intercept	5394.313	1	5394.313	202.900	.000	.835
Pretestinterest	26.577	1	26.577	1.000	.323	.024
Gender	24.295	1	24.295	.914	.345	.022
Error	1063.441	40	26.586			
Total	473724.000	43				
Corrected Total	1117.860	42				

a. R Squared = .049 (Adjusted R Squared = .001)

Data on interest scores of students in physical geography was subjected to a one-way analysis of covariance (ANCOVA) having two levels of gender Table four shows that the effect of gender was found statistically insignificant at the 0.05 level of significance. In the pretest, the result yielded F (1, 40) = 1.000, whereby P > 0.05. Since P value of 0.323 is greater than the 0.05 level of significance, the null hypothesis was retained implying that the difference between the interest mean score of the male and female students in physical geography is insignificant before the treatment. The main effect of gender yielded, F (1, 40) = 0.914, whereby P > 0.05. Since P value of 0.345 is greater than the 0.05 level of significance, the null hypothesis was also retained. It indicates that the interest score of male students did not significantly differ from that of female students in physical geography after the experiment. This shows that the effect of gender was statistically insignificant.

Research question 3: What is the interaction effect of treatment and gender on the interest of SS II students using project method in Physical Geography in Jos North Plateau State, Nigeria?

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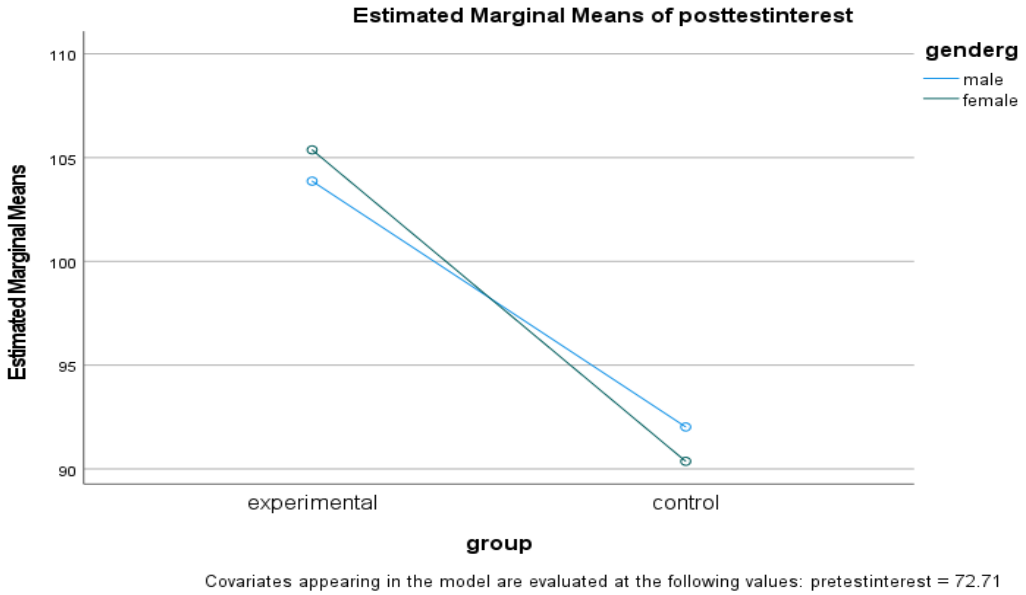


Figure 1: Interaction Effect of Treatment and Gender on Students' Interest

The profile plots of the test in Figure 2 provided further insights into the interaction effect of treatment and gender on the achievement mean score of students in physical Geography. The convergence of the male and female distributions in the profile plots signifies that the interaction effect is significant. However, the deviation of the plots from the p-value is attributed to random variation. Thus, it is safe to conclude that the achievement of students in physical Geography after the treatment using Project method is not a function of their gender. Hence, male and female students were affected equally by the treatment.

Hypothesis three: There is no significant difference in the interaction effect of treatment and gender on the interest of SS II students using project method in Physical Geography in Jos North Plateau State Nigeria.

Table 5

The Interaction Effect of Treatment and Gender on Interest

Source	Type III Sum of Squares	Df	Mean Square	F	ρ-value	Decision
Corrected Model	2842.724[a]	4	710.681	24.491	.000	Accept
Intercept	6263.986	1	6263.986	215.868	.000	
Pretestinterest	50.224	1	50.224	1.731	.193	
Group	2535.012	1	2535.012	87.361	.000	
Gender	.080	1	.080	.003	.958	
group * gender	35.802	1	35.802	1.234	.271	
Error	1741.060	60	29.018			

a. R Squared = .620 (Adjusted R Squared = .595)

Table 5 shows the test of the interaction effect of gender and treatment (Group*Gender) on the interest of students in Physical Geography was conducted using ANCOVA on SPSS. The calculated value (F) is 1.234, while the ρ–value is .271 at .05 level of significance. The hypothesis was retained, indicating that there is no statistically significant interaction effect of the treatment and gender on the mean interest score of students in Physical Geography. The evidence supports the conclusion that the interest of students in Physical Geography when taught using the Project method is not a product of their gender. This implies that, though the treatment generally improved students' interest in Physical Geography, there was no difference on a gender basis.

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DISCUSSION

The finding on the interest mean scores of experimental and control groups revealed that students' interest in physical Geography on both group was on the low side before exposure to the treatment this could be that the students do not have prior knowledge of the subject matter they are to be exposed to at the course of the experiment. Such results are not surprising to the researcher since they are yet to be taught. This is in line with the findings of Kidman (2017) that the factors for students' interest in physical geography are the practical nature of the subject, teaching method, opportunity for field trips and projects. The students' interest increased after the treatment in the two groups. The experimental group tends to be more interested better than the control group. Such findings are expected since only the experimental group that was exposed to the treatment which implies that with the improvement in their learning condition.

The ANCOVA result indicated that there is no significant differences in the interest mean scores of experimental and control groups of secondary school students in the pre-test. But in the post test the different was significant in favor of the experimental group. It was not surprising to the researcher to discover such result because experimental group learning process was more involving and practical in nature. This implies that the students were directly engaged and actively participating in the class than those in the control group. In support of this, Ibrahim (2018) and Augustine (2024) found out that field trip significantly improved students interest. This finding means the null hypothesis is rejected since the p-value is greater than the level of significant. It was also shown that the mean gain of experimental group is greater than that of the control group.

The findings on the interest mean scores of male and female students in the experimental and control groups in physical Geography after the experiment showed that the interest of male and female students were at the same level. This means project method positively affect student interest in respective of their gender. The ANCOVA result revealed that there is no significant difference between male and female students' interest mean scores in the experimental group after the treatment. This finding is supported by Wangu (2018) and Brace (2024) who found out that there is no significance difference in the male and female students' interest when learner centered method approach is applied.

The findings of the study also revealed that there was no statistically significant interaction effect between treatment and gender on students' interest in Physical Geography. The ANCOVA result indicated that gender did not influence the effect of the Project Method on students' interest. This implies that although the Project Method generally enhanced students' interest in Physical Geography, the improvement was similar for both male and female students. This finding is consistent with the study of Al-Khayat and Al-Barbari (2023), who examined the effect of project-based learning on students' outcomes in Geography reported that gender did not significantly moderate students' interest when learner-centered instructional strategies were employed. Contrary to this, Saad, Umar, and Musa (2025) investigates the impact of gender differences on academic achievement and interest in Regional Geography among secondary students and reported that the interaction and visual nature of concept mapping enhance students learning output and students interest in regional Geography.

SUMMARY OF FINDINGS

Based on the results obtained the following major findings emerged.

1. The project method significantly increased students' interest in learning Physical Geography in the experimental group

2. Gender has no significant effect on students' interest in experimental and control group before and after the experiment.

3. The interaction effects of treatment and gender on students' interest in physical Geography was not statistically significant.

CONCLUSION AND RECOMMENDATIONS

From the findings, the study drew the following conclusion: Students' low interest in studying Geography may be due to the methods used by Geography teacher to teach the content of physical

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Geography. Project method has found out to be an effective method in enhancing students' interest in studying Geography. There is a significant improvement of students' interest in physical Geography when project method is employed. The project method bridges gender differences in students' interest, thereby promoting inclusiveness and equal learning opportunities for both genders. Based on the findings the following recommendations were made.

1 Geography teachers adopt and integrate the project method as a regular instructional approach

2 Educational authorities should organize regular workshops and seminars to equip teachers with skills and knowledge required to effectively implement the project method in the classroom.

CONTRIBUTION TO KNOWLEDGE

The study establishes that project method enhanced students' interest in physical Geography regardless of their gender.

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EVDE SAĞLIK VE PALYATİF BAKIM HASTALARINDA BASINÇ ÜLSERİ OLUŞUMU İLE SOSYODEMOGRAFİK VE KLİNİK ÖZELLİKLERİN İLİŞKİSİ

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ÖZET

AMAÇ

Basınç ülserleri; özellikle ileri yaştaki, immobil, kronik hastalığı bulunan ve uzun süreli bakım gereksinimi olan bireylerde sık görülen önemli bir sağlık sorunudur. Bu çalışmada evde sağlık hizmetlerinden yararlanan ve palyatif bakım servisinde izlenen hastalarda basınç ülseri oluşumu ile sosyodemografik ve klinik özellikler arasındaki ilişkinin değerlendirilmesi amaçlanmıştır.

GEREÇ VE YÖNTEM

Çalışmaya evde sağlık hizmetlerinden yararlanan ve palyatif bakım servisinde yatan toplam 192 hasta dâhil edilmiştir. Katılımcıların 96'sı basınç ülseri bulunan hasta grubunu, 96'sı ise basınç ülseri bulunmayan kontrol grubunu oluşturmuştur. Hastaların sosyodemografik özellikleri, kronik hastalık ve ilaç kullanım durumları, sigara ve alkol kullanımları, antropometrik ölçümleri ve immobilite durumları değerlendirilmiştir. Basınç ülseri bulunan hastalarda ayrıca yaranın mevcut olma süresi kaydedilmiştir.

BULGULAR

Katılımcıların 110'u (%57,3) kadın, 82'si (%42,7) erkekti. Katılımcıların yaş ortalaması 72,56±17,64 yıl olup 181'inde (%94,3) en az bir kronik hastalık bulunmaktaydı. Toplam 135 (%70,3) katılımcı immobil olup ortalama immobilite süresi 2,58±2,71 yıl olarak saptandı. Basınç ülseri bulunan hastalarda yaranın mevcut olma süresi ortalama 0,77±0,52 yıldı. Basınç ülseri oluşumu ile cinsiyet (p=0,770), eğitim süresi (p=0,061), meslek (p=0,091), kronik ilaç kullanımı (p=0,053), alkol kullanımı (p=0,756) ve sigara kullanımı (p=0,654) arasında istatistiksel olarak anlamlı ilişki bulunmadı. Medeni durum ile basınç ülseri oluşumu arasında istatistiksel olarak anlamlı ilişki saptandı (p=0,006). En az bir kronik hastalığın bulunması basınç ülseri oluşumuyla anlamlı düzeyde ilişkiliydi (p=0,001). İmmobilite ile basınç ülseri oluşumu arasında güçlü bir ilişki bulundu (p<0,001). Ayrıca yaş arttıkça basınç ülseri görülme sıklığının arttığı (p=0,001), buna karşılık basınç ülseri bulunan grupta vücut ağırlığı (p=0,009) ve beden kütle indeksi (p=0,008) değerlerinin daha düşük olduğu saptandı.

SONUÇ

Bu çalışmada basınç ülseri oluşumunun ileri yaş, immobilite, kronik hastalık varlığı, medeni durum, düşük vücut ağırlığı ve düşük beden kütle indeksiyle ilişkili olduğu belirlenmiştir. Buna karşılık cinsiyet, eğitim süresi, meslek, kronik ilaç kullanımı, sigara ve alkol kullanımıyla anlamlı ilişki saptanmamıştır. Evde sağlık ve palyatif bakım hastalarında basınç ülserlerinin önlenebilmesi için özellikle ileri yaştaki, immobil, kronik hastalığı bulunan ve beden kütle indeksi düşük (kilo kaybı yaşayan) hastaların düzenli olarak değerlendirilmesi önem taşımaktadır. Bulgular ilişkisel nitelikte olup nedensellik göstermemektedir.

Anahtar Kelimeler: Basınç ülseri, evde sağlık hizmetleri, palyatif bakım, immobilite, kronik hastalık

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ABSTRACT

OBJECTIVE

Pressure ulcers are an important health problem, particularly among older individuals, patients with limited mobility, those with chronic diseases, and individuals requiring long-term care. This study aimed to evaluate the relationship between pressure ulcer development and sociodemographic and clinical characteristics among patients receiving home healthcare services and those followed in a palliative care unit.

MATERIALS AND METHODS

A total of 192 patients receiving home healthcare services or hospitalized in a palliative care unit were included in the study. Of these, 96 patients with pressure ulcers constituted the patient group, while 96 patients without pressure ulcers constituted the control group. Sociodemographic characteristics, presence of chronic diseases, regular medication use, smoking and alcohol use, anthropometric measurements, and immobility status were evaluated. Among patients with pressure ulcers, the duration of the ulcer was also recorded.

RESULTS

Of the participants, 110 (57.3%) were female and 82 (42.7%) were male. The mean age was 72.56±17.64 years, and 181 participants (94.3%) had at least one chronic disease. A total of 135 participants (70.3%) were immobile, with a mean duration of immobility of 2.58±2.71 years. Among patients with pressure ulcers, the mean duration of the ulcer was 0.77±0.52 years. No statistically significant association was found between pressure ulcer development and sex ($p=0.770$), duration of education ($p=0.061$), occupation ($p=0.091$), regular medication use ($p=0.053$), alcohol consumption ($p=0.756$), or smoking ($p=0.654$). Marital status was significantly associated with pressure ulcer development ($p=0.006$). The presence of at least one chronic disease was also significantly associated with pressure ulcer development ($p=0.001$). Immobility showed a strong association with pressure ulcer development ($p<0.001$). In addition, the occurrence of pressure ulcers increased with advancing age ($p=0.001$). Lower body weight ($p=0.009$) and lower body mass index (BMI) ($p=0.008$) were also significantly associated with pressure ulcer occurrence.

CONCLUSION

Pressure ulcer development was associated with advanced age, immobility, the presence of chronic disease, marital status, lower body weight, and lower body mass index. In contrast, no significant associations were observed with sex, duration of education, occupation, regular medication use, smoking, or alcohol consumption. Regular assessment of older, immobile patients with chronic diseases and lower body mass index may contribute to pressure ulcer prevention among patients receiving home healthcare and palliative care services. These findings represent associations and should not be interpreted as evidence of causality.

Keywords: Pressure ulcer, home healthcare, palliative care, immobility, chronic disease

GİRİŞ

Basınç ülseri; çoğunlukla kemik çıkıntıları üzerinde veya tıbbi bir cihazla ilişkili bölgede, uzun süreli basınç ya da basınç ile makaslama kuvvetinin birlikte etkisi sonucunda deri ve/veya deri altı dokularda gelişen lokalize hasar olarak tanımlanmaktadır. Lezyon, deri bütünlüğü korunmuşken alttaki dokularda gelişebileceği gibi açık ülserasyon şeklinde de izlenebilir. Uzun süreli mekanik yüklenme dokuda deformasyona neden olmakta; lokal perfüzyonun ve lenfatik drenajın bozulması ile doğrudan hücresel hasar aynı süreç içinde rol oynayabilmektedir. Doku toleransı ise yaş, beslenme durumu, cilt özellikleri ve eşlik eden hastalıklar gibi bireysel etkenlere göre değişmektedir (National Pressure Injury Advisory Panel, European Pressure Ulcer Advisory Panel, & Pan Pacific Pressure Injury Alliance, 2025).

Basınç ülserleri özellikle immobilite ve komorbid hastalıkların eşlik ettiği bireylerde sık karşılaşılan ve klinik seyri güçleştirebilen bir sorundur. Daha önce yapılan çalışmamızda da basınç ülserlerinin

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immobilite ve komorbiditelerle ilişkili ciddi bir komplikasyon olduğu, riskli hastaların erken belirlenmesinde standart değerlendirme araçlarının önemli bir yere sahip bulunduğu vurgulanmıştır (Zencirkıran et al., 2026). Yaşlı hastalarda ileri yaş, immobilite, duyusal ve perfüzyon bozuklukları, inkontinans, malnütrisyon, dehidratasyon ve çoklu komorbiditeler risk faktörleri arasında bildirilmektedir (Silva, 2025).

Risk faktörlerinin etkisi her hasta grubunda aynı değildir. Wu ve arkadaşlarının 23 çalışmayı ve 70340 yaşlı yatan hastayı kapsayan sistematik derleme ve metaanalizinde yaş, immobilite, inkontinans, beslenme riski, diabetes mellitus, yoğun bakımda kalış süresi, cerrahiye kadar geçen süre ve hastanede yatış süresi basınç ülseri ile ilişkili bulunmuştur (Wu et al., 2025). Palyatif bakım alanında da benzer biçimde çoklu sistemik hastalıkların, nörolojik bozuklukların ve bakım gereksiniminin ön plana çıktığı bildirilmektedir (Kaya & Şimşek, 2025). Bununla birlikte evde sağlık ve palyatif bakım popülasyonlarında sosyodemografik değişkenlerin etkisini değerlendiren çalışmalar daha sınırlıdır. Evde palyatif bakım alan kanser hastalarında yapılan bir çalışmada cinsiyet, yaş, eğitim ve birlikte yaşama durumu ile basınç ülseri arasında anlamlı ilişki gösterilememiştir (Queiroz et al., 2014).

Basınç ülserlerinin önlenmesinde riskin erken fark edilmesi temel yaklaşımlardan biridir. Risk değerlendirmesi, cilt bakımı, uygun destek yüzeylerinin kullanılması ve hasta eğitimi koruyucu yaklaşımın önemli bileşenleri arasında yer almaktadır. Güncel bir sistematik derlemede risk değerlendirme araçları, yeniden pozisyon verme, sağlık çalışanlarının eğitimi, destek yüzeyleri ve çok bileşenli bakım uygulamalarının koruyucu programlarda öne çıktığı bildirilmiştir (Silva, 2025). Daha önceki sistematik derleme verileri de uygun destek yüzeyleri, pozisyon değişikliği, beslenme durumunun optimize edilmesi ve cilt bakımının basınç ülserlerini önlemeye yönelik temel uygulamalar arasında olduğunu göstermektedir (Reddy et al., 2006).

Evde sağlık hizmetlerinden yararlanan ve palyatif bakımda izlenen hastalar; ileri yaş, fonksiyon kaybı, immobilite ve çoklu hastalık yükü nedeniyle basınç ülseri açısından özellikli bir grubu oluşturmaktadır. Bu çalışmada, bu hasta grubunda basınç ülseri varlığı ile sosyodemografik özellikler, kronik hastalık ve ilaç kullanımı, sigara ve alkol kullanımı, antropometrik ölçümler ve immobilite arasındaki ilişkinin değerlendirilmesi amaçlandı.

GEREÇ VE YÖNTEM

Hastaların yaş, cinsiyet, eğitim süresi, meslek ve medeni durum bilgileri; kronik hastalık ve düzenli ilaç kullanım durumları; sigara ve alkol kullanımları; boy, vücut ağırlığı ve beden kütle indeksi (BKİ) değerleri ile immobilite durumları değerlendirildi. İmmobil hastalarda immobilite süresi, basınç ülseri bulunan hastalarda ise yaranın mevcut olma süresi kaydedildi. Basınç ülseri bulunan olgularda yara evresi 1, 2, 3 ve 4 olarak sınıflandırılmıştı.

Sürekli değişkenlerin dağılımları Kolmogorov-Smirnov ve Shapiro-Wilk testleri ile değerlendirildi. Tanımlayıcı istatistikler sayı, yüzde, ortalama ve standart sapma ile gösterildi. Basınç ülseri bulunan ve bulunmayan grupların kategorik değişkenler açısından karşılaştırılmasında ki-kare testi, sürekli değişkenler açısından karşılaştırılmasında Mann-Whitney U testi kullanıldı. İstatistiksel anlamlılık sınırı $p<0,05$ olarak kabul edildi.

BULGULAR

Çalışmaya dâhil edilen 192 hastanın yaş ortalaması 72,56±17,64 yıl olup yaşlar 16 ile 98 yıl arasında değişmekteydi. Katılımcıların 110'u (%57,3) kadın, 82'si (%42,7) erkekti. Ortalama eğitim süresi 4,93±4,19 yıl, ortalama boy 164,29±9,92 cm, ortalama vücut ağırlığı 66,01±10,00 kg ve ortalama BKİ 24,43±2,94 kg/m² idi. Hastaların 181'inde (%94,3) en az bir kronik hastalık, 160'ında (%83,3) düzenli ilaç kullanımı bulunmaktaydı. Sigara kullananların sayısı 71 (%37,0), alkol kullananların sayısı 11 (%5,7) idi. Toplam 135 (%70,3) hasta immobil olup immobilite süresi ortalama 2,58±2,71 yıl olarak hesaplandı. Basınç ülseri bulunan hastalarda yaranın mevcut olma süresi ortalama 0,77±0,52 yıldı. Basınç ülseri bulunan 96 hastanın 9'unda (%9,4) evre 1, 34'ünde (%35,4) evre 2, 31'inde (%32,3) evre 3 ve 22'sinde (%22,9) evre 4 yara mevcuttu (Tablo 1).

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Tablo 1. Katılımcıların sosyodemografik ve klinik özellikleri

Değişken	Değer
Yaş (yıl), ort±SS	72,56±17,64
Eğitim süresi (yıl), ort±SS	4,93±4,19
Boy (cm), ort±SS	164,29±9,92
Vücut ağırlığı (kg), ort±SS	66,01±10,00
BKİ (kg/m²), ort±SS	24,43±2,94
İmmobilite süresi (yıl), ort±SS	2,58±2,71
Basınç ülseri süresi (yıl), ort±SS	0,77±0,52
Cinsiyet, n (%)	
Erkek	82 (42,7)
Kadın	110 (57,3)
Medeni durum, n (%)	
Bekâr/dul	103 (53,6)
Evli	89 (46,4)
Kronik hastalık varlığı, n (%)	181 (94,3)
Düzenli ilaç kullanımı, n (%)	160 (83,3)
Sigara kullanımı, n (%)	71 (37,0)
Alkol kullanımı, n (%)	11 (5,7)
İmmobilite, n (%)	135 (70,3)
Basınç ülseri evresi (n=96), n (%)	
Evre 1	9 (9,4)
Evre 2	34 (35,4)
Evre 3	31 (32,3)
Evre 4	22 (22,9)

Basınç ülseri varlığı ile cinsiyet, eğitim grubu ve meslek arasında istatistiksel olarak anlamlı ilişki saptanmadı (sırasıyla p=0,770, p=0,061 ve p=0,091). Buna karşılık medeni durum ile basınç ülseri varlığı arasında anlamlı ilişki vardı (p=0,006); basınç ülseri bulunan grupta bekâr/dul hastaların oranı daha yüksekti. Kronik hastalık varlığı da basınç ülseri ile anlamlı düzeyde ilişkiliydi (p=0,001). Basınç ülseri bulunan 96 hastanın tamamında en az bir kronik hastalık bulunurken, kontrol grubunda bu sayı 85 (%88,5) idi. Düzenli ilaç kullanımı açısından gruplar arasındaki fark istatistiksel anlamlılık sınırına ulaşmadı (p=0,053). Alkol (p=0,756) ve sigara kullanımı (p=0,654) ile basınç ülseri varlığı arasında da anlamlı ilişki görülmedi. İmmobilite en belirgin farklılıklardan biriydi; basınç ülseri bulunan grubun %96,9'u, kontrol grubunun ise %43,8'i immobil idi (p<0,001) (Tablo 2).

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Tablo 2. Kategorik değişkenlerin basınç ülseri varlığına göre dağılımı

Değişken	Kategori	Basınç ülseri yok n (%)	Basınç ülseri var n (%)	p
Cinsiyet	Erkek	42 (43,8)	40 (41,7)	0,770
	Kadın	54 (56,3)	56 (58,3)	
Eğitim süresi	0 yıl	32 (33,3)	31 (32,3)	0,061
	5 yıl	26 (27,1)	40 (41,7)	
	8 yıl	20 (20,8)	18 (18,8)	
	12 yıl	15 (15,6)	7 (7,3)	
	16 yıl	3 (3,1)	0 (0,0)	
Meslek	Memur	6 (6,3)	0 (0,0)	0,091
	İşçi	5 (5,2)	3 (3,1)	
	Esnaf	1 (1,0)	0 (0,0)	
	Çalışmıyor	11 (11,5)	8 (8,3)	
	Ev hanımı	41 (42,7)	53 (55,2)	
	Emekli	32 (33,3)	32 (33,3)	
Medeni durum	Bekâr/dul	42 (43,8)	61 (63,5)	0,006
	Evli	54 (56,3)	35 (36,5)	
Kronik hastalık	Yok	11 (11,5)	0 (0,0)	0,001
	Var	85 (88,5)	96 (100,0)	
Düzenli ilaç	Yok	21 (21,9)	11 (11,5)	0,053
	Var	75 (78,1)	85 (88,5)	
Alkol	Yok/bırakmış	91 (94,8)	90 (93,8)	0,756
	Var	5 (5,2)	6 (6,3)	
Sigara	Yok/bırakmış	59 (61,5)	62 (64,6)	0,654
	Var	37 (38,5)	34 (35,4)	
İmmobilite	Yok	54 (56,3)	3 (3,1)	<0,001
	Var	42 (43,8)	93 (96,9)	

Yüzdeler basınç ülseri bulunan ve bulunmayan grupların kendi içindeki dağılımı göstermektedir. p değerleri Pearson ki-kare testine aittir.

Sürekli değişkenlerin Mann-Whitney U testi ile karşılaştırılmasında basınç ülseri bulunan hastaların yaş sıra ortalaması 110,22, kontrol grubunun ise 82,78 idi ve fark istatistiksel olarak anlamlıydı (U=3290,50; p=0,001). Vücut ağırlığı için sıra ortalaması basınç ülseri bulunan grupta 86,09, kontrol grubunda 106,91 (U=3609,00; p=0,009); BKİ için ise sırasıyla 85,78 ve 107,22 olarak saptandı (U=3579,00; p=0,008). Bu bulgular basınç ülseri bulunan grupta vücut ağırlığı ve BKİ değerlerinin daha düşük yönde dağıldığını göstermekteydi. Boy uzunluğu ve immobilite süresi açısından gruplar arasında anlamlı fark saptanmadı (sırasıyla p=0,316 ve p=0,883) (Tablo 3).

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Tablo 3. Sürekli değişkenlerin basınç ülseri varlığına göre karşılaştırılması

Değişken	BÜ yok sıra ort.	BÜ var sıra ort.	Mann-Whitney U	p
Yaş (yıl)	82,78	110,22	3290,50	0,001
Boy (cm)	100,52	92,48	4222,00	0,316
Vücut ağırlığı (kg)	106,91	86,09	3609,00	0,009
İmmobilite süresi (yıl)	69,22	68,17	1968,50	0,883
BKİ (kg/m²)	107,22	85,78	3579,00	0,008

TARTIŞMA

Bu çalışmada evde sağlık ve palyatif bakım hastalarında basınç ülseri varlığı; ileri yaş, immobilite, kronik hastalık varlığı ve medeni durum ile ilişkili bulundu. Basınç ülseri bulunan grupta vücut ağırlığı ve BKİ sıra ortalamalarının daha düşük olması da dikkat çeken bir diğer bulguydu. Buna karşılık cinsiyet, eğitim grubu, meslek, düzenli ilaç kullanımı, sigara ve alkol kullanımı açısından gruplar arasında anlamlı fark saptanmadı. Bulguların en belirgin yönü, basınç ülseri bulunan hastaların neredeyse tamamının immobil olması ve tamamında en az bir kronik hastalık bulunmasıydı.

İleri yaş ile basınç ülseri arasındaki ilişki, farklı bakım ortamlarında yürütülen çalışmaların önemli bir bölümünde de gösterilmiştir. Artico ve arkadaşlarının 13 hospiste 992 hastayı prospektif olarak izlediği çalışmada 80 yaş üzerinde olmak, hospis kabulünde basınç ülseri bulunma olasılığını yaklaşık iki kat artırmıştır (OR=2,01). Toplumda yaşayan 6961 yaşlı bireyin değerlendirildiği Cai ve arkadaşlarının çalışmasında da yaş, çok değişkenli modelde bağımsız değişken olarak kalmış; 100 yaş üzerindeki bireylerde basınç ülseri olasılığı 65-79 yaş grubuna göre 3,28 kat yüksek bulunmuştur (Cai et al., 2019; Artico et al., 2020). Jakobsen ve arkadaşlarının ileri evre kanser hastalarını kapsayan hospis kohortunda yeni basınç ülseri gelişenlerin yaş ortalamasının daha yüksek olması da aynı yöndedir (Jakobsen et al., 2020). Bu farklılık, yaşın tek başına değil, hastanın işlevsel durumu ve eşlik eden klinik yükle birlikte değerlendirilmesi gerektiğini düşündürmektedir.

İmmobilite, çalışmamızda basınç ülseri ile en güçlü ilişki gösteren değişkenlerden biriydi. Basınç ülseri bulunan grubun %96,9'u immobil iken kontrol grubunda bu oran %43,8'di. Cai ve arkadaşlarının toplumda yaşayan yaşlılarda yaptığı çalışmada ağır düzeyde işlevsel kısıtlılık, basınç ülseri açısından 5,25 kat artmış riskle ilişkili bulunmuştur (Cai et al., 2019). Jaul ve arkadaşları ise yaşlılarda basınç ülseri gelişimini açıklarken immobiliteyi doğrudan etkili temel faktörlerden biri olarak değerlendirmiş; uzun süreli yatak bağımlılığının kronik hastalık, frajilite ve azalmış doku perfüzyonu ile birlikte riski artırdığını vurgulamıştır (Jaul et al., 2018). Bu bulgular, çalışmamızdaki immobilite ilişkisinin yalnızca bakım bağımlılığını değil, dokunun uzun süreli basınca maruz kalmasını ve hastanın genel fizyolojik rezervindeki azalmayı da yansıtabileceğini göstermektedir.

Çalışmamızda, kronik hastalık varlığı açısından gruplar belirgin biçimde ayrıştı. Basınç ülseri bulunan hastaların tamamında en az bir kronik hastalık mevcutken bu oran kontrol grubunda %88,5'ti. Jaul ve arkadaşları kardiyovasküler hastalıklar, diyabet, kronik akciğer ve böbrek hastalıkları ile nörodejeneratif hastalıkların; anemi, malnütrisyon, inkontinans, polifarmasi, frajilite ve immobilite gibi ek durumlarla birlikte basınç ülseri gelişimine katkıda bulunduğunu bildirmiştir (Jaul et al., 2018). Palyatif bakım hastalarında Kaya ve Şimşek de nörolojik, gastrointestinal, üriner ve kardiyovasküler hastalıklarla basınç ülseri gelişimi arasında ilişki saptamıştır (Kaya & Şimşek, 2025). Cai ve arkadaşlarının toplum örnekleminde ise kanser ve demans çok değişkenli analizde bağımsız risk faktörleri arasında yer almıştır (Cai et al., 2019). Dolayısıyla kronik hastalık varlığına ilişkin bulgumuz, tek bir tanıdan çok, hastanın toplam klinik yükünün ve buna eşlik eden işlev kaybının önemini desteklemektedir.

Cinsiyet ile basınç ülseri arasında anlamlı ilişki saptanmaması, bazı çalışmalarla uyumluyken bütün literatürle aynı yönde değildir. Queiroz ve arkadaşlarının evde palyatif bakım hastalarında, Jakobsen ve arkadaşlarının hospis kohortunda ve Kaya ile Şimşek'in palyatif bakım örnekleminde cinsiyet açısından anlamlı fark bildirilmemiştir (Queiroz et al., 2014; Jakobsen et al., 2020; Kaya & Şimşek, 2025). Cai ve

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arkadaşlarının geniş toplum örnekleminde de cinsiyet tek değişkenli analizde anlamlı bulunmamıştır (Cai et al., 2019). Buna karşılık Artico ve arkadaşlarının zamana bağlı analizinde erkek cinsiyet, ölümden yaklaşık üç hafta öncesine kadar gelişen yeni basınç ülserleri için prediktif faktörlerden biri olarak belirlenmiştir (OR=1,68) (Artico et al., 2020). Bu durum, cinsiyetin etkisinin hasta grubuna ve hastalığın dönemine göre değişebileceğini, tek başına sabit bir risk göstergesi olarak ele alınmaması gerektiğini düşündürmektedir.

Çalışmamızda eğitim grubu ve meslek ile basınç ülseri varlığı arasında anlamlı ilişki saptanmadı. Cai ve arkadaşlarının ulusal toplum örnekleminde eğitim yılı ile basınç ülseri arasında anlamlı fark bulunmamış, yaşam koşulu tek değişkenli analizde ilişki gösterse de çok değişkenli modelde bağımsız bir belirleyici olarak kalmamıştır (Cai et al., 2019). Buna karşılık bizim çalışmamızda medeni durum anlamlıydı ve basınç ülseri bulunan grupta bekâr/dul hastaların oranı daha yüksekti. Ancak çalışmamızda bakım veren varlığı, günlük bakım süresi, sosyal destek düzeyi veya hastayla birlikte yaşayan kişi sayısı gibi değişkenler bulunmadığından, medeni durumun bu ilişkiyi hangi mekanizma üzerinden yansıttığını söylemek mümkün değildir.

Antropometrik ölçümlerde vücut ağırlığı ve BKİ açısından gruplar arasında anlamlı fark bulunmuş; her iki değişkende de sıra ortalamaları basınç ülseri bulunan grupta daha düşüktü. Jaul ve arkadaşları uzun süreli kronik hastalığın hareket azalması ve kilo kaybıyla birlikte basınç ülserine duyarlılığı artırabileceğini; yetersiz beslenmenin de bu sürece eşlik eden önemli sorunlardan biri olduğunu belirtmiştir (Jaul et al., 2018). Queiroz ve arkadaşlarının çalışmasında düşük kilolu olma (BKİ<18,5 kg/m²) basınç ülseri olanlarda daha sık görülmüş, ancak fark istatistiksel anlamlılık sınırına ulaşmamıştır (p=0,062) (Queiroz et al., 2014). Wu ve arkadaşlarının metaanalizinde de BKİ için anlamlı bir ilişki gösterilemezken beslenme riski basınç ülseri ile ilişkili bulunmuştur (Wu et al., 2025). Bu nedenle çalışmamızdaki ağırlık ve BKİ bulgusu, doğrudan malnütrisyon göstergesi şeklinde yorumlanmamalı; antropometrik veriler laboratuvar ve klinik beslenme değerlendirmeleriyle birlikte ele alınmalıdır.

Sigara ve alkol kullanımı çalışmamızda basınç ülseri ile ilişkili değildi. Cai ve arkadaşlarının çalışmasında alkol kullanımı açısından gruplar arasında fark saptanmamış; sigara kullanımı tek değişkenli analizde ilişki gösterse de çok değişkenli modelde bağımsız belirleyici olarak kalmamıştır (Cai et al., 2019). Queiroz ve arkadaşları da evde palyatif bakım hastalarında sigara ve alkol kullanımıyla basınç ülseri arasında anlamlı ilişki bildirmemiştir (Queiroz et al., 2014). Düzenli ilaç kullanımı için çalışmamızda elde edilen p=0,053 değeri anlamlılık sınırının hemen üzerinde kalmıştır. Jaul ve arkadaşlarının değerlendirmesinde polifarmasi, ileri yaştaki hastalarda basınç ülseri gelişimini etkileyebilecek karmaşık klinik yükün bir parçası olarak ele alınmaktadır (Jaul et al., 2018). Bununla birlikte daha ileri bir nedensel yorum ancak ilaç grubu, ilaç sayısı gibi veriler varlığında değerlendirilebilir.

Basınç ülseri açısından riskli hastaların erken tanınması önemini korumakla birlikte, palyatif bakımda koruyucu yaklaşımın hastalığın evresine göre bireyselleştirilmesi gerekir. Zencirkıran ve arkadaşları risk değerlendirmesi, cilt bakımı, destek yüzeyleri ve hasta eğitiminin koruyucu yaklaşımın temel bileşenleri olduğunu belirtmiş; sistematik derlemelerde yeniden pozisyon verme, destek yüzeyleri, sağlık çalışanı eğitimi ve çok bileşenli bakım uygulamaları öne çıkmıştır (Zencirkıran et al., 2026; Silva, 2025; Reddy et al., 2006). Bununla birlikte Artico ve arkadaşları hospis hastalarında basınç ülserinin belirleyicilerinin hastalığın son döneminde değiştiğini, yeni yaralanmaların önemli bir bölümünün yaşamın son günlerinde ortaya çıktığını ve bu dönemde klasik risk değerlendirmesinin öngörü gücünün azaldığını bildirmiştir (Artico et al., 2020). Eisenberger ve Zeleznik'in hospis çalışanlarıyla yaptığı nitel çalışmada da pozisyon verme ve pansuman gibi uygulamaların bazı hastalarda ağrıyı artırabildiği, aktif ölüm döneminde konforun kimi zaman standart önleme ve yara iyileştirme hedeflerinin önüne geçebildiği gösterilmiştir (Eisenberger & Zeleznik, 2003). Bu nedenle özellikle palyatif bakım hastalarında amaç yalnızca ülser gelişimini engellemek değil; hastanın klinik seyri, bakım hedefleri ve konfor gereksinimiyle uyumlu bir risk yönetimi oluşturmaktır.

Çalışmanın bazı sınırlılıkları bulunmaktaydı. Basınç ülseri bulunan ve bulunmayan gruplar eşit sayıda oluşturulduğu için bu örneklemden basınç ülseri prevalansı hesaplanamadı. Analizler iki değişkenli karşılaştırmalara dayandığından, saptanan ilişkilerin diğer değişkenlerden bağımsız olup olmadığı gösterilememekteydi. Ayrıca medeni durum, vücut ağırlığı ve BKİ ile saptanan ilişkilerin altında yatan

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mekanizmaları açıklayacak sosyal destek, bakım veren özellikleri, ayrıntılı beslenme değerlendirmesi, fonksiyonel kapasite ve hastalık şiddeti gibi değişkenler mevcut verilerde yer almamaktaydı. Evde sağlık ve palyatif bakım hastalarının aynı çalışma içinde değerlendirilmiş olması da farklı bakım ortamlarına özgü etkilerin ayrıştırılmasını sınırlandırmaktaydı. Bu nedenle sonuçlar ilişki düzeyinde ele alındı ve nedensellik yorumu yapılamadı.

SONUÇ

Evde sağlık ve palyatif bakım hastalarının değerlendirildiği bu çalışmada basınç ülseri varlığı özellikle ileri yaş, immobilite ve kronik hastalık yükü ile birlikteydi; medeni durum da basınç ülseri varlığıyla ilişkili bulunan sosyodemografik değişken oldu. Basınç ülseri bulunan grupta vücut ağırlığı ve BKİ sıra ortalamalarının daha düşük olması, bu hasta grubunda antropometrik özelliklerin ayrıca değerlendirilmesi gerektiğini düşündürmektedir. Buna karşılık cinsiyet, eğitim grubu, meslek, düzenli ilaç kullanımı, sigara ve alkol kullanımı açısından anlamlı ilişki saptanmadı. Elde edilen bulgular, basınç ülseri riskinin tek bir değişken üzerinden değil; yaş, hareket kapasitesi, kronik hastalık yükü ve bakım koşullarının birlikte ele alındığı bütüncül bir değerlendirmeyle izlenmesi gerektiğini göstermektedir.

Klinik uygulamada özellikle immobil ve ileri yaştaki hastaların düzenli aralıklarla değerlendirilmesi, kronik hastalıkların ve beslenme durumunun izlenmesi, cilt bütünlüğünün korunması ve uygun basınç azaltıcı bakımın sürdürülmesi öncelikli olmalıdır. Bununla birlikte palyatif bakım hastalarında hastalığın ilerleyen dönemlerinde bakım hedefleri değişebileceğinden, koruyucu uygulamalar hastanın konforu ve klinik seyriyle birlikte planlanmalıdır. Çalışmamızın kesitsel, ilişkisel yapısı ve çok değişkenli analiz içermemesi nedeniyle saptanan ilişkiler nedensellik göstermemektedir. Bundan sonraki çalışmalarda evde sağlık ve palyatif bakım gruplarının ayrı olarak değerlendirildiği, fonksiyonel durum, bakım veren ve sosyal destek özellikleri, ayrıntılı beslenme göstergeleri ve kronik hastalık yükünü birlikte içeren prospektif ve çok değişkenli modellerin kullanılması, hangi hastalarda hangi faktörlerin bağımsız biçimde öne çıktığını daha net gösterecektir.

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EFFECTS OF GRAPHENE OXIDE-BASED NANOMATERIALS ON SYNDECAN GENE EXPRESSION IN TONGUE SQUAMOUS CELL CARCINOMA CELLS

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ABSTRACT

Tongue squamous cell carcinoma (TSCC) is an aggressive oral malignancy shaped by inflammatory, cell-adhesion, and extracellular-matrix (ECM) signalling. Syndecans (SDC1–SDC4) are transmembrane heparan-sulfate proteoglycans that organise growth-factor, adhesion, and ECM cues. This study evaluated whether graphene oxide (GO) and reduced graphene oxide (rGO) induce a coordinated syndecan-family transcriptional response in SCC-25 human tongue squamous carcinoma cells. Cells were exposed to GO or rGO at 0, 1, 10, 50, or 100 µg/mL for 24 or 48 h, with three replicate measurements per condition. SDC1–SDC4 expression was quantified by TaqMan qRT-PCR, normalised to ACTB, and evaluated using the $2^{-\Delta\Delta Ct}$ method. A factorial material × concentration × time framework and Benjamini–Hochberg false-discovery control were specified. GO and rGO increased all four syndecan transcripts relative to untreated controls. STRING v12.0 analysis identified a fully connected four-protein network with six associations, a mean node degree of 3.0, zero expected edges, and significant interaction enrichment ($P=7.72\times10^{-9}$). Functional enrichment implicated cell-adhesion molecules, proteoglycans in cancer, exosome assembly, ECM–receptor interaction, and cell migration (all FDR<0.05). The results support coordinated remodelling of syndecan-dependent extracellular signalling, but they do not by themselves demonstrate anticancer activity. Protein-level and phenotypic validation is required to define whether the response promotes adaptation, stress, migration, or cell death.

Keywords: graphene oxide; reduced graphene oxide; syndecan; SDC1–SDC4; SCC-25; tongue squamous cell carcinoma; extracellular matrix; qRT-PCR.

1. INTRODUCTION

Tongue squamous cell carcinoma is a clinically aggressive form of oral squamous cell carcinoma in which local invasion, regional dissemination, and treatment resistance are strongly influenced by reciprocal signalling between tumour cells and their extracellular environment. Cell-surface proteoglycans are central to this interface because they regulate the presentation of soluble ligands, the organisation of adhesion receptors, and the transmission of mechanical and biochemical information across the plasma membrane.

The syndecan family comprises four single-pass transmembrane heparan-sulfate proteoglycans, SDC1, SDC2, SDC3, and SDC4. Through their extracellular glycosaminoglycan chains and conserved cytoplasmic domains, syndecans participate in growth-factor binding, integrin cooperation, cytoskeletal organisation, migration, inflammatory signalling, and extracellular-matrix remodelling. Their roles in cancer are context dependent: altered expression may either restrain or facilitate tumour progression according to tumour type, cellular compartment, shedding status, and microenvironmental conditions [1]. Consequently, coordinated changes across the entire syndecan family may provide more biologically meaningful information than the analysis of a single family member.

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Graphene oxide and reduced graphene oxide are two-dimensional carbon-based nanomaterials with large reactive surfaces and distinct oxygen-containing functional groups. These characteristics support extensive interactions with biomolecules and cell membranes and have stimulated investigation of graphene derivatives as drug carriers and biologically active materials. In oral squamous cell carcinoma models, graphene oxide has been investigated as a targeted delivery platform; an HN-1-functionalised graphene oxide system increased doxorubicin uptake and cytotoxicity in CAL-27 and SCC-25 cells [5]. Nevertheless, graphene-associated responses cannot be assumed to be uniformly therapeutic. In other carcinoma models, graphene oxide has promoted TGF-β-dependent epithelial–mesenchymal transition and migration, underscoring the importance of dose, material properties, cellular context, and exposure duration [4].

Despite the importance of membrane and extracellular-matrix signalling in TSCC, the transcriptional response of the complete syndecan family to GO and rGO has not been sufficiently characterised. The present study therefore examined SDC1–SDC4 expression in SCC-25 cells following graded GO or rGO exposure at two time points. The analysis further assessed whether the observed transcriptional pattern was coherent at the protein-interaction and functional-enrichment levels. The central hypothesis was that GO-based nanomaterials would induce a coordinated, rather than isolated, syndecan-family response.

2. MATERIALS AND METHODS

2.1. Study design and cell model

Human SCC-25 tongue squamous carcinoma cells were used as the experimental model. Culture conditions and confluence were standardised across treatment groups. The design compared two graphene-derived materials, GO and rGO, across five concentrations and two exposure windows. Untreated SCC-25 cells served as the reference condition. Three replicate measurements were obtained for each condition. Only methodological details documented in the source presentation are reported; supplier, lot, dispersion, and complete culture-medium information were not reconstructed.

Table 1. Experimental design.

Factor	Levels
Cell model	Human SCC-25 tongue squamous carcinoma cells
Material	Graphene oxide (GO); reduced graphene oxide (rGO)
Concentration	0, 1, 10, 50, and 100 µg/mL
Exposure duration	24 h and 48 h
Replication	Three replicate measurements per condition

2.2. RNA isolation and quantitative real-time PCR

Total RNA was isolated using TRIzol reagent. RNA quantity and purity were assessed spectrophotometrically using the A260/A280 ratio before reverse transcription. SDC1, SDC2, SDC3, and SDC4 transcript abundance was measured using TaqMan quantitative real-time polymerase chain reaction assays. ACTB was used as the reference transcript. RNA quality, reference-gene stability, and replicate concordance were evaluated before relative-expression analysis.

For each target, ΔCt was calculated as Ct(target)−Ct(ACTB). ΔΔCt values were then determined relative to the corresponding untreated control, and relative transcript abundance was expressed as $2^{-\Delta\Delta Ct}$, following the established comparative-Ct method [2].

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2.3. Statistical and bioinformatic analysis

The analytical plan used a factorial framework incorporating material type, concentration, and exposure duration. Multiplicity across the four syndecan genes was controlled using the Benjamini–Hochberg false-discovery rate, with $q \leq 0.05$ specified as the threshold. Relative-expression profiles were interpreted together at the syndecan-family level and integrated with protein-association and functional-enrichment analyses.

Functional coherence among SDC1–SDC4 was investigated using STRING v12.0 for Homo sapiens at medium confidence [3]. Network topology was summarised by the number of nodes, observed associations, expected edges, mean node degree, and protein–protein interaction enrichment probability. Functional enrichment categories were interpreted descriptively because the analysis was intentionally restricted to a focused four-gene family.

3. RESULTS

3.1. Coordinated induction of SDC1–SDC4 transcripts

Comparative qRT-PCR analysis demonstrated coordinated transcriptional upregulation of SDC1, SDC2, SDC3, and SDC4 following GO and rGO exposure relative to untreated SCC-25 cells. The concordant family-level response is consistent with remodelling of the cell-surface proteoglycan system and provides the experimental anchor for the subsequent network analysis. Figure 1 integrates the four regulated genes into their complete pairwise functional-association network and places this network within the principal enriched biological contexts.

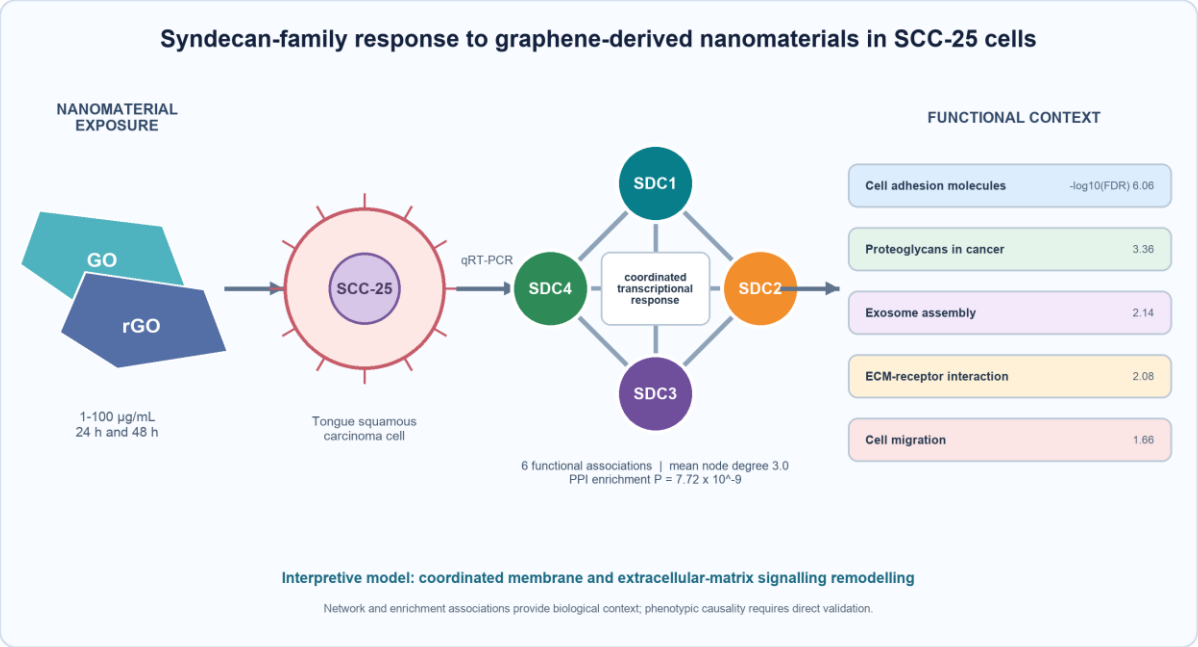


Figure 1. Scientific model of the GO/rGO-associated syndecan-family response in SCC-25 cells. SDC1–SDC4 are shown as a fully connected four-gene module comprising six functional associations. The enriched biological processes provide pathway-level context and do not by themselves establish a causal phenotypic outcome.

3.2. Syndecan protein–protein interaction network

STRING analysis produced a fully connected syndecan-family network. The network contained four proteins and six observed associations, corresponding to every possible pairwise connection within a four-node set. The mean node degree was 3.0. No edges were expected by chance for a random protein set of this size under the specified model, whereas six were observed. Protein–protein interaction enrichment was highly significant ($P=7.72\times10-9$), demonstrating that SDC1–SDC4 constitute a

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functionally coherent protein family rather than a random collection of independently responding transcripts.

Table 2. STRING v12.0 network statistics.

Metric	Result
Organism	Homo sapiens
Confidence setting	Medium
Number of proteins	4
Observed associations	6
Expected edges	0
Mean node degree	3.0
PPI enrichment probability	7.72 × 10−9

3.3. Functional enrichment

Functional enrichment linked the syndecan network to processes at the tumour cell–microenvironment interface. Cell-adhesion molecules showed the strongest enrichment signal, followed by proteoglycans in cancer. Exosome assembly, ECM–receptor interaction, and cell migration were also significant. All reported categories met an FDR threshold below 0.05. As the input was deliberately limited to four related genes, these results provide functional context for the coordinated transcriptional response and should not be interpreted as an unbiased genome-wide pathway screen.

Table 3. Functional enrichment of the SDC1–SDC4 network.

Functional category	−log10(FDR)	Interpretive domain
Cell adhesion molecules	6.06	Cell–cell and cell–matrix interactions
Proteoglycans in cancer	3.36	Tumour-associated extracellular signalling
Exosome assembly	2.14	Vesicular communication
ECM–receptor interaction	2.08	Matrix sensing and signalling
Cell migration	1.66	Motility and invasion-related regulation

4. DISCUSSION

The principal finding is that GO and rGO elicited concordant upregulation of SDC1–SDC4 in SCC-25 cells. This pattern supports a coordinated transcriptional remodelling programme at the plasma membrane and extracellular interface. Because syndecans jointly regulate ligand presentation, adhesion-receptor organisation, cytoskeletal coupling, and matrix interactions, simultaneous induction of all four family members may represent an integrated cellular response to nanomaterial contact rather than four unrelated transcriptional events [1].

The network analysis strengthens this interpretation. All four syndecans were connected to one another, producing six associations and a highly significant enrichment probability. This network result is not

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evidence of direct physical binding under the experimental conditions; STRING associations may integrate experimentally supported, curated, co-expression, and other functional evidence [3]. It nevertheless demonstrates that the observed gene set is biologically coherent. The accompanying enrichment profile places the response within cell adhesion, cancer-associated proteoglycan biology, extracellular-matrix signalling, vesicle formation, and migration—functions that align closely with established syndecan biology.

The response should be interpreted cautiously with respect to therapeutic significance. Syndecan induction may accompany adaptive membrane repair, altered glycocalyx architecture, oxidative or inflammatory stress, increased ligand capture, changes in exosome biology, or migratory reprogramming. It is not intrinsically pro-apoptotic or antitumour. This distinction is important because graphene-based systems have produced divergent outcomes across experimental settings. Targeted graphene oxide nanocarriers can improve drug uptake and cytotoxicity in SCC-25 cells when coupled to a tumour-directed peptide and doxorubicin [5], but that finding concerns a functionalised drug-delivery system rather than unmodified GO exposure. Conversely, low-dose graphene oxide promoted TGF-β-dependent epithelial–mesenchymal transition and migration in other carcinoma models [4]. Together, these studies reinforce the context-dependent nature of graphene–cancer interactions.

A plausible working model is that GO and rGO first interact with the cell surface and extracellular milieu, triggering an early transcriptional adjustment of syndecan-dependent signalling. Increased SDC expression could then modify the availability of growth factors, the organisation of integrins and other receptors, the composition of the glycocalyx, and the exchange of extracellular vesicles. The phenotypic outcome may differ according to material oxidation state, concentration, aggregation and dispersion, protein-corona composition, exposure duration, and the basal molecular state of the tumour cell. This model is compatible with the presented results but requires direct experimental testing.

The study has several strengths. It evaluates both GO and rGO, uses a graded concentration design and two exposure windows, examines all four syndecan genes, and integrates targeted transcriptional analysis with network and functional-enrichment assessment. The use of a complete syndecan-family panel reduces the risk of overinterpreting a single marker and provides a coherent framework for subsequent mechanistic studies.

5. FUTURE EXPERIMENTAL VALIDATION

Future studies should establish whether the coordinated transcriptional regulation of SDC1–SDC4 is translated into changes at the protein and phenotype levels. Total and membrane-associated syndecan abundance, soluble ectodomains, reactive oxygen species, mitochondrial activity, apoptosis, cell-cycle distribution, migration, invasion, and extracellular-vesicle release should be quantified across the material, concentration, and time conditions. Normal oral keratinocytes should be studied in parallel to determine tumour selectivity. Mechanistic experiments using syndecan knockdown, pathway inhibition, and TGF-β/SMAD or integrin-signalling readouts would help distinguish adaptive, pro-migratory, and cytotoxic responses. Detailed physicochemical characterisation of GO and rGO—including lateral size, thickness, zeta potential, oxidation state, dispersion stability, and endotoxin status—will further strengthen reproducibility and biological interpretation.

6. CONCLUSION

GO and rGO exposure induced a coordinated increase in SDC1–SDC4 transcripts in SCC-25 tongue squamous carcinoma cells. The associated STRING network was fully connected and significantly enriched, while functional analysis linked the response to cell adhesion, cancer-associated proteoglycans, exosome assembly, extracellular-matrix interaction, and migration. These findings establish a testable framework in which graphene-based nanomaterials remodel syndecan-dependent extracellular signalling. They do not, however, establish anticancer activity. Protein-level, phenotypic, and mechanistic validation—supported by complete effect-size reporting—is required before therapeutic conclusions can be drawn.

7. ACKNOWLEDGEMENTS AND FUNDING

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SİMETRİK VE ASİMETRİK KARBON/KEVLAR HİBRİT ÇİFT KAVİSLİ KOMPOZİT YAPILARDA KATMAN DİZİLİMİNİN YARI-STATİK BATMA DAVRANIŞINA ETKİSİNİN KARŞILAŞTIRILMASI

COMPARISON OF THE EFFECT OF STACKING SEQUENCE ON THE QUASI-STATIC INDENTATION BEHAVIOR OF SYMMETRIC AND ASYMMETRIC CARBON/KEVLAR HYBRID DOUBLE-CURVED COMPOSITE STRUCTURES

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ÖZET

Karbon ve Kevlar fiber takviyeli hibrit kompozit yapılar, yüksek özgül dayanım, rijitlik ve enerji absorpsiyon özelliklerinin bir arada elde edilebilmesi nedeniyle havacılık, savunma, otomotiv ve denizcilik gibi farklı mühendislik alanlarında önemli bir kullanım potansiyeline sahiptir. Bu yapıların mekanik performansı yalnızca kullanılan takviye malzemelerinin özelliklerine değil, aynı zamanda fiber mimarisi, laminat simetrisi ve katmanların yapı içerisindeki yerleşim düzenine de bağlıdır. Bu çalışmada, farklı katman dizilimlerine sahip simetrik ve asimetrik karbon/Kevlar hibrit çift kavisli kompozit yapıların yarı-statik batma davranışları deneysel olarak karşılaştırılmıştır. Çalışmanın temel amacı, laminat simetrisinin, karbon fiber dokuma mimarisinin ve karbon/Kevlar katmanlarının yapı içerisindeki dağılımının mekanik davranış üzerindeki etkisini ortaya koymaktır. Bu kapsamda düz dokuma karbon (PC), dimi dokuma karbon (TC) ve Kevlar (K) takviye malzemeleri kullanılarak farklı katman dizilimlerine sahip sekiz katmanlı hibrit kompozit yapılar hazırlanmıştır. Simetrik yapılarda karbon katmanlarının dış yüzeylerde gruplandırıldığı ve karbon/Kevlar katmanlarının yapı içerisinde dağıtıldığı farklı konfigürasyonlar incelenmiştir. Elde edilen deneysel sonuçlar, aynı yükleme koşullarında test edilen asimetrik karbon/Kevlar hibrit kompozit yapıların sonuçlarıyla karşılaştırılmıştır. Yarı-statik batma deneyleri 1,25 mm/dk yükleme hızında gerçekleştirilmiş ve numunelerin kuvvet-yer değiştirme davranışları ile maksimum kuvvet değerleri değerlendirilmiştir. Karşılaştırmalar sonucunda, simetrik katman düzeninin her iki karbon dokuma mimarisinde de asimetrik yapılara kıyasla maksimum yük taşıma kapasitesini artırdığı belirlenmiştir. Düz dokuma karbon/Kevlar esaslı yapılarda simetrik konfigürasyonun asimetrik yapıya göre maksimum kuvvette yaklaşık %5,86, dimi dokuma karbon/Kevlar esaslı yapılarda ise yaklaşık %2,47 artış sağladığı tespit edilmiştir. Bununla birlikte, simetrik yapıların kendi içerisindeki değerlendirilmesi, katmanların gruplandırılmış veya dağıtılmış biçimde konumlandırılmasının etkisinin karbon fiber dokuma mimarisine bağlı olarak değiştiğini ortaya koymuştur. Düz dokuma karbon/Kevlar sisteminde dağıtılmış katman yerleşiminin yük taşıma kapasitesine olumlu katkı sağladığı, dimi dokuma karbon/Kevlar sisteminde ise karbon katmanlarının dış yüzeylerde gruplandırıldığı konfigürasyonun daha yüksek maksimum kuvvet sergilediği belirlenmiştir. Sonuç olarak, çift kavisli karbon/Kevlar hibrit kompozit yapıların yarı-statik batma performansının yalnızca laminat simetrisine bağlı olmadığı; karbon fiber dokuma mimarisi ile katman yerleşim düzeni arasındaki etkileşimin de mekanik performans üzerinde belirleyici olduğu ortaya konulmuştur. Elde edilen sonuçların, farklı yükleme koşullarına yönelik hibrit

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çift kavisli kompozit yapıların katman tasarımının geliştirilmesine katkı sağlayabileceği değerlendirilmiştir.

Anahtar Kelimeler: Karbon/Kevlar, hibrit kompozitler, çift kavisli yapılar, katma dizilimi, yarı-statik batma.

ABSTRACT

Carbon- and Kevlar-fiber-reinforced hybrid composite structures have significant potential for use in various engineering fields, including aerospace, defense, automotive, and marine applications, due to their ability to combine high specific strength, stiffness, and energy absorption characteristics. The mechanical performance of these structures depends not only on the properties of the reinforcing materials but also on the fiber architecture, laminate symmetry, and stacking sequence. In this study, the quasi-static indentation behavior of symmetric and asymmetric carbon/Kevlar hybrid double-curved composite structures with different stacking sequences was experimentally compared. The main objective was to investigate the effects of laminate symmetry, carbon-fiber weave architecture, and the distribution of carbon/Kevlar layers within the structure on mechanical behavior. For this purpose, eight-layer hybrid composite structures with different stacking sequences were manufactured using plain carbon (PC), twill carbon (TC), and Kevlar (K) reinforcements. In the symmetric configurations, different arrangements were investigated in which the carbon layers were either grouped on the outer surfaces or distributed throughout the laminate together with the Kevlar layers. The experimental results obtained from these symmetric configurations were compared with those of asymmetric carbon/Kevlar hybrid composite structures tested under the same loading conditions. Quasi-static indentation tests were performed at a loading rate of 1.25 mm/min, and the force-displacement responses and maximum force values of the specimens were evaluated. The comparison results showed that the symmetric stacking arrangement increased the maximum load-carrying capacity compared with the asymmetric structures for both carbon weave architectures. The symmetric configuration provided an approximately 5.86% increase in maximum force compared with the asymmetric configuration in plain carbon/Kevlar structures, while an approximately 2.47% increase was obtained in twill carbon/Kevlar structures. Furthermore, the comparison among the symmetric configurations demonstrated that the influence of grouped and distributed layer arrangements varied depending on the carbon-fiber weave architecture. In the plain carbon/Kevlar system, the distributed stacking arrangement contributed positively to the load-carrying capacity, whereas in the twill carbon/Kevlar system, the configuration in which the carbon layers were grouped on the outer surfaces exhibited a higher maximum force. Consequently, the quasi-static indentation performance of double-curved carbon/Kevlar hybrid composite structures cannot be explained solely by laminate symmetry; the interaction between carbon-fiber weave architecture and stacking sequence also plays a determining role in mechanical performance. The findings may contribute to the development and optimization of stacking designs for hybrid double-curved composite structures subjected to different loading conditions.

Keywords: Carbon/Kevlar, hybrid composites, double-curved structures, stacking sequence, quasi-static indentation

1. GİRİŞ

Kompozit malzemeler, yüksek özgül dayanım ve rijitlik, düşük yoğunluk ve tasarım esnekliği gibi avantajları nedeniyle havacılık, savunma, otomotiv, denizcilik ve enerji sektörleri başta olmak üzere birçok mühendislik uygulamasında yaygın olarak kullanılmaktadır. Bununla birlikte, tek bir takviye malzemesiyle tüm mekanik gereksinimlerin karşılanmasının güç olması, farklı fiber türlerinin aynı yapı içerisinde bir araya getirildiği hibrit kompozit sistemlere olan ilgiyi artırmıştır. Karbon fiberler yüksek rijitlik ve yük taşıma kapasitesi sağlarken, Kevlar fiberler yüksek tokluk, enerji absorpsiyonu ve hasar toleransı özellikleriyle yapısal performansa katkıda bulunmaktadır. Bu iki takviye malzemesinin aynı laminat içerisinde uygun katman dizilimleriyle bir araya getirilmesi, tek bir fiber sistemiyle elde edilmesi güç olan mekanik özelliklerin dengeli biçimde sağlanmasına olanak tanımaktadır (Wang ve

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ark., 2024). Hibrit kompozitlerin mekanik davranışı yalnızca kullanılan fiber ve matris malzemelerinin özelliklerine bağlı değildir. Katman dizilimi, fiberlerin laminat içerisindeki konumu, dokuma mimarisi ve laminat simetrisi; yük aktarımı, hasar gelişimi ve yük taşıma kapasitesini belirleyen temel tasarım parametreleri arasında yer almaktadır. Özellikle lokal yüklemelerde temas yüzeyine yakın katmanların konumu, yükün laminat boyunca aktarılması ve hasarın ilerleme biçimi üzerinde önemli rol oynayabilmektedir. Bu nedenle aynı fiber içeriğine sahip hibrit laminatlar, yalnızca katman yerleşiminin değiştirilmesiyle farklı kuvvet–yer değiştirme davranışları sergileyebilmektedir. Katman diziliminin yük taşıma kapasitesi, enerji absorpsiyonu ve hasar mekanizmaları üzerindeki etkisi önceki çalışmalarda da ortaya konulmuştur (Bulut & Erkliğ, 2018; Pach & Kuterek, 2021; Wang ve ark., 2024). Kompozit yapıların lokal yükleme davranışlarının değerlendirilmesinde yarı-statik batma (Quasi-Static Indentation, QSI) deneyleri, düşük hızlı darbe (Low-Velocity Impact, LVI) davranışının araştırılmasında kullanılan önemli deneysel yaklaşımlardan biridir (Bulut ve ark., 2016; Djele & Karakuzu, 2021). Düşük hızlı darbe deneylerinde yükleme süresinin kısa olması nedeniyle hasar gelişiminin ayrıntılı olarak izlenmesi güçleşirken, QSI deneyleri kontrollü yükleme koşulları altında kuvvet–yer değiştirme davranışının ve hasar ilerlemesinin incelenmesine olanak sağlamaktadır. Bu nedenle QSI deneyleri; delaminasyon, matris çatlakları ve fiber kırılması gibi hasar mekanizmalarının değerlendirilmesinde ve düşük hızlı darbe davranışının yorumlanmasında yaygın olarak kullanılmaktadır (Gebhardt ve ark., 2023; Wang ve ark., 2025). Sıcaklık ve yükleme koşullarının QSI ve darbe davranışları üzerindeki etkileri de literatürde araştırılmıştır. Djele ve Karakuzu (2021), kompozit laminatların farklı sıcaklıklardaki (23 °C, 40 °C, 60 °C ve 80 °C) batma davranışlarını incelemiş ve belirli yarı-statik test hızlarında penetrasyon için gerekli enerjinin düşük hızlı darbe testlerinden elde edilen değerlerle benzer seviyelerde olduğunu bildirmiştir. Yükleme açısının hasar gelişimi üzerindeki etkisini inceleyen Jayababu ve ark. (2020) ise normal ve 20° eğimli düzlemlerde gerçekleştirdikleri batma deneylerinde Akustik Emisyon (AE) izleme tekniğinden yararlanarak farklı yükleme koşullarında meydana gelen hasar başlangıcı ve ilerleme süreçlerini değerlendirmiştir. AE yönteminin kompozit laminatlarda farklı hasar mekanizmalarının yükleme süresince izlenmesinde kullanılabildiği ayrıca farklı çalışmalarda da gösterilmiştir (Andrew ve ark., 2017). Katman diziliminin mekanik davranış üzerindeki etkisi, çift kavisli kompozit yapılarda geometrik etkilerle birlikte değerlendirilmelidir. Düz laminatlardan farklı olarak eğrisel geometrilerde lokal yükleme altında oluşan yapısal cevap, malzeme özelliklerinin yanı sıra geometrinin oluşturduğu yük aktarım mekanizmalarından da etkilenmektedir. Eğrisel yüzeylerde lokal yükleme sırasında eğilme ve membran etkilerinin birlikte ortaya çıkması, katmanlar arası yük transferini ve deformasyon davranışını daha karmaşık hâle getirebilmektedir. Bu nedenle çift kavisli kompozit yapıların mekanik performansının değerlendirilmesinde fiber türü ve katman diziliminin yanı sıra yapı geometrisinin de dikkate alınması gerekmektedir (Hosseini ve ark., 2013; Işıktaş ve ark., 2025). Eğrisel kompozit yapıların lokal batma davranışının açıklanmasına yönelik analitik, deneysel ve sayısal çalışmalar literatürde yer almaktadır. Hosseini ve ark. (2013), çift kavisli kompozit sandviç paneller için analitik bir batma kanunu (indentation law) geliştirerek batma davranışının modellenmesine yönelik bir yaklaşım ortaya koymuştur. Deneysel ve veri tabanlı modelleme açısından Işıktaş ve ark. (2025), yapay sinir ağları (YSA) tabanlı modeller kullanarak kavisli kompozitlerin batma kuvveti–yer değiştirme davranışını modellemiş ve farklı kavis geometrilerinin mekanik cevap üzerindeki etkisini değerlendirmiştir. Bunun yanında, kavisli kompozit panellerde lokal hasarın izlenmesine yönelik ince hibrit sensör sistemlerinin kullanılabilirliği de araştırılmıştır (Tabatabaeian ve ark., 2025). Karbon fiber takviyeli kompozitlerde dokuma mimarisi, mekanik davranışı belirleyen önemli tasarım parametrelerinden biridir. Düz (düz) ve dimi (dimi) dokuma karbon kumaşlar; fiberlerin örgü yapısı, iplik geçişleri ve buna bağlı yük aktarım mekanizmaları bakımından farklılık göstermektedir. Bu yapısal farklılıklar, lokal yükleme altında laminatın rijitliğini, yük taşıma kapasitesini ve hasar gelişimini etkileyebilmektedir. Bunun yanında, karbon ve Kevlar katmanlarının laminat içerisinde dağıtılması veya belirli bölgelerde gruplandırılması da katmanlar arasındaki yük paylaşımını değiştirebilmekte ve batma davranışında farklı mekanik cevapların ortaya çıkmasına neden olabilmektedir. Dolayısıyla hibrit kompozitlerin mekanik performansı yalnızca kullanılan fiber türleri üzerinden değil, dokuma mimarisi ve katman diziliminin birlikte oluşturduğu yapısal düzen dikkate alınarak değerlendirilmelidir (Pach & Kuterek, 2021; Wang ve ark., 2024). Hibrit kompozitler üzerine gerçekleştirilen çalışmalar, farklı fiber türlerinin ve katman yerleşimlerinin lokal yükleme altındaki mekanik davranışı önemli ölçüde etkileyebildiğini

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göstermektedir. Doğal ve sentetik fiberlerin birlikte kullanıldığı yapılarda hibritleşmenin yarı-statik batma performansı üzerindeki etkileri incelenmiş (Pach ve ark., 2020; Abu Hassan ve ark., 2022), sandviç yapılarda hibrit yüzey tabakalarının lokal yükleme direncine katkısı araştırılmıştır (Anbazhagan ve ark., 2022). Ayrıca farklı istifleme düzenlerine sahip dokuma hibrit kompozitlerde katman diziliminin yarı-statik batma ve batma sonrası mekanik davranış üzerinde belirleyici olabildiği bildirilmiştir (Herath ve ark., 2025). Bu bulgular, hibrit kompozitlerin lokal yükleme performansının yalnızca fiber türüne değil, fiberlerin yapı içerisindeki konumuna ve oluşturulan laminat mimarisine de bağlı olduğunu göstermektedir. Literatürde karbon, cam ve aramid esaslı kompozit yapıların yarı-statik batma ve düşük hızlı darbe davranışlarını inceleyen çok sayıda çalışma bulunmasına rağmen, mevcut çalışmaların önemli bir bölümü düz laminatlar veya belirli katman konfigürasyonları üzerinde yoğunlaşmaktadır. Hibrit kompozitlerde katman dizilimi ve fiber yerleşiminin mekanik davranış üzerindeki etkileri farklı çalışmalarda araştırılmış olmakla birlikte, düz ve dimi karbon dokuma mimarilerinin, simetrik ve asimetrik katman düzenleriyle birlikte çift kavisli karbon/Kevlar hibrit yapılardaki yarı-statik batma davranışı üzerindeki etkilerini karşılaştırmalı olarak ele alan çalışmalar sınırlıdır (Bulut & Erkliğ, 2018; Pach & Kuterek, 2021; Wang ve ark., 2024). Bu durum, dokuma mimarisi, laminat simetrisi ve katman yerleşiminin çift kavisli hibrit yapıların lokal yük taşıma davranışı üzerindeki birleşik etkilerinin deneysel olarak incelenmesini gerekli kılmaktadır. Bu çalışmada, farklı katman dizilimlerine sahip simetrik ve asimetrik karbon/Kevlar hibrit çift kavisli kompozit yapıların 1,25 mm/dk yükleme hızındaki yarı-statik batma davranışları deneysel olarak incelenmiştir. Çalışma kapsamında düz dokuma karbon (PC), dimi dokuma karbon (TC) ve Kevlar (K) takviye katmanlarından oluşturulan farklı laminat konfigürasyonlarının kuvvet–yer değiştirme davranışları ve maksimum batma kuvvetleri karşılaştırılmıştır. Bu kapsamda laminat simetrisinin, karbon dokuma mimarisinin ve karbon/Kevlar katmanlarının laminat içerisindeki yerleşim düzeninin mekanik davranış üzerindeki etkileri birlikte değerlendirilmiştir. Çalışmanın temel özgünlüğü, aynı fiber içeriği ve toplam katman sayısı korunarak dokuma mimarisi ile katman yerleşiminin çift kavisli hibrit kompozitlerin yarı-statik batma performansı üzerindeki etkilerinin karşılaştırmalı olarak ortaya konulmasıdır. Böylece çift kavisli karbon/Kevlar hibrit yapıların tasarımında katman mimarisinin belirlenmesine katkı sağlayabilecek deneysel bulguların elde edilmesi amaçlanmıştır.

2. ARAŞTIRMA VE BULGULAR

2.1 Materyal ve Metot

2.1.1. Malzemeler

Bu çalışmada hibrit kompozit laminatların üretiminde takviye malzemesi olarak düz dokuma (düz) karbon fiber, dimi dokuma (dimi) karbon fiber ve Kevlar® 29 aramid fiber kumaş kullanılmıştır. İki farklı karbon dokuma mimarisinin tercih edilmesindeki temel amaç, karbon/Kevlar hibritleşmesinin yanı sıra karbon fiber dokuma yapısının yarı-statik batma davranışı üzerindeki etkisinin karşılaştırmalı olarak değerlendirilmesidir.

Matris sistemi olarak Hexion LR285 epoksi reçinesi ve LH287 sertleştiricisi kullanılmıştır. Reçine ve sertleştirici, üretici tavsiyesine uygun olarak 100:40 ağırlık oranında karıştırılmıştır. Hazırlanan reçine sistemi, el yatırma (hand lay-up) yöntemiyle her bir fiber tabakasına homojen biçimde uygulanmıştır. Tüm numune gruplarında aynı reçine sistemi ve üretim koşulları kullanılarak üretim kaynaklı değişkenlerin sınırlandırılması amaçlanmıştır.

Çalışmada kullanılan tüm hibrit laminatlar sekiz fiber katmanından oluşturulmuş ve karbon/Kevlar takviye oranı deney grupları arasında sabit tutulmuştur. Numuneler arasındaki temel değişkenler, kullanılan karbon fiberin dokuma mimarisi (düz veya dimi), karbon ve Kevlar katmanlarının laminat içerisindeki yerleşimi ve laminatın simetrik/asimetrik yapısı olarak belirlenmiştir. Böylece deney grupları arasında gözlenen mekanik davranış farklılıklarının bu tasarım parametreleri üzerinden karşılaştırılması hedeflenmiştir.

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2.1.2. Numune Tasarımı ve Üretim Yöntemi

Karbon ve Kevlar fiberlerin farklı katman yerleşimleri ile karbon fiber dokuma mimarisinin yarı-statik batma davranışı üzerindeki etkisini incelemek amacıyla altı farklı hibrit kompozit laminat konfigürasyonu hazırlanmıştır. Deney gruplarında toplam fiber katman sayısı, karbon/Kevlar katman sayısı, reçine sistemi ve üretim yöntemi sabit tutulmuş; karbon fiber dokuma tipi (düz ve dimi), karbon/Kevlar katmanlarının laminat içerisindeki yerleşimi ve laminat simetrisi değiştirilmiştir.

Hibrit laminatlar simetrik ve asimetrik katman yerleşimlerine göre tasarlanmıştır. Simetrik yapılarda karbon katmanları dış yüzeylerde gruplandırılmış veya laminat boyunca dağıtılmış şekilde konumlandırılmıştır. Asimetrik yapılarda ise karbon ve Kevlar katmanlarının laminat içerisindeki yerleşimi simetrik yapılardan farklı olacak şekilde düzenlenmiştir. Çalışmada değerlendirilen numune kodları ve katman konfigürasyonları **[**Tablo 1]'de verilmiştir.

Tablo 1. Değerlendirilen hibrit kompozit laminat konfigürasyonları

Numune Kodu	Katman Dizilimi / Temel Tasarım Özelliği
PC2K2S	PC–PC–K–K–K–K–PC–PC (Simetrik, dışta gruplanmış düz karbon)
TC2K2S	TC–TC–K–K–K–K–TC–TC (Simetrik, dışta gruplanmış dimi karbon)
PCK2S	PC–K–PC–K–K–PC–K–PC (Simetrik, laminat boyunca dağıtılmış düz karbon)
TCK2S	TC–K–TC–K–K–TC–K–TC (Simetrik, laminat boyunca dağıtılmış dimi karbon)
PCK8R	Asimetrik düz karbon/Kevlar hibrit yapı
TCK8R	Asimetrik dimi karbon/Kevlar hibrit yapı

Not: PC: düz dokuma (düz) karbon fiber, TC: dimi dokuma (dimi) karbon fiber, K: Kevlar® 29 aramid fiber katmanını ifade etmektedir.

Kompozit laminatlar el yatırma (hand lay-up) yöntemi kullanılarak üretilmiştir. Üretim öncesinde karbon ve Kevlar kumaşlar belirlenen katman dizilimlerine uygun olarak hazırlanmış, LR285 epoksi reçinesi ve LH287 sertleştiriciden oluşan matris sistemi üretici tarafından önerilen 100:40 ağırlık oranında hazırlanmıştır. Reçine sistemi her bir fiber tabakasına homojen biçimde uygulanmış ve katmanlar önceden belirlenen dizilim sırasına uygun olarak çift kavisli kalıp üzerine yerleştirilmiştir.

Üretim sırasında katman sıralamasının ve fiber yerleşiminin korunmasına dikkat edilmiş, tüm deney gruplarında aynı üretim prosedürü uygulanmıştır. Laminatlar kürlenme işleminin ardından oda sıcaklığına getirilmiş ve deney numunesi boyutlarında hazırlanmıştır. Böylece numune grupları arasındaki karşılaştırmalarda üretim yönteminden kaynaklanabilecek farklılıkların sınırlandırılması amaçlanmıştır.

2.1.3. Yarı-Statik Batma (Quasi-Static Indentation, QSI) Deneyi

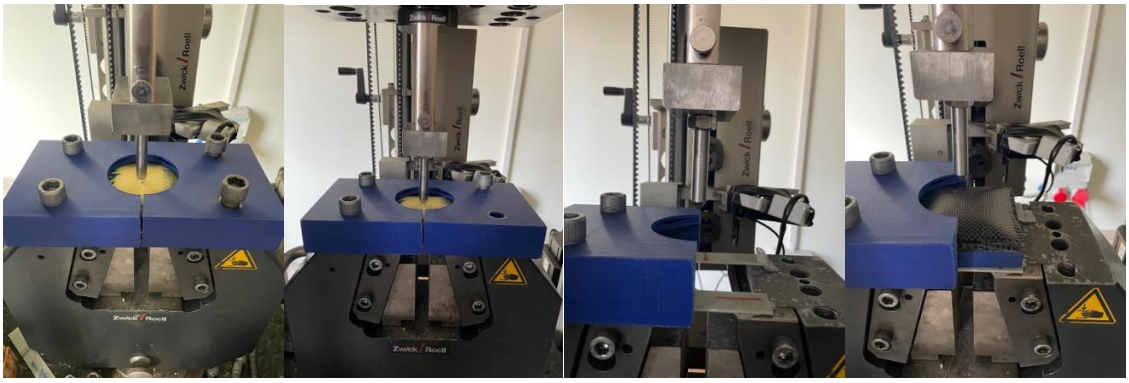
Üretilen hibrit kompozit numunelerin yarı-statik batma davranışlarının belirlenmesi amacıyla deneyler ASTM D6264/D6264M standardı esas alınarak gerçekleştirilmiştir. Deneyler Zwick/Roell Z250 üniversal test cihazında gerçekleştirilmiş ve yükleme sırasında hemisferik uç geometrisine sahip çelik bir indenter kullanılmıştır. İndenter, numunenin geometrik merkezine dik doğrultuda uygulanmış; indenter geometrisi, yükleme yönü ve numune bağlama koşulları tüm deney gruplarında sabit tutulmuştur.

Yükleme işlemi 1,25 mm/dk sabit ilerleme hızında gerçekleştirilmiş ve deney süresince uygulanan kuvvet ile indenter yer değiştirmesi sürekli olarak kayıt altına alınmıştır. Elde edilen kuvvet–yer

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değiştirme verileri kullanılarak her bir numune grubunun maksimum batma kuvveti belirlenmiş ve farklı katman konfigürasyonlarının mekanik cevapları karşılaştırılmıştır.

Deneyler tamamlandıktan sonra numuneler görsel olarak incelenmiş; matris çatlağı, delaminasyon, lokal ezilme ve fiber hasarı gibi gözlemlenebilir hasar mekanizmaları kuvvet–yer değiştirme davranışıyla birlikte değerlendirilmiştir. Böylece karbon fiber dokuma mimarisi, katman yerleşimi ve laminat simetrisinin yarı-statik batma davranışı üzerindeki etkilerinin karşılaştırılması amaçlanmıştır. Yarı-statik batma deneylerinde kullanılan deney düzeneği ve numunelerin test sırasındaki konumları [Şekil 1]'de gösterilmiştir.

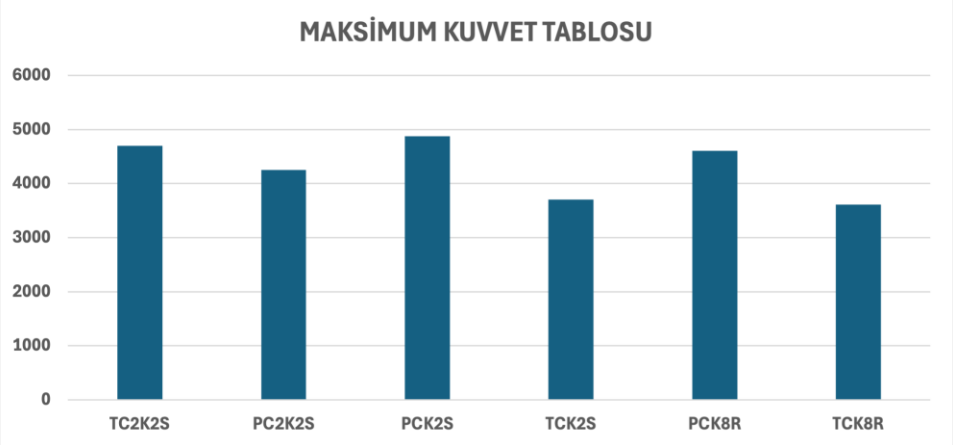


Şekil 1. Yarı-statik batma deneylerinde kullanılan Zwick/Roell Z250 test sistemi, deney fikstürü ve yarı küresel batıcı uç.

2.2 Bulgular ve Tartışma

2.2.1. Maksimum Batma Kuvveti Değerlerinin Değerlendirilmesi

Yarı-statik batma deneylerinden elde edilen maksimum kuvvet değerleri incelendiğinde, hibrit kompozit laminatların mekanik davranışının karbon fiber dokuma mimarisi ve katman yerleşimine bağlı olarak önemli ölçüde değiştiği görülmüştür. Deney grupları içerisinde en yüksek maksimum batma kuvveti 4876,417 N ile PCK2S numunesinde elde edilirken, bunu sırasıyla 4699,672 N ile TC2K2S, 4606,664 N ile PCK8R, 4253,988 N ile PC2K2S, 3703,430 N ile TCK2S ve 3614,235 N ile TCK8R numuneleri izlemiştir. Numunelere ait maksimum batma kuvvetlerinin karşılaştırılması [Şekil 2]'de verilmiştir.



Şekil 2. Farklı karbon/Kevlar hibrit kompozit konfigürasyonlarının maksimum batma kuvvetlerinin karşılaştırılması

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Düz karbon/Kevlar grubu kendi içerisinde değerlendirildiğinde, simetrik ve laminat boyunca dağıtılmış katman tablyerleşimine sahip PCK2S numunesinin maksimum batma kuvvetinin, asimetrik PCK8R numunesine göre yaklaşık %5,86 daha yüksek olduğu belirlenmiştir. Benzer şekilde dimi karbon/Kevlar grubunda TCK2S numunesi, TCK8R numunesine göre yaklaşık %2,47 daha yüksek maksimum kuvvet göstermiştir. Bu sonuçlar, incelenen dağıtılmış katman konfigürasyonlarında simetrik yerleşimin maksimum yük taşıma kapasitesine olumlu katkı sağlayabildiğini göstermektedir.

Bununla birlikte, simetrik laminatlar kendi içerisinde karşılaştırıldığında katman yerleşiminin etkisinin karbon dokuma mimarisine bağlı olarak değiştiği görülmüştür. Düz karbon/Kevlar grubunda laminat boyunca dağıtılmış karbon katmanlarına sahip PCK2S numunesi, karbon katmanlarının dış bölgelerde gruplandırıldığı PC2K2S numunesinden yaklaşık %14,63 daha yüksek maksimum kuvvet göstermiştir. Buna karşılık dimi karbon/Kevlar grubunda ters bir eğilim ortaya çıkmış; karbon katmanlarının dış bölgelerde gruplandırıldığı TC2K2S numunesinin maksimum kuvveti, dağıtılmış katman düzenine sahip TCK2S numunesinden yaklaşık %26,90 daha yüksek bulunmuştur.

Aynı katman yerleşim düzenine sahip düz ve dimi karbon yapılar karşılaştırıldığında da dokuma mimarisinin etkisinin katman konfigürasyonuna bağlı olduğu görülmektedir. Karbon katmanlarının dış bölgelerde gruplandırıldığı yapılarda TC2K2S, PC2K2S'ye göre yaklaşık %10,48 daha yüksek maksimum kuvvete ulaşırken; karbon katmanlarının laminat boyunca dağıtıldığı yapılarda PCK2S, TCK2S'ye göre yaklaşık %31,67 daha yüksek maksimum kuvvet göstermiştir. Dolayısıyla deney sonuçları, düz veya dimi dokuma mimarilerinden birinin tüm katman konfigürasyonlarında mutlak olarak üstün olduğunu göstermemekte; dokuma mimarisi ile katman yerleşimi arasında belirgin bir etkileşim bulunduğuna işaret etmektedir.

Literatürde de karbon/Kevlar hibrit laminatların yarı-statik batma davranışının katman dizilimi ve takviye katmanlarının laminat içerisindeki konumundan etkilendiği, farklı istifleme düzenlerinin yük taşıma kapasitesi ve hasar gelişiminde farklı mekanik cevaplar oluşturabildiği bildirilmektedir (Bulut & Erkliğ, 2018; Pach & Kuterek, 2021; Wang ve ark., 2024). Bu bağlamda mevcut deney sonuçları, katman yerleşiminin etkisinin tek başına değerlendirilmemesi gerektiğini; karbon fiber dokuma mimarisi ile birlikte ele alınmasının çift kavisli karbon/Kevlar hibrit yapıların yarı-statik batma performansının yorumlanmasında daha uygun olduğunu göstermektedir

2.2.2. Simetrik ve Asimetrik Hibrit Yapıların Karşılaştırılması

Laminat simetrisinin yarı-statik batma davranışı üzerindeki etkisini değerlendirmek amacıyla simetrik ve asimetrik karbon/Kevlar hibrit yapılar karşılaştırılmıştır. Düz karbon/Kevlar grubunda simetrik ve dağıtılmış katman dizilimine sahip PCK2S numunesinin maksimum batma kuvveti 4876,417 N**,** asimetrik PCK8R numunesinin ise 4606,664 N olarak belirlenmiştir. Buna göre PCK2S, PCK8R'ye kıyasla yaklaşık %5,86 daha yüksek maksimum kuvvet göstermiştir. Dimi karbon/Kevlar grubunda ise simetrik TCK2S numunesinde 3703,430 N**,** asimetrik TCK8R numunesinde 3614,235 N maksimum kuvvet elde edilmiş ve simetrik yapıdaki artış yaklaşık %2,47 olarak hesaplanmıştır.

Her iki dokuma grubunda da incelenen simetrik dağıtılmış konfigürasyonların karşılık gelen asimetrik yapılardan daha yüksek maksimum kuvvete ulaşması, laminat simetrisinin yük taşıma davranışına katkı sağlayabildiğini göstermektedir. Bununla birlikte, düz grubunda gözlenen %5,86'lık ve dimi grubunda gözlenen %2,47'lik artışların birbirinden farklı olması, simetri etkisinin karbon fiber dokuma mimarisinden bağımsız ve sabit bir mekanizma olarak değerlendirilmemesi gerektiğine işaret etmektedir.

Çift kavisli kompozit yapılarda bu davranışın değerlendirilmesinde yapı geometrisi de dikkate alınmalıdır. Eğrisel geometrilerde lokal batma yükü altında oluşan eğilme ve membran gerilmeleri birlikte etkili olmakta ve katmanlar arası yük aktarımını düz laminatlara kıyasla daha karmaşık hâle getirebilmektedir. Literatürde çift kavisli ve eğrisel kompozit yapıların lokal yükleme davranışının geometri, katman yapısı ve yükleme koşullarının birlikte etkisi altında geliştiği bildirilmektedir (Hosseini ve ark., 2013; Işıktaş ve ark., 2025).

Bu nedenle mevcut çalışmada simetrik yapıların asimetrik yapılara göre gösterdiği maksimum kuvvet artışı yalnızca laminat simetrisine bağlanmamalıdır. Elde edilen sonuçlar, laminat simetrisi, karbon fiber

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dokuma mimarisi ve katman yerleşiminin birlikte değerlendirilmesi gerektiğini göstermektedir. Özellikle düz ve dimi gruplarında simetrik–asimetrik yapılar arasında farklı oranlarda artış elde edilmesi, çift kavisli hibrit kompozitlerin tasarımında tek bir yapısal parametre üzerinden genelleme yapılmasının yeterli olmayacağını ortaya koymaktadır.

2.2.3. Katman Yerleşiminin Mekanik Davranış Üzerindeki Etkisi

Hibrit kompozit laminatlarda mekanik performansı belirleyen temel parametrelerden biri katman dizilimidir. Aynı fiber türleri ve aynı toplam katman sayısı kullanılsa dahi karbon ve Kevlar katmanlarının laminat içerisindeki konumlarının değiştirilmesi, yük aktarım mekanizmasını ve buna bağlı olarak maksimum yük taşıma kapasitesini önemli ölçüde değiştirebilmektedir. Bu nedenle hibrit kompozit tasarımında yalnızca kullanılan takviye malzemelerinin özellikleri değil, farklı mekanik özelliklere sahip katmanların laminat içerisindeki dağılımı da birlikte değerlendirilmelidir (Bulut & Erkliğ, 2018; Wang ve ark., 2024).

Bu çalışmada katman yerleşiminin etkisi, aynı karbon dokuma mimarisine sahip simetrik laminatlar kendi içerisinde karşılaştırılarak açık biçimde gözlenmiştir. Düz karbon/Kevlar grubunda karbon katmanlarının laminat boyunca dağıtıldığı PCK2S numunesinde maksimum batma kuvveti 4876,416 N olarak belirlenirken, karbon katmanlarının dış bölgelerde gruplandırıldığı PC2K2S numunesinde bu değer 4253,988 N olarak elde edilmiştir. Buna göre dağıtılmış katman yerleşimine sahip PCK2S, PC2K2S'ye kıyasla yaklaşık %14,63 daha yüksek maksimum kuvvet göstermiştir. Bu sonuç, düz karbon mimarisinde karbon ve Kevlar katmanlarının laminat boyunca dağıtılmasının yükün katmanlar arasında daha etkin aktarılmasına katkı sağladığını göstermektedir.

Dimi karbon/Kevlar laminatlarda ise katman yerleşiminin etkisi ters yönde gerçekleşmiştir. Karbon katmanlarının dış bölgelerde gruplandırıldığı TC2K2S numunesinde maksimum batma kuvveti 4699,67 N iken, karbon katmanlarının laminat boyunca dağıtıldığı TCK2S numunesinde 3703,430 N maksimum kuvvet elde edilmiştir. Böylece TC2K2S numunesinin TCK2S'ye göre yaklaşık %26,90 daha yüksek maksimum kuvvet taşıdığı belirlenmiştir. Düz karbon grubunda dağıtılmış yerleşim avantaj sağlarken, dimi karbon grubunda dış bölgelerde gruplandırılmış karbon katmanlarının daha yüksek yük taşıma kapasitesi sağlaması, katman yerleşiminin etkisinin dokuma mimarisinden bağımsız değerlendirilemeyeceğini ortaya koymaktadır.

Elde edilen bulgular, hibrit laminatlarda tek başına "karbonun dışta bulunması" veya "karbonun laminat boyunca dağıtılması" şeklinde genel bir optimum yerleşim tanımlamanın yeterli olmadığını göstermektedir. Optimum katman diziliminin kullanılan karbon fiber dokuma mimarisine bağlı olarak değiştiği görülmektedir. Dolayısıyla çift kavisli karbon/Kevlar hibrit kompozitlerin tasarımında katman yerleşimi ile dokuma mimarisinin birlikte değerlendirilmesi, maksimum yük taşıma kapasitesinin geliştirilmesi açısından kritik önem taşımaktadır.

2.2.4. Düz ve Dimi Dokuma Karbon Fiber Dokuma Mimarilerinin Karşılaştırılması

Bu çalışmada incelenen temel tasarım parametrelerinden biri karbon fiber dokuma mimarisidir. Aynı karbon/Kevlar oranına ve benzer katman yerleşim prensibine sahip laminatlarda karbon fiber dokuma tipinin değiştirilmesi, maksimum batma kuvvetinde belirgin farklılıkların ortaya çıkmasına neden olmuştur. Bu durum, dokuma mimarisinin çift kavisli hibrit kompozitlerin yarı-statik batma performansını doğrudan etkileyen önemli bir tasarım değişkeni olduğunu göstermektedir.

Karbon katmanlarının dış bölgelerde gruplandırıldığı simetrik yapılar karşılaştırıldığında, TC2K2S numunesinde maksimum batma kuvveti 4699,672 N, PC2K2S numunesinde ise 4253,988 N olarak belirlenmiştir. Buna göre dimi karbon kullanılan TC2K2S numunesi, düz karbon kullanılan PC2K2S numunesine kıyasla yaklaşık %10,48 daha yüksek maksimum kuvvet göstermiştir. Bu sonuç, karbon katmanlarının dış bölgelerde gruplandırıldığı konfigürasyonda dimi dokuma mimarisinin yük taşıma kapasitesi açısından avantaj sağlayabildiğini göstermektedir.

Buna karşılık karbon katmanlarının laminat boyunca dağıtıldığı simetrik yapılar karşılaştırıldığında farklı bir davranış ortaya çıkmıştır. PCK2S numunesinde maksimum batma kuvveti 4876,416 N olarak elde edilirken, TCK2S numunesinde bu değer 3703,430 N olarak belirlenmiştir. Böylece düz karbon

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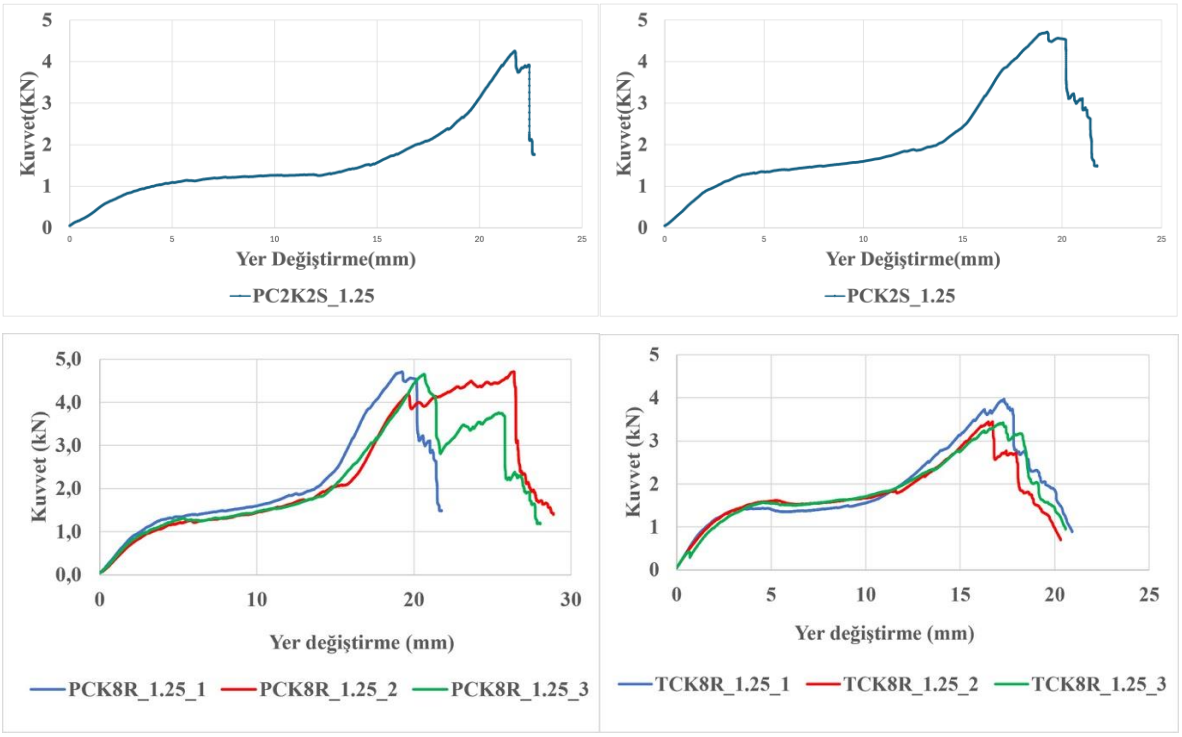
kullanılan PCK2S numunesinin, aynı dağıtılmış katman yerleşimine sahip TCK2S numunesine göre yaklaşık %31,67 daha yüksek maksimum kuvvet taşıdığı görülmüştür. Dolayısıyla dimi dokumanın dışta gruplandırılmış karbon düzeninde sağladığı avantajın, karbon katmanlarının laminat boyunca dağıtılması durumunda devam etmediği belirlenmiştir.

Düz ve dimi dokuma karbon fiberler arasındaki lif geçişleri ve lif kıvrımı (crimp) gibi mimari farklılıklar, laminat içerisindeki yük aktarım mekanizmasını, rijitliği ve hasar gelişimini etkileyebilmektedir. Bununla birlikte bu çalışmanın sonuçları, dokuma mimarisinin etkisinin katman yerleşiminden bağımsız olarak değerlendirilmemesi gerektiğini göstermektedir. Benzer şekilde literatürde de dokuma mimarisi ve hibrit katman düzeninin kompozit yapıların mekanik ve yarı-statik batma davranışında belirleyici olabileceği bildirilmektedir (Pach & Kuterek, 2021; Wang ve ark., 2024).

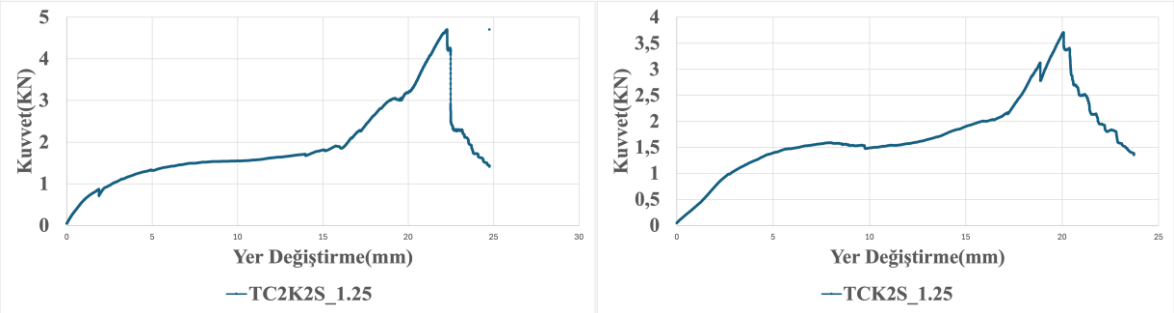
Bu sonuçlar birlikte değerlendirildiğinde, çift kavisli karbon/Kevlar hibrit laminatlarda belirli bir karbon dokuma mimarisinin tüm katman dizilimleri için mutlak bir üstünlüğünden söz etmek mümkün değildir. Dimi karbon dış bölgelerde gruplandırıldığında daha yüksek maksimum kuvvet sağlarken, dağıtılmış katman düzeninde düz karbon daha yüksek performans göstermiştir. Bu nedenle dokuma mimarisi ile katman yerleşimi arasında mekanik performansı belirleyen bir etkileşim bulunduğu ve optimum laminat tasarımının bu iki parametrenin birlikte değerlendirilmesiyle oluşturulması gerektiği sonucuna ulaşılmıştır.

2.2.5. Kuvvet–Yer Değiştirme Eğrileri ve Hasar Mekanizmalarının Değerlendirilmesi

Deneyler sonucunda elde edilen kuvvet–yer değiştirme eğrileri, farklı karbon/Kevlar hibrit laminat konfigürasyonlarının yarı-statik batma yükleri altındaki mekanik tepkilerinin karşılaştırılması amacıyla değerlendirilmiştir. İncelenen numunelere ait kuvvet–yer değiştirme eğrileri [Şekil 3]'te verilmiştir.



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Şekil 3. Karbon/Kevlar hibrit kompozit numunelerine ait yarı-statik batma kuvvet–yer değiştirme eğrileri.

Kuvvet–yer değiştirme eğrileri, hibrit kompozit laminatların yarı-statik batma yükleri altındaki mekanik tepkisinin değerlendirilmesinde temel göstergelerden biridir. Eğrinin başlangıç bölgesindeki eğim laminatın yükleme altındaki başlangıç rijitliği hakkında bilgi verirken, doğrusal davranıştan meydana gelen sapmalar kompozit yapı içerisinde hasar mekanizmalarının gelişmeye başladığı bölgelerle ilişkilendirilebilmektedir. Maksimum kuvvet sonrasında gözlenen yük değişimleri ise hasarın ilerleme karakterinin değerlendirilmesinde kullanılmaktadır (Bulut & Erkliğ, 2018; Pach & Kuterek, 2021).

Bu çalışmada elde edilen kuvvet–yer değiştirme davranışları, laminat konfigürasyonunun yarı-statik batma tepkisi üzerinde belirleyici olduğunu göstermektedir. Numune grupları arasında maksimum kuvvet değerlerinin önemli ölçüde değişmesi, karbon fiber dokuma mimarisi ve karbon/Kevlar katman yerleşiminin yük aktarım mekanizmasını etkilediğini ortaya koymaktadır. İncelenen konfigürasyonlar arasında PCK2S 4876,416 N ile en yüksek**,** TCK8R ise 3614,235 N ile en düşük maksimum kuvvet değerini göstermiştir. Böylece yalnızca kullanılan takviye malzemelerinin değil, bu malzemelerin laminat içerisindeki mimari düzeninin de lokal yükleme altındaki mekanik tepkiyi önemli ölçüde değiştirdiği görülmüştür.

Karbon/Kevlar hibrit laminatlarda karbon fiberlerin yüksek rijitlik ve yük taşıma özellikleri ile Kevlar fiberlerin daha yüksek deformasyon ve hasar toleransı özelliklerinin birlikte kullanılması, yarı-statik batma davranışının tek tip fiber takviyeli yapılardan farklı gelişmesine neden olabilmektedir. Literatürde karbon/Kevlar hibritleşmesinde katman sıralamasının değiştirilmesinin maksimum yük, deformasyon davranışı ve hasar direnci üzerinde belirleyici olduğu; oluşabilecek başlıca hasar mekanizmalarının ise matris çatlağı, delaminasyon ve fiber hasarı gibi mekanizmaları içerdiği bildirilmektedir (Wang ve ark., 2024).

Bununla birlikte, mevcut çalışmada maksimum kuvvet değerlerinde belirlenen farklılıklar tek başına belirli bir hasar mekanizmasının gerçekleştiğini kanıtlamak için yeterli değildir. Bu nedenle katman dizilimi ve dokuma mimarisinin hasar başlangıcı ve ilerlemesi üzerindeki etkisinin kesin olarak ortaya konulabilmesi için kuvvet–yer değiştirme eğrilerinin numune yüzeylerindeki hasar gözlemleriyle birlikte değerlendirilmesi gerekmektedir. Bu yaklaşım, özellikle maksimum kuvvet sonrasındaki yük kayıplarının matris çatlağı, delaminasyon veya fiber hasarı gibi mekanizmalarla ilişkilendirilmesinde daha güvenilir bir değerlendirme sağlayacaktır.

3. SONUÇ

Bu çalışmada, farklı katman dizilimlerine sahip simetrik ve asimetrik karbon/Kevlar hibrit çift kavisli kompozit yapıların 1,25 mm/dk yükleme hızındaki yarı-statik batma davranışları karşılaştırılmıştır. Değerlendirmelerde laminat simetrisinin yanı sıra düz ve dimi karbon dokuma mimarileri ile karbon/Kevlar katmanlarının yapı içerisindeki konumlarının maksimum batma kuvveti üzerindeki etkileri incelenmiştir. Elde edilen deneysel sonuçlardan aşağıdaki çıkarımlar yapılmıştır:

- İncelenen yapılar arasında en yüksek maksimum batma kuvveti 4876,416 N ile PCK2S numunesinde elde edilmiştir. Bu sonuç, düz karbon ve Kevlar katmanlarının laminat boyunca dağıtıldığı simetrik dizilimin yüksek yük taşıma kapasitesi sağladığını göstermiştir.

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- Simetrik ve asimetrik yapılar karşılaştırıldığında, düz karbon/Kevlar grubunda PCK2S, PCK8R'ye göre yaklaşık %5,86; dimi karbon/Kevlar grubunda ise TCK2S, TCK8R'ye göre yaklaşık %2,47 daha yüksek maksimum batma kuvveti göstermiştir. Bu bulgular, incelenen konfigürasyonlarda simetrik düzenlemenin maksimum yük taşıma kapasitesi açısından avantaj sağladığını ortaya koymuştur.

- Simetrik düz karbon/Kevlar yapılar kendi içerisinde değerlendirildiğinde, karbon katmanlarının laminat boyunca dağıtıldığı PCK2S, karbon katmanlarının dış bölgelerde gruplandırıldığı PC2K2S numunesine kıyasla yaklaşık %14,63 daha yüksek maksimum batma kuvveti göstermiştir. Bu sonuç, düz karbon mimarisinde dağıtılmış katman yerleşiminin daha yüksek yük taşıma kapasitesi sağladığını göstermektedir.

- Dimi karbon/Kevlar yapılarında ise katman yerleşiminin etkisi farklı yönde gerçekleşmiştir. Karbon katmanlarının dış bölgelerde gruplandırıldığı TC2K2S, dağıtılmış katman düzenine sahip TCK2S numunesine kıyasla yaklaşık %26,90 daha yüksek maksimum batma kuvveti göstermiştir. Böylece optimum katman yerleşiminin kullanılan karbon dokuma mimarisine bağlı olarak değişebildiği belirlenmiştir.

- Aynı katman yerleşimine sahip düz ve dimi karbon yapılar karşılaştırıldığında, dışta gruplandırılmış karbon konfigürasyonunda TC2K2S, PC2K2S'ye göre yaklaşık %10,48 daha yüksek maksimum batma kuvvetine ulaşmıştır. Buna karşılık dağıtılmış katman düzeninde PCK2S, TCK2S'ye göre yaklaşık %31,67 daha yüksek maksimum batma kuvveti göstermiştir. Bu sonuç, dokuma mimarisinin mekanik performans üzerindeki etkisinin katman yerleşimine bağlı olarak değiştiğini açıkça ortaya koymaktadır.

- Genel olarak deneysel bulgular, çift kavisli karbon/Kevlar hibrit kompozit yapılarda laminat simetrisi, karbon fiber dokuma mimarisi ve katman yerleşiminin birbirinden bağımsız tasarım parametreleri olarak değerlendirilmemesi gerektiğini göstermiştir. Aynı fiber oranı ve toplam katman sayısına sahip yapılarda yalnızca katmanların konumlarının ve karbon dokuma mimarisinin değiştirilmesiyle maksimum yük taşıma kapasitesinde belirgin farklılıkların ortaya çıkması, bu parametrelerin birlikte optimize edilmesinin mekanik performans açısından önemli olduğunu ortaya koymuştur.

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STATISTICAL ANALYSIS OF MATCH OUTCOMES AND PRE-MATCH BETTING ODDS IN SWISS PROFESSIONAL FOOTBALL LEAGUES (2013–2025)

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ÖZET

Bu çalışmanın amacı, 2013–2025 döneminde İsviçre Süper Ligi, Challenge League ve Promotion League'de oynanan karşılaşmaları maç sonucu, gol yapısı, ilk yarı göstergeleri ve maç öncesi bahis oranları açısından karşılaştırmalı olarak incelemektir. Araştırma, araştırmacı tarafından maç bazında manuel olarak derlenen, kodlanan ve standartlaştırılan toplam 4.696 karşılaşmayı kapsamaktadır. Verilerin analizinde tanımlayıcı istatistikler, Pearson Ki-kare testi ve Cramer's V katsayısı kullanılmış; bahis oranlarının ligler arasında karşılaştırılmasında Welch ve Games–Howell testlerinden yararlanılmıştır. Bulgular, ilk yarı sonucu ile maç sonucu arasında anlamlı ve orta düzeyde bir ilişki bulunduğunu göstermiştir (V=0,433). Maç sonucu ile 2,5 Alt/Üst (V=0,307) ve karşılıklı gol (V=0,230) arasında da anlamlı ilişkiler belirlenmiştir. Lig düzeyi ile maç sonucu arasında anlamlı ilişki bulunmazken, bazı gol ve ilk yarı göstergelerinde düşük etki büyüklüğüne sahip farklılıklar saptanmıştır. Ayrıca bahis oranlarının lig düzeyine göre anlamlı biçimde farklılaştığı belirlenmiştir. Sonuç olarak üç lig temel maç sonucu dağılımları bakımından büyük ölçüde benzerlik gösterirken, bazı gol göstergeleri ve bahis oranları açısından farklılaşmaktadır.

Anahtar Kelimeler: İsviçre Futbol Ligleri, Spor Analitiği, Maç Sonucu, Gol Analizi, Bahis Oranları.

ABSTRACT

This study aimed to comparatively examine matches played in the Swiss Super League, Challenge League, and Promotion League during the 2013–2025 period in terms of match outcomes, goal-related characteristics, first-half indicators, and pre-match betting odds. The study included 4,696 matches manually compiled, coded, and standardized by the researcher on a match-by-match basis. Descriptive statistics, Pearson's chi-square test, and Cramer's V were used, while Welch's test and Games–Howell post hoc comparisons were applied to compare betting odds across leagues. The results revealed a significant, moderate association between the first-half result and the final match result (V=0.433). Significant associations were also found between the final match result and Over/Under 2.5 goals (V=0.307) and Both Teams to Score (V=0.230). No significant association was found between league level and final match result, whereas differences with small effect sizes were observed for several goal-related and first-half indicators. Betting odds also differed significantly across league levels. Overall, the three leagues showed largely similar final match outcome distributions but differed in certain goal-related indicators and betting odds.

Keywords: Swiss Football Leagues, Sports Analytics, Match Outcome, Goal Analysis, Betting Odds.

GİRİŞ

Futbol karşılaşmalarının sonuçları; teknik, taktik, fiziksel ve durumsal birçok faktörün etkileşimiyle ortaya çıkmaktadır. Bu nedenle maç sonucu, gol sayısı, ilk yarı sonucu, iç saha avantajı ve karşılaşmanın skor gelişimi gibi göstergelerin nicel yöntemlerle incelenmesi spor analitiği literatüründe önemli bir araştırma alanı oluşturmaktadır. Maçın oynandığı yer, skor durumu ve karşılaşmanın farklı dönemlerindeki gelişmelerin takım performansını etkileyebildiği gösterilmiştir (Taylor vd., 2008). İç saha avantajının da futbol liglerinde uzun dönemli ve yaygın bir olgu olduğu bildirilmektedir (Pollard, 2008).

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Futbolda özellikle maçın erken dönemlerinde oluşan skor yapısının nihai sonuçla ilişkisi dikkat çekmektedir. İlk golü atan veya ilk yarıyı üstün tamamlayan takımların karşılaşmayı kazanma olasılıklarının yükseldiği çeşitli çalışmalarla ortaya konmuştur. Türkiye Süper Lig ve TFF 1. Lig karşılaşmalarını inceleyen Göral vd. (2021), ilk golü atan takımların karşılaşmayı galibiyetle tamamlama oranlarının yüksek olduğunu bildirmiştir. Bu durum, ilk yarı sonucu ile nihai maç sonucu arasındaki ilişkinin futbol performans analizinde önemli bir gösterge olarak değerlendirilmesini desteklemektedir.

Farklı liglerin maç ve gol özellikleri bakımından karşılaştırılması, futbolun rekabet yapısının değerlendirilmesine katkı sağlamaktadır. Li ve Zhao (2021), Avrupa'nın beş büyük futbol ligindeki gol örüntülerini karşılaştırmış ve ligler arasında bazı göstergeler bakımından farklılıklar bulunmasına rağmen temel özelliklerde benzerliklerin de sürdüğünü belirlemiştir. Bu bulgu, aynı ülke futbol sistemi içerisinde farklı rekabet düzeylerindeki liglerin ortak ve ayrışan özelliklerinin incelenmesinin önemini göstermektedir. Mevcut literatürün önemli bir bölümünün üst düzey ligler ve uluslararası organizasyonlara odaklanması, alt ligleri de içeren uzun dönemli karşılaştırmalı araştırmalara duyulan gereksinimi artırmaktadır.

Sportif performans göstergelerinin yanında maç öncesi bahis oranları da takımların göreli güçlerine ve olası maç sonuçlarına ilişkin piyasa değerlendirmelerini yansıtan nicel göstergelerdir. Direr (2013), Avrupa futbolunda bahis oranlarında yer alan bilginin bahis piyasalarının değerlendirilmesinde kullanılabileceğini göstermiştir. Angelini ve De Angelis (2019) ise 11 Avrupa futbol ligindeki 33.060 karşılaşmayı inceleyerek bahis piyasalarının etkinlik düzeylerinin ligler arasında farklılaşabildiğini belirlemiştir. Dolayısıyla gerçekleşen sportif sonuçlarla bahis oranlarının birlikte ele alınması, liglerin yalnızca saha içi performansları açısından değil, piyasa tarafından nasıl değerlendirildikleri açısından da karşılaştırılmasına olanak sağlamaktadır.

Bu çerçevede İsviçre futbolunun farklı rekabet düzeylerini temsil eden Süper Lig, Challenge League ve Promotion League'in aynı değişken seti ve uzun dönemli bir veri yapısı üzerinden karşılaştırılması, ligler arasındaki benzerlik ve farklılıkların belirlenmesi açısından önem taşımaktadır. Özellikle maç sonucu, gol göstergeleri, ilk yarı özellikleri ve bahis oranlarının birlikte değerlendirilmesi, sportif performans ile piyasa değerlendirmelerinin aynı araştırma çerçevesinde incelenmesine olanak sağlamaktadır.

ARAŞTIRMANIN AMACI

Bu çalışmanın amacı, 2013–2025 döneminde İsviçre Süper Ligi, Challenge League ve Promotion League'de oynanan 4.696 karşılaşmayı maç sonucu, gol özellikleri, ilk yarı göstergeleri ve maç öncesi bahis oranları açısından karşılaştırmalı olarak incelemektir. Bu kapsamda maç içi göstergeler ile nihai maç sonucu arasındaki ilişkilerin belirlenmesi, söz konusu göstergelerin lig düzeylerine göre farklılaşıp farklılaşmadığının ortaya konulması ve bahis oranlarının üç lig arasında karşılaştırılması amaçlanmıştır.

YÖNTEM

Araştırma Modeli

Bu araştırma, İsviçre futbol liglerinde oynanan karşılaşmaların maç sonucu, gol yapısı, ilk yarı göstergeleri ve bahis oranları açısından incelenmesini ve söz konusu değişkenler arasındaki ilişkilerin ortaya konulmasını amaçlayan nicel, retrospektif ve ilişkisel bir araştırma olarak tasarlanmıştır. Araştırmada geçmiş dönemlerde gerçekleşmiş futbol karşılaşmalarına ait veriler kullanılmış; herhangi bir deneysel müdahalede bulunulmaksızın mevcut maç verileri üzerinden betimsel ve karşılaştırmalı istatistiksel analizler gerçekleştirilmiştir.

Araştırmanın temel yaklaşımı, yalnızca değişkenlere ilişkin frekans ve yüzde dağılımlarının ortaya konulmasıyla sınırlı tutulmamış; farklı lig düzeylerinin karşılaştırılması, maç içi göstergelerin nihai maç sonucuyla ilişkilerinin belirlenmesi ve tespit edilen ilişkilerin büyüklüğünün değerlendirilmesi hedeflenmiştir. Bu doğrultuda kategorik değişkenler arasındaki ilişkiler Ki-kare testi ve Cramer's V katsayısı ile, sürekli değişken niteliğindeki bahis oranlarının lig düzeylerine göre farklılıkları ise uygun parametrik/robust karşılaştırma yöntemleriyle incelenmiştir.

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Araştırmanın Evreni ve Veri Seti

Araştırmanın veri setini, 2013–2025 döneminde İsviçre futbolunun üç farklı lig düzeyinde oynanan karşılaşmalar oluşturmaktadır. Çalışma kapsamında İsviçre Süper Ligi (Super League), Challenge League ve Promotion League karşılaşmaları incelenmiştir. Üç ligden elde edilen verilerin birleştirilmesi sonucunda araştırmanın ana veri seti toplam 4.696 futbol karşılaşmasından oluşmuştur.

Araştırmada uzun bir zaman aralığının ve farklı rekabet düzeylerindeki üç ligin birlikte ele alınması, kısa dönemli veya tek bir lig üzerinden yapılabilecek değerlendirmelerin ötesinde daha kapsamlı bir karşılaştırma yapılmasına olanak sağlamıştır. Böylelikle İsviçre futbolunda gözlenen maç sonucu ve gol örüntülerinin yalnızca belirli bir sezonun koşullarını yansıtma olasılığının azaltılması ve uzun dönemli yapının ortaya konulması amaçlanmıştır.

Bahis oranlarına ilişkin analizlerde ana veri setindeki beş karşılaşmaya ait bahis oranı verilerinin bulunmaması nedeniyle bu karşılaşmalar ilgili analizlerin dışında bırakılmıştır. Dolayısıyla kategorik maç değişkenlerine ilişkin analizler N=4.696, bahis oranlarının karşılaştırılmasına ilişkin analizler ise N=4.691 karşılaşma üzerinden gerçekleştirilmiştir. Bu ayrım, eksik bahis verilerinin diğer maç değişkenlerine ilişkin analizlerde gereksiz veri kaybına yol açmasını önlemek amacıyla yapılmıştır.

Verilerin Toplanması ve Hazırlanması

Araştırmada kullanılan karşılaşma verilerinin temel kaynağını Sahadan.com üzerinde yayımlanan geçmiş futbol karşılaşmalarına ilişkin kayıtlar oluşturmuştur. Bununla birlikte araştırmada kullanılan veri seti, ilgili internet sitesinden araştırmaya hazır ve bütünleşik bir veri dosyası biçiminde doğrudan elde edilmemiştir. Araştırmanın gerektirdiği değişkenlerin tamamını aynı veri yapısı içerisinde içeren hazır bir veri seti bulunmadığından, veriler uzun bir zaman dilimi içerisinde karşılaşma bazında manuel olarak derlenmiş ve araştırmacı tarafından sistematik biçimde yapılandırılmıştır.

Her karşılaşmaya ilişkin bilgiler tek tek incelenmiş; araştırmanın amaçları doğrultusunda gerekli değişkenler belirlenmiş, sınıflandırılmış ve kodlanmıştır. Farklı sezon ve liglerden elde edilen kayıtların ortak bir analiz yapısında kullanılabilmesi amacıyla değişken tanımları ve kodlama sistemi standartlaştırılmıştır. Böylece farklı dönemlerde toplanmış verilerin aynı değişken yapısı altında karşılaştırılabilir olması sağlanmıştır.

Veri hazırlama sürecinde yalnızca ham maç sonuçlarının kaydedilmesiyle yetinilmemiştir. Nihai maç skoru ve ilk yarı skorlarından hareketle araştırmada kullanılacak kategorik değişkenler araştırmacı tarafından oluşturulmuş ve kodlanmıştır. Bu süreçte her karşılaşmanın maç sonucu, toplam gol yapısı, ilk yarı sonucu ve diğer skor türevi göstergeleri analiz edilebilir kategorilere dönüştürülmüştür. Bahis oranları ise ev sahibi galibiyeti, beraberlik ve deplasman galibiyeti olmak üzere ayrı sayısal değişkenler olarak veri setine aktarılmıştır.

Bu yönüyle araştırmanın veri seti, farklı kaynaklardan hazır biçimde birleştirilmiş ikincil bir analiz dosyası olmaktan ziyade, uzun dönemli maç kayıtlarının araştırmanın amaçlarına uygun biçimde manuel olarak derlenmesi, kontrol edilmesi, kodlanması ve standartlaştırılması sonucunda oluşturulmuş özgün bir araştırma veri tabanı niteliğindedir.

Araştırmada Kullanılan Değişkenler

Araştırmada lig düzeyi temel karşılaştırma değişkeni olarak kullanılmış ve karşılaşmalar Süper Lig, Challenge League ve Promotion League olmak üzere üç grupta değerlendirilmiştir.

Nihai maç sonucu; ev sahibi galibiyeti, beraberlik ve deplasman galibiyeti şeklinde üç kategoride sınıflandırılmıştır. İlk yarı sonucu da aynı biçimde ev sahibi üstünlüğü, beraberlik ve deplasman üstünlüğü şeklinde kategorize edilmiştir.

Gol yapısının değerlendirilmesinde karşılaşmaların toplam gol sayısından hareketle 2,5 Alt/Üst, Tek/Çift, karşılıklı gol Var/Yok ve gol aralığı değişkenleri oluşturulmuştur. Gol aralığı değişkeni karşılaşmada kaydedilen toplam gol sayısına göre 0–1 gol, 2–3 gol ve 4+ gol kategorileri altında değerlendirilmiştir.

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İlk yarıya ilişkin analizlerde ilk yarı sonucu, ilk yarı karşılıklı gol Var/Yok, ilk yarı 1,5 Alt/Üst ve ilk yarı 2,5 Alt/Üst değişkenleri kullanılmıştır. Ayrıca ilk yarı sonucu ile nihai maç sonucunun birlikte değerlendirilmesine olanak sağlayan ilk yarı/maç sonucu kombinasyonları analiz edilmiştir.

Bahis piyasasına ilişkin nicel değişkenler ise ev sahibi galibiyeti oranı, beraberlik oranı ve deplasman galibiyeti oranı olarak belirlenmiştir. Böylelikle araştırmada hem sportif sonuçlara ilişkin kategorik değişkenlerin hem de bahis piyasasının karşılaşma öncesi fiyatlamasını temsil eden sürekli değişkenlerin aynı veri yapısı içerisinde değerlendirilmesi mümkün olmuştur.

Verilerin Analizi

Araştırma verilerinin istatistiksel analizleri IBM SPSS Statistics programı kullanılarak gerçekleştirilmiştir. Analizlere başlamadan önce veri setindeki değişkenlerin kodlamaları, kategori tanımları ve eksik gözlemler kontrol edilmiştir.

İlk aşamada araştırmada kullanılan değişkenlerin genel yapısını ortaya koymak amacıyla tanımlayıcı istatistiklerden frekans ve yüzde dağılımları hesaplanmıştır. Böylelikle üç ligdeki maç sayıları, maç sonucu dağılımları, gol göstergeleri ve ilk yarıya ilişkin değişkenlerin temel dağılımları belirlenmiştir.

Kategorik değişkenler arasındaki ilişkilerin değerlendirilmesinde Pearson Ki-kare (χ^2) bağımsızlık testi kullanılmıştır. Bu kapsamda öncelikle lig düzeyi ile maç sonucu, 2,5 Alt/Üst, Tek/Çift, karşılıklı gol, gol aralığı, ilk yarı sonucu, ilk yarı/maç sonucu kombinasyonları, ilk yarı karşılıklı gol, ilk yarı 1,5 Alt/Üst ve ilk yarı 2,5 Alt/Üst değişkenleri arasındaki ilişkiler incelenmiştir. Ayrıca seçilmiş maç içi göstergelerin nihai maç sonucuyla ilişkileri ayrı çapraz tablolar ve Ki-kare analizleriyle değerlendirilmiştir.

Ki-kare testinde istatistiksel anlamlılığın tek başına ilişkinin büyüklüğü hakkında yeterli bilgi vermemesi nedeniyle, anlamlılığın yanında Cramer's V etki büyüklüğü katsayısı hesaplanmıştır. Böylelikle özellikle büyük örneklemlerde düşük büyüklükteki ilişkilerin yalnızca p değerine dayanılarak güçlü ilişkiler şeklinde yorumlanmasının önüne geçilmesi amaçlanmıştır. Lig düzeyine ilişkin bazı karşılaştırmalarda $p<0,05$ bulunmasına rağmen Cramer's V değerlerinin 0,040–0,058 aralığında kalması, bu ayrımın araştırma açısından önemini göstermektedir.

Bahis oranları sürekli değişken olarak ele alınmış ve üç lig düzeyine göre ortalama bahis oranları karşılaştırılmıştır. Ligler arasındaki ortalama karşılaştırmalarından önce Levene varyans homojenliği testi uygulanmıştır. Levene testi sonucunda ev sahibi galibiyeti oranı ($p<0,001$), beraberlik oranı ($p=0,014$) ve deplasman galibiyeti oranı ($p<0,001$) için varyansların homojenliği varsayımının sağlanmadığı belirlenmiştir.

Bu nedenle klasik tek yönlü ANOVA'nın eşit varyans varsayımına dayanmak yerine, varyans homojenliği ihlaline karşı daha dayanıklı olan Welch testi kullanılmıştır. Welch testi sonucunda istatistiksel olarak anlamlı farklılık belirlenen bahis oranlarında, farklılığın hangi lig çiftlerinden kaynaklandığını ortaya koymak amacıyla eşit varyans varsayımını gerektirmeyen Games–Howell çoklu karşılaştırma testi uygulanmıştır. Bu yaklaşım sonucunda ev sahibi galibiyeti, beraberlik ve deplasman galibiyeti bahis oranlarının tamamında ligler arasında anlamlı farklılıklar belirlenmiş ve ikili lig karşılaştırmaları Games–Howell sonuçları üzerinden değerlendirilmiştir.

Tüm istatistiksel analizlerde anlamlılık düzeyi $p<0,05$ olarak kabul edilmiştir. Bununla birlikte sonuçların değerlendirilmesinde yalnızca istatistiksel anlamlılığa dayanılmamış; özellikle Ki-kare analizlerinde Cramer's V katsayıları dikkate alınarak ilişkinin büyüklüğü de yorumlanmıştır. Böylelikle büyük örneklem büyüklüğünün istatistiksel anlamlılık üzerindeki olası etkisi göz önünde bulundurularak, bulguların hem istatistiksel hem de pratik açıdan daha dengeli biçimde değerlendirilmesi amaçlanmıştır.

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BULGULAR

Çalışma sonucunda elde edilen sonuçlar bu kısımda tablolar halinde verilmiştir.

Tablo 1. İsviçre Futbol Liglerinde İlk Yarı Sonuçları ile Maç Sonuçları Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
Beraberlik	650 (35,5)	660 (36,0)	522 (28,5)	1832
İlk yarı ev sahibi galibiyet	263 (16,0)	1278 (77,7)	104 (6,3)	1645
İlk yarı deplasman galibiyet	256 (21,0)	133 (10,9)	830 (68,1)	1219
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
1762,36	**4**	**<0,001**	**0,433**	

Tablo 1'e göre ilk yarı sonucu ile maç sonucu arasında istatistiksel olarak anlamlı ve orta düzeyde bir ilişki bulunmaktadır (χ^2=1762,36; sd=4; p<0,001; Cramer's V=0,433). İlk yarıyı ev sahibi takımın önde tamamladığı maçların %77,7'si ev sahibi, deplasman takımının önde tamamladığı maçların ise %68,1'i deplasman galibiyetiyle sonuçlanmıştır. Bu bulgu, ilk yarıda elde edilen üstünlüğün önemli ölçüde maç sonuna taşındığını göstermektedir.

Tablo 2. İsviçre Futbol Liglerinde Karşılıklı Gol Durumu ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
VAR	935 (33,0)	1122 (39,5)	780 (27,5)	2837
YOK	234 (12,6)	949 (51,0)	676 (36,4)	1859
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
249,376	**2**	**<0,001**	**0,230**	

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Karşılıklı gol durumu ile maç sonucu arasında istatistiksel olarak anlamlı ancak düşük düzeyde bir ilişki belirlenmiştir (χ^2=249,376; sd=2; p<0,001; Cramer's V=0,230). Karşılıklı gol atılmayan maçlarda ev sahibi galibiyetinin %51,0'a yükselmesi ve beraberliğin %12,6'ya düşmesi dikkat çekmektedir.

Tablo 3. İsviçre Futbol Liglerinde Gol Aralığı ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
Gol aralığı 0-1	234 (27,3)	336 (39,3)	286 (33,4)	856
Gol aralığı 2-3	540 (26,4)	867 (42,4)	640 (31,3)	2047
Gol aralığı 4+	395 (22,0)	868 (48,4)	530 (29,6)	1793
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
26,156	**4**	**<0,001**	**0,053**	

Gol aralığı ile maç sonucu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki bulunmaktadır (χ^2=26,156; sd=4; p<0,001; Cramer's V=0,053). Gol sayısı arttıkça ev sahibi galibiyeti oranının yükseldiği görülmekle birlikte, ilişkinin etki büyüklüğü oldukça düşüktür.

Tablo 4. İsviçre Futbol Liglerinde 2,5 Alt/Üst Gol Durumu ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
2,5 ALT	774 (40,9)	614 (32,5)	504 (26,6)	1892
2,5 ÜST	395 (14,1)	1457 (52,0)	952 (34,0)	2804
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
443,773	**2**	**<0,001**	**0,307**	

Maçların 2,5 Alt/Üst durumu ile maç sonucu arasında istatistiksel olarak anlamlı ve orta düzeyde bir ilişki belirlenmiştir (χ^2=443,773; sd=2; p<0,001; Cramer's V=0,307). Beraberlik oranı 2,5 Alt maçlarda %40,9 iken 2,5 Üst maçlarda %14,1'e düşmektedir. Bu sonuç, toplam gol yapısının maç sonucu dağılımıyla ilişkili olduğunu göstermektedir.

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Tablo 5. İsviçre Futbol Liglerinde İlk Yarı 1,5 Alt/Üst Gol Durumu ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
İY 1,5 ÜST	379 (20,4)	918 (49,4)	562 (30,2)	1859
İY 1,5 ALT	790 (27,8)	1153 (40,6)	894 (31,5)	2837
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
45,147	**2**	**<0,001**	**0,098**	

İlk yarı 1,5 Alt/Üst durumu ile maç sonucu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki belirlenmiştir (χ^2=45,147; sd=2; p<0,001; Cramer's V=0,098). İlk yarısı 1,5 Üst olan karşılaşmalarda ev sahibi galibiyeti daha yüksek olmakla birlikte, ilişkinin etki büyüklüğü sınırlıdır.

Tablo 6. İsviçre Futbol Liglerinde İlk Yarı Karşılıklı Gol Durumu ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
İY KGV	324 (29,7)	465 (42,6)	302 (27,7)	1091
İY KGY	845 (23,4)	1606 (44,5)	1154 (32,0)	3605
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
18,946	**2**	**<0,001**	**0,064**	

İlk yarıda karşılıklı gol durumu ile maç sonucu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki bulunmaktadır (χ^2=18,946; sd=2; p<0,001; Cramer's V=0,064). Bu nedenle istatistiksel anlamlılığa rağmen ilişkinin pratik etkisinin sınırlı olduğu söylenebilir.

Tablo 7. İsviçre Futbol Liglerinde Tek/Çift Gol Durumu ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
ÇİFT	1169 (48,4)	763 (31,6)	485 (20,1)	2417
TEK	0 (0)	1308 (57,4)	971 (42,6)	2279
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
1471,859	**2**	**<0,001**	**0,560**	

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Tek/çift gol durumu ile maç sonucu arasında istatistiksel olarak anlamlı ve güçlü bir ilişki belirlenmiştir (χ^2=1471,859; sd=2; p<0,001; Cramer's V=0,560). Bununla birlikte bu güçlü ilişki büyük ölçüde skorun matematiksel yapısından kaynaklanmaktadır; beraberlikte toplam gol sayısı zorunlu olarak çift olduğundan tek toplam gole sahip maçlarda beraberlik mümkün değildir.

Tablo 8. İsviçre Futbol Liglerinde İlk Yarı 2,5 Alt/Üst Gol Durumu ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

Maç sonucu	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
İY 2,5 ÜST	120 (16,6)	383 (52,9)	221 (30,5)	724
İY 2,5 ALT	1049 (26,4)	1688 (42,5)	1235 (31,1)	3972
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
38,887	**2**	**<0,001**	**0,091**	

İlk yarı 2,5 Alt/Üst durumu ile maç sonucu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki belirlenmiştir (χ^2=38,887; sd=2; p<0,001; Cramer's V=0,091). İlk yarısı 2,5 Üst olan maçlarda ev sahibi galibiyeti daha yüksek olmakla birlikte, ilişkinin etki büyüklüğü oldukça düşüktür.

Tablo 9. İsviçre Futbol Liglerinde Lig Düzeyi ile Maç Sonucu Arasındaki İlişkinin İncelenmesi

LİG	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
Super League	580(25,7)	989 (43,8)	691 (30,6)	2260
Promotion League	226 (23,1)	431 (44,1)	321 (32,8)	978
Challenge League	363 (24,9)	651 (44,7)	444 (30,5)	1458
Toplam	1169 (24,9)	2071 (44,1)	1456 (31,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
3,269	**4**	**0,514**	**0,019**	

Lig düzeyi ile maç sonucu arasında istatistiksel olarak anlamlı bir ilişki bulunmamıştır (χ^2=3,269; sd=4; p=0,514; Cramer's V=0,019). Üç ligde maç sonucu dağılımlarının birbirine oldukça yakın olması, lig düzeyinin maç sonucu üzerindeki etkisinin ihmal edilebilir olduğunu göstermektedir.

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Tablo 10. İsviçre Futbol Liglerinde Lig Düzeyi ile 2,5 Alt/Üst Gol Durumu Arasındaki İlişkinin İncelenmesi

LİG	2,5 ALT	2,5 ÜST	Toplam
Super League	930 (41,2)	1330 (58,8)	2260
Promotion League	357 (36,5)	621 (63,5)	978
Challenge League	605 (41,5)	853 (58,5)	1458
Toplam	1892 (40,3)	2804 (59,7)	4696
χ^2	**sd**	**p**	**Cramer's V**
7,406	**2**	**0,025**	**0,040**

Lig düzeyi ile 2,5 Alt/Üst durumu arasında istatistiksel olarak anlamlı bir ilişki belirlenmiştir (χ^2=7,406; sd=2; p=0,025). Promotion League %63,5 ile en yüksek 2,5 Üst oranına sahip olmakla birlikte, Cramer's V değerinin 0,040 olması ligler arasındaki farklılığın oldukça düşük düzeyde olduğunu göstermektedir.

Tablo 11. İsviçre Futbol Liglerinde Lig Düzeyi ile Tek/Çift Gol Durumu Arasındaki İlişkinin İncelenmesi

LİG	ÇİFT	TEK	Toplam
Super League	1166 (51,6)	1094 (48,4)	2260
Promotion League	486 (49,7)	492 (50,3)	978
Challenge League	765 (52,5)	693 (47,5)	1458
Toplam	2417 (51,5)	2279 (48,5)	4696
χ^2	**sd**	**p**	**Cramer's V**
1,832	**2**	**0,400**	**0,020**

Lig düzeyi ile toplam gol sayısının tek/çift olması arasında istatistiksel olarak anlamlı bir ilişki bulunmamıştır (χ^2=1,832; sd=2; p=0,400; Cramer's V=0,020). Üç ligdeki dağılımların birbirine yakın olduğu görülmektedir.

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Tablo 12. İsviçre Futbol Liglerinde Lig Düzeyi ile Karşılıklı Gol Durumu Arasındaki İlişkinin İncelenmesi

LİG	VAR	YOK	Toplam
Super League	1363 (60,3)	897 (39,7)	2260
Promotion League	614 (62,8)	364 (37,2)	978
Challenge League	860 (59,0)	598 (41,0)	1458
Toplam	2837 (60,4)	1859 (39,6)	4696
χ^2	**sd**	**p**	**Cramer's V**
3,547	**2**	**0,170**	**0,027**

Lig düzeyi ile karşılıklı gol durumu arasında istatistiksel olarak anlamlı bir ilişki bulunmamıştır (χ^2=3,547; sd=2; p=0,170; Cramer's V=0,027). Bu sonuç, karşılıklı gol dağılımının incelenen üç ligde büyük ölçüde benzer olduğunu göstermektedir.

Tablo 13. İsviçre Futbol Liglerinde Lig Düzeyi ile Gol Aralığı Arasındaki İlişkinin İncelenmesi

LİG	0-1 gol	2-3 gol	4+ gol	Toplam
Super League	427 (18,9)	993 (43,9)	840 (37,2)	2260
Promotion League	171 (17,5)	381 (39,0)	426 (43,6)	978
Challenge League	258 (17,7)	673 (46,2)	527 (36,1)	1458
Toplam	856 (18,2)	2047 (43,6)	1793 (38,2)	4696
χ^2	**sd**	**p**	**Cramer's V**	
17,755	**4**	**<0,001**	**0,043**	

Lig düzeyi ile gol aralığı arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki belirlenmiştir (χ^2=17,755; sd=4; p<0,001; Cramer's V=0,043). Promotion League'de 4 ve üzeri gollü maçların (%43,6), Challenge League'de ise 2–3 gollü maçların (%46,2) daha yüksek oranda gerçekleştiği görülmektedir.

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Tablo 14. İsviçre Futbol Liglerinde Lig Düzeyi ile İlk Yarı Sonucu Arasındaki İlişkinin İncelenmesi

LİG	Beraberlik	Ev sahibi galibiyet	Deplasman galibiyet	Toplam
Super League	879 (38,9)	772 (34,2)	609 (26,9)	2260
Promotion League	394 (40,3)	332 (33,9)	252 (25,8)	978
Challenge League	559 (38,3)	541 (37,1)	358 (24,6)	1458
Toplam	1832 (39,0)	1645 (35,0)	1219 (26,0)	4696
χ^2	**sd**	**p**	**Cramer's V**	
5,166	**4**	**0,271**	**0,023**	

Lig düzeyi ile ilk yarı sonucu arasında istatistiksel olarak anlamlı bir ilişki bulunmamıştır (χ^2=5,166; sd=4; p=0,271; Cramer's V=0,023). İlk yarı sonuçlarının üç ligde benzer bir dağılım gösterdiği belirlenmiştir.

Tablo 15. İsviçre Futbol Liglerinde Lig Düzeyi ile İlk Yarı Karşılıklı Gol Durumu Arasındaki İlişkinin İncelenmesi

LİG	İY KG VAR	İY KG YOK	Toplam
Super League	505 (22,3)	1755 (77,7)	2260
Promotion League	272 (27,8)	706 (72,2)	978
Challenge League	314 (21,5)	1144 (78,5)	1458
Toplam	1091 (23,2)	3605 (76,8)	4696
χ^2	**sd**	**p**	**Cramer's V**
14,849	**2**	**<0,001**	**0,056**

Lig düzeyi ile ilk yarıda karşılıklı gol durumu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki belirlenmiştir (χ^2=14,849; sd=2; p<0,001; Cramer's V=0,056). Promotion League %27,8 ile ilk yarıda karşılıklı gol oranının en yüksek olduğu ligdir; ancak etki büyüklüğü oldukça düşüktür.

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Tablo 16. İsviçre Futbol Liglerinde Lig Düzeyi ile İlk Yarı 1,5 Alt/Üst Gol Durumu Arasındaki İlişkinin İncelenmesi

LİG	İY 1,5 ÜST	İY 1,5 ALT	Toplam
Super League	859 (38,0)	1401 (62,0)	2260
Promotion League	436 (44,6)	542 (55,4)	978
Challenge League	564 (38,7)	894 (61,3)	1458
Toplam	1859 (39,6)	2837 (60,4)	4696
χ^2	**sd**	**p**	**Cramer's V**
13,050	**2**	**<0,001**	**0,053**

Lig düzeyi ile ilk yarı 1,5 Alt/Üst durumu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki belirlenmiştir (χ^2=13,050; sd=2; p<0,001; Cramer's V=0,053). Promotion League'de ilk yarı 1,5 Üst oranı %44,6 ile diğer iki ligden daha yüksek olmakla birlikte, farklılığın etki büyüklüğü sınırlıdır.

Tablo 17. İsviçre Futbol Liglerinde Lig Düzeyi ile İlk Yarı 2,5 Alt/Üst Gol Durumu Arasındaki İlişkinin İncelenmesi

LİG	İY 2,5 ÜST	İY 2,5 ALT	Toplam
Super League	332 (14,7)	1928 (85,3)	2260
Promotion League	190 (19,4)	788 (80,6)	978
Challenge League	202 (13,9)	1256 (86,1)	1458
Toplam	724 (15,4)	3972 (84,6)	4696
χ^2	**sd**	**p**	**Cramer's V**
15,707	**2**	**<0,001**	**0,058**

Lig düzeyi ile ilk yarı 2,5 Alt/Üst durumu arasında istatistiksel olarak anlamlı ancak çok zayıf düzeyde bir ilişki belirlenmiştir (χ^2=15,707; sd=2; p<0,001; Cramer's V=0,058). Promotion League %19,4 ile en yüksek ilk yarı 2,5 Üst oranına sahip olmakla birlikte, lig düzeyinin etkisi oldukça düşüktür.

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Tablo 18. İsviçre Futbol Liglerinde Bahis Oranlarının Lig Düzeyine Göre Karşılaştırılması

Bahis oranı	Süper Lig Ort.	Challenge Ort.	Promotion Ort.	
Ev sahibi galibiyeti	2,1384	2,1479	2,0318	
Beraberlik	3,3801	3,3426	3,4137	
Deplasman galibiyeti	3,1366	2,9479	2,8123	

Bahis oranı	Welch	sd1	sd2	p	Games-Howell
Ev sahibi galibiyeti	9,568	2	2615,261	<0,001	S-P***,C-P***
Beraberlik	7,525	2	2518,943	0,001	S-C*,C-P***
Deplasman galibiyeti	22,562	2	2677,646	<0,001	S-C***,S-P***,C-P*

Not: S = Süper Lig; C = Challenge League; P = Promotion League

*p<0,05; ***p<0,001

Bahis verisi bulunmayan 5 karşılaşma analiz dışı bırakılmıştır (N=4.691)

Bahis oranlarında varyans homojenliği sağlanmadığından lig karşılaştırmalarında Welch, ikili karşılaştırmalarda Games–Howell testi kullanılmıştır. Welch testi, ev sahibi galibiyeti (Welch=9,568; p<0,001), beraberlik (Welch=7,525; p=0,001) ve deplasman galibiyeti (Welch=22,562; p<0,001) oranlarının tamamında ligler arasında anlamlı farklılık bulunduğunu göstermiştir. Games–Howell sonuçlarına göre ev sahibi galibiyeti oranında Promotion League diğer iki ligden farklılaşırken, Süper Lig ile Challenge League arasında fark bulunmamıştır (p=0,939). Beraberlik oranında Süper Lig–Challenge League ve Challenge League–Promotion League arasında anlamlı farklılık belirlenmiştir. Deplasman galibiyeti oranında ise üç ligin tamamı birbirinden anlamlı biçimde farklılaşmış; ortalamalar Süper Lig'de 3,1366, Challenge League'de 2,9479 ve Promotion League'de 2,8123 olarak gerçekleşmiştir. Bu bulgular, bahis oranlarındaki lig farklılaşmasının özellikle deplasman galibiyeti oranlarında belirgin olduğunu göstermektedir.

TARTIŞMA

Bu araştırmada İsviçre Süper Ligi, Challenge League ve Promotion League'de oynanan karşılaşmalar; maç sonucu, ilk yarı göstergeleri, gol özellikleri ve bahis oranları açısından incelenmiştir. Bulgular genel olarak, maç içi skor ve gol değişkenlerinin nihai maç sonucuyla ilişkili olduğunu, buna karşılık lig düzeyinin birçok temel maç göstergesi üzerindeki etkisinin sınırlı kaldığını göstermektedir. Bahis oranlarının lig düzeyine göre farklılaşması ise sportif sonuçlarla piyasa değerlendirmelerinin aynı yapıyı bütünüyle yansıtmadığını ortaya koyan dikkat çekici bir bulgudur.

Araştırmanın öne çıkan sonuçlarından biri, ilk yarı sonucu ile maç sonucu arasında anlamlı ve orta düzeyde bir ilişkinin belirlenmesidir (Cramer's V=0,433). İlk yarıyı ev sahibi takımın önde tamamladığı karşılaşmaların %77,7'sinin ev sahibi galibiyetiyle, deplasman takımının önde tamamladığı karşılaşmaların ise %68,1'inin deplasman galibiyetiyle sonuçlanması, ilk yarıda elde edilen skor üstünlüğünün önemli ölçüde maç sonuna taşındığını göstermektedir. Bu sonuç, Türkiye liglerinde ilk

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golü atan takımların karşılaşmayı kazanma olasılıklarının yüksek olduğunu bildiren Göral vd. (2021) ile genel olarak uyumludur. Ev sahibi takımların ilk yarı üstünlüğünü yüksek oranda maç sonuna taşıması, futbolda ev sahibi avantajının yaygın bir olgu olduğunu belirten Pollard (2008) ve Türkiye profesyonel futbolunda ev sahibi avantajını ortaya koyan Seçkin ve Pollard'ın (2008) bulgularıyla da birlikte değerlendirilebilir.

Gol göstergeleri açısından, 2,5 Alt/Üst durumu ile maç sonucu arasında anlamlı ve orta düzeyde bir ilişki bulunmuştur (Cramer's V=0,307). Özellikle 2,5 Alt karşılaşmalarda beraberlik oranının %40,9 olmasına karşılık 2,5 Üst karşılaşmalarda %14,1'e düşmesi, toplam gol yapısının maç sonucu dağılımıyla ilişkili olduğunu göstermektedir. Benzer biçimde Mattera (2023), futbol karşılaşmalarının tahminine yönelik çalışmasında Alt/Üst ve karşılıklı gol göstergelerini modellemiştir. Alberti vd. (2013) ile Kubayi ve Toriola (2019) tarafından ortaya konulan gol üretiminin maç süresince homojen dağılmadığına ilişkin bulgular da gol özelliklerinin maçın sonuç yapısıyla birlikte değerlendirilmesinin önemini desteklemektedir. Bununla birlikte mevcut çalışma bir tahmin modeli geliştirmeyi değil, söz konusu göstergeler arasındaki ilişkileri ortaya koymayı amaçladığından, bu çalışmalarla yapılan karşılaştırmalar yöntemsel farklılıklar dikkate alınarak değerlendirilmelidir.

Toplam gol sayısının tek/çift olması ile maç sonucu arasında güçlü bir ilişki bulunması (Cramer's V=0,560) ise futbol skorlarının matematiksel yapısı dikkate alınarak yorumlanmalıdır. Tek toplam golle sonuçlanan bir karşılaşmanın beraberlikle tamamlanması mümkün olmadığından, yüksek ilişki katsayısının yalnızca sportif veya taktiksel bir ilişkiyi temsil ettiği düşünülmemelidir.

Ligler arası karşılaştırmalarda Süper Lig, Challenge League ve Promotion League arasında maç sonucu dağılımı bakımından anlamlı bir farklılık belirlenmemiştir. Benzer şekilde tek/çift gol, karşılıklı gol ve ilk yarı sonucu değişkenlerinde de ligler arasında anlamlı farklılık bulunmamıştır. Buna karşılık 2,5 Alt/Üst, gol aralığı ve bazı ilk yarı gol göstergelerinde anlamlı farklılıklar görülmüştür. Promotion League'de 2,5 Üst (%63,5), ilk yarı karşılıklı gol (%27,8), ilk yarı 1,5 Üst (%44,6) ve ilk yarı 2,5 Üst (%19,4) oranlarının görece yüksek olması bu ligin bazı gol göstergeleri açısından ayrıştığını göstermektedir. Bununla birlikte söz konusu ilişkilerin Cramer's V değerlerinin oldukça düşük olması, farklılıkların pratik büyüklüğünün sınırlı olduğunu ortaya koymaktadır. Büyük örneklemlerde küçük farklılıkların da istatistiksel anlamlılığa ulaşabileceği dikkate alındığında, bu sonuçların güçlü bir lig etkisi olarak yorumlanmaması gerekir. Ligler arasında bazı özelliklerin benzer, bazılarının ise farklılaşması, Avrupa'nın beş büyük liginde gol örüntülerini karşılaştıran Li ve Zhao'nun (2021) sonuçlarıyla genel olarak uyumludur.

Bahis oranlarına ilişkin sonuçlar ise araştırmanın dikkat çekici bulgularından biridir. Maç sonucu dağılımları ligler arasında anlamlı biçimde farklılaşmamasına rağmen ev sahibi galibiyeti, beraberlik ve deplasman galibiyeti oranlarının lig düzeyine göre anlamlı biçimde farklılaştığı belirlenmiştir. Özellikle deplasman galibiyeti oranlarının Süper Lig'de 3,1366, Challenge League'de 2,9479 ve Promotion League'de 2,8123 olması ve üç ligin birbirinden anlamlı biçimde farklılaşması, bahis piyasasının lig düzeyine duyarlı bir fiyatlandırma yapısı sergilediğini göstermektedir.

Bu bulgu, futbol bahis oranlarının yalnızca geçmiş maç sonuçlarının doğrudan yansıması olarak değerlendirilmemesi gerektiğine işaret etmektedir. Angelini ve De Angelis (2019), Direr (2013) ve Hegarty ve Whelan (2025), futbol bahis piyasalarında oranların bilgi içeriği ve piyasa etkinliğinin liglere ve piyasa türlerine göre farklılaşabileceğini göstermiştir. Mevcut araştırmada da gerçek maç sonuçlarının genel dağılımları büyük ölçüde benzer olmasına rağmen bahis oranlarının liglere göre farklılaşması bu açıdan önemlidir. Bununla birlikte çalışma doğrudan bahis piyasası etkinliğini veya bahis stratejilerinin kârlılığını test etmediğinden, elde edilen farklılıklar piyasa etkinsizliğinin kanıtı olarak yorumlanmamalıdır; bulgular yalnızca bahis oranlarının lig düzeyine göre farklılaştığını göstermektedir.

Genel olarak bulgular, İsviçre futbol liglerinde maç sonucunun özellikle ilk yarı skor durumu ve gol yapısıyla ilişkili olduğunu, lig düzeyinin ise temel maç sonucu dağılımları üzerindeki etkisinin sınırlı kaldığını göstermektedir. Promotion League'in bazı gol göstergelerinde ayrışması ve bahis oranlarının lig düzeyine göre farklılaşması, sportif performans göstergeleri ile piyasa değerlendirmelerinin birlikte incelenmesinin futbol analitiği açısından önemli bir araştırma alanı oluşturabileceğine işaret etmektedir.

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SONUÇ VE ÖNERİLER

Bu araştırmada, 2013–2025 döneminde İsviçre Süper Ligi, Challenge League ve Promotion League'de oynanan 4.696 karşılaşma; maç sonucu, gol özellikleri, ilk yarı göstergeleri ve maç öncesi bahis oranları açısından karşılaştırmalı olarak incelenmiştir. Elde edilen sonuçlar, maç içi skor ve gol dinamiklerinin nihai maç sonucuyla ilişkili olduğunu, buna karşılık lig düzeyinin birçok temel maç göstergesi üzerindeki etkisinin sınırlı kaldığını ortaya koymuştur.

Araştırmanın en belirgin sonuçlarından biri, ilk yarı sonucu ile maç sonucu arasında anlamlı ve orta düzeyde bir ilişkinin bulunmasıdır (Cramer's V=0,433). İlk yarıda elde edilen skor üstünlüğünün önemli ölçüde maç sonuna taşındığı belirlenmiştir. Benzer şekilde 2,5 Alt/Üst ve karşılıklı gol değişkenleri ile maç sonucu arasında anlamlı ilişkiler bulunmuş, ancak bazı ilk yarı gol göstergelerinde ilişkilerin etki büyüklüklerinin düşük olduğu görülmüştür. Bu durum, özellikle geniş örneklemli araştırmalarda istatistiksel anlamlılığın etki büyüklüğü ile birlikte değerlendirilmesinin önemini göstermektedir.

Ligler arası karşılaştırmalarda Süper Lig, Challenge League ve Promotion League arasında maç sonucu dağılımı bakımından anlamlı bir farklılık belirlenmemiştir. Tek/çift gol, karşılıklı gol ve ilk yarı sonucu açısından da ligler büyük ölçüde benzerlik göstermiştir. Buna karşılık 2,5 Alt/Üst, gol aralığı ve bazı ilk yarı gol göstergelerinde ligler arasında anlamlı farklılıklar ortaya çıkmıştır. Özellikle Promotion League'in bazı gol göstergelerinde diğer liglerden ayrıştığı görülmüş, ancak düşük Cramer's V değerleri bu farklılıkların etki büyüklüğünün sınırlı olduğunu göstermiştir.

Bahis oranlarının karşılaştırılması ise lig düzeyinin piyasa değerlendirmeleri bakımından daha belirgin bir farklılaşma oluşturduğunu ortaya koymuştur. Ev sahibi galibiyeti, beraberlik ve deplasman galibiyeti oranlarının tamamında ligler arasında anlamlı farklılıklar belirlenmiş; özellikle deplasman galibiyeti oranlarında üç lig birbirinden anlamlı biçimde farklılaşmıştır. Buna karşılık gerçek maç sonucu dağılımlarının ligler arasında anlamlı biçimde farklılaşmaması, bahis oranlarının yalnızca gerçekleşmiş sonuçların genel dağılımını yansıtmadığını düşündürmektedir. Bununla birlikte mevcut araştırma doğrudan bahis piyasası etkinliğini veya bahis stratejilerinin kârlılığını test etmediğinden, bu sonuçların piyasa etkinsizliğinin kanıtı olarak değerlendirilmemesi gerekmektedir. Bahis analizlerinin 4.691 karşılaşma üzerinden gerçekleştirildiği de dikkate alınmalıdır.

Gelecek çalışmalarda bahis oranlarının ima ettiği olasılıkların gerçekleşen sonuçlarla karşılaştırılması, bahis şirketlerinin marjlarının hesaplanması ve piyasa etkinliğinin lig düzeylerine göre incelenmesi önerilebilir. Ayrıca takım gücü, lig sıralaması, sezon dönemi, iç saha ve deplasman performansı ile geçmiş maç performansı gibi değişkenlerin analize dahil edilmesi, ligler arasındaki farklılıkların daha ayrıntılı açıklanmasına katkı sağlayabilir.

Araştırmada oluşturulan uzun dönemli ve geniş kapsamlı veri yapısı, gelecekte makine öğrenmesi ve tahmine dayalı yöntemlerin uygulanmasına da olanak sağlamaktadır. Maç sonucu ve gol özelliklerinin tahminine yönelik modeller geliştirilmesi ve benzer analizlerin farklı ülke ve liglere uygulanması, mevcut bulguların genellenebilirliğinin değerlendirilmesini sağlayabilir.

Sonuç olarak bu çalışma, İsviçre futbol liglerinde maç sonucu, ilk yarı ve gol göstergeleri ile bahis oranlarını aynı analitik çerçevede ele alarak üç farklı lig düzeyinin uzun dönemli yapısını ortaya koymaktadır. Bulgular, ilk yarı skorunun maç sonucuyla belirgin biçimde ilişkili olduğunu, lig düzeyinin birçok temel sportif gösterge üzerindeki etkisinin sınırlı kaldığını ve buna karşılık bahis oranlarının lig düzeyine göre farklılaşabildiğini göstermektedir. Bu yönüyle araştırma, sportif performans göstergeleri ile bahis piyasası verilerinin birlikte incelendiği gelecekteki çalışmalara temel oluşturabilecek kapsamlı bir veri ve bulgu yapısı sunmaktadır.

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İLKÖĞRETİM KURUMLARINDA ÇEVRESEL SÜRDÜRÜLEBİLİRLİK UYGULAMALARININ DEĞERLENDİRİLMESİ*

EVALUATION OF ENVIRONMENTAL SUSTAINABILITY PRACTICES IN PRIMARY EDUCATION INSTITUTIONS *

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ÖZET

İnsanlığın yaşamını tehdit eden iklim krizi ve doğal kaynak tükenmesi gibi küresel zorluklar, sürdürülebilirliği eğitim sistemlerinin yapısal dönüşümünde en stratejik odak noktası haline getirmiştir. Bu çalışma, ilköğretim kurumlarında yürütülen çevresel sürdürülebilirlik uygulamalarını; UNESCO'nun "Sürdürülebilir Kalkınma için Eğitim (SKE) 2030 Yol Haritası" kapsamında tanımlanan beş öncelikli eylem alanı üzerinden analiz etmeyi amaçlamaktadır. Araştırma, geleneksel yaklaşımların ötesine geçerek sürdürülebilirliği; politika, öğrenme ortamları, eğitimci kapasitesi, gençlerin güçlendirilmesi ve yerel çözümler boyutlarıyla bütüncül bir kurum yaklaşımı ekseninde incelemektedir. Araştırmada nitel araştırma desenlerinden durum çalışması kullanılmıştır. Veri toplama süreci iki aşamada gerçekleştirilmiştir: İlk aşamada ulusal ve uluslararası üst politika belgeleri (On İkinci Kalkınma Planı, MEB Stratejik Planı, Türkiye Yüzyılı Maarif Modeli vb.) doküman analizine tabi tutulmuştur. İkinci aşamada ise Gaziantep ilinde çevresel sürdürülebilirlik uygulamalarıyla model kurum niteliği taşıyan bir devlet ilköğretim okulunda görev yapan sekiz eğitimci (1 müdür, 7 öğretmen) ile yarı yapılandırılmış görüşmeler gerçekleştirilmiştir. Bulgular Türkiye'de sürdürülebilirliğin politika düzeyinde "Sürdürülebilirlik Okuryazarlığı" başlığı altında tüm disiplinlerle ilişkilendirilen yatay bir beceri kümesi olarak yapılandırıldığını göstermektedir. Saha verileri, okulların "Enerji Dostu Mavi-Yeşil Okul" ve "Sıfır Atık" projeleriyle fiziksel bir dönüşüm geçirdiğini; "AGRO kütüphaneler" ve yaşayan laboratuvarlar aracılığıyla teorik bilginin gündelik yaşam pratiğine dönüştüğünü kanıtlamaktadır. Eğitimcilerin değişim ajanı olarak TEKNOFEST ve TÜBİTAK gibi proje tabanlı süreçlerle kapasitelerini geliştirdikleri, öğrencilerin ise bu projelerde aktif sorumluluk alarak öğrenci özerkliği kazandıkları saptanmıştır. Yerel düzeyde belediyelerle kurulan operasyonel iş birliklerinin süreci hızlandırdığı, ancak maddi yetersizlikler ve toplumsal duyarsızlığın kurumsallaşma önündeki temel engeller olduğu belirlenmiştir, Sonuç olarak çalışma, sürdürülebilirliğin eğitim ortamlarında başarıyla yapılandırılmasının sadece müfredat içeriğiyle değil, yönetimsel irade ve fiziksel mekanın pedagojik dönüşümünü kapsayan sistemsel bir vizyonla mümkün olduğunu ortaya koymaktadır.

Anahtar Kelimeler: Çevresel Sürdürülebilirlik, SKE 2030 Yol Haritası, Bütüncül Kurum Yaklaşımı, Değişim Ajanı

ABSTRACT

Global challenges such as the climate crisis and the rapid depletion of natural resources, which threaten human survival, have positioned sustainability as the most strategic focal point in the structural transformation of education systems. This study aims to analyze environmental sustainability practices in primary education institutions through the five priority action areas defined in UNESCO's "Education for Sustainable Development (ESD) for 2030 Roadmap". Moving beyond traditional approaches, the research examines sustainability within the framework of a "whole-institution approach," encompassing

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the dimensions of policy, learning environments, educator capacity, youth empowerment, and local solutions.

A qualitative case study design was employed in this research. The data collection process was conducted in two stages: first, national and international high-level policy documents (Twelfth Development Plan, Ministry of National Education Strategic Plan, Türkiye Century Education Model, etc.) were subjected to document analysis. In the second stage, semi-structured interviews were conducted with eight educators (one principal and seven teachers) working at a public primary school in Gaziantep, which serves as a "model institution" for its environmental sustainability practices.

The findings indicate that at the policy level in Türkiye, sustainability is structured as a horizontal skill set integrated across disciplines under the heading of "Sustainability Literacy." Field data demonstrate that schools have undergone a physical transformation through projects such as "Energy-Friendly Blue-Green School" and "Zero Waste"; furthermore, theoretical knowledge has been translated into daily practice via "AGRO libraries" and living laboratories. Educators, acting as "change agents," enhanced their capacity through project-based initiatives such as TEKNOFEST and TÜBİTAK, while students developed "student agency" by taking active responsibility in these projects. At the local level, operational collaborations with municipalities were found to accelerate this transformation, although financial constraints and social indifference remain the primary obstacles to institutionalization. In conclusion, the study reveals that the successful integration of sustainability into educational environments requires a systemic vision encompassing administrative will and the pedagogical transformation of physical spaces, rather than mere curriculum integration.

Keywords: Environmental Sustainability, ESD for 2030 Roadmap, Whole-Institution Approach, Change Agent.

GİRİŞ

İnsanlığın karşı karşıya olduğu iklim krizi, doğal kaynakların hızlanan tükenmesi ve derinleşen sosyal eşitsizlikler, sürdürülebilirliği çağımızın en önemli küresel tartışmalarından biri haline getirmiştir. Sürdürülebilirlik, ekonomik, ekolojik ve sosyal sistemlerin ayrı alanlar olarak değil, birbirine bağlı ve karşılıklı olarak güçlendirici boyutlar olarak anlaşıldığı bütüncül bir çerçeve sunmaktadır (OECD, 2001; Milne & Gray, 2013; Mensah & Enu-Kwesi, 2018; Tjarve & Zemite, 2016; Purvis, Mao, & Robinson, 2018). Bu bütünleşik bakış açısı, eğitimi sürdürülebilir kalkınma hedeflerine ulaşmak için kilit bir politika alanı olarak konumlandırmakta ve eğitim sistemlerinin yapısal dönüşümüne ilişkin küresel tartışmaları şekillendirmektedir. Çevre eğitimi, 1960'larda uluslararası bir alan olarak ortaya çıkmış ve ekolojik krizleri, iklim değişikliğini ve biyoçeşitlilik kaybını temel eğitim kaygıları olarak ön plana çıkarmıştır (UNESCO, 2017). Normatif temelleri, çevre korumasını küresel bir öncelik ve dünya çapındaki hükümetlerin ortak sorumluluğu olarak tanımlayan 1972 Stockholm Konferansı ile atılmıştır (BM, 1972). Belgrad Şartı (1975) daha sonra çevre eğitiminin amaç ve ilkelerini ortaya koyarken, Tiflis Deklarasyonu (1977) disiplinlerarası ve pedagojik entegrasyonunu güçlendirmiştir. Bu tarihsel süreç, çevre eğitiminden Sürdürülebilir Kalkınma için Eğitime (ESD) doğru bir geçişi işaret eden Brundtland Raporu ile daha da gelişmiştir; bu geçişte eğitim artık izole bir konu olarak değil, müfredat ve günlük okul yaşamına entegre edilmiş bir süreç olarak çerçevelenmiştir (BM, 1987). Bu dönüşüm, sürdürülebilirliği eğitim sistemlerine entegre etmek için ortak bir yönelim sağlayan UNESCO'nun Sürdürülebilir Kalkınma için Eğitim 2030 Yol Haritası ile kurumsallaştırılmıştır. Yol Haritası beş öncelikli eylem alanını tanımlar: politika geliştirme; öğrenme ve eğitim ortamlarının dönüşümü; eğitimciler için kapasite geliştirme; gençlerin güçlendirilmesi ve katılımı; ve yerel düzeyde sürdürülebilir çözümlerin hızlandırılması (UNESCO, 2020). Bu çerçevenin merkezinde, eğitim kurumlarını müfredat, yönetim, mesleki uygulamalar ve topluluk ilişkilerinin bütünleşik bir şekilde ele alındığı kapsamlı sistemler olarak kavramsallaştıran bütüncül bir kurum yaklaşımı yer almaktadır. Avrupa bağlamında, sürdürülebilir kalkınma için eğitim, giderek farkındalığa dayalı girişimlerin ötesine geçerek eğitim politikasının yapısal bir bileşeni haline gelmiştir. Avrupa Komisyonu tarafından yayınlanan Çevresel Sürdürülebilirlik için Öğrenmeye İlişkin Konsey Tavsiyesi, sürdürülebilirliğin sadece müfredat açısından değil, aynı zamanda okul yönetimi, kurumsal organizasyon ve yerel

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paydaşlarla işbirliğini kapsayan bir politika alanı olarak da çerçevelendiğini göstermektedir (Avrupa Komisyonu, 2022). UNESCO tarafından 22 Avrupa ülkesinde yapılan karşılaştırmalı analizler de benzer şekilde sürdürülebilirliğin pedagojik, örgütsel ve toplumsal boyutlara sahip bütünsel bir kurumsal uygulama olarak yapılandırıldığını göstermektedir (UNESCO, 2024). Türkiye'de sürdürülebilirlik, Maarif Modeli ve Milli Eğitim Bakanlığı (MEB, 2023) tarafından yayınlanan politika belgeleri aracılığıyla eğitim sisteminin temel bir yönelimi olarak çerçevelenmiştir. Bununla birlikte, Sürdürülebilir Kalkınma için Eğitimin eğitim sistemine entegrasyonu, müfredat reformunun ötesine geçmekte ve pedagojik yaklaşımların, öğretim ve değerlendirme uygulamalarının, okul operasyonlarının ve kurumsal kültürün eş zamanlı olarak ele alınmasını gerektirmektedir (UNESCO, 2012, Swain & Mohanty, 2021'de alıntılanmıştır). Bu kapsamlı çerçeveye rağmen, mevcut literatür ağırlıklı olarak öğrencilerin bilgi, tutum ve davranışlarına odaklanırken, okulların örgütsel yapılarına, öğretmenlerin mesleki rollerine ve daha geniş politika bağlamına sınırlı dikkat göstermiştir (UNESCO, 2017; Sterling, 2016; Toy, 2025). Bu boşluğu ele alan bu çalışma, çevresel sürdürülebilirliğin ilköğretim içinde çok düzeyli bir yapılandırma süreci olarak nasıl ele alındığını incelemektedir. Bu doğrultuda, bu çalışma ilkokullarda çevresel sürdürülebilirlik uygulamalarının bireysel, örgütsel ve sistem düzeylerinde nasıl yapılandırıldığını analiz etmektedir. UNESCO'nun Sürdürülebilir Kalkınma için Eğitim 2030 Yol Haritası'nı analitik referans çerçevesi olarak kullanan çalışma, Türkiye'de eğitim politikaları ve kurumsal uygulamalar aracılığıyla çevresel sürdürülebilirliğin nasıl çerçevelendiğini ve hayata geçirildiğini haritalamayı amaçlamaktadır.

KAVRAMSAL ÇERCEVE

Bu çalışmanın kavramsal altyapısı, çevre eğitiminin tarihsel süreç içerisinde geçirdiği yapısal ve paradigmal dönüşüme dayanmaktadır. Pedagojik bağımsız bir alan olarak 1960'lı yıllarda filizlenen geleneksel çevre eğitimi; Stockholm Konferansı (1972), Belgrad Şartı (1975) ve Tiflis Bildirgesi (1977) gibi uluslararası normatif metinlerle kurumsal bir zemin kazanmıştır (UNESCO, 2017). Bu ilk evrede ağırlıklı olarak doğayı koruma refleksine ve biyofiziksel çevre bilgisine dayanan dar kapsamlı korumacı vizyon, 1987 yılında yayımlanan Brundtland Raporu (Ortak Geleceğimiz) ile köklü bir kırılma yaşamıştır (WCED, 1987). Rapor sonrasında eğitim anlayışı, salt doğayı koruma hedefinden sıyrılarak ekolojik dengenin sosyo-ekonomik dinamiklerle kesiştiği "Sürdürülebilir Kalkınma için Eğitim (SKE)" modeline evrilmiştir.

Gelişen bu çok boyutlu SKE paradigması, odağını yalnızca çevresel krizlerin teşhisinden çıkarıp toplumsal adalet ve ekonomik dönüşümün pedagojik boyutlarını da kapsayan bütüncül bir hatta taşımıştır. Nitekim bu yapı, UNESCO SKE 2030 Yol Haritası'nın politika, öğrenme ortamları, eğiticilerin kapasite gelişimi, gençlik ve yerel eylemden oluşan 5 öncelikli eylem alanı üzerinden küresel ölçekte sisteme entegre edilmiştir (UNESCO, 2020).

Söz konusu pedagojik evrim, yalnızca bireysel farkındalık veya tutum değişikliği yaratmanın ötesine geçerek; kurumsal yapıları, yönetsel şemaları ve okul iklimini topyekûn dönüştüren radikal ve sistematik bir mekanizma önermektedir (Sterling, 2016). Bu sistemik dönüşümün okul ekosisteminde somutlaşabilmesi ise Bütüncül Kurum Yaklaşımı (Whole-Institution Approach) ile olanaklı kılınmaktadır. Bütüncül yaklaşım doğrultusunda okul; yalnızca formel müfredatın aktarıldığı mekanik bir derslik alanı değil; idari karar alma süreçleri, fiziksel kampüs altyapısı, paydaş ilişkileri ve insan kaynaklarıyla sürdürülebilirliği içselleştiren "yaşayan bir bütün" ve dinamik bir mikro-ekosistem olarak kavramsallaştırılmaktadır.

YÖNTEM

Araştırmanın Modeli

Bu çalışma, Türk ilköğretiminde çevresel sürdürülebilirliğin nasıl yapılandırıldığını ve önceliklendirildiğini incelemek amacıyla nitel araştırma desenlerinden çerçeve odaklı belge analizini (framework-driven document analysis) benimsemektedir. Yöntemsel kurgu, üç temel metodolojik geleneğin entegrasyonuna dayanmaktadır: nitel belge analizi (Bowen, 2009), yönlendirilmiş nitel içerik analizi (Hsieh & Shannon, 2005) ve özellikle politika odaklı araştırmalara uygun olan çerçeve analizi yaklaşımı (Ritchie & Spencer, 1994; Gale vd., 2013). Bu kurguda analitik çerçeve, UNESCO'nun Sürdürülebilir Kalkınma için Eğitim (ESD) 2030 Yol Haritası tarafından sunulan beş öncelikli eylem

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alanı (politika geliştirme, öğrenme ortamlarının dönüşümü, eğitimcilerin kapasite gelişimi, gençlerin güçlendirilmesi ve yerel eylemlerin hızlandırılması) üzerinden operasyonelleştirilmiştir. Bu strateji doğrultusunda geniş ölçekli metinsel veriler, önceden tanımlanmış boyutlar arasında sistematik karşılaştırmaya olanak tanıyan analitik bir matrise eşleştirilerek çözümlenmiştir.

Veri Toplama ve Etik İlkelerin İncelenmesi

Araştırmanın veri kümesini; Millî Eğitim Bakanlığı (MEB) tarafından yayımlanan ulusal eğitim politikası belgeleri, ilköğretim kademesine ait resmi öğretim programları (müfredatlar) ve ilgili uygulama kılavuzları oluşturmaktadır. Bu kurumsal metinler, salt teknik veya idari kayıtlar olarak değil; eğitimsel önceliklerin, kurumsal normların ve yönetim mantıklarının üretildiği ve meşrulaştırıldığı söylemsel araçlar olarak ele alınmıştır (Bowen, 2009). Araştırmada incelenen tüm belgeler, ilgili kamu kurumunun resmi portalları ve açık erişimli kurumsal veri tabanları üzerinden kamuya açık (public domain) belgeler olarak temin edilmiştir. Çalışma herhangi bir insan veya hayvan katılımcı içermediğinden ve bütünüyle kamuya açık birincil nitelikteki resmi dokümanlara dayandığından etik kurul onay muafiyeti kapsamındadır; veri analizi sürecinde metinlerin bağlamından koparılmadan, yansız ve bilimsel dürüstlük ilkelerine bağlı kalınarak incelenmesine azami özen gösterilmiştir.

Araştırma Probleminin Analizi

Araştırma probleminin çözümlenmesinde, verilerin önceden belirlenmiş normatif bir çerçeve üzerinden kodlandığı yönlendirilmiş nitel içerik analizi (Hsieh & Shannon, 2005) ve politika uygulama perspektifi (Ball, Maguire ve Braun, 2012) esas alınmıştır. UNESCO'nun uluslararası geçerliliği haiz beş öncelikli eylem alanı, Türk politika belgelerindeki vurgu, uyum ve eksiklik kalıplarının çözümlendiği analitik bir düzenleyici süzgeç görevi görmüştür. Bu perspektif doğrultusunda politika metinleri yalnızca biçimsel reçeteler olarak değil; eğitim sistemi içinde neyin düşünülebilir, meşru ve eyleme geçirilebilir olduğunu inşa eden yapılar olarak değerlendirilmiştir. Böylece ulusal düzeydeki resmi metinler üzerinden çevresel sürdürülebilirliğin Türk ilköğretiminde nasıl çerçevelendiği, yönetsel düzeyde nasıl kodlandığı ve kurumsallaşma biçimleri eleştirel ve sistematik bir yaklaşımla ortaya konulmuştur.

BULGULAR

Araştırma bulguları, Türkiye'deki ilköğretim kademesinde çevresel sürdürülebilirliğin spesifik veya dönemsel projeler olmaktan çıkarak; makro politikalarla yapısal bir paralellik kazandığını göstermektedir. Bu bulguları UNESCO'nun 5 eylem alanına göre haritalandırdığımızda şu sonuçlara ulaşılmıştır *Politika Geliştirme ve Öğrenme Ortamları;* Çevresel sürdürülebilirlik, kalkınma planlarında uzun vadeli bir eğitim önceliği olarak konumlandırılmış; ayrı bir ders yerine Fen Bilimleri ve Sosyal Bilgiler gibi birçok disiplinleri etkileyen müfredat yetkinliği olarak yapılandırılmıştır. Öğrenme ortamlarının dönüşümü ise "Enerji Dostu Mavi-Yeşil Okul Projesi" gibi ulusal girişimlerle kurumsallaştırılmıştır. Bu süreç, okulların atık yönetimi ve enerji verimliliği gibi fiziksel altyapı iyileştirmelerini eylem planlarıyla birleştirerek açık hava ve deneyimsel öğrenme mekanlarına dönüştürmesini teşvik etmektedir. Eğitimci Kapasitesi, Gençlik Özneliği ve Yerel Çözümler; Analizler, sürdürülebilirliğin eğitimcilerin mesleki standartlarına, kariyer ilerleme çerçevelerine (Öğretmenlik Meslek Kanunu vb.) ve hizmet içi eğitim programlarına sistematik olarak entegre edildiğini göstermektedir. Gençlerin katılımı**,** pasif bir öğrenme sürecinden ziyade teknoloji odaklı programlar ve proje tabanlı ekosistemlerle (TÜBİTAK, TEKNOFEST) erken yaşta teşvik edilmektedir. Son olarak yerel çözümler olarak; okullar ve belediyeler arasındaki operasyonel ortaklıkların, özellikle atık yönetimi ve kaynak verimliliği alanında okul içi pratiklerin yerel topluluğa yayılmasını sağlayacak şekilde yapılandırıldığı saptanmıştır.

SONUÇ VE TARTIŞMA

Bu çalışma, UNESCO'nun Sürdürülebilir Kalkınma için Eğitim (ESG) 2030 Yol Haritası'nda tanımlanan beş öncelikli eylem alanıyla uyumlu olarak, Türkiye'deki ilköğretimde çevresel sürdürülebilirliğin nasıl yapılandırıldığını araştırmaktadır. Analiz, belirli girişimlerin etkinliğini veya sonuçlarını değerlendirmeyi amaçlamamaktadır; bunun yerine, sürdürülebilirliğin eğitim sistemine nasıl yerleştirildiğini gösteren politika çerçevelerini, kurumsal düzenlemeleri ve uygulama mekanizmalarını haritalamaya odaklanmaktadır. Bulgular, politika geliştirme alanında, çevresel sürdürülebilirliğin, üst

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düzey politika belgeleri, ulusal kalkınma planları ve eğitimi sürdürülebilir kalkınma hedefleriyle açıkça ilişkilendiren stratejik çerçeveler aracılığıyla uzun vadeli bir eğitim önceliği olarak konumlandırıldığını göstermektedir. Müfredat düzeyinde, sürdürülebilirlik, bağımsız bir ders olmaktan ziyade, disiplinler arası bir yeterlilik olarak ele alınmakta ve fen, sosyal bilgiler ve sanat eğitimi gibi disiplinlerdeki öğrenme çıktılarıyla desteklenmektedir. Öğrenme ve eğitim ortamlarının dönüşümü, özellikle Enerji Dostu Mavi-Yeşil Okul Projesi olmak üzere, ülke çapındaki girişimler aracılığıyla kurumsallaştırılmıştır. Bu girişim, okul temelli eylem planlamasını, enerji verimliliği ve atık yönetim sistemleri gibi fiziksel altyapı iyileştirmelerini ve deneyimsel ve açık hava öğrenimini desteklemek üzere tasarlanmış öğrenme ortamlarını teşvik etmektedir. Eğitimciler için kapasite geliştirme açısından, sürdürülebilirlik, öğretmen mesleki standartlarına, kariyer ilerleme çerçevelerine ve hizmet içi eğitim programlarına entegre edilmiştir. Bu mekanizmalar, çevresel sürdürülebilirliği öğretmenlerin mesleki yeterliliklerinin bir parçası olarak çerçevelendirir ve günlük öğretim uygulamalarına ve okul kültürüne entegrasyonunu destekler. Gençlerin güçlendirilmesi ve katılımı, erken farkındalığı, proje tabanlı öğrenmeyi ve sürdürülebilirlikle ilgili faaliyetlere aktif katılımı teşvik eden bir dizi okul temelli, müfredat dışı ve bilim ve teknoloji odaklı program aracılığıyla ele alınmaktadır. Son olarak, yerel düzeyde sürdürülebilir çözümlerin hızlandırılması, özellikle atık yönetimi ve kaynak verimliliği gibi alanlarda okullar ve belediyeler arasındaki işbirliği yoluyla desteklenmekte ve okul temelli uygulamaların yerel topluluklara yayılması sağlanmaktadır. Genel olarak, bulgular, Türkiye'deki Sürdürülebilir Kalkınma Eğitimi 2030 önceliklerinin, ulusal politikaları, okul uygulamalarını, eğitimci kapasitesini, gençlerin katılımını ve yerel ortaklıkları birbirine bağlayan çok düzeyli ve çok aktörlü bir yönetim yapısı aracılığıyla ele alındığını göstermektedir. Bu çalışma, Türkiye'de ilköğretimde çevresel sürdürülebilirliğin, ESD 2030'da tanımlanan beş öncelikli eylem alanıyla uyumlu olarak nasıl yapılandırıldığını incelemektedir. Analiz, belirli girişimlerin etkinliğini değerlendirmek yerine, sürdürülebilirliğin eğitim sistemine nasıl entegre edildiğini gösteren politika çerçevelerini, kurumsal düzenlemeleri ve uygulama mekanizmalarını haritalamaya odaklanmaktadır. Bulgular, politika geliştirme alanında, çevresel sürdürülebilirliğin, üst düzey politika belgeleri, ulusal kalkınma planları ve eğitimi sürdürülebilir kalkınmayla ilişkilendiren stratejik çerçeveler aracılığıyla uzun vadeli bir eğitim önceliği olarak konumlandırıldığını göstermektedir. Müfredat düzeyinde ise sürdürülebilirlik, bağımsız bir ders olmaktan ziyade disiplinler arası bir yeterlilik olarak çerçevelenmekte ve fen, sosyal bilgiler ve sanat eğitimi gibi disiplinler genelinde öğrenme çıktılarıyla desteklenmektedir. Öğrenme ve eğitim ortamlarının dönüşümü, özellikle Enerji Dostu Mavi-Yeşil Okul Projesi olmak üzere ülke çapındaki girişimlerle kurumsallaştırılmıştır. Bu girişim, okul temelli eylem planlamasını, enerji verimliliği ve atık yönetimi uygulamaları da dahil olmak üzere fiziksel altyapıdaki iyileştirmelerle birleştirerek, deneyimsel öğrenmeyi destekleyen öğrenme ortamlarını teşvik etmektedir. Eğitimciler için kapasite geliştirme açısından, sürdürülebilirlik, öğretmen mesleki standartlarına, kariyer ilerleme çerçevelerine ve hizmet içi eğitim programlarına entegre edilmiştir. Bu mekanizmalar, çevresel sürdürülebilirliği öğretmenlerin mesleki yeterliliklerinin bir parçası olarak konumlandırır ve günlük öğretim uygulamalarına ve okul kültürüne entegrasyonunu destekler. Gençlerin güçlendirilmesi ve katılımı, erken farkındalığı, proje tabanlı öğrenmeyi ve sürdürülebilirlikle ilgili faaliyetlere aktif katılımı teşvik eden okul tabanlı, müfredat dışı ve teknoloji odaklı programlar aracılığıyla ele alınmaktadır. Son olarak, yerel düzeyde sürdürülebilir çözümlerin hızlandırılması, özellikle atık yönetimi ve kaynak verimliliği gibi alanlarda okullar ve belediyeler arasındaki işbirliği yoluyla desteklenmekte ve okul tabanlı uygulamaların yerel topluluklara yayılması sağlanmaktadır. Genel olarak, bulgular, Türkiye'deki Sürdürülebilir Kalkınma Eğitimi 2030 önceliklerinin, ulusal politikaları, okul uygulamalarını ve eğitim sistemlerini birbirine bağlayan çok düzeyli bir yönetim yapısı aracılığıyla ele alındığını göstermektedir.

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KADIN SAĞLIĞI HEMŞİRELİĞİNDE DERİN ÖĞRENME UYGULAMALARI: 2025 SONRASI LİTERATÜRÜN DERLEMESİ

DEEP LEARNING APPLICATIONS IN WOMEN'S HEALTH NURSING: A REVIEW OF THE POST-2025 LITERATURE

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ÖZET

Yapay zekâ (YZ) ve alt alanı olan derin öğrenme (DÖ), kadın sağlığı hizmetlerinde risklerin erken belirlenmesi, klinik verilerin değerlendirilmesi, fetal sağlığın izlenmesi ve kanserlerin tarama ve tanısının desteklenmesi amacıyla giderek daha fazla kullanılmaktadır. Bu derlemenin amacı, 2025 yılı ve sonrasında yayımlanan güncel derleme çalışmaları doğrultusunda kadın sağlığı hemşireliğiyle ilişkili YZ ve DÖ uygulamalarını incelemektir. Literatür; hemşirelik araştırmaları ve YZ'nin benimsenmesi, maternal-fetal sağlık, meme ve jinekolojik kanserler ile klinik uygulamaya entegrasyon başlıkları altında anlatısal olarak değerlendirilmiştir. Bulgular, YZ ve DÖ modellerinin gebelikte risk tahmini, fetal izlem verilerinin yorumlanması, mamografi, Pap smear, kolposkopi ve diğer tıbbi görüntülerin değerlendirilmesi gibi alanlarda klinik kararları destekleyebildiğini göstermektedir. Bununla birlikte çalışmaların çoğunun retrospektif ve tek merkezli olması, dış doğrulama eksikliği sorunları önemli sınırlılıklardır. Hemşirelerin YZ bilgisi, dijital yeterliliği, aldığı eğitim ve teknolojiye ilişkin kaygısı da benimsemeyi etkileyebilmektedir. Sonuç olarak YZ ve DÖ, kadın sağlığı hemşireliğinde riskli kadınların erken belirlenmesi ve bakımın bireyselleştirilmesi açısından önemli bir potansiyel taşımaktadır. Ancak bu sistemler hemşirenin klinik değerlendirmesinin ve kadınla kurduğu bakım ilişkisinin yerini alan uygulamalar olarak değil; güvenli, açıklanabilir, etik ve insan odaklı karar destek araçları olarak geliştirilmelidir.

Anahtar kelimeler: Yapay zekâ, derin öğrenme, kadın sağlığı hemşireliği, maternal-fetal sağlık, jinekolojik onkoloji.

ABSTRACT

Artificial intelligence (AI) and its subfield, deep learning (DL), are increasingly being used in women's health services to facilitate the early identification of risks, evaluation of clinical data, monitoring of fetal health, and screening and diagnosis of cancers. This review aimed to examine AI and DL applications related to women's health nursing based on recent review studies published in 2025 and thereafter. The literature was narratively evaluated under the themes of nursing research and AI adoption, maternal–fetal health, breast and gynecological cancers, and integration into clinical practice. The findings indicate that AI and DL models can support clinical decision-making in areas such as pregnancy risk prediction, interpretation of fetal monitoring data, and evaluation of mammograms, Pap smears, colposcopy findings, and other medical images. However, the predominantly retrospective and single-center designs of existing studies and the lack of external validation remain important limitations.

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Nurses' AI knowledge, digital competence, training, and technology-related anxiety may also influence the adoption of these technologies. In conclusion, AI and DL have considerable potential to facilitate the early identification of high-risk women and the individualization of care in women's health nursing. Nevertheless, these systems should not be developed as substitutes for nurses' clinical judgment or the therapeutic relationships they establish with women, but rather as safe, explainable, ethical, and human-centered decision-support tools.

Keywords: Artificial intelligence, deep learning, women's health nursing, maternal-fetal health, gynecologic oncology.

GİRİŞ

Yapay zekâ, büyük ve karmaşık verilerden örüntü çıkararak sınıflandırma, tahmin ve karar desteği sağlayan yöntemleri kapsamakta; derin öğrenme ise çok katmanlı yapay sinir ağları aracılığıyla özellikle görüntü ve fizyolojik sinyal analizinde kullanılmaktadır. Veri üretiminin hızla artması ve dijital sağlık teknolojilerinin yaygınlaşmasıyla birlikte bu yöntemler, sağlık hizmetlerinde erken tanı, risk değerlendirmesi, izlem ve bireyselleştirilmiş bakımın desteklenmesi açısından giderek daha fazla önem kazanmaktadır (Ruksakulpiwat et al., 2025).

Bu gelişmelerin önemli uygulama alanlarından biri de kadın sağlığı hemşireliğidir. Gebelik öncesi dönemden doğum sonrasına, fetal izlemeden jinekolojik kanserlerin erken tanısına kadar geniş bir bakım alanını kapsayan kadın sağlığı hemşireliğinde; YZ temelli risk tahmini, uzaktan izlem ve görüntü değerlendirme sistemleri giderek daha fazla kullanılmaktadır. Bu sistemler hemşirelerin değerlendirme, izlem, eğitim, danışmanlık ve yönlendirme rollerini doğrudan etkilemektedir. Güncel hemşirelik literatürü, YZ teknolojilerinin risk belirleme ve klinik sonuçları tahmin etmede önemli fırsatlar sunduğunu; ancak güvenli ve etkili kullanım için yöntemsel sağlamlık, etik yönetim ve hemşirelerin sürece etkin katılımının gerekli olduğunu göstermektedir (Choi et al., 2025; Ruksakulpiwat et al., 2025). Bu doğrultuda derlemede, 2025 yılı ve sonrasında öne çıkan uygulamaların kadın sağlığı hemşireliği açısından sentezlenmesi amaçlanmıştır.

ARAŞTIRMA VE BULGULAR

Tarama yaklaşımı

Bu anlatısal derlemede PubMed/PMC, Wiley Online Library, Frontiers ve MDPI üzerinden ulaşılan, ağırlıklı olarak 2025-2026 yıllarında yayımlanmış sistematik derlemeler, kapsam belirleme çalışmaları ve güncel anlatısal derlemeler incelenmiştir. Literatür; hemşirelikte YZ'nin kullanımı ve benimsenmesi, maternal-fetal sağlık, meme ve jinekolojik kanserlerin tarama ve tanısı ile uygulamaya entegrasyon temaları altında değerlendirilmiştir. Çalışma birincil sistematik derleme olarak tasarlanmadığından bulgular anlatısal olarak sentezlenmiştir.

Hemşirelikte yapay zekanın kullanımı ve benimsenmesi

Hemşirelik araştırmalarında YZ; risk sınıflandırma, sonuç tahmini ve klinik karar desteği amacıyla kullanılmaktadır. Mevcut literatürde, kanıtların henüz gelişme aşamasında olduğu, bu teknolojilerin hemşirelik sonuçlarına katkısının açık biçimde gösterilmesi ve hemşirelerin yalnızca kullanıcı olarak değil, sistemlerin geliştirilmesi ve değerlendirilmesinde etkin bir paydaş olarak yer alması gerektiği vurgulanmaktadır (Choi et al., 2025; Ruksakulpiwat et al., 2025). Hemşireler ve hemşirelik öğrencileri genel olarak YZ'ye temkinli fakat olumlu yaklaşmaktadır. Önceden eğitim alma, dijital beceri ve öz yeterlilik benimseme niyetini güçlendirirken; hata, mahremiyet, mesleki özerklik ve insan unsurunun zayıflamasıyla ilgili kaygılar hazır oluşu azaltabilmektedir (El Arab et al., 2025a). Bu nedenle hizmet içi eğitimlerin teknik kullanımın yanı sıra etik, veri güvenliği, eleştirel değerlendirme ve klinik sorumluluğu da kapsaması gerekmektedir.

Benimseme açısından kurum desteği de belirleyicidir. Güncel sistematik derlemede, liderlik desteği ve kullanıcı merkezli aşamalı uygulamaların hazır oluşu güçlendirdiği; yetersiz altyapı, kaynak kısıtlılığı ve beceri kaybı endişesinin ise kullanımı zorlaştırdığı bildirilmiştir (El Arab et al., 2025a). Hemşirelerin modelin güçlü ve zayıf yönlerini tanıması, çıktıyı sorgulayabilmesi ve gerektiğinde klinik bulgularla

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çelişen öneriyi reddedebilmesi güvenli uygulamanın temelidir. YZ okuryazarlığı bu nedenle yalnızca program kullanma becerisi değil, çıktıların geçerliliğini ve olası yanlılıklarını değerlendirme yeterliliği olarak görülmelidir (Choi et al., 2025).

Maternal-fetal sağlık ve doğum öncesi izlem

Maternal-fetal sağlık, YZ uygulamalarının yoğunlaştığı başlıca alanlardan biridir. Güncel derlemelerde gebelik risklerinin, preeklampsi, gestasyonel diyabet, erken doğum, postpartum kanama ve olumsuz perinatal sonuçların tahminine yönelik modeller; ultrason ve kardiyotokografi verilerinin değerlendirilmesi; giyilebilir sensörler ve ev temelli izlem sistemleri ele alınmaktadır (El Arab et al., 2025b; Giaxi et al., 2025). Bu uygulamalar, daha yakın izleme gereksinimi bulunan kadınların erken belirlenmesine ve hemşirelerin eğitim, danışmanlık ve yönlendirme süreçlerini bireyselleştirmesine katkı sağlayabilir. YZ destekli uzaktan izlem, özellikle hizmete erişimin güç olduğu durumlarda sürekliliği destekleme potansiyeline sahiptir.

Ancak modellerin yüksek teknik performans göstermesi, tek başına klinik yarar sağladıkları anlamına gelmemektedir. İncelenen derlemeler, kanıtların önemli bir bölümünün retrospektif ve tek merkezli çalışmalara dayandığını; dış doğrulama ve gerçek yaşam uygulamalarının ise sınırlı kaldığını göstermektedir (El Arab et al., 2025b; Giaxi et al., 2025). Fetal izlem gibi güvenlik açısından kritik alanlarda model çıktılarının klinik bağlam, kadının bireysel özellikleri ve profesyonel değerlendirmeyle birlikte ele alınması gerekmektedir.

Kardiyotokografi gibi sürekli ve karmaşık sinyallerde DÖ modelleri, örüntülerin tanınması ve olası fetal risklerin işaretlenmesi için kullanılabilmektedir. Ancak kayıt kalitesinin düşük olması, hareket artefaktları ve farklı cihazlardan elde edilen veriler model performansını etkileyebilir. Yanlış pozitif uyarılar gereksiz kaygı ve girişimlere, yanlış negatif sonuçlar ise riskin gecikmiş fark edilmesine yol açabileceğinden, uyarı eşikleri ve klinik sonuçlar birlikte değerlendirilmelidir. Uzaktan izlemde de kesintisiz bağlantı, cihaz doğruluğu, verinin güvenli aktarımı ve kadının teknolojiyi kullanabilmesi önem taşımaktadır. Bu sistemler yüz yüze bakımın alternatifi değil, uygun kadınlarda izlemin sürekliliğini güçlendiren tamamlayıcı uygulamalar olarak planlanmalıdır (El Arab et al., 2025b; Sivasankari & Mohan, 2026).

Meme ve jinekolojik kanserlerin tarama ve tanısı

Derin öğrenme, kadınlarda görülen kanserlerin tarama ve tanısında ağırlıklı olarak tıbbi görüntülerin sınıflandırılması, lezyonların belirlenmesi ve segmentasyonu için kullanılmaktadır. Mamografi çalışmalarını inceleyen güncel bir sistematik derleme, modellerin özellikle lezyon sınıflandırmasına odaklandığını; ancak farklı toplumları temsil eden veri setleri ve dış doğrulama gereksiniminin sürdüğünü ortaya koymuştur (Amin et al., 2025). Serviks kanserinde ise Pap smear, kolposkopi, histopatoloji ve görüntüleme verileriyle geliştirilen makine ve derin öğrenme uygulamalarının büyük kısmı tanıya odaklanmakta; prognoz ve tedaviye ilişkin çalışmalar daha sınırlı kalmaktadır (Vazquez et al., 2025). Jinekolojik kanserlerde YZ, tanısal değerlendirme ve risk sınıflandırmasını destekleyebilmekle birlikte, rutin kullanıma geçmeden önce tekrarlanabilirlik ve klinik geçerliliğin gösterilmesi gerekmektedir (Paiboonborirak et al., 2025).

Görüntü tabanlı modellerin performansı; görüntünün elde edilme tekniği, cihaz özellikleri, etiketleme kalitesi ve veri setindeki kadınların özelliklerinden etkilenmektedir. Örneğin meme yoğunluğu ve toplumlar arasındaki görüntüleme farklılıkları, belirli bir grupta geliştirilen modelin başka bir gruba aktarılmasını güçleştirebilir (Amin et al., 2025). Jinekolojik malignitelerde farklı görüntüleme yöntemleri ile patoloji verilerinin bütünleştirilmesi umut verici sonuçlar sunmakla birlikte, standartlaştırılmış ve erişilebilir veri setlerinin yetersizliği çalışmalar arasında karşılaştırma yapılmasını güçleştirmektedir. Kadın sağlığı hemşiresi açısından bu uygulamaların değeri, tarama sonucunun doğru iletişimi, ileri değerlendirmeye gereksinim duyan kadınların zamanında yönlendirilmesi ve takip kaybının azaltılmasıyla ortaya çıkacaktır (Paiboonborirak et al., 2025).

Hemşirelik uygulamalarına yansımalar ve sınırlılıklar

Kadın sağlığı hemşireliği açısından YZ'nin temel katkısı, bakım gereksinimi yüksek kadınların daha erken belirlenmesini ve veriye dayalı izlemi desteklemesidir. Hemşire, model çıktısını kadının klinik

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durumu, tercihleri ve bakım gereksinimleriyle birlikte değerlendirmeli; anlaşılır bilgi sunmalı ve gerekli yönlendirmeyi yapmalıdır. Dolayısıyla YZ, hemşirelik kararını otomatikleştiren değil, klinik muhakemeyi destekleyen bir araç olarak konumlandırılmalıdır (Sivasankari & Mohan, 2026).

Açıklanabilirlik, özellikle risk sınıflandırması ve kanser taraması gibi sonuçların kadın için önemli etkiler doğurduğu alanlarda kritik bir gereksinimdir. Sağlık profesyonelinin yalnızca 'yüksek risk' uyarısını görmesi yeterli değildir; sistemin hangi veri veya özelliklere dayanarak bu sonuca ulaştığını, belirsizliğin düzeyini ve modelin hangi koşullarda güvenilirliğinin azaldığını bilmesi gerekir. Açıklanamayan sonuçlar hem klinik sorumluluğun paylaşımını güçleştirebilir hem de kadının bilgilendirilmiş karar sürecine katılımını sınırlandırabilir (Sivasankari & Mohan, 2026).

İncelenen çalışmalarda öne çıkan başlıca sınırlılıklar; araştırmaların çoğunlukla tek merkezli ve retrospektif olarak yürütülmesi, veri setlerinin küçük olması ve farklı kadın gruplarını yeterince temsil etmemesidir. Ayrıca modellerin farklı klinik ortamlarda doğrulanmaması, karar süreçlerinin yeterince açıklanamaması, veri güvenliği ve mahremiyete ilişkin sorunlar ile elektronik sağlık kayıtlarına entegrasyon güçlükleri bulunmaktadır. Bu sınırlılıklar, modellerin belirli kadın gruplarında daha fazla hata yapmasına ve sağlık hizmetlerinde mevcut eşitsizlikleri artırmasına neden olabilir. Bu nedenle gelecekte YZ modelleri; çok merkezli ve prospektif çalışmalarla, farklı yaş ve sosyodemografik özelliklere sahip kadınlarda doğrulanmalıdır. Değerlendirme sürecinde yalnızca teknik performans değil; klinik yarar, iş akışına uyum, kullanıcı deneyimi ve sağlık eşitliği de dikkate alınmalıdır (El Arab et al., 2025b; Ruksakulpiwat et al., 2025).

Kanıtların klinik uygulama açısından değerlendirilmesi

İncelenen literatür, YZ ve DÖ modellerinin bazı görevlerde umut verici sonuçlar verdiğini göstermekle birlikte, teknik başarı ile klinik etkililik arasında önemli bir geçiş aşaması bulunduğuna işaret etmektedir. Bir modelin doğruluk, duyarlılık veya özgüllük değerinin yüksek olması; bakım sürecini hızlandırdığı, komplikasyonları azalttığı ya da kadınların bakım deneyimini iyileştirdiği anlamına gelmemektedir. Klinik uygulamaya geçişte model çıktısının ne kadar sürede üretildiği, yanlış uyarıların iş yüküne etkisi, mevcut kayıt sistemleriyle uyumu ve sonuçların sağlık profesyonelleri tarafından anlaşılabilirliği değerlendirilmelidir. Bu nedenle yeni sistemlerin yalnızca laboratuvar koşullarında değil, gerçek bakım ortamlarında ve rutin iş akışı içinde sınanması gerekmektedir (Ruksakulpiwat et al., 2025).

Kadın sağlığı hemşireliği açısından değerlendirilmesi gereken sonuçlar arasında erken risk belirlemenin yanı sıra bakım planının bireyselleştirilmesi, eğitim ve danışmanlığın zamanında sunulması, yönlendirme süresinin kısalması, takip kaybının azalması ve kadınların bakım sürecine katılımı bulunmaktadır. Ayrıca YZ kullanımının hemşirenin karar verme süresine, iş yüküne, mesleki özerkliğine ve kadınla iletişimine etkisi ölçülmelidir (Choi et al., 2025).

Gelecekteki çalışmaların çok merkezli, prospektif ve farklı kadın gruplarını kapsayan tasarımlarla yürütülmesi önceliklidir. Modeller yeni merkezlerde bağımsız olarak doğrulanmalı; yaş, gebelik özellikleri, eşlik eden hastalıklar, sosyoekonomik durum ve farklı görüntüleme cihazları gibi etkenlere göre performans raporlanmalıdır. Uygulama öncesinde veri yönetimi, sorumluluk paylaşımı, hata bildirimi ve insan denetimini tanımlayan kurumsal süreçler oluşturulmalıdır. Hemşirelerin teknoloji geliştirme ekiplerine erken aşamadan katılması, kullanılabilirlik sorunlarının ve bakım gereksinimlerinin tasarıma yansıtılmasını sağlayabilir..

SONUÇ

2025 ve sonrasında yayımlanan güncel derlemeler, YZ ve DÖ uygulamalarının kadın sağlığı hemşireliğiyle ilişkili alanlarda hızla geliştiğini göstermektedir. En belirgin kullanım alanları maternal-fetal risk tahmini ve izlem, meme ve jinekolojik kanserlerin tarama ve tanısı ile klinik karar desteğidir. Bu teknolojiler riskli kadınların erken belirlenmesine, izlemin bireyselleştirilmesine ve zamanında yönlendirmeye katkı sağlamaktadır. Bu potansiyelin güvenli ve etkili biçimde klinik uygulamaya aktarılabilmesi için modellerin farklı kadın gruplarında doğrulanması, karar süreçlerinin açıklanabilir olması, verilerin yeterli ve temsil edici nitelik taşıması, mahremiyetin korunması ve sistemlerin klinik iş akışına uygun şekilde geliştirilmesi gerekmektedir. YZ'nin güvenli kullanımı; hemşirelerin teknoloji

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geliştirme, değerlendirme ve uygulama süreçlerine katılımını ve uygun eğitimlerle desteklenmesini gerektirmektedir. Sonuç olarak YZ, hemşirenin klinik kararının ve kadınla kurduğu bakım ilişkisinin yerini alan bir sistem olarak değil; insan odaklı, etik ve bireyselleştirilmiş bakımı destekleyen bir karar destek aracı olarak değerlendirilmelidir.

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THE DISCOURSE OF POWER AND TRUTH IN POETIC WORKS (LITERATURE AND ART): AN INTRODUCTION

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ABSTRACT

Friedrich Nietzsche argued that truth is nothing but "a mobile army of metaphors and metonyms" and that knowledge is one of the forms of "the will to power." Following Nietzsche, Foucault (pragmatist philosopher as Nietzsche) created his archaeology out of this specific point. Truth is what is considered true if reinforced by the discourse of power. For Rorty, another pragmatist philosopher, truth is high esteem, approval, and "social commendation." That is, truth is a social construct that lacks any obligation or necessity that might be inherent in the nature of things.

Therefore, it can be concluded that whomever does not exercise power, does not possess the truth either.

However, examining power relations as a comprehensive network that encompasses all aspects of human activity, leads the pragmatist to strip the ethical distinction between the oppressor and the oppressed of its meaning. This is because every individual's will, is subsumed under the will to power.

Although initially, we follow Rorty's model—which replaces objectivity with two methods, 'ironism' versus solidarity, i.e., adopting concepts and values through the creation of the self by individual freedom of choice, we still in this paper insist on challenging the pragmatic method through discussing the following question:

What about the truth (reflected in poetic works) that is, in its essence, an absolute rejection of the will to power?

Keywords: Nietzsche, Foucault, Rorty, truth, power, pragmatic method.

Injustices may not be perceived as injustices, even by those who suffer them, until somebody invents a previously unplayed role. Only if somebody has a dream, and a voice to describe that dream, does what looked like nature begin to look like culture, what looked like fate begin to look like a moral abomination. For until then only the language of the oppressor is available, and most oppressors have had the wit to teach the oppressed a language in which the oppressed will sound crazy - *even to themselves* - if they describe themselves *as* oppressed.[1]

Introduction

Fredrick Nietzsche (1844-1900), the German philosopher who opened wide the gate to postmodernism, argued that truth is nothing but "a mobile army of metaphors and metonyms" and that knowledge is one of the forms of "the will to power."[2] From this perspective, truth seems to be a prisoner of rhetoric. Truth then, is caged by language (precisely like everything else, including this paper). Knowledge also seems structural and infinite in terms of concepts, situations, and interpretations. The only spine that holds it upright is the ideology of the ambition for domination. Therefore, the idea of pure knowledge, according to Nietzsche, is discounted since what is "right" and "true" is nothing but "the expediency of

[1] Richard Rorty, "Feminism and Pragmatism," in *Pragmatism*, ed. R. S. Goodman (New York, 1995), p. 126.
[2] Friedrich Nietzsche, "On Truth and Lies in an Extra Moral Sense," in *The Portable Nietzsche*, ed. Walter Kaufmann (London, 1968), pp. 46-47.

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a certain race and species – their utility alone is their truth. Truth is what is considered true if reinforced by the discourse of power."[3]

Indebted to Nietzsche, Michel Foucault (1926-1984) created his archaeology out of this specific point. According to cultural studies, power is the ability to accomplish one's goals and serve one's own interests (individually or collectively) regardless of others. On the other hand, truth is a social creation, or it is what becomes "true" through the activation of power, i.e., "the systems of power" as Foucault called them.

For the romantic, revolutionary, liberal, and idealistic philosopher Richard Rorty (1931-2007), truth is high esteem, approval, and "social commendation." That is, truth is a social construct that lacks any obligation or necessity that might be inherent in the nature of things.[4]

Therefore, it can be concluded that whomever does not exercise power or authority does not possess the truth either. In addition, Rorty's pragmatist philosophy, similar to that adopted by Nietzsche and Foucault, does not uphold the marginalized until one of them "invents a previously unplayed role" and stops referring to him/herself as oppressed within the framework of socialization or conversability[5]—thus, establishing a reasonably relative balance between social cooperation and private beatitude, following the example of philosophers such as Socrates (399-469 BC) and Spinoza (1632-1677).[6]

Discussion

Chapter 1:

Truth as an Absolute Rejection of the Will to power

However, examining power relations as a comprehensive network that encompasses all aspects of human activity, leads the pragmatist to strip the ethical distinction between the oppressor and the oppressed of its meaning. This is because every individual's will is subsumed under the will to power. Although initially we will follow Rorty's model—which replaces objectivity with two methods, ironism versus solidarity, i.e., espousing concepts and values through the creation of the self by individual freedom of choice, we still insist on posing the following question: What about the truth that is, in its essence, an absolute rejection of the will to power?

Chapter 2:

Live for it, or at least write about it

Since we concur with Derrida (Jacques Derrida, 1930-2007), who concurs with Saussure (Ferdinand de Saussure, 1857-1913), that meaning emerges from the relationships of difference among signifiers rather than from an objective, independent reality,[7] then the aesthetic truth we are seeking in creative works, may become clearer and clearer the more it opposes whatever appears in the text as an oppressive act by one of the forces of power and domination.[8]

Foucault, relying upon Nietzsche, elaborates on the definition of power and power relationships, which include knowledge, by illuminating their manifestations in different regimes and institutions. However, he places truth on (or outside) the margins of discourse in the disentangled self because it is an epistemological concern.[9] In our view, the discourse of truth in this context is among the aesthetics of protest, rejection, disobedience, criticism, and resistance to the living conditions and the intellectual, political, and economic hierarchies that do not appeal to the critic or the artist because they are governed,

[3] Friedrich Nietzsche, *The Will to Power*, trans. Walter Kaufmann and R. J. Hollingdale (New York, 1967), p. 515.
[4] See Richard Rorty, "Pragmatism, Relativism and Irrationalism," in *Consequences of Pragmatism* (Minneapolis 1982), pp. 160-175; C. Barker, *Cultural Studies: Theory and Practice* (London, 2012) 508, 512.
[5] Rorty, "Feminism," p. 126.
[6] Richard Rorty, *Truth, Politics and "Post-modernism"* (Assen, 1997), pp. 8-9.
[7] See Jacques Derrida, *Of Grammatology*, trans. Gayatri Chakravorty Spivak (Baltimore, 1976).
[8] This argument does not deny the fact that meaning is only available within the context of representation or that truth is not an accurate representation of a natural order. See Rorty, *Truth*, p. 8.
[9] See Sayid wild-Abah, *History and Truth in Michel Foucault* (Beirut, 1994), p. 90.

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in his/her perspective, by the relationships of oppression that lack the moral drive to alleviate suffering and injustice for the individuals and groups controlled by these relationships. This discourse always develops within a culture of critique, which stems from a commitment to live for truth, or at least to write about it. This culture would contain every intellectual, creative, oppositional, rebellious, and resisting urge. The arts, not as a copy but as a unique rhetorical representation of reality, create aesthetic strategies to construct a specific understanding of the world. Every true art is nothing but an innovation that simultaneously builds and destroys. This is why the history of art is the history of breaking down normalized and legitimized conventions as well as exposing the cultural formations and structures that support power and domination. This innovation essentially comes into being through doubting, investigating, and questioning truths; through uncovering implicit meanings; and through criticizing the aesthetic formations and mechanisms of controlling, directing, repressing, and policing the cultural discourse. These norms and structures activate a set of rules for banning, excluding, marginalizing, and silencing other public formations and mechanisms (whether aesthetic, political, social, or economic).

Chapter 3:

Back to the Ancient Carnival

But what are the means used by the arts to break down and investigate? How does oppositional art dismantles normalized and common discourses? How can we arrive at definitions of power—including its functions and its rise as well as its decline and castration? Is truth, as explained above, solely the outcome of power relations, which is the drive of the Foucauldian position that derives from Nietzsche? Or is it a challenge that is hard to explain except within its emotional rejection of these relations and its rebellion against a history that keeps repeating itself? Also, who grants power to whom? What are the connections between "power" and "truth" that emerge within the creative work?

Parody, satire, irony, paradox, oxymoron, caricature, antithesis, the grotesque, ambivalence or ambiguity, humor, allegory, symbolism, and all other literary and rhetorical devices have been and still are, (through their binary oppositions), rhetorical strategies essential to inventing new interpretations by breaking apart old cultural texts, hierarchies and systems, and erecting new ones over their ruins.[10] The Russian critic Mikhail Bakhtin (1895-1975) identified techniques to place texts under the microscope and to analyze them according to postmodern principles that have been in practice since the age of medieval carnivals.[11] As a fertile ground for destroying discourse, the carnival provided elements of

[10] Parody (from the Greek *para ode*), is the sarcastic distortion of the original text. The text may be literary or it may reflect reality as long as it is familiar or recognized by the recipients. Satire is a carnivalesque mixing of the serious and the humorous or the prosaic and the poetic, a criticism of values and social norms, and an attack on corrupt political systems. Irony expresses the opposite of what is presented, so as to create sarcasm in order to deepen dislike or contempt. Paradox is a statement that initially seems irrational but, after some consideration and contemplation, reveals a level of truth and accuracy (For example, "You marvel at my illness/It is my health that is the marvel" (Abu Nuwas, 756-814) See Al-Sayid Muhsin Al-Amin, *Abu Nawwas* (Beirut, 2004), p. 151.
Oxymoron is an explicit contradiction between two statements to create admiration (in the original Greek: "that which is intentionally meaningless"). That is, explicit contradiction is an attempt to reveal a profound truth, such as "he is a hostile friend." Caricature is the exaggerated distortion or magnification of the flaws in someone or something so as to evoke laughter. Antithesis is the combination of two or more opposites (as in, "You would think them awake, while they are asleep" [Quran, Al-Kahf 18:18]). The grotesque is the ludicrous and awesome mixing of two oppositional elements to create a strangeness outside the normal, the expected, and the perfect and to present states of horror. Ambivalence or ambiguity means the word's potential for more than one meaning.

[11] Bakhtin is considered the pioneer of a new school of criticism called aesthetic history. In his examination of literary genres, Bakhtin deployed a sociological perspective. At the core of his analysis is an emphasis on the strong link between the carnival as a historical phenomenon and literature. Specifically, Bakhtin reveals how carnivalesque principles made their way into the structure of the European novel in his study of Rabelais (1494-1553), Cervantes (1547-1616), and Dostoevsky (1821-1881). He distinguished two main trends in the historical development of the literary tradition in Europe: the first is the poetic literary types that developed at the center of intellectual, ideological, linguistic, official, and monolithic life. The second is the narrative prose types that took

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duality and ambivalence. All of these phenomena are carnivalesque forms activating the process of breaking down and overturning the power sites within the images of the world, as depicted in the different fields of discourse. In other words, the carnivalesque act relocates to the margins what is presumed to be central, and what is supposed to be marginal to the center, at least for a short while.[12] In this respect, one of the most powerful definitions of culture, according to Cultural Studies, is that culture is a field of knowledge where meaning is infinitely interrogated and contested. In the carnival, the marginal meaning wins over the meanings that the center has worked so tirelessly to establish as truth. But this victory is not absolute; it is a temporary comedic relief or a short-lived victory within the forever-renewed festival of time. In the case of art, which is a central representative practice and an indispensable and vastly significant aspect of culture, this definition gains more support and strength in a unique way. Thus, art functions as an aesthetic theater because it displays on its "stage" texts constantly battling over meaning. Within artistic discourse, these texts appear as a space for generating meaning. **But where are power and truth in this discourse?**

Chapter 4:

How Can We Comprehend Power but Not Truth?

From the Foucauldian point of view, discourse is the language of power and oppression. In this respect, Foucault states that "it is in discourse that power and knowledge are joined together…. Discourse transmits and produces power; it reinforces it, but also undermines and exposes it, renders it fragile and makes it possible to thwart it."[13] Here Foucault highlights power and knowledge as codependent and inseparable. But he does not leave room for the notion of truth to emerge within this construct. There is no truth there, only "systems of truth," that is, what the person who controls the discourse declares to be the truth. "Foucault believes that the true world is beyond human comprehension. Whatever we know about it is limited and subject to our arbitrary linguistic formations"[14] and "he who possesses power defines the knowledge he needs to protect his power. He who does not have power, needs an alternative knowledge with which to resist. Therefore, each society has its own system of power determined by the dominant discourse."[15]

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an alternative course in the margins of that life, such as public markets and traveling theater companies where the language of jest and multivocality emerged, completely aware of the role it played as a satire and parody of the monolithic center.

For more information, see: Mikhael M. Bakhtin, *Rabelais and his World*, trans. Hélène Iswolsky (Cambridge, 1968); Mikhael M. Bakhtin and Pavel N. Medvedev, *The Formal Method in Literary Scholarship: A Critical Introduction to Sociological Poetics*, trans. Albert J. Wehrle (Baltimore, 1978); Mikhael M. Bakhtin, *The Dialogic Imagination: Four Essays*, trans. Caryl Emerson and Michael Holquist (Austin, 1981); Mikhael M. Bakhtin, *Problems of Dostoevsky's Poetics*, ed. and trans. Caryl Emerson (Minneapolis, 1984).

[12] See: Bakhtin, *Problems*.

[13] Michel Foucault, *The History of Sexuality: An Introduction*, trans. Robert Hurley (London, 1984), pp. 100, 101. In a different context, Foucault expresses the opinion that the production of truth is grasped through power relations and that the strategies of power are impressed by the desire for knowledge. These strategies are the "political economy" of this desire. See *The History of Sexuality: The Will to Knowledge*, particularly the fourth chapter "The Deployment of Sexuality" (trans. Robert Hurley [New York, 1978-1988]). Also: "We must conceive of discourse as a violence which we do to things, or in any case as a practice which we impose on them; and it is in this practice that the events of discourse find the principle of their regularity." See: Michel Foucault, "The Order of Discourse," in *Untying the Text: A Post Structuralist Reader*, ed. Robert Young (Boston, 1981), p. 67.

[14] See: Michel Foucault, *The Order of Things: An Archeology of Human Sciences* (New York, 1970), pp. 303-387; Kais Firro, *Historical Knowledge in the West* (Beirut, 2013), p. 86.

[15] See: Michel Foucault, *Power/Knowledge: Selected Interviews and Other Writings*, ed. Colin Gordon (New York, 1980): pp. 52, 131; Firro, *Historical Knowledge*, p. 90. Foucault, *Introduction*.

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However, if the true world is beyond human comprehension, how then can we (he, Foucault) consider (s) power as a truth that we can comprehend?

Nonetheless, Foucault still refers to truth in his discussion of the Fool: "Strange powers not held by any other may be attributed to the madman's speech: the power of uttering a hidden truth. . . It is curious to note that for centuries in Europe the speech of the madman was not heard at all or else taken for the word of truth."[16]

The language Foucault describes is the language of repressive "rational" discourse. It plays a critical, ideological role in shaping the images of the past, the present, and the future by producing tyrannical meanings to serve the interests of the dominant discourses and groups that seek to establish their hegemony over the oppressed masses. Foucault builds his project on a semi-fictitious balance between the oppressor and the oppressed. To a certain extent, he overlooks the weight each one can deploy in the arena of conflict; he focuses more on the foundational network of power relations within this arena and on the rules that govern it rather than on the position of the "players" themselves. He tends to recommend looking at discourse as a multiplicity of elements employing different strategies of perceiving the world and its objects. These elements are so interwoven that the line between the discourse of the dominant and the dominated, or between acceptable (imposed) and unacceptable discourse, is blurred.[17] In this sense, truth becomes a "rare commodity" but worthless wisdom nonetheless, left to rot and decomposition in the mouths of fools.

Homi K. Bhabha (1949-) makes a nearly similar move when he describes the "hybridity" that emerges from cross-cultural interbreeding.[18] Bhabha overlooks the significant role played by the inequality between the colonizer and the colonized (even in post-colonialism) in shaping and designing this "hybridity." It is as if inequality is not a significant factor in determining how "hybridity" becomes the "third space" that enables a noble negotiation and exchange among the cultures at the center and marginalized ones. Thus, the difference between deploying power and counterattacking it, may be lost in the Foucauldian power relations network. It is also possible for centralization and marginalization to become blurred in the "mixture" of Bhabha's hybridity. All of this leads to the following question: What then becomes of the "alternative knowledge," in Foucault's words, or of the discourses of the single individuals and of the oppressed masses?

Chapter 5:

"The Systems of Truth" and the "Magic Fish"

Here, we suggest reconsidering Foucault's approach. When the discourse of the oppressed rejects power as a matter of principle: not out of weakness, but out of absolute rejection, and not just for the time being, this discourse becomes the language of truth and the oppression of oppression. Even if these individuals and groups (nationalities, beliefs, classes, or any other categories) use the same language,

[16] Foucault, *Order of Discourse*, p. 53. A provocative application of this timid confession can be found in the discourse on madness in Arabic culture. See: Muhammad Hayyan Al-Samman, *The Discourse of Madness in Arabic Culture* (Cypress, 1993). On the other hand, it is important not to forget Foucault's spontaneous sympathy towards "writers, artists, and poets' protest against a world that tries to domesticate madness" as stated by Jean Lacroix in "The Meaning of Madness according to Michel Foucault" (in *The Order of Discourse*, trans. Muhammad Sabila [Beirut, 1984], p. 77). There is also Foucault's fondness for the Greek model characterized by plurality rather than exclusion, which existed before the split between the ontic and the ontological and the self and the subject: "His Nietzscheism reveals a sense of tragedy that is read in all his work" (Lacroix, "Meaning," p. 80)

[17] See: Foucault, *Introduction*, p. 100.

[18] Here it is crucial to refer to what Kamal Abu Deeb writes in his introduction to Edward Said's *Culture and Imperialism* about Bhabha's use of the term "hybridity": "When writers like Bhabha use this term, in my opinion, they overlook the danger implicit in the word's close connection to animal breeding. With such pride and admiration, they describe entire cultures as 'hybrid.' I believe that this produces a contemptuous reaction among (pure) whites and gives them a weapon to fight against these studies and this cultural concept by arguing that it defines itself in a way that is degrading, low, and animalistic." Kamal Abu Deeb, "Introduction," in Edward Said, *Culture and Imperialism*, trans. Kamal Abu Deeb (Beirut, 1997).

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they take a contrary direction and deploy new creative tools so that they can create their own visions of their past, present, and future. Thus, through emasculating and destroying the authoritarian meanings and unmasking "the systems of truth" that belong to the face of power, the discourse of the oppressed tries to shatter the hegemony that weaponizes these masking meanings and hides behind them.

In the end, we ultimately wish to define truth as "the system of truth" adopted by the downtrodden who do not wish to control others, but rather to be completely free of being controlled by them. On the other hand, the Foucauldian "system of truth" may be evoked only when it applies to the person who controls truth and wishes to maintain his control as well as to the weak who wish to replace the oppressor. As for truth, it may indeed be attained by the oppressed who wish to resist power without trying to possess it, or by the oppressor who voluntarily gives up power (not as a favor, but as a rejection of the idea of favoritism altogether). In other words, truth should be pursued neither as a "system of truth" within power relations nor as a foundational strategy to legitimize domination, but as a moral and existential rejection of the power that rests on oppression. Nevertheless, as Rorty indicates, truth is inseparable from culture. Therefore, truth is simultaneously positional, temporal, and spatial.[19] The same applies to meanings, which can be expressed only within specific historical contexts. As a result, they are relative, subjective, and ideologized. In addition, the text, the event, and the practice are not the primary sources of meaning, but only the spaces where ever-changing meanings take shape. Given the relativity of what produces different interpretations of the same text, event, or practice, meanings are always contested sites. Accordingly, ideology is one of the most prominent and important areas in the field of cultural studies.[20] Ideology is what brings dry objectivity down from its high throne by exposing its main focus on falsifying balance, distance, and neutrality, and thereby, camouflaging and covering up the nature and roots of dispute. The field of culture, on the other hand, is the main site for ideological struggle, where acceptance and resistance take place, where hegemony wins or loses, and where the fiery dots of subjectivity fall on the dry letters of objectivity.

Meaning is, thus, the outcome of the conflict and the process of negotiation both among competing frameworks of various referentialities and among different motives and experiments conducted by individuals belonging to diverse cultures across time and to different racial, class, educational, ethnic, and national groups. Examining the creative discourse of dissent, requires defining the nature of the conflict and its parties, and their motives, actions, and positions in the equation of power and truth. **If the will to power is the desire to dominate the Other and to subsume them in one's own ego, then the will to truth is in the existential and emotional act of confronting this desire. Thus, meaning may emerge as sparks our eyes can see despite "cultural hegemony" or "the ideological state apparatus," emerging out of the friction between the "body" of power and the "soul" of truth.** Yet, truth is always like a fish, as long as it is never exposed to the air of control or compliance, it survives in the water of rejection and in the "oppositional critical awareness" ocean.[21]

Chapter 6:

The Role of the Intellectual

"Critical awareness" and especially "oppositional critical awareness," which Edward Said (1935-2003) emphasizes in his grand project, may be an effective mechanism not only to deconstruct western narrative texts and expose their connections to the desire for control and expansion, but also to highlight

[19] See: Richard Rorty, *Philosophy and the Mirror of Nature* (Cambridge, 1980); Richard Rorty, *Contingency, Irony and Solidarity* (Cambridge, 1989).

[20] The most commonly accepted definitions of ideology is the one provided by Stuart Hall, "The Rediscovery of Ideology: The Return of the Repressed in Media Studies," in *Subjectivity and Social Relations*, ed. Veronica Beechey and James Donald (Milton Keynes, 1985).

[21] Regarding "the ideological state apparatuses," see Louis Althusser, "Ideology and Ideological State Apparatuses," in *Lenin and Philosophy and other Essays*, trans. Ben Brewster (London, 1971), pp. 121-176. It is important to mention here the distinction Althusser makes between the repressive state apparatuses (the state, the administration, the army, the police, the courts, and the prisons) and the ideological state apparatuses (religious, educational, familial, legal, political—the political system and its parties—and the ones related to workers' unions, to the media, and to the culture).

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the rejection of all forms of control. In other words, oppositional critical awareness can be used as a technique of rebelling against all efforts to obfuscate oppression whether they come from outside or from within any social structure, since control, repression, and exclusion are general human traits and not just western political tools.[22]

The Arab dictatorial regimes, with which we have been familiar for decades, have been repressing their citizens in the name of nationalism since their so-called independence. In the last decade, we watched them locked in a deadly struggle against new/old brutal groups, such as Al-Qaida and Isis, vying for their place.[23] For this reason, analyzing Arab creative work should prioritize creative writing that rebels against oppression specifically within the Arab establishment and its dangerous ties to the western repressive machine. As for the "contrapuntal reading" developed by Said, which takes into account the imperialist operation and its resistance, it would be better to broaden its scope so as to trace the trajectory of power and the trajectory of resistance as common phenomena regardless of time and place.[24]

"The purpose of the intellectual's activity is to advance human freedom and knowledge."[25] That is how Said describes what we have been referring to here as the discourse of truth in the aesthetics of "cultural criticism," in both its creative and its methodological aspects:

The central fact for me is, I think, that the intellectual is an individual endowed with a faculty for representing, embodying, articulating a message, a view, an attitude, philosophy or opinion to, as well as for, a public, in public. And this role has an edge to it, and cannot be played without a sense of being someone whose place is to raise embarrassing questions, to confront orthodoxy and dogma (rather than to produce them), to be someone who cannot easily be co-opted by governments or corporations . . . someone whose whole being is staked on a critical sense, a sense of being unwilling to accept easy formulas, or ready-made clichés, or the smooth, ever-so-accommodating confirmations of what the powerful or conventional have to say, and what they do. Not just passively unwilling, but actively willing to say so in public.[26]

[22] The western penchant for hegemony has led to the formation of different literary experiments whose authors descend from various geographies within the colonized world. These experiments have taken the shape of counter journeys or counter invasions of the western world by contesting the biased theses and distortions it has inflicted on the histories of these colonies and the identities of their peoples. This counter-narrative is what Edward Said calls "cultural resistance" and what Bill Ashcroft has termed *The Empire Writes Back*, the title of a book he authored with other critics. Cultural resistance enables the colonized nation to restore its identity and reconstruct its status by reviving the nationalist elements that were dismissed by the colonizer in the first place because contribute to preserving and upholding its collective memory. Cultural resistance is not simply a reaction to imperialism. It is much larger than imperialism can ever contain because it emerges from cultural interaction, hybridity, and investment in other cultures to undermine the structures of control within its own culture and within its narratives of self, history, and identity. See further: Idris Al-Khadrawi, "Narrative as a Topic in Cultural Studies: Towards Understanding the Relationship between the Novel and the Dialectics of Cultural Control and Resistance," *Tabayyun*, 7:2 (Winter 2014): 129.

[23] In the introduction to his book *Savage Texts,* Al-Deery writes: "In this book I try to provide a historical reading of the texts of *takfir* within three political environments that have used *takfir* against their enemies. The environment of the Seljuk Empire (eleventh century) through the texts of Al-Ghazaly; the environment of the Almuahhideen Rule (twelfth century) through the texts of Ibn Tumart; and the environment of the Mamluk Sultanate (fourteenth century) through the texts of Ibn Taymiyyah." See: Ali Ahmed Al-Deery, *Savage Texts: Takfir from the Orthodoxy of the Seljuks to the Salafism of Ibn Taymiyyah* (Manama, 2015).

[24] Said's contrapuntal reading explores the dialectic of control and resistance embedded in narrative structures, within the context of the imperialist system. It combines "breaking down the mechanisms of control within the cultural imperialist discourse with reading the patriotic resistance to imperialism and its reflection on culture" (Al-Khadrawy, "Narrative," p. 107). For more on contrapuntal reading, see also: Ezz-el-Din Al-Manasrah, "Edward Said and the Comparative Cultural Criticism: A Contrapuntal Reading," *Fusul* 64 (Summer 2004): 127.

[25] Edward Said, *Representations of the Intellectual* (London, 1994), p. 13.

[26] Said, *Representations*, pp. 9, 17.

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LOGISTICS RELIABILITY AS A FACTOR OF TRADE INTEGRATION IN THE WESTERN BALKANS: AN EMPIRICAL PERSPECTIVE ON BOSNIA AND HERZEGOVINA

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ABSTRACT

This paper examines the extent to which trade integration in the Western Balkan economies can be explained by a combination of investment flows, production structure, institutional quality, and logistics reliability. Rather than treating geographical proximity to the European Union as a sufficient development advantage, the analysis starts from the assumption that such proximity creates economic value only when transport routes, border procedures, and logistics services are reliable enough to support time-sensitive supply chains. The empirical section uses a panel of WB6 economies for the period 2010-2024, with trade openness as the dependent variable and FDI, the share of manufacturing, economic size, Government Effectiveness, and the Logistics Performance Index as the key explanatory variables. The results indicate a stable positive relationship between FDI and trade openness, while the interpretation of logistics indicators is constrained by the limited number of available LPI observations. For Bosnia and Herzegovina, the findings suggest that development policy should focus on reducing the time and uncertainty associated with the movement of goods, while simultaneously attracting investments that integrate domestic firms into European supplier networks.

Keywords: logistics reliability, trade integration, Western Balkans, Bosnia and Herzegovina, foreign direct investment, transport corridors, LPI, institutional quality

INTRODUCTION

Modern supply chains are increasingly organized around criteria other than the lowest possible cost. Disruptions in international transport, geopolitical uncertainty, changes in industrial policy, and the growing importance of security of supply have increased the value of market proximity, but also the reliability of the entire logistics system. Under such conditions, the competitiveness of a location depends not only on production costs, but also on the extent to which transit time, administrative processing, border delays, and final delivery can be predicted.

For the Western Balkan economies, this shift changes the development perspective. The region is located in the immediate vicinity of the European Union and has the potential to participate in nearshoring processes, but geographical position alone does not guarantee entry into higher-tier supplier networks. An advantage emerges only when proximity to the market translates into measurable time savings, delivery stability, and lower transaction costs. Therefore, transport connectivity must be considered together with the quality of institutions, customs procedures, and logistics services.

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Bosnia and Herzegovina is a particularly relevant case because of its strong trade orientation toward the European Union. According to the Agency for Statistics of Bosnia and Herzegovina, in 2024 merchandise exports amounted to EUR 8,218,941 thousand, imports to EUR 14,650,806 thousand, while the export-to-import coverage ratio was 56.1%. At the same time, 73.1% of exports were directed to the EU market and 17.3% to CEFTA countries. This structure shows that the competitiveness of Bosnia and Herzegovina cannot be separated from the quality of road and rail connections, access to the Port of Ploce, transit duration, and the efficiency of border procedures.

The aim of the paper is to distinguish nominal trade openness from the quality of participation in supply chains. The empirical section examines the relationship between trade openness and FDI, industrial structure, economic size, and institutional quality, while the logistics component is additionally considered through the LPI. Particular attention is given to whether Bosnia and Herzegovina can transform its proximity to the European market into a more stable supplier position through more reliable transport, digitalized procedures, and better institutional coordination.

Conceptual Framework: From Geographical Proximity to Logistics Reliability

In the classical approach to location competitiveness, small open economies are often assessed through labor costs, the tax burden, and market size. However, in production systems characterized by short delivery deadlines and frequent cross-border movements of components, a significant part of total costs is generated outside the factory. Border delays, unreliable transport routes, weak institutional coordination, and insufficient digitalization can offset the advantage of lower production costs. Logistics reliability therefore becomes an integral part of investment and industrial competitiveness.

The EBRD (2024) views trade and investment as important channels through which the Western Balkans can converge toward EU standards, while the OECD (2024) identifies limitations in Bosnia and Herzegovina related to the digital trade environment and institutional capacity. Taken together, these findings indicate that the region's development advantage does not depend solely on physical infrastructure. Predictability of procedures, paperless trade solutions, pre-arrival processing, AEO mechanisms, and inter-institutional coordination are equally important.

Trade openness is used in this paper as an operational proxy for participation in international flows. It does not directly capture the technological complexity of exports, domestic value added, or the precise position of a firm or country within a value chain. Nevertheless, the advantage of this measure is the availability of a long and comparable series for all six WB6 economies. Linking trade openness with FDI, the share of manufacturing, economic size, institutional quality, and the LPI makes it possible to analyze several dimensions of integration within a single framework.

For Bosnia and Herzegovina, the infrastructure backbone is Corridor Vc, which the WBIF describes as the main north-south connection through the country toward Central Europe and the Port of Ploce. Its importance for supply chains lies not only in increasing capacity, but also in reducing travel-time variability and improving delivery predictability. For a producer integrated into a European supply chain, the difference between average transport time and reliable transport time may be just as important as distance itself.

The World Bank Logistics Performance Index enables logistics to be viewed more broadly than physical transport alone. The index covers customs efficiency, infrastructure, international shipments, the quality of logistics services, tracking and tracing, and timeliness. In this paper, the LPI is therefore used as an indicator of the system's capacity to ensure stable and predictable movement of goods, complementing the investment and institutional variables.

RESEARCH AND FINDINGS

Data, Variables, and Methodology

Research Focus and Expected Relationships

The empirical analysis is based on three questions: (1) whether higher FDI inflows are associated with greater trade openness in WB6 economies; (2) whether institutional quality contributes to this relationship after controlling for production structure and economic size; and (3) whether the available

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LPI data provide an additional signal regarding the role of logistics reliability. The expected sign of FDI and Government Effectiveness is positive, while a positive relationship is also expected for the LPI, with the caveat that limited temporal coverage may weaken statistical precision.

The analysis covers Albania, Bosnia and Herzegovina, Kosovo (1244), Montenegro, North Macedonia, and Serbia over the period 2010-2024. The dependent variable is Trade (% of GDP), defined as the sum of exports and imports of goods and services relative to GDP. The explanatory variables include net foreign direct investment inflows (% of GDP), Manufacturing value added (% of GDP), the logarithm of real GDP, Government Effectiveness, and the Logistics Performance Index. This specification allows trade integration to be examined through investment, production, institutional, and logistics dimensions.

The baseline estimation uses country and year fixed effects. Country fixed effects control for characteristics that change slowly or remain relatively constant, while year effects capture common shocks affecting the region at the same time. This shifts the focus from a simple comparison of levels across countries to changes within individual economies over time.

$$Trade\_it = \beta0 + \beta1FDI\_it + \beta2Manufacturing\_it + \beta3lnGDP\_it + \mu\_i + \lambda\_t + \varepsilon\_it$$

The extended model introduces Government Effectiveness as an institutional control. The LPI is estimated in a separate specification because data are available in waves for 2010, 2012, 2014, 2016, 2018, and 2023. The stability of the results is further tested by winsorizing FDI at the 5th and 95th percentiles and re-estimating the model without Montenegro, which represents a more FDI-intensive case within the regional sample.

Table 1

Coverage and Availability of Variables in the WB6 Panel

Variable	Source	Period	Obs.	Countries
Trade (% GDP)	World Bank WDI	2010-2024	90	ALB, BIH, XKX, MNE, MKD, SRB
FDI net inflows (% GDP)	World Bank WDI	2010-2024	90	ALB, BIH, XKX, MNE, MKD, SRB
Manufacturing value added (% GDP)	World Bank WDI	2010-2024	90	ALB, BIH, XKX, MNE, MKD, SRB
GDP (constant 2015 US$)	World Bank WDI	2010-2024	90	ALB, BIH, XKX, MNE, MKD, SRB
Government Effectiveness (WGI estimate)	World Bank WGI (2024 update)	2010-2023	84	ALB, BIH, XKX, MNE, MKD, SRB
LPI overall score	World Bank LPI (2023 database)	2010, 2012, 2014, 2016, 2018, 2023	29	ALB, BIH, MNE, MKD, SRB

Note. Government Effectiveness uses the World Bank WGI 2024 update, which covers 1996–2023 and is the data vintage used in the reported models. LPI observations are from the World Bank LPI waves for 2010, 2012, 2014, 2016, 2018, and 2023; Kosovo has no comparable LPI series in the working sample.

Empirical Findings

In the baseline model M1, FDI has a positive and statistically significant coefficient at the 1% level. The estimate of 1.251 means that a one-percentage-point increase in FDI as a share of GDP is associated

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with approximately 1.251 percentage points higher trade openness, holding other model conditions constant. Manufacturing and lnGDP are not statistically significant in the same specification. In model M2, FDI remains positive, while Government Effectiveness enters with a positive coefficient. This pattern suggests that trade integration is not solely a function of production capacity, but also of the way investments and institutions connect an economy to cross-border flows.

Table 2

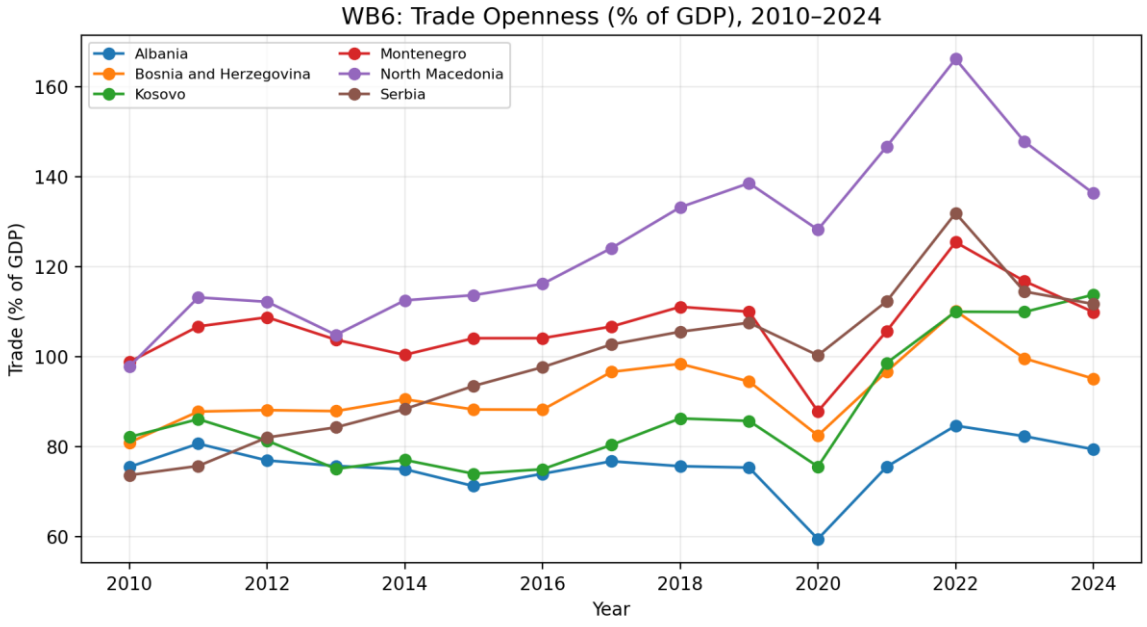
Main Results of the Fixed-Effects Models

Variable	M1	M2	M3
FDI / FDI_w	1.251*** (0.447)	0.937** (0.467)	1.309* (0.721)
Manufacturing	-0.672 (0.714)	-0.337 (0.836)	-0.206 (0.843)
lnGDP	-30.193 (30.345)	-54.804* (28.894)	-47.844 (31.729)
Government Effectiveness	-	7.272* (4.133)	7.086* (4.041)
N	90	84	84
R^2	0.893	0.902	0.902

Note. HC1 standard errors are shown in parentheses. M1 includes country and year fixed effects. M2 adds Government Effectiveness. M3 uses FDI winsorized at the 5th and 95th percentiles. *** p < .01. ** p < .05. * p < .10.

Figure 1

Trade Openness of WB6 Economies, 2010-2024



Note. Values represent the sum of exports and imports of goods and services as a percentage of GDP. Source: World Bank, World Development Indicators (WDI), study sample 2010–2024; author's calculations.

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Stability of the Findings and Limitations of the Logistics Indicator

The results remain qualitatively similar under alternative specifications. In model M3, with winsorized FDI, the coefficient is 1.309 and remains positive, with marginal significance at the 10% level. When Montenegro is excluded from the sample, the FDI effect in model M4 rises to 1.923 and is statistically significant at the 5% level. This reduces the likelihood that the baseline result is driven solely by a single FDI-intensive case and strengthens the interpretation that investment flows have broader importance for the region's trade integration.

In the LPI specification, the coefficient on the logistics indicator is not statistically significant. However, M5 contains only 29 observations, the data are available in irregular waves, and Kosovo lacks a comparable series. Therefore, this result cannot be used as a basis for concluding that logistics has no economic significance. A more precise interpretation is that the available sample does not allow sufficiently strong identification of an independent LPI effect after fixed effects and macroeconomic controls are included.

Table 3

Results of Robustness Checks

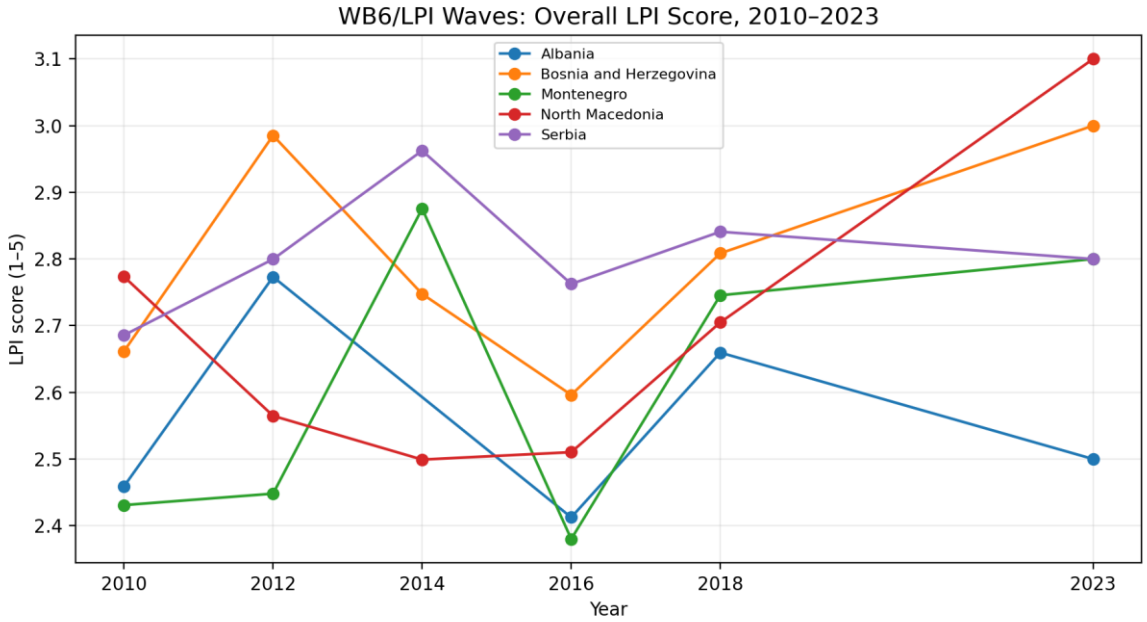
Variable	M4: without Montenegro	M5: LPI waves
FDI	1.923** (0.965)	0.409 (0.381)
Manufacturing	-0.977 (0.742)	-0.107 (1.327)
lnGDP	-56.783 (36.372)	-190.840*** (54.904)
LPI	-	-6.271 (9.887)
N	75	29
R^2	0.911	0.949

Note. M4 estimates the baseline fixed-effects model without Montenegro. M5 introduces the LPI in the wave sample for 2010, 2012, 2014, 2016, 2018, and 2023. *** p < .01. ** p < .05. * p < .10.

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Figure 2

LPI Waves for WB6 Economies with Available Data



Note. Kosovo is not included because no comparable LPI series is available for the selected waves in the working sample. Source: World Bank, Logistics Performance Index (LPI), selected waves 2010–2023; author's calculations.

Discussion: What the Results Imply for the Region's Logistics Competitiveness

The results do not show that logistics by itself automatically increases trade openness, nor can such a conclusion be drawn from the limited LPI specification. What can be stated more reliably is that investment and institutional connectedness are important correlates of deeper trade integration. In practice, FDI linked to cross-border supplier networks raises the demands placed on transport, customs procedures, and delivery deadlines, making logistics reliability a condition for sustaining and expanding investment integration.

For the Western Balkans, this changes the priorities of public policy: it is not enough to increase road capacity or attract a nominally larger volume of investment. Measures that reduce total transit time and its variability, connect border institutions, and enable digital exchange of documents have greater development value. In this way, the region's proximity to the EU is transformed from a geographical fact into an operational advantage for producers and logistics operators.

Bosnia and Herzegovina: From Trade Openness to the Quality of Integration

During the observed period, Bosnia and Herzegovina recorded a high level of trade openness relative to the size of its economy, while at the same time maintaining a pronounced trade deficit and limited technological depth in part of its export structure. The high share of the EU in total exports shows that the country is functionally linked to the European market. The development challenge is therefore not the absence of trade connectivity, but the quality of that connectivity: the speed, reliability, and value added with which domestic firms participate in cross-border flows.

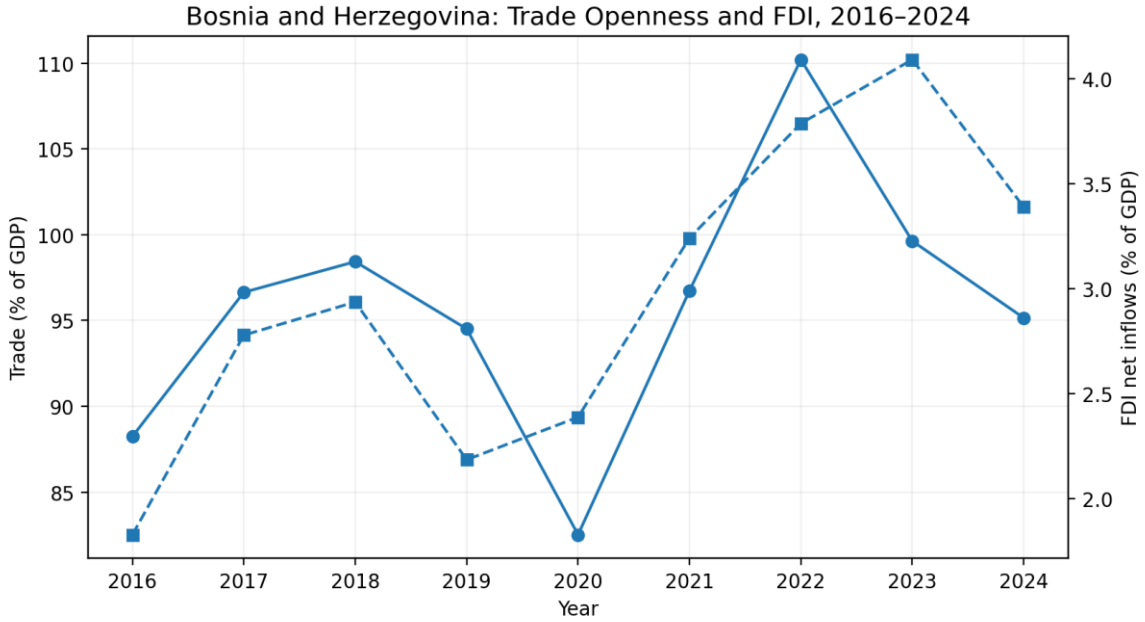
The positive relationship between FDI and trade openness in the regional panel has an important practical implication for Bosnia and Herzegovina. Not all investments are equal from the perspective of value-chain development. Projects that integrate domestic suppliers into standardized production systems, require reliable logistics, and transfer organizational and technological practices may generate stronger effects. At the same time, the positive sign of Government Effectiveness indicates that the competitiveness of such investments does not end at the industrial site, but also includes the performance of customs, public administration, and transport institutions.

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From this perspective, infrastructure projects such as Corridor Vc should be viewed as part of a broader logistics reform. A new transport corridor alone does not guarantee a higher quality of integration if border procedures, digital documentation, and terminal organization remain slow or unpredictable. For Bosnia and Herzegovina, the relevant approach is therefore a combination of physical connectivity, a digitalized trade-facilitation environment, and institutional coordination that reduces not only average transit time but also uncertainty around that time.

Figure 3

Bosnia and Herzegovina: Trade Openness and FDI Trends, 2016-2024



Note. The chart presents the descriptive movement of trade openness and FDI used in the empirical framework. Source: World Bank, World Development Indicators (WDI), 2016–2024; author's calculations.

CONCLUSION

The empirical analysis shows that trade integration of the WB6 economies is not merely the result of geographical proximity to the European Union. The most stable finding concerns the positive relationship between FDI and trade openness, which persists across several specifications and robustness checks. Institutional quality also enters with a positive sign, while the limited LPI series does not provide sufficient statistical power for a reliable estimate of an independent logistics effect.

For Bosnia and Herzegovina, the central development message is that openness to trade should be transformed into higher-quality and more resilient integration. This entails attracting investments that create linkages with domestic suppliers, strengthening industrial capacity, accelerating customs and transit procedures, digitalizing documentation, and developing transport corridors that reduce delivery-time variability. In this sense, logistics reliability is not an auxiliary service, but an element of the country's overall competitiveness.

The paper has several limitations. Trade openness is an indirect rather than a direct measure of a country's position in global value chains, while the LPI is not available as an annual series and does not cover all WB6 economies in a comparable format. Future research could include data on border-crossing times, export structure by technological intensity, the share of domestic value added in exports, and sectoral FDI flows. Such an approach would allow a more precise separation of the effects of infrastructure, institutions, and investment on the quality of regional integration.

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APPENDIX A

Overview of the empirical specifications used and their interpretation.

M1. Baseline model with country and year fixed effects for the period 2010-2024.

M2. M1 with the addition of the institutional control Government Effectiveness, sample 2010-2023.

M3. M2 with FDI winsorized at the 5th and 95th percentiles to reduce the influence of extreme values.

M4. Baseline fixed-effects model without Montenegro as a robustness check for possible FDI-intensive specificity.

M5. Wave fixed-effects model with the LPI for 2010, 2012, 2014, 2016, 2018, and 2023.

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NON-COGNITIVE APPROACH: A HISTORICAL-DIAGNOSTIC ANALYSIS OF MATRIX DIAGONALISATION ERRORS IN 2011, 2018 AND 2025

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The analysis of errors continues to represent a significant challenge in mathematics education. This analysis is shifting from the cognitive level towards the influence of non-cognitive factors such as the curricular context and technological developments. This is an area of research that has not yet been sufficiently explored. The aim of this article is to identify the similarities, differences and factors influencing the evolution of error types in matrix diagonalisation among first-year engineering students across three time periods: 2011, 2018 and 2025. The methodology employed follows a qualitative-descriptive approach structured in three phases, comprising the coding of the difficulties encountered, their concrete illustration and the intertemporal analysis of their history. The results of the study show that cognitive, linguistic, and logical reasoning errors remain constant over the years. By contrast, categories such as mathematical reasoning and communication, lack of control, self-control and work organisation show a general upward trend. The main factors behind these results are changes to the curriculum, technologies such as computational support, and the use of artificial intelligence tools to aid reasoning. This article offers a historical and diagnostic insight into the difficulties faced by students and provides pedagogical guidance on how curricular and technological changes are reshaping their reasoning, communication, and mastery of knowledge.

Keywords: non-cognitive approaches, difficulties in mathematics, matrix diagonalisation, curricula, digital technologies

INTRODUCTION

The analysis of mathematical errors has been, and continues to be, one of the fundamental approaches in research into mathematics education, with a tradition dating back to the early 20th century. Radatz's seminal work (1979) proposed a classification of mathematical errors based on information-processing mechanisms, identifying sources such as linguistic difficulties, a lack of mastery of prior concepts, and the application of irrelevant or incorrect rules. Similarly, VanLehn (1990) demonstrated that pupils' errors in arithmetic are not random, but stem from the systematic application of 'procedural errors', that is, incorrect but systematically learnt rules that produce common and repeatable errors. Other studies have demonstrated the principle that errors should not be regarded simply as a 'lack of knowledge and skills', but as a window into the student's conceptual structure, a principle that also underpins the classification scheme used in this study (Pepkolaj, 2015).

Whilst traditional approaches view errors primarily as indicators of individual cognitive structures, contemporary research has shifted its focus more towards classroom practice. Three approaches to errors are identified: diagnostic, interventionist and exploratory, whilst also highlighting significant gaps in digital/AI integration and the need for comparative studies on errors (Shimizu & Kang, 2025). In line with this, other studies (Dello Iacono & Pepkolaj, 2026) show that the current direction of error analysis is increasingly incorporating generative AI tools as a means of promoting students' self-awareness and error correction, rather than simply as an external object of study.

Linear algebra has long been recognised as one of the most challenging subjects for students. The study by Dorier and Sierpinska (2001) identified two main sources of difficulty: the very nature of linear algebra, with conceptual difficulties linked to the high degree of abstraction of the concepts, and the type of cognitive thinking involved, with difficulties linked to the transition from concrete-algorithmic thinking to structural-abstract thinking. In particular, the concept of diagonalisation has been identified as a topic presenting significant difficulties. The research directly explored students' typical difficulties

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in diagonalising matrices, such as algorithmic/procedural thinking (Karjanto, N. (2023). Although there are numerous studies on the difficulties of linear algebra and on specific errors in diagonalisation, most of them are static in nature, i.e. they analyse students' difficulties at a given moment, without diachronic comparisons.

Three years were selected for the diachronic study. 2011 is characterised by a curriculum with a typically behaviourist approach, with an emphasis on the acquisition of knowledge rather than necessarily on the development of skills. (MAS, 2009). 2018, as it is representative of the new curriculum framework, officially introduced in 2014 and based on constructivist principles and the development of skills, rather than the mere transmission of knowledge. This makes this year a key reference point for analysing the nature of the challenges within a skills-oriented educational context, in contrast to the traditional model of 2011 (MAS, 2014). The yehas025 represents the most recent educational context, characterised by significant factors such as the widespread adoption of artificial intelligence tools, which have significantly altered the way in which students learn, practise and solve problems. This year allows us to observe whether and how the types of difficulties have evolved in a new context, in which the constructivist approach to the curriculum coexists with new technological tools that may have influenced the nature of the errors made by students (MAS, 2024).

This article aims to analyse and compare the types of difficulties encountered by first-year computer and electrical engineering students at the Metropolitan University of Tirana, Albania, in diagonalising matrices across three time periods: 2011, 2018 and 2025, using the framework proposed by Pepkolaj (2015). The specific objective is to identify possible similarities and differences linked to developments in the curriculum, digital technologies, and artificial intelligence tools. Based on the study's objective, the following research questions are formulated:

How have the types of difficulties encountered in the diagonalisation of endomorphisms evolved for first-year engineering students across the three periods (2011, 2018 and 2025)?

What are the main factors underlying the evolution of these difficulties?

Given the nature and purpose of this study, some limitations to bear in mind when interpreting the results are set out below.

Given the nature and purpose of this study, it is important to bear in mind certain limitations when interpreting the results. The study did not consider any changes in the wording of the questions from one year to the next, nor the lack of control over the original test conditions. Further research into metacognition could contribute to a deeper understanding of difficulties that do not clearly fall within existing classification categories.

THEORETICAL FRAMEWORK

The analysis of pupils' errors continues to be an important topic in research into mathematics education. Such analysis is fundamental because it provides a concrete roadmap from product to process, enables improvements to be made to the functioning of the teaching system and, at the same time, can offer ideas for interventions and remedial programmers. Radatz (1979) presented one of the first classifications of mathematical errors, linking them to: linguistic difficulties, difficulties in processing information, a lack of mastery of prior concepts, incorrect associations or mental rigidity, and the application of irrelevant rules or strategies.

Other researchers have used diagnostic interviews to identify at which specific stage of problem-solving students made errors (Watson, 1980). Building on Radatz's work, Movshovitz-Hadar, Zaslavsky and Inbar (1987) developed a broader empirical model comprising six categories of errors. These were based on the specific stage of the solution at which the error occurs, rather than on the general cognitive causes proposed by Radatz. In parallel, VanLehn (1990) demonstrated that many errors stem from systematically learnt 'procedural misunderstandings' (bugs). It is precisely within this cognitive tradition that Pepkolaj's (2015) framework was developed; as discussed at length in the following section, this framework offers a categorisation specifically designed for difficulties in linear algebra (Albano & Pepkolaj, 2014). In the specific field of linear algebra, other studies have identified similar

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difficulties. Karjanto (2023) identified typical difficulties in matrix diagonalisation, mainly linked to algorithmic thinking.

Error analysis is moving beyond the traditional cognitive level, expanding into two additional dimensions: (a) the metacognitive level, where the focus shifts from the error itself to the student's ability to recognise, monitor and reflect on their own error (Dello Iacono & Pepkolaj, 2026); (b) the non-cognitive level, where the focus shifts to contextual, socio-institutional and teaching practice factors that influence the error, beyond the student's individual cognitive process (Shimizu & Kang, 2025). This study is situated precisely within this new approach, retaining the classical cognitive analysis of difficulties, using Pepkolaj's (2015) framework as its methodological basis, but placing it within a cross-temporal comparative framework that also considers the possible influence of non-cognitive factors (technological developments, curricular context), an area of research not yet widely addressed in the literature.

Pepkolaj's (2015) classification framework for difficulties, which constitutes the main analytical tool of this study, is presented in detail below.

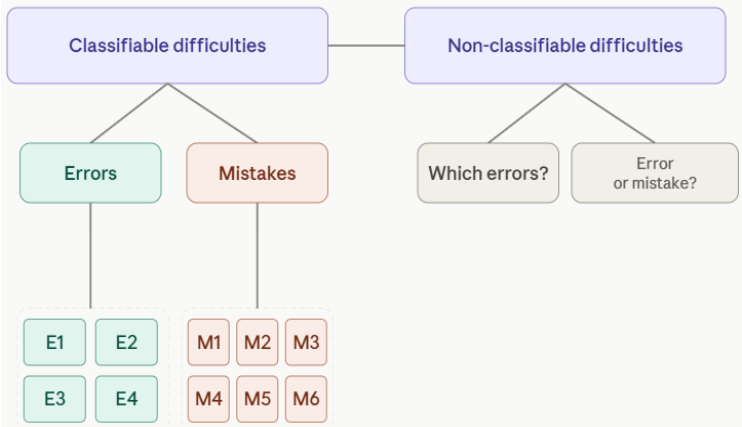


Figure 1. Pepkolaj's (2015) classification scheme of difficulties in linear algebra

E1. Incorrect use of data

The student shows difficulty in processing or linking the required information with that provided, due to difficulties in:

- reading: the pupil fails to identify the key words or symbols in the question.
- decoding: the pupil does not understand the meaning of the words, symbols, and text of the question.
- coding: the student understands the data in the problem but is unable to transcribe it correctly into the most appropriate symbolic system to arrive at the answer.

E2. Linguistic difficulties

The student has difficulty switching between everyday language and mathematical language, or vice versa. This includes an inability to understand different forms of representation (formulas, graphs, tables, icons, etc.) relating to the problems:

- syntactic: how symbols are combined and interrelated.
- semantic: what meaning the words, symbols, phrases, and the text have.

E3. Gaps in knowledge and skills

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The student experience difficulties caused by fundamental gaps or a lack of conceptual links in definitions, propositions and properties, observations, inferences, theorems, algorithms, or procedures, often due to several reasons at the same time.

E4. Logically flawed deduction

The student applies inappropriate rules or strategies.

M1. Lack of self-control and critical thinking

The student does not explain, step by step, the reasoning behind the solution, nor do they check the concepts or results. On the exam paper, they write only the result without any working, or, conversely, fill the paper with excessive calculations that should not be there. Furthermore, they do not explain the steps followed in words or use their own abbreviations.

M2. Technical mistakes

Incorrect arithmetic calculations (addition, subtraction, multiplication, division), as well as specific errors relating to signs, brackets, symbols, or letters (for example, confusing one sign with another).

M3. Harlow's 'error factors'

The student completes the task correctly, but not the one required.

M4. Complete neglect of certain topics in the syllabus

The student completely ignores certain problems or questions, leaving them unanswered without even attempting them.

M5. Formatting/organization issues

The student fails to number the pages, does not write their name on the exam paper, does not arrange the answers in the correct order for the questions (for example, answering point b) instead of point a), or problem 2 instead of point 1), or solves point b) before point a) even when these are related.

M6. Inability to assess the difficulty of a problem in advance

The student finds it difficult to choose the simplest solution and to estimate the time required and is unable to identify the most appropriate solution strategy.

METHODOLOGY

This article aims to identify and examine the nature of the difficulties students encounter when diagonalising matrices, considering three different time periods. The main objective is not only to identify errors, but also to investigate possible similarities and differences across these time periods. These interpretations may be linked to changes in the curriculum, the use of digital technologies and modern artificial intelligence tools. Based on this objective, the study adopts a qualitative-descriptive approach and, for the analysis of these difficulties, uses Pepkolaj's (2015) classification scheme as its main analytical framework.

Selected years of study

The document focuses on the years 2011, 2018 and 2025 as representative of three different educational systems. 2011: a traditional curriculum based on typical behaviorist approaches. 2018: a curriculum based on typical constructivist approaches. Use of technology as a computational aid. 2025: use of artificial intelligence tools. The choice of these three years – spaced out over time and not in continuous sequence – offers us the opportunity to identify important similarities and differences over time.

Key topic of the study

The diagonalisation of matrices was chosen as the sole central theme of the analysis for the following reasons: it is one of the core concepts of linear algebra that requires knowledge of many other topics; it is a subject of great importance for numerous applications in engineering; and the literature indicates that it is a particularly difficult topic for students. Diagonalisation forms an integral part of the

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curriculum across the three years under consideration, thereby allowing for comparability across different time periods.

Sample and data

The data for the study were drawn from the examination scripts for the first-semester Linear Algebra course at the Metropolitan University of Tirana, Albania. These scripts consist of the written answers submitted in the final examination for the course, which are held in the university's archives for each of the three time periods. The sample analysed comprises first-year students on the Computer Engineering and Electrical Engineering degree programmes, where Linear Algebra forms part of the curriculum. The anonymity of the participating students is fully guaranteed; therefore, no link to the students' actual identities is maintained at any stage of the analysis or presentation of the results. The research is based on students' actual responses, with no possibility of intervention or alteration of the test conditions. The number of test protocols analysed varies from year to year due to the availability of institutional archives. For this reason, the analysis does not aim to provide a quantitative comparison of error frequency, but rather to identify and carry out a qualitative comparison of the types of errors present in each year. One factor that reinforces the comparative validity of this study is the fact that the exercises used in the 2011, 2018 and 2025 tests are identical in terms of requirements and structure. This allows for a direct and methodologically sound comparison of the types of errors made by pupils in different temporal and curricular contexts, without the risk that the differences observed are the result of a change to the assessment tool itself.

Procedure for analysing difficulties

The analysis of students' difficulties with diagonalisation was carried out in three stages: In the first stage, for each time (2011, 2018, 2025), an independent coding of the difficulties encountered was carried out, in accordance with Pepkolaj's (2015) classification scheme. For each year, the categories of the scheme present were identified, as well as the specific form in which they manifested within the proposed problem. In the second stage, for each main category of difficulty identified, typical examples were selected, drawn directly from the scanned material of the protocols, to illustrate the classification in concrete terms and increase the analytical transparency of the coding. In the third phase, an intertemporal analysis was conducted of the results obtained in the two previous phases, examining (a) the similarities and differences in the types of difficulties across the three years under consideration; (b) the main factors that influenced point (a).

ANALYSIS AND DISCUSSION

The analysis of the corpus of students' difficulties was carried out in three stages, to ensure an in-depth descriptive study and to allow for a comparison across different time periods. In the first stage, the data were coded according to Pepkolaj's (2015) classification scheme for difficulties. Coding was carried out separately for each of the three periods considered in the study; 2011, 2018 and 2025, to familiarise the analysis with the details prior to any comparison. In the second phase, typical examples of all the types of difficulty encountered were selected from the coded corpus; these serve to illustrate specifically the categories identified in the scheme used and to provide as comprehensive a qualitative picture as possible. In the third phase, a systematic intertemporal comparison of the three periods under consideration was carried out, with the aim of identifying trends: which types of difficulties remain stable over time, which have increased or decreased, and how these trends can be interpreted in relation to possible curricular factors, digital technologies and AI tools that have influenced the respective periods.

The requirements for the exercises analysed are the same for all years: Given the matrix A, is the matrix A diagonaliseable? If so, find the matrix P that diagonalises A.

Figures illustrate concrete examples, taken from scanned protocols from 2011. These are accompanied by the respective tables covering the first and second stages of analysis, namely coding according to the classification scheme and the concrete illustration.

The case where A = (2 0 0; −12 5 6; 12 −3 −4).

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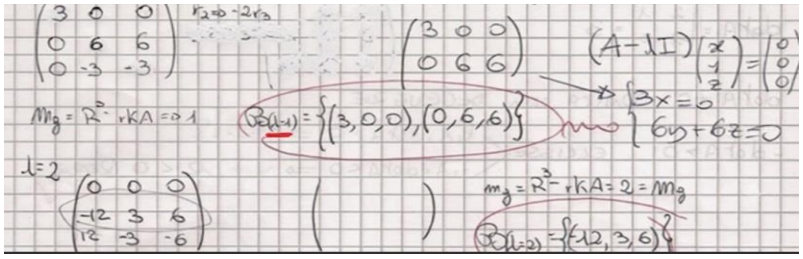


Figure 2 *Excerpt from student protocols, year 2011*

Code	Concrete illustration
E3	The fundamental flaw in the construction of the conceptual node of the eigenspace: it confuses it with the space generated by the rows of (A−λI) reduced to echelon form, instead of the correct definition as the kernel/nucleo of (A−λI), i.e. the set of vectors v that solve (A−λI)v = 0; for λ = −1 it writes B(λ = −1) = {(3,0,0), (0,6,6)} taking the rows of the reduced matrix themselves as basis vectors
E3/E4?	As a direct consequence of the conceptual misunderstanding (E3), he applies an inappropriate strategy/procedure ("take the rows of the reduced matrix as basis vectors") instead of the correct procedure (solve the homogeneous system (A−λI)v = 0 and parametrize the free variables); for λ = 2 he simply takes the second row of (A−2I), i.e. (−12, 3, 6), as the "basis" of V_2, without solving the system at all (E4)
M1	It does not verify (does not replace) any of the vectors taken as "basis" in the initial equation (A−λI)v = 0, such a check would have immediately revealed the error: e.g. substituting (3,0,0) into (A+I)v gives (9, −36, 36) ≠ (0,0,0), so (3,0,0) is not a valid eigenvector at all
E2	The λ values are written/highlighted (circled, underlined) in places in the expression where they should not appear (according to the remark: "The highlighted λ symbols should not be written", syntactic misuse of the λ symbol, confusing its role as a parameter of the characteristic equation with the notation within the result/final notation of the basis of the eigenspace

Table 1 *Typologies of difficulties for Figure 2*

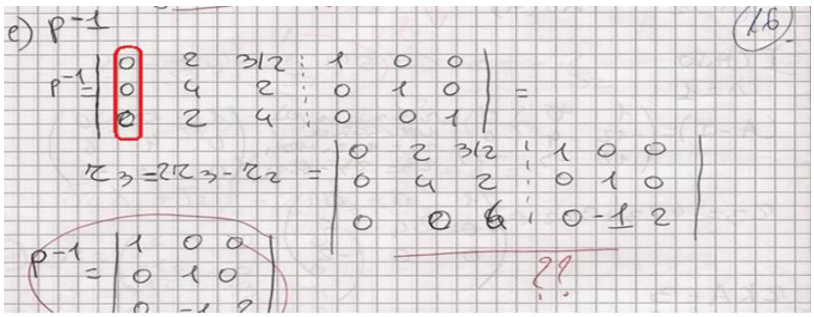


Figure 3 *Excerpt from student protocols, year 2011*

FULL TEXTS BOOK

Code	Concrete illustration
E4	It applies the Gauss-Jordan algorithm for computing P^{-1} without stopping when its basic condition (invertible P, no zero column) is clearly violated, it continues with row operations (e.g. $r_3 = 2r_3 - r_2$) on a first column (0, 0, 0) that mathematically can never return to (1,0,0), i.e. blindly continuing the procedure even after it has itself identified (circled in red) the problem
M1	(a) Again ignores the self-observation made (red encirclement of column zero), just like in the previous case with the construction of P; (b) the final result $P^{-1} = (1, 0, 0; 0, 1, 0; 0, -1, 2)$ written at the end does not match at all with the operations of the rows shown above (the first left column always remains zero), lack of comparison/check between the process and the final result
E3	The conceptual understanding is missing that a zero column in the augmented matrix [P|I] immediately indicates, from the outset (without the need for any row operations), that P is not invertible and that the entire Gauss-Jordan process is doomed to fail

Table 2 *Typologies of difficulties for Figure 3*

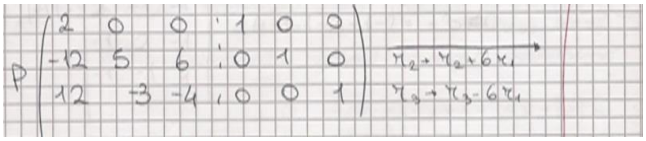


Figure 4 *Excerpt from student protocols, year 2011*

Code	Concrete illustration
E3/E1?	Takes the matrix A (2, 0, 0; −12, 5, 6; 12, −3, −4) itself and starts the Gauss-Jordan process to calculate A^{-1}, representing this as the matrix P, E3: fundamental conceptual lack of distinction between A (the original given matrix) and P (the matrix specially constructed from the eigenvectors, after finding λ and solving the systems $(A-\lambda I)v = 0$); there is no trace of calculating λ or the eigenvectors before this step, which indicates a continuation of the same pattern of A/P confusion observed earlier ($A-\lambda I$ confused with P). E1: at a superficial level, the very act of writing "P = " over the numbers of A shows an additional moment of lack of observation/distinguishment of symbols during writing, the student does not notice/read carefully which matrix he is labeling, simply confusing the symbol "P" with "A" on the paper
E4	As a direct consequence of the A/P confusion (E3/E1): it applies the full Gauss-Jordan procedure for inversion on the wrong object (A instead of P), producing a result (A^{-1}) that has no relation to what is required by the exercise (P^{-1}, the matrix that diagonalizes A)

Table 3 *Typologies of difficulties for Figure 4*

FULL TEXTS BOOK

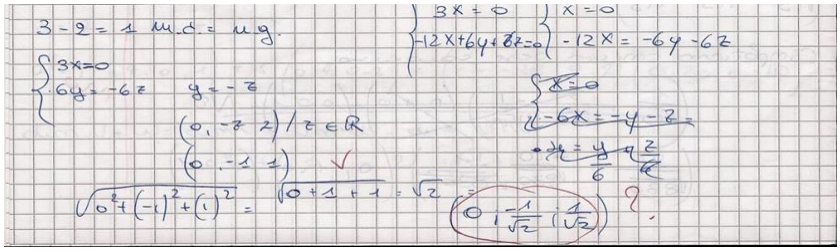


Figure 5 *Excerpt from student protocols, year 2011*

Code	Concrete illustration
M3	After correctly finding the eigenvector (0, −1, 1), it also performs the unnecessary calculation of the norm $\sqrt{(0^2 + (-1)^2 + 1^2)} = \sqrt{2}$ and presents the "normalized" vector as the result, while the exercise only requires P and P^{-1}, not vectors with norm = 1, Harlow's "error factor": does something well, but not what is required
M1	He questions the result (0, 1/√2, 1/√2), indicating that he himself feels uncertain about it, but does not follow up this self-doubt with any real verification (e.g., substituting the normalized vector into the original equation), a lack of closing the process with a concrete check, despite the expressed awareness.

Table 4 *Typologies of difficulties for Figure 5*

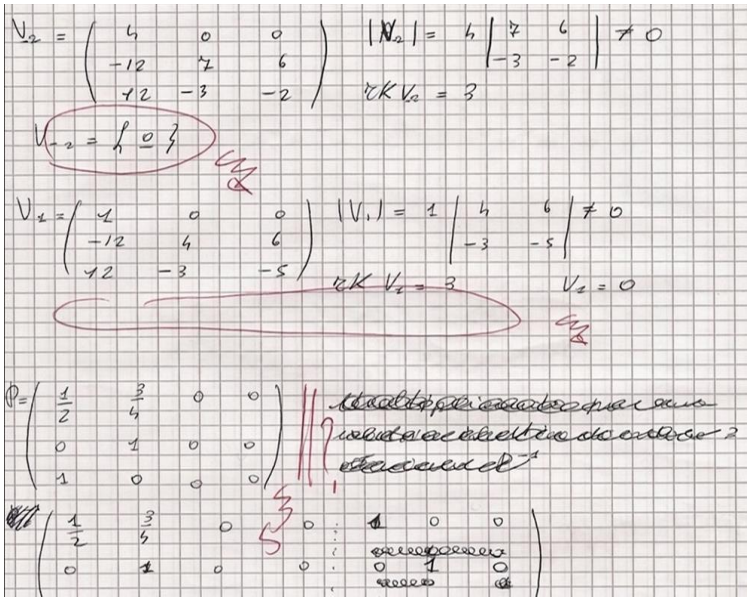


Figure 6 *Excerpt from student protocols, year 2011*

FULL TEXTS BOOK

Code	Concrete illustration
E2/E3?	For V_{-2}, I use the same symbol "V" for two completely different objects: once as the name of the matrix (A+2I), calculating $\|V_{-2}\|$ as its determinant, once as the name of the eigenspace itself (the set of solution vectors, "dim $V_{-2} = 0$"); syntactic overlap of the symbol that may have also contributed to the subsequent conceptual error (E3), incorrectly connecting "the determinant of the matrix ≠0" with "the space is {0}"
E3	Fundamental conceptual flaw, repeated twice within the same exercise: for V_{-2} and for V_1, from rk = 3 (so det ≠ 0) it incorrectly concludes dim = 0 and takes as "basis" the zero vector itself, while the eigenspace can never be {0} (otherwise the corresponding value would not be an eigenvalue at all); the repetition of the error without correction shows that the principle is not consolidated, not just a random slip
E4	Consequently: (a) it inserts the zero vector twice as additional columns of P, making P a non-square matrix (n>3 columns, instead of exactly 3); (b) nevertheless continues the process towards P^{-1} even though it clearly turns out that P = 0, blind continuation of the procedure even when its basic condition (P square and invertible) is violated
M1	Lack of control over the successive contradictions that arise during the process: P becomes non-square, P = 0 turns out, and the exercise requires P^{-1}, none of these clear signals stop or return the student to review the previous steps

Table 5 *Typologies of difficulties for Figure 6*

This picture emerges from the 2011 protocols analysed. Of the difficulties (shortcomings) identified, 80 per cent are classifiable (their cause is clearly known) and 20 per cent are unclassifiable (the cause is unclear), falling into the categories of error/mistake, error/error and mistake/mistake. Among the errors, the highest number is found in category E3 (shortcomings in knowledge and skills), mainly due to a lack of understanding of the concept of free space, the use of Gauss's algorithm, and fundamental gaps in calculating determinants and solving third-degree equations. Next comes type E4 (logically incorrect deduction), for example the application of Gauss's algorithm to incorrect objects, and type E2 (linguistic difficulties), involving the improper syntactic use of the term 'eigenvalue' and semantic overlap of the same concept. Type E1 (inappropriate use of data) is found in a very limited number of cases, where the data in the initial matrix are read incorrectly. Whilst the most common type of mistake is M1 (lack of checking and feedback), they do not provide verbal explanations, do not comment on the steps in the solution, and do not check the solutions they have arrived at, which affects their ability to continue with the problem. Next comes type M2 (technical mistakes), missing symbols, brackets, using the wrong type of bracket, substituting one matrix for another, etc. Then there are types M6 (inability to assess the difficulty of a problem in advance), M4 (giving up in advance on tackling problems relating to certain areas of the syllabus) and M5 (coding issues), where they fail to organise the solution to the problem correctly. Finally, type M3 (Harlow's error factors) is almost incomprehensible. Figures 7–10 below illustrate concrete examples, taken from scanned examination scripts from 2018.

FULL TEXTS BOOK

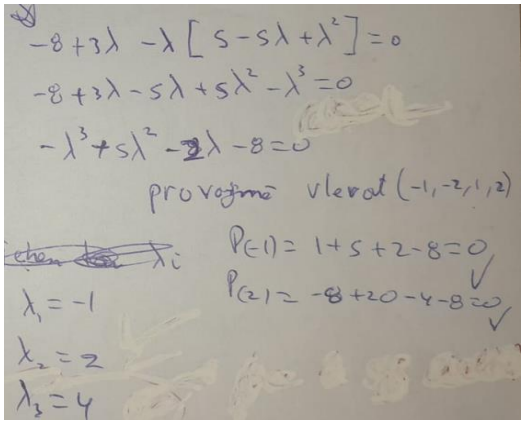


Figure 7 *Excerpt from student protocols, year 2018*

Code	Concrete illustration
M1/M6?	To find the first roots (−1 and 2), uses the trial/error method instead of initially implementing the most efficient strategy (polynomial division/Ruffini after finding the first root), failure to assess in advance the most appropriate way to solve the cubic equation; then, even though he correctly performs the polynomial division and derives the second-order polynomial, he writes the cubic root as the answer without verifying it in the original equation, lack of control/feedback in the final step of the solution

Table 6 *Typologies of difficulties for Figure 7*

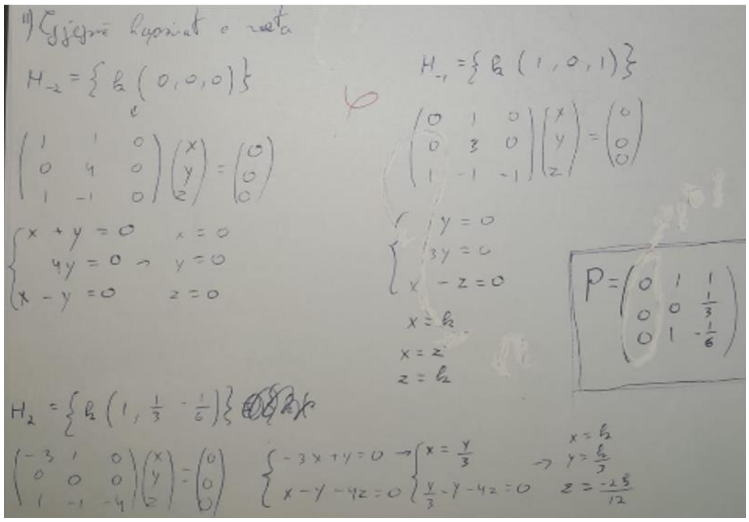


Figure 8 *Excerpt from student protocols, year 2018*

FULL TEXTS BOOK

Code	Concrete illustration
E3	Lack of knowledge/concept of a basis composed of linearly independent vectors, the student constructs the matrix P with the columns of the eigenvectors found without ensuring that they are linearly independent (a necessary condition for their set to form a basis of the space and for A to be diagonalizable); since one column results in the zero vector (from the wrong H_{-2}), the vectors cannot be linearly independent, so P cannot form a basis, a kind of conceptual knot (on the definition of linear independence/basis) that is missing or not applied
E1	He does not notice the absence of the symbol z in the equation $x-y = 0$ (which has nothing to do with z) and mistakenly uses this equation to derive $z = 0$, instead of recognizing z as a free variable (the third column of the matrix is zero in all three rows)
M1	(a) Does not verify that the result $H_{-2} = \{k(0,0,0)\}$ contradicts the basic definition of the eigenspace (no eigenvector can be the zero vector); (b) does not verify the final vector (1, 1/3, −1/6) of $\lambda = 2$ by substituting it into the initial equation $-3x+y = 0$; (c) does not note that the constructed matrix P (with zero column from H_{-2}) turns out to be non-invertible, in direct contradiction to the exercise's requirement to find P^{-1}; (d) never verbally comments on the solution steps, only symbols and consecutive results, without any written justification or logical connection ("personal shorthand")
M2	Technical error in the final parameterization/substitution of the eigenvector for $\lambda = 2$, the correct relation $x = y/3$ results in the vector (1, 1/3, −1/6), which does not itself satisfy the equation $-3x+y = 0$ (it should have been e.g. (1, 3, −1/2) or another consistent scaling)

Table 7 *Typologies of difficulties for Figure 8*

The case of the matrix A = (−1 1 0; 0 2 0; 1 −1 −2). The matrix P that diagonalizes A and P^{-1} is required.

The matrix P that diagonalizes A and P^{-1} is required.

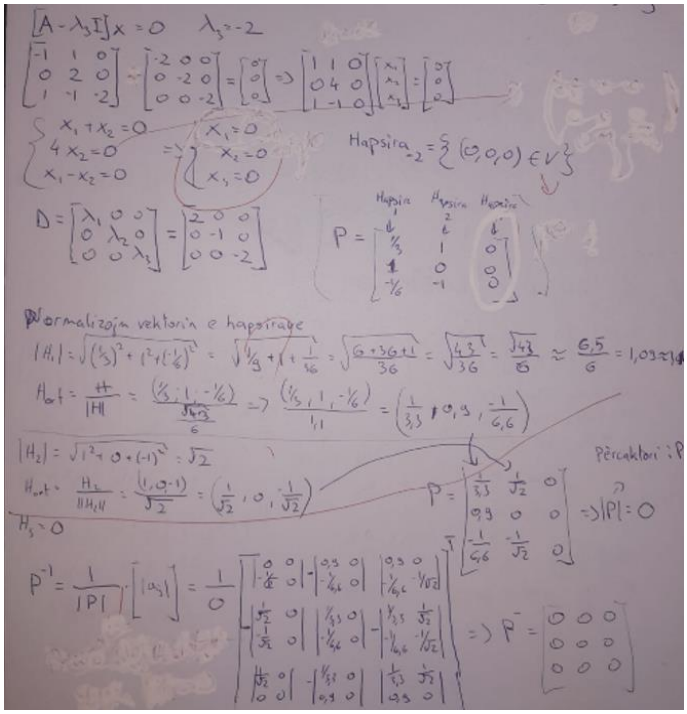


Figure 9 *Excerpt from student protocols, year 2018*

Code	Concrete illustration
E2	On the columns of the matrix P, it writes “Space”, “Space”, “Space”, that is, the name/concept of the repeated self-space, instead of the concrete basis vectors of each space themselves (which are the ones that should be placed as columns of P); it semantically confuses the self-space as a set/concept (H_x) with the specific element (vector) of this set that enters P
E3	Lack of knowledge/concept of a basis consisting of linearly independent vectors, constructs the matrix P with the columns of the eigenvectors without ensuring that they are linearly independent (a necessary condition for a basis and for the diagonalizability of A); since one column results in the zero vector, the vectors cannot be linearly independent, so P does not form a basis
E1	He does not notice the absence of the symbol z in the equation $x - y = 0$ (which has nothing to do with z) and mistakenly uses this equation to derive $z = 0$, instead of recognizing z as a free variable (the third column of the matrix is zero in all three rows)
M1	(a) Does not verify that the result $H_{-2} = \{k(0,0,0)\}$ contradicts the basic definition of the eigenspace (no eigenvector can be the zero vector); (b) does not verify the final vector (1, 1/3, −1/6) of $\lambda = 2$ by substituting it into the initial equation $-3x+y = 0$; (c) does not note that the constructed matrix P turns out to be non-invertible, in direct contradiction to the exercise's requirement to find P^{-1}; (d) never verbally comments on the solution steps, only symbols and consecutive results, without any written justification or logical connection (“personal shorthand”)
M2	Technical error in the final parameterization/substitution of the eigenvector for $\lambda = 2$, the correct relation $x = y/3$ results in the vector (1, 1/3, −1/6), which does not itself satisfy the equation $-3x + y = 0$ (it should have been e.g. (1, 3, −1/2) or another consistent scaling)
E1/ M3?	Misinterprets the exercise requirement and adds the unnecessary step of normalizing the eigenvectors (Decoding: the text only requires P and P^{-1}, not vectors with norm = 1), it does something that was not requested (S3, “they do well but not what was asked for”). Within this unnecessary step, an arithmetic error also occurs (it calculates 1/9 as 6/36 instead of 4/36 under the square root, taking $\sqrt{43}/6$ instead of $\sqrt{41}/6$), and in the end the "normalized" vector comes out identical to the original, so the operation of dividing by the norm itself is not actually performed
M1	Self-correction ignored: the result $H_{-2} = \{(0,0,0)\}$ is circled in red as questionable/incorrect, but the corresponding column remains zero in the construction of P below, the visual feedback is not used to correct the solution before continuing
E4	Logically incorrect deduction: after deducing $\lvert P\rvert = 0$ (due to the zero column), it mechanically continues to apply the formula $P^{-1} = (1/\lvert P\rvert)\cdot\text{adj}(P)$ without checking the fulfillment of its condition ($\lvert P\rvert \neq 0$), blind continuation of an algorithm even when its premise fails, producing a logically impossible result (P^{-1} = zero matrix)
M1	The apparent contradiction between the intermediate result (set P = 0, so P is not invertible) and the exercise requirement itself (find P^{-1}) does not raise any “alarm” in the student, a pronounced lack of control/feedback over the meaning of the results themselves during the process.

Table 8 *Typologies of difficulties for Figure 9*

FULL TEXTS BOOK

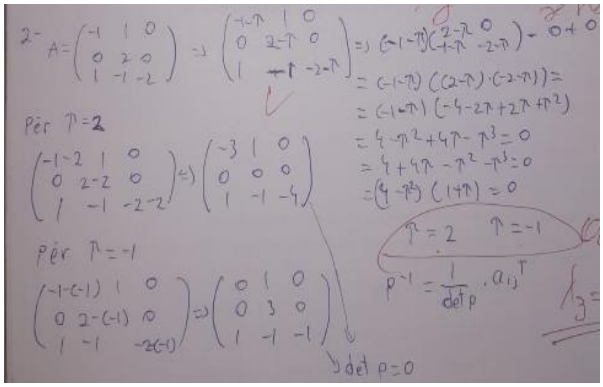


Figure 10 *Excerpt from student protocols, year 2018*

Code	Concrete illustration
E4	From the characteristic equation $(4-\lambda^2)(1+\lambda)=0$ (correctly calculated) it extracts only two roots ($\lambda = 2$, $\lambda = -1$) instead of three roots: from the factor $(1+\lambda) = 0$ it extracts correctly $\lambda = -1$, but from the factor $(4-\lambda^2) = 0$, i.e. $\lambda^2 = 4$, it obtains only the positive root $\lambda = 2$, losing the negative root $\lambda = -2$, incomplete application of the rule for extracting roots from an equation of the form $\lambda^2 = k$ (both $\pm\sqrt{k}$ are needed)
E3	Fundamental conceptual confusion between the matrix $A-\lambda I$ (the auxiliary matrix used only to find the eigenvalues/vectors, via $\det(A-\lambda I) = 0$ and $(A-\lambda I)v = 0$) and the matrix P (the matrix constructed later from the eigenvectors as columns), take $A-\lambda I$ itself as P; this also explains the notation "det P = 0" that arises as a direct consequence of the confusion, since $\det(A-\lambda I) = 0$ is precisely the condition that determines the eigenvalues, not a true property of the diagonalization matrix P (which has not yet been constructed with the eigenvectors at all)

Table 9 *Typologies of difficulties for Figure 10*

We have compiled this summary from the protocols analysed in 2018. Of the difficulties encountered, 75 per cent are classifiable and 25 per cent are unclassifiable, falling into the categories of 'error/mistake', 'error/error' and 'mistake/mistake'. Among the errors, the highest number is found in category E3, where the most common issues are the omission of propositions and observations regarding diagonalisation; students' lack of knowledge of the auxiliary properties that would facilitate reasoning; and, in rare cases, genuine gaps in basic knowledge relating to the solution of homogeneous linear systems and cubic equations. In some protocols, a recurring conceptual error is also observed: the construction of the diagonalising matrix P with a column containing a zero element, an error linked to a misunderstanding of the properties of linear independence of eigenvectors. The list of errors continues with types E4, calculation of the inverse of a matrix with a zero determinant and E2 for example, semantic confusion between the eigenspace of a matrix and a set or concept. Type E1 continues to be found in a relatively small number of cases, mainly due to a failure to recognise the symbols. The highest number of errors, however, is found in type M2, involving symbols, missing brackets and reversed objects, etc. This is followed by type M1, a lack of checking/feedback in the final stage of the solution; type M5, a failure to organise the problem-solving process; type M6, a failure to assess in advance the most appropriate method for solving the problem; and type M4, a failure to address or solve parts of the problem. Type M3 is virtually insignificant. Figures 11-18 onwards illustrate concrete examples, taken from scanned protocols from 2025.

FULL TEXTS BOOK

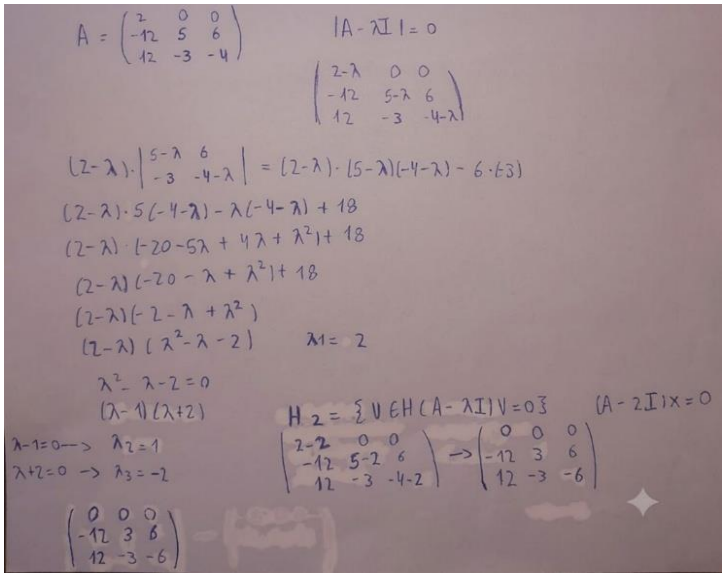


Figure 11 *Excerpt from student protocols, year 2025*

Code	Concrete illustration
E2	Non-substitution of λ⟶2 within the definition of H_2 (abstract formula remains); careless change of variable v⟶x within the same step. Syntactic-symbolic difficulty.
E2/S2?	Semiotic distinction ( ) and | | as concepts. Parentheses ( ) instead of | | for the determiner
E3	Wrong factorization of $\lambda^2-\lambda-2=0 \rightarrow (\lambda-1)(\lambda+2)$ instead of $(\lambda-2)(\lambda+1)$. Basic gap
E3	Ignoring the algebraic multiplicity of λ=2, the diagonalizability criterion is not checked.
M4/E3?	It starts with H_2 (in error) but leaves it halfway, missing Gaussian elimination to the actual H_2
M1	No explanatory words/comments during the process; roots and steps performed are not verified
M2	Missing "= 0" during the expansion of the characteristic polynomial; missing square brackets [ ] in the calculation/expansion of the second-order determinant
M2/E3?	Sign confusion. Error in finding H_{-2}. H_2 is calculated for $\lambda = 2$ instead of $\lambda_3 = -2$ (self-found)

Table 10 *Typologies of difficulties for Figure 11*

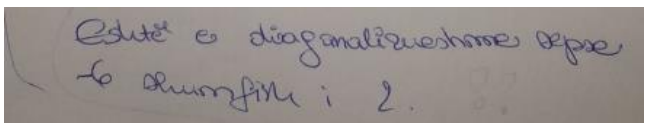


Figure 12 *Excerpt from student protocols, year 2025*

FULL TEXTS BOOK

Code	Concrete illustration
E4	Justifies diagonalizability with "-6 multiple of 2", arbitrary numerical relation, unrelated to real criterion (mg = ma or distinct eigenvalues)

Table 11 *Typologies of difficulties for Figure 12*

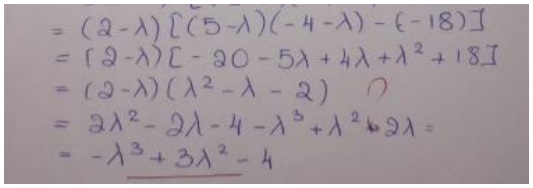


Figure 13 *Excerpt from student protocols, year 2025*

Code	Concrete illustration
E3/M6?	It is faced with (order I)·(order II) = 0 and performs the multiplication on a polynomial of order III instead of applying the property "product=0 → each factor = 0"; it may be a lack of the principle itself or a non-optimal choice of the easiest strategy/path

Table 12 *Typologies of difficulties for Figure 13*

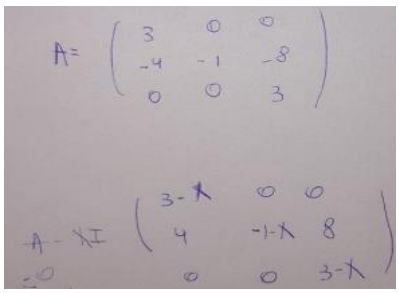


Figure 14 *Excerpt from student protocols, year 2025*

Code	Concrete illustration
E1	Misreading of a data item in matrix A (e.g. −8 is read/copied as 8), loss of sign during transcription of the original data
M2	Missing "=0"

Table 13 *Typologies of difficulties for Figure 14*

FULL TEXTS BOOK

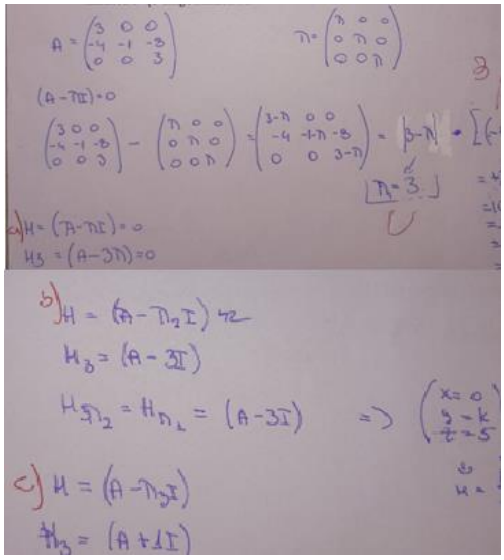


Figure 15 *Excerpt from student protocols, year 2025*

Code	Concrete illustration
E2/E3?	Writes λ instead of λI, fails to differentiate that scalar–matrix subtraction necessarily requires the identity matrix (may be symbolic misuse or lack of definition itself)
E2	Confuses (A−λI) = 0 (matrix equation) with ‖A−λI‖ = 0 (scalar/determinant equation), syntactic confusion between two different mathematical objects
E2/E3?	Equates a 3×3 matrix to the value of its determinant, does not distinguish the matrix (object) from the determinant (scalar); may just be a notation error or a conceptual lack of the determinant itself
E3/M1?	Defines the eigenspace H = (A−λI) = 0 (without kernel/vector v), then slides from H_3 to H_λ1 = H_λ2 = (A−3I), missing the exact definition of Hλ = ker(A−λI), accompanied by personal shorthand/lack of index control

Table 14 *Typologies of difficulties for Figure 15*

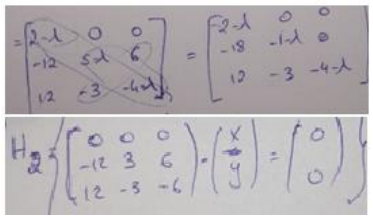


Figure 16 *Excerpt from student protocols, year 2025*

FULL TEXTS BOOK

Code	Concrete illustration
E4	Subtracts a row by its 3rd element during the elimination process (e.g. R2 → R2 − a32·R3), incorrect/invented application of the Gaussian elimination step instead of the correct pivot row multiple subtraction rule
E2/E3?	Writes $H_2 = (3\times3)(2\times1) = (0,0)$, matrix-vector multiplication with incompatible dimensions; ignores that a 3×3 matrix requires a 3×1 vector, and the eigenspace Hλ lives in $\mathbb{R}^3$, not $\mathbb{R}^2$

Table 15 *Typologies of difficulties for Figure 16*

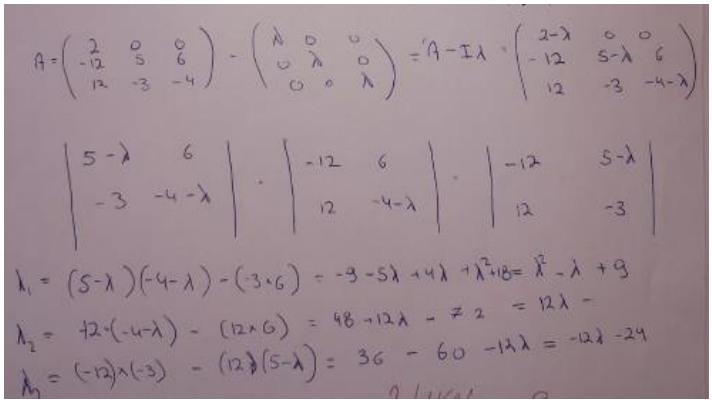


Figure 17 *Excerpt from student protocols, year 2025*

Code	Concrete illustration
E3	Decomposes the 3rd order determinant as the product M11·M12·M13 instead of the sum with alternating signs a11M11 − a12M12 + a13M13, missing Laplace's rule
E2/E3/M1?	The eigenvalues are “extracted” as polynomials (algebraic expressions), not as numbers/roots of the characteristic equation, confusing the “polynomial” object with the “solution” object, or stopping before closing the process at = 0 The student stops at the polynomial expression without taking the process to numbers/roots, it could be (E2) confusing the “polynomial” object with the "eigenvalue/number" object, (E3) lack of the conceptual connection between the characteristic polynomial and the eigenvalues, or (M1) lack of control that the process has closed to the end (= 0, solution)
E3/M6?	Each minor Mij separately equates to 0 (e.g. M11 = 0, M12 = 0, M13 = 0 as independent equations) instead of constructing the full determinant expression and then equating it to zero. The knowledge seems to exist, but the strategic judgment fails, precisely the territory of M6.

Table 16 *Typologies of difficulties for Figure 17*

FULL TEXTS BOOK

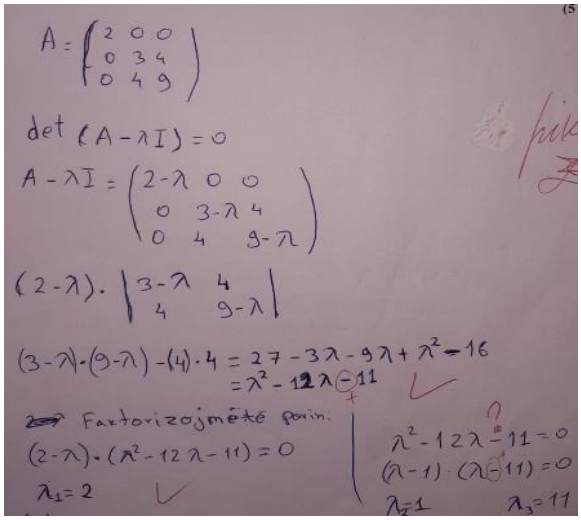


Figure 18 *Excerpt from student protocols, year 2025*

Code	Concrete illustration
M1/M2?	Calculates (3−λ)(9−λ)−16 and writes λ²−12λ−11 (wrong sign on the constant term; correct would be +11), then factors as (λ−1)(λ+11), which itself does not match λ²−12λ−11 (expands as λ²+10λ−11); the final roots (λ = 1, λ = 11) are however correct, which indicates an uncontrolled discrepancy between the written steps
M5	Unclear/inconsistent labeling of the second eigenvalue index — writes "λ̄ = 1" instead of λ2 = 1; furthermore, the final eigenvalues (λ1 = 2, λ2 = 1, λ3 = 11) are not arranged together as a single organized answer, but are scattered across different locations/columns of the sheet, lack of clear coding/organization of the answer within the solution protocol

Table 17 *Typologies of difficulties for Figure 18*

From the protocols analysed from 2025, we have compiled this summary. Of the difficulties encountered, 65 per cent are classifiable and 35 per cent are unclassifiable, falling into the categories of 'error/mistake', 'error/error' and 'mistake/mistake'. There are also cases of ambiguity, such as 'error/error/mistake'. Among the errors, the highest number is found in category E3, where there is a lack of procedures and algorithms, as well as basic propositions and properties; examples include a lack of knowledge of the diagonalisation theorem, a failure to distinguish between algebraic and geometric multiplicity, and a lack of understanding of the concept of an eigenspace. Also, within category E3, some cases are specifically linked to prior gaps in knowledge, such as the factorisation and multiplication of polynomials, the incorrect solution of second- or third-degree equations, errors in calculating the determinant itself, and errors in solving systems of linear equations. Then there are the E2 types, involving syntactic and semantic confusion, and E4 types, for example when algebraic multiplicity is mistakenly interpreted as 'ordinary multiplicity' without any connection to its specific meaning within the theory of diagonalisation. E1 occurs in a relatively small number of cases, where the data in the matrix are interpreted incorrectly. At the same time, and in a relatively large number of cases, there are technical errors of type M2: sign errors, spelling mistakes involving the determinant symbol confused with matrix brackets, failure to apply the equality to zero, confusion between the identity matrix and the zero matrix, and the eigenspace H itself being mistaken for the matrix A. Then there is the M1 type: students do not write out their reasoning, do not comment step-by-step on the solution to the problem, and do not check their understanding of the concepts or their solutions. The list continues with the M5 type, where answers to questions are not organised; M4, where the problem and

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the questions jump from one part to another, leaving the problem and the question in the middle; and M6, where students struggle to choose the simplest way to solve the problem. Ultimately, M3 is almost insignificant.

Let us now turn to the discussion relating to the first research question: a comparative analysis of the difficulties encountered in different years. In 2011, many of the difficulties observed clearly fell within the classifiable categories, whilst only a small proportion belonged to the unclassifiable categories. In 2018, unclassifiable difficulties increased, indicating that they were taking on more complex forms and did not fit entirely into any single category of the framework. This trend became even more pronounced in 2025, when over a third of the difficulties could not be definitively attributed to a single category. This continuous year-on-year increase in the unclassifiable proportion suggests an evolution in the very nature of the difficulties: whilst in the past they were more 'clear-cut' and distinct (for example, a simple technical error or a simple conceptual shortcoming), over time the origin of the difficulties has become less defined. Further concrete measures are therefore needed to understand the types of difficulties involved, namely, whether they fall into one category or the other, both, or whether something else is emerging.

Similarities: E3 remains constant and is at its highest level across all years; conceptual/knowledge-related difficulty is the most frequent and consistent issue across the three study periods. E4 is also among the most frequently occurring codes in all years, where, together with E3, it dominates category E. E3 and E4 dominate the category of unclassifiable difficulties. M2 is high and relatively stable amongst the main M categories in all years. M3 consistently remains the code with the lowest frequency. In all years, difficulties are found across all types of the scheme.

Differences: Gradual decline in E4: from (2011) → (2018) → (2025), a clear downward trend. This could suggest a slight improvement over time in the application of logical rules and strategies. Increase in unclassifiable difficulties: 20 per cent (2011) → 25 per cent (2018) → 35 per cent (2025); difficulties are becoming increasingly complex/hybrid (as we have also shown with the combinations E./E., E./M., M./M.), making it difficult to place them in a single category of the scheme. M1 and M2 have shown a significant increase over the years. M5 shows a clear upward trend, perhaps linked to the rise in organisational carelessness amongst students in recent years. E1 increased from 2011 to 2018, then decreased in 2025; this is not a linear trend, but rather a slight fluctuation. E2 decreases in 2018 compared with 2011 and 2025, showing a non-linear fluctuation, in contrast to E4. M4 is relatively stable, with only a slight increase in 2025.

Whilst the difficulties in category E generally show stability or a slight improvement (E3 remains constant, E4 is decreasing), those in category M (M1, M4, M5) show a general upward trend, alongside an increase in the percentage of unclassified cases. This might suggest that students in more recent years have slightly improved their conceptual-logical skills, but are encountering increasing difficulties with attention, self-control, and work organisation.

Type E difficulties, primarily E3, E4 and E2, that is, errors at the cognitive, logical, and linguistic levels – remain constant over the years, as they are linked to the brain's basic capabilities. Memory, the ability to make logical deductions and the understanding of abstract concepts form part of the brain's natural 'hardware', which does not change significantly over time or because of changes in teaching approaches.

The significant increase in M1 cases in recent years points to a gradual decline in the culture of mathematical reasoning and communication. Students tend to provide only the result, without explaining or documenting the logical process that led them to that result; the intermediate steps are 'lost' or simply not recorded at all. Students no longer feel the need to demonstrate or verify their solution step by step, as if the thought process remained only 'in their head and not on paper'. This is accompanied by a tendency towards a sort of 'personal shorthand' – brief symbolic notes, comprehensible only to the student themselves, rather than a complete and communicable mathematical language. The opposite also occurs sometimes the page is full of superfluous calculations that ought not to be there, as if the student were unable to distinguish between what is essential to communicate and what is not, or were failing to organise the solution correctly, hence the emergence of M5. This increase in M1 can be interpreted as a sign of a broader shift: from a teaching culture that demanded explanation, justification, and complete

transparency of the process, towards a more 'fast-paced' and results-oriented approach, in which the very act of reasoning in writing – the foundation of mathematical thinking – is significantly weakening among younger generations of students.

The M2 score has also risen due to several factors, including: a growing reliance on technology, which has weakened the ability to perform mental calculations; increasingly limited time for independent study; the accumulation of gaps in basic knowledge; and anxiety about the difficulty of the subject.

We now turn to the discussion relating to the second research question: factors that have determined the similarities and differences identified in the first research question.

Each generation of students included in this study followed a different educational model, and this allows us to interpret the evolution of errors not simply as a random 'deterioration', but as a direct reflection of the different teaching philosophies that have shaped the mathematical thinking of each generation.

2011 – The legacy of the old curriculum

The students of 2011 came from a curriculum heavily influenced by the Eastern model: teacher-centred teaching, a behaviourist approach in which knowledge was imparted as something ready-made and reproduced through repeated practice, and a strong emphasis on logical rigour and mathematical abstraction. Although this model is now criticised for its lack of a student-centred approach, it produced students who were disciplined in the formal structure of thought: step-by-step procedures, clear proofs and strict adherence to symbolic syntax were part of the very culture of teaching. This perhaps explains why, in 2011, we had the highest rate of classifiable difficulties (80 per cent) and a relatively low proportion of M1 students, not necessarily because these students 'understood more', but because they had been systematically trained to show every step and to argue their case in writing, even when the thought process itself was mechanical.

2018 – The shift towards constructivist approaches, competence-based curricula, and technologies as computational support

The 2018 cohort marks a turning point: the new competence-based curriculum shifts the emphasis from 'reproduced knowledge' to 'the ability to apply', a pedagogically sound objective, but one which in practice has often led to a relaxation of the requirement for formal reasoning and step-by-step demonstration. At the same time, the gradual introduction of technology (graphical calculators, online resources, digital platforms) has begun to partially replace manual calculation and the full written out of the procedure. The rise in 'unclassifiable' answers to 25 per cent and the increase in M2 (technical errors) and M1 can be interpreted as the first sign of this transition: students are beginning to rely more on the result and less on documenting the procedure, whilst the nature of the difficulties is becoming more interlinked (E/M combinations), as the new skills require the simultaneous integration of conceptual, linguistic, and strategic knowledge.

2025 – The same curriculum, but with new disruptions brought about by digital technologies such as 'reasoning systems and the use of artificial intelligence tools

Pupils in 2025 are formally following the same curriculum with the same skills as those in 2018, but with at least two significant additional factors: the pandemic, which led to months of online or hybrid teaching during their formative years in primary and secondary school, a period when written reasoning and self-regulation skills are usually consolidated, and the widespread introduction of artificial intelligence, which offers pupils the opportunity to receive ready-made answers without necessarily having to follow their own thought process. This largely explains two key trends in the data: the rise in M1 (lack of reasoning, control, 'description' of the process) and the rise in M5 (organisation/coding problems). In a context where the answer can be obtained quickly and 'ready-made', whether from a digital tool or from the habit acquired during online learning of seeking the quickest shortcut, the very act of written reasoning, of explaining step by step why and how a result is achieved, loses its perceived value as a necessity. The student achieves the result, but 'maps out' the path to it less and less.

CONCLUSIONS

This study suggests a two-fold interpretation. On the one hand, category E (conceptual errors, logical deductions, linguistics) remains stable over the years. Therefore, the ability to understand concepts has not changed, regardless of curricular factors, digital technologies, and artificial intelligence tools. On the other hand, category M (technical errors, attention, organisation, self-control, communication) shows a decline, increasing from one generation to the next, particularly for types M1, M2 and M5. This leads us to the interpretation that the difficulties faced by today's pupils do not lie solely in 'mathematical knowledge' itself, but in self-control and the communication of that knowledge. This competence was present in the 2011 behaviorist curriculum model but was diluted with the transition to a competence-based curriculum in 2018 and has deteriorated further in 2025 due to factors such as digital technologies and current artificial intelligence tools, which have not enabled students to move beyond verbal writing and the communication of mathematical thought.

The gradual increase in the proportion of unclassifiable difficulties (20%→25%→35%) reinforces the interpretation of the idea: today's difficulties are increasingly less 'pure', 'distinct' and 'isolated', because the very nature of modern learning – mediated by technology and disconnected from the old routine of in-depth reasoning, produces hybrid difficulties, in which a conceptual shortcoming may not be clearly distinguishable from a failure in communication or organisation. This is, in fact, the analytical essence of the article: relatively 'pure' errors are set against a new educational reality in which the very boundaries between categories are becoming increasingly blurred. This article offers an important pedagogical insight: today's students have a great need for specific training not only in mathematical content, but also in reasoning, written expression, and self-regulation.

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GENÇ YETİŞKİNLERDE MEDİAL LONGİTUDİNAL ARKIN CİNSİYET, AYAK DOMİNANSI VE BEDEN KİTLE İNDEKSİNE GÖRE DEĞERLENDİRİLMESİ

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ÖZET

ARKA PLAN: Medial longitudinal ark (MLA), ayağın fonksiyonel kapasitesini, şok absorpsiyonunu ve yürüyüş dinamiğini belirleyen temel yük taşıyıcı anatomik arktır.

AMAÇ: Bu çalışma; MLA'nın cinsiyet, beden kitle indeksi (BKİ) ve ayak baskınlığına göre farklılaşıp farklılaşmadığını değerlendirmeyi ve iki farklı MLA değerlendirme yönteminin birbiriyle ve bu faktörlerle olan ilişkisini incelemeyi amaçlamaktadır.

YÖNTEM: Ayak deformitesi bulunmayan, 18–25 yaş arasındaki 120 sağlıklı gönüllü (60 erkek, 60 kadın) çalışmaya dahil edilmiştir. Bilateral MLA parametreleri, Staheli Ark İndeksi ve Normalize Edilmiş Kısaltılmış Naviküler Yükseklik (NTNH) yöntemleriyle ölçülmüştür. Ayak izleri, literatürde tanımlanan mürekkepsiz yöntemlerden uyarlanmış su bazlı baskı tekniğiyle elde edilmiş, naviküler tüberozite palpe edilerek işaretlenmiş ve demir cetvelle yüksekliği ölçülmüştür. Staheli İndeksi ve NTNH değerleri hesaplanmış; istatistiksel değerlendirmeler Pearson korelasyon katsayıları (Spearman ile doğrulanmış) ve Karma ANOVA testleri kullanılarak yapılmıştır.

BULGULAR: Ayak baskınlığının her iki indeks üzerinde de anlamlı bir etkisi bulunmamıştır (Staheli: $p = 0,311$; NTNH: $p = 0,689$); her iki indeks için dominant, non-dominant ayak korelasyonları yüksek bulunmuş (sırasıyla $r = 0,881$ ve $r = 0,814$), bu durum bilateral simetrinin korunduğuna işaret etmektedir. Buna karşın cinsiyet × BKİ etkileşimi her iki indeks için de anlamlı bulunmuştur (Staheli: $p = 0,031$; NTNH: $p = 0,009$). Bu etkileşim ağırlıklı olarak obez kadınlar tarafından yönlendirilmekte olup her iki indeks bu grupta, normal kilolu gruptan anlamlı biçimde farklılaşmaktadır (sırasıyla $p = 0,006$ ve $p = 0,001$) ancak zıt yönlerde: Staheli İndeksi artmış (daha düşük ark) ve NTNH de artmıştır (daha yüksek ark). Erkeklerde böyle bir ayrışma gözlenmemiştir. İki indeks arasındaki korelasyon zayıf bulunmuştur (dominant ayak: $r = -0,140$; non-dominant ayak: $r = -0,195$); oysa her indeksin kendi içindeki bilateral güvenilirliği yüksektir. Bu durum, iki yöntemin arkın farklı anatomik boyutlarını ölçtüğüne işaret etmektedir.

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SONUÇ: Ayak baskınlığı MLA morfolojisini etkilemezken, cinsiyet ve BKİ etkileşimli olarak MLA'yı şekillendirmektedir. En belirgin ve kendi içinde çelişkili değişimler obez kadınlarda gözlenmektedir. Ayak izi temelli bir ölçüm (Staheli) ile iskelet temelli bir ölçüm (NTNH) arasındaki ayrışma, bu popülasyonda vücut ağırlığı altında yumuşak doku değişiklikleri ile kemiğin yapısal değişiminin örtüşmeyebileceğine ve ark morfolojisini tek bir yöntemle karakterize etmenin yetersiz kalabileceğine işaret etmektedir. Obez kadınlarda MLA'nın klinik değerlendirmesinde ayak izi temelli ve iskelet temelli ölçümlerin birlikte kullanılması faydalı olabilir.

Anahtar Kelimeler: Medial Longitudinal Ark, Ayak, Cinsiyet Faktörleri, Staheli Ark İndeksi, Normalize Edilmiş Kısaltılmış Naviküler Yükseklik, Beden Kitle İndeksi, Genç Yetişkin, Ayak Baskınlığı

GİRİŞ

MLA, ayağın yük taşıma ile şok emme kapasitesini ve yürüyüş dinamiğini belirleyen ayaktaki üç büyük anatomik arktan (medial ve lateral longitudinal arklar ile transvers tarsal ark [TTA]) birisidir (Gwani ve ark., 2017; Babu & Bordoni, 2024). MLA; kemik yapılar, ligamentöz destek unsurları ve plantar fasya birlikte, tüm vücut ağırlığını taşıyabilen elastik ve adapte olabilen bir taban oluşturur. MLA'yı oluşturan kemik yapılar kalkaneusun medial kısmı, talus, naviküler kemik, üç kuneiform kemik ve ilk üç metatarsal kemiktir (Babu ve Bordoni, 2024).

MLA sayesinde ayak, yürüme döngüsünün (gait cycle) farklı evrelerinde esnek veya rijit bir yapıya bürünebilir (Bevans, 1992). Bu çift karakterli (dikotomik) işlev, birbirini tamamlayan iki mekanizmayla açıklanır: ark-yay (arch-spring) mekanizması ve windlass mekanizması (Ker ve ark., 1987). Topuğun yere değmesiyle başlayan erken duruş evresinde, ark-yay mekanizması devreye girerek MLA'nın esnek bir şekilde çökmesine ve kinetik enerjinin plantar fasya ile ligamentöz yapılarda elastik enerji olarak depolanmasına olanak tanır (Ker ve ark., 1987). Geç duruş evresinde ise metatarsofalangeal eklemlerin dorsifleksiyonu, plantar fasyanın metatars başları etrafında sarılmasına (windlass etkisi) yol açarak arkı yükseltir, ayağı rijit bir kaldıraç koluna dönüştürür ve depolanan enerjinin itiş (propulsion) için serbest bırakılmasını sağlar (Bevans, 1992; Ker ve ark., 1987; Jastifer & Gustafson, 2014; Sorrentino ve ark., 2023).

Bu mekanizma bipedal lokomosyon sergileyen hominin soy hattına, arboreal primatlara kıyasla, yürüyüşte daha yüksek bir metabolik verimlilik (Leonard ve Robertson, 1995) ve uzun mesafe koşu kapasitesi (endurance running) bakımından belirgin bir avantaj sağlar (Bramble ve Lieberman, 2004; Sorrentino ve ark., 2023). Öte yandan, insan ayağının en yakın akrabası olan şempanzeye kıyasla yürüyüş sırasında orta ayak bölgesinde belirgin biçimde daha geniş bir hareket açıklığı sergilediği gösterilmiştir (Holowka ve ark., 2017). Ayrıca bu işlevsel avantajda yalnızca MLA değil, metatarsal arası dokular aracılığıyla ayağın boylamasına sertliğine %40'tan fazla katkı sağlayan TTA'nın da kritik bir rol oynadığı ortaya konmuştur (Venkadesan ve ark., 2020). Bu denli temel bir işleve sahip olmasına rağmen, MLA'nın bireyler arasında ne ölçüde farklılık gösterdiği ve bu farklılığı hangi faktörlerin belirlediği net değildir.

Literatürde MLA'nın cinsiyet, beden kitle indeksi (BKİ) ve ayak baskınlığı gibi faktörlere göre farklılık gösterebildiği çeşitli ölçüm yöntemleriyle incelenmiştir. Örneğin, footprint temelli ölçümlerin obez bireylerde plantar yağ yastığı kalınlaşmasından etkilenerek gerçek kemik yapısından bağımsız sonuçlar verebileceği bildirilmiştir (Wearing ve ark., 2012). Cinsiyetler arası farkların ise kadınlarda görülen daha yüksek ligament laksitesi ve MLA'nın ağırlık taşıma altında daha fazla deforme olmasıyla ilişkilendirildiği gösterilmiştir (Fukano & Fukubayashi, 2012); nitekim kadınlarda ark yüksekliğinin erkeklere kıyasla daha düşük olduğu da ayrıca doğrulanmıştır (Zhao ve ark., 2020). Ancak bu bulgunun aksine, bazı çalışmalar yük taşıma altındaki naviküler yükseklik değişiminin cinsiyete göre anlamlı farklılık göstermediğini bildirmiştir (Hussain ve ark., 2024). Ayak baskınlığının MLA üzerindeki etkisi konusunda ise literatür tutarsızdır. Bazı çalışmalar dinamik ve statik koşullarda dominant ve dominant olmayan ayak arasında grup düzeyinde anlamlı bir fark bulunmadığını bildirirken (Molitor ve ark., 2024; Yu ve ark., 2020), bazı çalışmalar özellikle çocuklarda dominant olmayan ayakta daha sık anormal ark tipi bildirmiştir (Hadoush ve ark., 2025). Benzer şekilde, BKİ'nin MLA üzerindeki etkisi konusunda da

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fikir birliği yoktur, bazı çalışmalar anlamlı bir ilişki bulamazken (Soni & Shah, 2025), bazıları BKİ gruplarına göre anlamlı farklar bildirmiştir (Rosende-Bautista ve ark., 2021). Ayrıca naviküler temelli ölçümler ile footprint indeksleri arasındaki ilişkinin orta düzeyde kaldığı ve yöntemlerin birbiriyle tam olarak örtüşmediği gösterilmiş, bu durum yöntemler arası karşılaştırılabilirliği sınırlayan bir faktör olarak öne çıkmıştır (Zuil-Escobar ve ark., 2018). Ancak MLA değerlendirmesinde ve ayak ark tipinin sınıflandırılmasında tüm bu durumlar için geçerli tek bir optimal ölçüm yöntemi bulunmamaktadır (Razeghi ve Batt, 2002; Queen ve ark., 2007). Farklı ölçüm yöntemlerinin farklı sonuçlar ortaya koyabilmesi, yöntemler arasındaki ilişkilerin ve ölçümlerin karşılaştırılabilirliğinin değerlendirilmesini önemli kılmaktadır.

Bu araştırmada MLA'nın cinsiyet, BKİ ve ayak baskınlığına göre değişimi iki farklı ölçüm tekniğiyle incelenmiş, bu tekniklerden elde edilen değerlerin kendi içlerindeki ve birbirleriyle olan ilişkileri kesitsel bir tasarımla değerlendirilmiştir.

YÖNTEM VE GEREÇLER

Katılımcıların Demografik Özellikleri

Çalışmaya 18-25 yaş arasında, çalışmayı etkileyecek bilinen alt ekstremite deformitesi, geçirilmiş ayak cerrahisi veya nöromüsküler hastalığı olmayan 60'ı erkek (%50,0) ve 60'ı kadın (%50,0) olmak üzere toplam 120 gönüllü dâhil edilmiştir. Katılımcılar beden kitle indeksi (BKİ) değerlerine göre normal, fazla kilolu ve obez olmak üzere üç gruba ayrılmış, her grupta 20 erkek ve 20 kadın yer alacak şekilde dengeli bir dağılım sağlanmıştır (Tablo 1). Analizlerde eksik veri bulunmamaktadır.

Tablo 1. Katılımcıların cinsiyet ve BKİ grubuna göre dağılımı

Cinsiyet	Normal	Fazla kilolu	Obez	Toplam
Erkek	20 (%33,3)	20 (%33,3)	20 (%33,3)	60 (%50,0)
Kadın	20 (%33,3)	20 (%33,3)	20 (%33,3)	60 (%50,0)
Toplam	**40 (%33,3)**	**40 (%33,3)**	**40 (%33,3)**	**120 (%100)**

Yüzde değerleri satır içi orandır. BKİ: Beden kitle indeksi.

Medial Longitudinal Ark (MLA) Değerlendirme Yöntemleri (Evaluation Methods of MLA)

MLA'nın vücut ağırlığı altında statik ayak yapısının değerlendirilmesinde, Staheli Ark İndeksi (SI) ve Normalized Truncated Navicular Height (NTNH) parametreleri kullanılmıştır.

SI: ayak izinde orta taban bölgesinin en dar genişliğinin (A), topuk bölgesinin en geniş yerine (B) oranlanması (A/B) esasına dayanır. Staheli Ark İndeksinin değerlendirilmesi için alınan ayak izinde, literatürde tanımlanmış mürekkepli ayak izi yöntemlerinden uyarlanmış olan su bazlı (inkless/mürekkepsiz) ayak izi tekniği kullanılmıştır (Staheli ve ark., 1987; Williams ve McClay, 2000; Zuil-Escobar ve ark., 2016; Ramos ve ark., 2021). Staheli Ark İndeksi değerinin 1,0'ın üzerinde olması düşük ark (pes planus), 0,7–1,0 aralığında olması normal ark yapısı, 0,7'nin altında olması ise yüksek ark (pes cavus) olarak değerlendirilmiştir (Akıl ve Çolak, 2020).

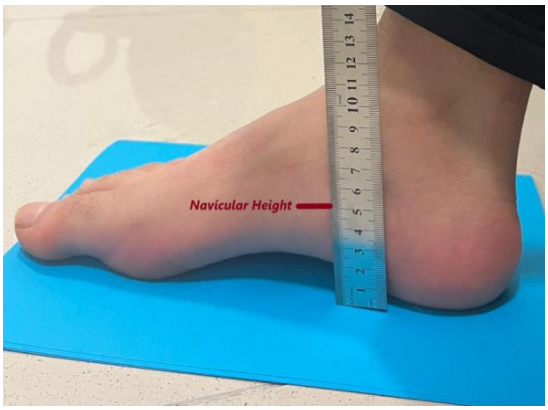
NTNH: Naviküler Yükseklik (NH) değerinin Kısaltılmış Ayak Uzunluğuna (Truncated Foot Length /TFL) bölünmesi ile elde edilir (Williams ve McClay, 2000; Murley ve ark., 2009; Aboelnasr ve ark., 2018). NH, naviküler kemiğin zemine olan dik mesafesidir. TFL ise, ayak uzunluğundan ayak parmak uzunlukları çıkarılarak elde edilir. NTNH için değer aralığı: ≤0,21 düşük ark (düz taban), ≥0,22 ve <0,32 normal ark, ≥0,32 yüksek ark olarak kabul edilmiştir (Murley ve ark., 2009).

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Prosedür

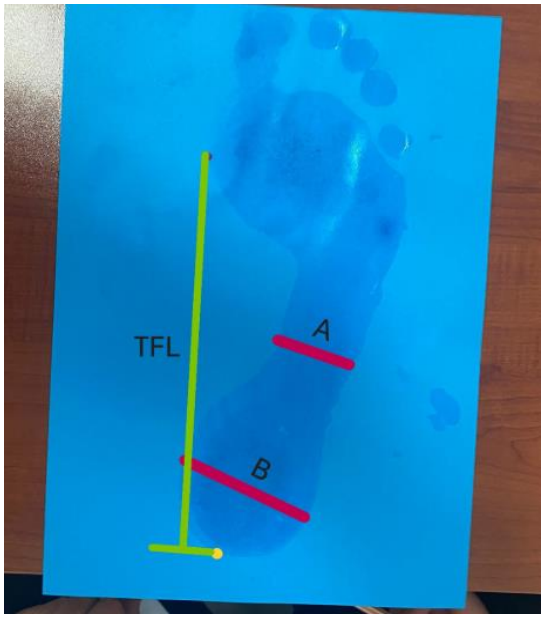
Çalışmaya dahil edilen her bir gönüllüye veri gizliliğini sağlamak amacıyla bir kimlik numarası verildi. Gönüllülerin cinsiyet bilgisi sorgulandı, baskın ayak, top tekmeleme testi ile belirlendi. Vücut ağırlığı ve boy ölçümleri ise boy ölçerli baskül aracılığıyla elde edildi. Beden kitle indeksi, ağırlığın (kg) boyun karesine (m^2) bölünmesiyle hesaplandı (kg/m^2).

Ölçümler öncesinde katılımcılardan ayakkabı ve çoraplarını çıkarmaları istendi. Ayak izini en net gösteren renk olarak belirlenen açık mavi renkte 2 adet A4 kağıdı zemin üzerine yerleştirildi. Ayak izi elde etmek amacıyla katılımcıların ayak tabanları su spreyi ile eşit şekilde ıslatıldı; fazla suyun kağıttan taşmasını önlemek için fazla nem kağıt havlu ile alındı. Ardından katılımcıların vücut ağırlıklarını her iki ayağa eşit dağıtacak şekilde, dizler ekstansiyonda ve nötral ayakta duruş pozisyonunda kâğıda basmaları sağlandı. Ayak izinin net bir şekilde çıktığından emin olunduktan sonra katılımcıların ayaklarını kağıttan kaldırmaları sağlandı. Katılımcılar aynı nötral duruş pozisyonundayken naviküler kemik tüberositesi palpe edilerek silinebilir bir kalemle işaretlendi. İşaretlenen noktanın zeminle olan dik mesafesi demir cetvel aracılığıyla ölçülerek NH değeri elde edildi (Şekil 1).



Şekil 1. Naviküler yükseklik ölçümü.

Ayak izleri üzerinden; orta taban bölgesinin en dar genişliği (A) ile topuk bölgesinin en geniş noktası (B) işaretlenerek demir cetvel ile ölçüldü. TFL elde etmek amacıyla, 1. metatarsofalangeal eklem noktası ile topuğun en posterior noktası işaretlenerek bu noktalardan birbirine paralel iki teğet çizgi çekildi; bu iki çizgi arasındaki dik mesafe ölçüldü (Şekil 2).



Şekil 2. Ayak izi üzerinde Staheli indeksi A/B ve kısaltılmış ayak uzunluğu (TFL) ölçümleri.

İstatistiksel Analiz (Statistical Analysis)

Örneklem büyüklüğü G*Power yazılımı ile a priori güç analizi kullanılarak belirlendi. Cinsiyet (2) × BKİ grubu (3) tasarımında, her katılımcıdan baskın ve baskın olmayan ayak olmak üzere iki tekrarlı ölçüm alındığından tekrarlı ölçümlü ANOVA modeli temel alındı. $f = 0,20$ etki büyüklüğü ($\eta^2 = 0,04$; Sun ve ark., 2010), $\alpha = 0,05$, güç = 0,80 ve tekrarlı ölçümler arası $r = 0,50$ varsayımlarıyla her hücrede en az 20 katılımcı, toplamda en az $n = 120$ gerektiği hesaplandı.

Tüm analizler IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, ABD) ile yürütüldü; anlamlılık düzeyi $p < 0,05$ kabul edildi. Sürekli değişkenler ortalama ± standart sapma olarak sunuldu, etki büyüklükleri kısmi eta kare (η^2_p) ile raporlandı. Normal dağılıma uygunluk Shapiro-Wilk testi, çarpıklık-basıklık katsayıları ve Q-Q grafikleri ile; varyans homojenliği medyan temelli Levene testi ile değerlendirildi. NTNH ölçümleri her iki varsayımı da karşılarken, Staheli indeksinde varyans homojenliği sağlanmadı ($p < 0,001$). Küresellik varsayımı, kişi içi faktörün iki düzeyli olması nedeniyle sağlandı (Mauchly $W = 1,000$).

Ana analizde ayak baskınlığı kişi içi, cinsiyet ve BKİ grubu kişiler arası faktör olarak tanımlanarak her indeks için ayrı karma desen varyans analizi uygulandı. Cinsiyet × BKİ grubu etkileşimi her iki indekste

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de anlamlı bulunduğundan ana etkiler tek başına yorumlanmadı; veri seti cinsiyete göre bölünerek basit etki analizi yapıldı. Varyansların homojen olduğu karşılaştırmalarda klasik F istatistiği ve Tukey HSD, homojenliğin sağlanmadığı karşılaştırmalarda Welch düzeltmeli F istatistiği ve Games-Howell testi kullanıldı.

Staheli indeksinde varsayımlar tam olarak karşılanmadığından parametrik sonuçlar non-parametrik testlerle doğrulandı (Mann-Whitney U, Kruskal-Wallis H ve Bonferroni düzeltmeli Dunn testi). Baskın ve baskın olmayan ayak farkı ayrıca Wilcoxon işaretli sıralar testi ile sınandı. İndeksler arası ilişkiler Pearson korelasyon katsayısı ile incelendi ve Spearman sıra korelasyonu ile doğrulandı.

BULGULAR

Ark İndeks Değerlerinin Dağılımı

Staheli indeksi ve normalize edilmiş kısaltılmış naviküler yüksekliği (NTNH) değerlerinin cinsiyet ve BKİ grubuna göre dağılımı Tablo 2'de sunulmuştur. Staheli indeksinde her iki cinsiyette de BKİ arttıkça değerlerin yükseldiği, NTNH'de ise erkekler ile kadınların zıt yönde değiştiği dikkat çekmektedir. Obez kadınlarda Staheli indeksi standart sapması (0,384) diğer tüm hücrelerden belirgin biçimde yüksek bulunmuştur.

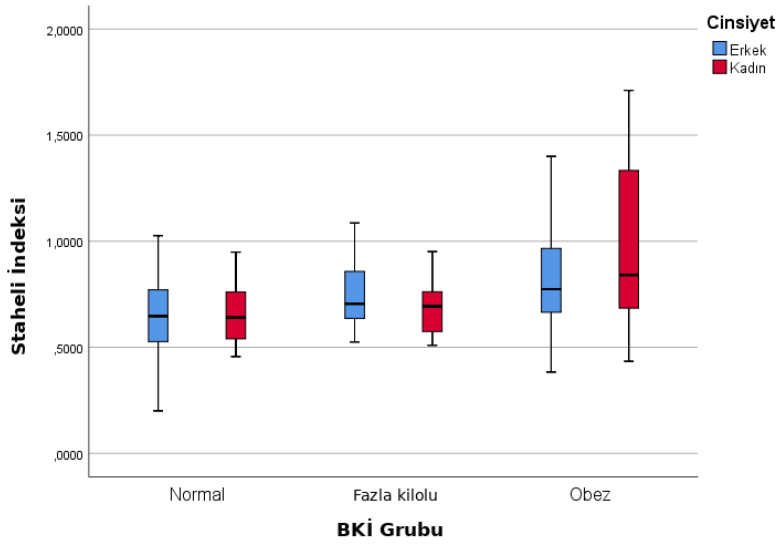
Tablo 2. Ark indeks değerlerinin cinsiyet ve BKİ grubuna göre dağılımı (ortalama ± standart sapma)

İndeks / Cinsiyet	Normal	Fazla kilolu	Obez	Toplam
Staheli – Baskın				
Erkek	0,624 ± 0,200	0,754 ± 0,159	0,803 ± 0,246	0,727 ± 0,215
Kadın	0,659 ± 0,139	0,685 ± 0,125	0,970 ± 0,384	0,771 ± 0,281
Toplam	0,642 ± 0,171	0,719 ± 0,145	0,887 ± 0,330	0,749 ± 0,250
Staheli – Baskın olmayan				
Erkek	0,619 ± 0,199	0,722 ± 0,183	0,746 ± 0,199	0,696 ± 0,198
Kadın	0,697 ± 0,156	0,679 ± 0,101	0,967 ± 0,331	0,781 ± 0,253
Toplam	0,658 ± 0,181	0,701 ± 0,147	0,856 ± 0,292	0,738 ± 0,230
NTNH – Baskın				
Erkek	0,281 ± 0,031	0,290 ± 0,039	0,270 ± 0,042	0,280 ± 0,038
Kadın	0,265 ± 0,039	0,283 ± 0,024	0,302 ± 0,028	0,283 ± 0,034
Toplam	0,273 ± 0,036	0,287 ± 0,032	0,286 ± 0,039	0,282 ± 0,036
NTNH – Baskın olmayan				
Erkek	0,275 ± 0,037	0,289 ± 0,031	0,269 ± 0,043	0,278 ± 0,038
Kadın	0,280 ± 0,041	0,280 ± 0,021	0,302 ± 0,024	0,287 ± 0,031
Toplam	0,278 ± 0,039	0,284 ± 0,026	0,286 ± 0,038	0,283 ± 0,035

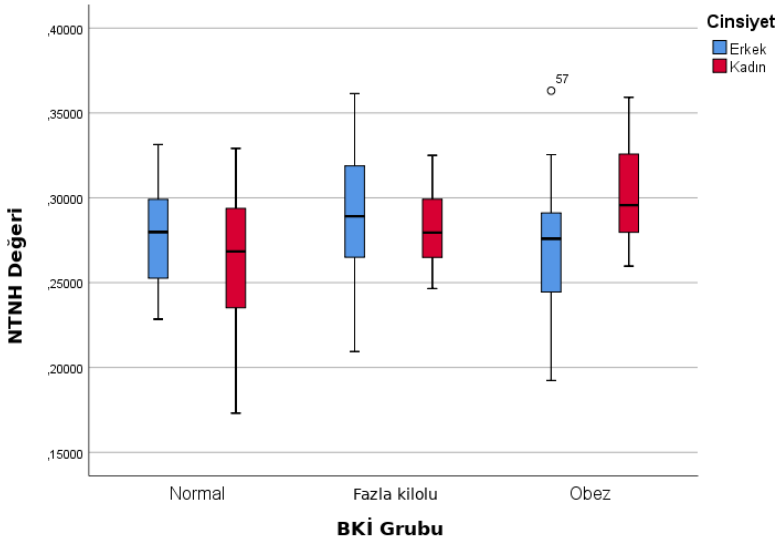
Her hücrede n = 20; cinsiyet toplamlarında n = 60, genel toplamda n = 120. NTNH: Normalize edilmiş kısaltılmış naviküler yüksekliği.

İndeks değerlerinin gruplar içindeki dağılımı Şekil 3 ve Şekil 4'te gösterilmiştir. Staheli indeksinde obez kadın grubundaki yayılımın diğer tüm gruplardan belirgin biçimde geniş olduğu, NTNH'de ise böyle bir genişlemenin bulunmadığı görülmektedir.

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Şekil 3. Staheli indeksi (baskın ayak) değerlerinin BKİ grubu ve cinsiyete göre dağılımı. Obez kadın grubunda değerler 0,434 ile 1,711 arasında dağılmakta olup bu grubun standart sapması (0,384) diğer hücrelerin iki-üç katıdır.



Şekil 4. NTNH (baskın ayak) değerlerinin BKİ grubu ve cinsiyete göre dağılımı. Staheli indeksinden farklı olarak obez kadın grubunda yayılım genişlemesi gözlenmemektedir (standart sapma = 0,028).

Ayak Baskınlığının Etkisi

Ayak baskınlığının kişi içi faktör olarak alındığı karma desen varyans analizinde, baskınlığın ana etkisi her iki indekste de anlamlı bulunmamıştır (Staheli: $F(1;114) = 1,037$, $p = 0,311$, $\eta^2_p = 0,009$ — NTNH: $F(1;114) = 0,161$, $p = 0,689$, $\eta^2_p = 0,001$). Aynı sonuç Wilcoxon işaretli sıralar testiyle de doğrulanmıştır (Staheli: $Z = -0,255$, $p = 0,799$ — NTNH: $Z = -0,131$, $p = 0,896$). Baskın ve baskın olmayan ayak değerleri arasındaki korelasyon her iki indekste de yüksektir (Staheli $r = 0,881$, NTNH $r = 0,814$; $p < 0,001$), bu da bilateral simetrinin korunduğunu göstermektedir. Karma desen varyans analizinin ayrıntılı sonuçları Ek 1'de sunulmuştur.

Cinsiyet ve BKİ Grubunun Etkileşimi

Karma desen varyans analizinde cinsiyet × BKİ grubu etkileşimi her iki indekste de anlamlı bulunmuştur (Staheli: $F(2;114) = 3,579$, $p = 0,031$, $\eta^2_p = 0,059$ — NTNH: $F(2;114) = 4,864$, $p = 0,009$, $\eta^2_p = 0,079$). Kadınlarda her iki indeks de anlamlı fark göstermekle birlikte, bu farkların yönü zıttır. Baskın ayakta normal gruptan obez gruba geçildiğinde Staheli indeksi 0,659'dan 0,970'e yükselirken ($p = 0,006$),

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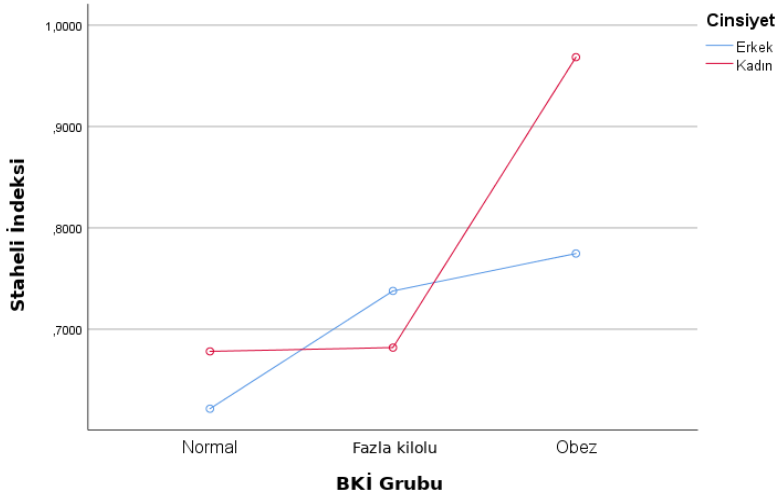
NTNH değeri de 0,265'ten 0,302'ye yükselmiştir (p = 0,001). Staheli indeksinde yüksek, NTNH'de ise düşük değerler daha düşük ark yüksekliğine işaret ettiğinden, iki indeks obez kadınlarda karşıt sonuçlar üretmektedir. Erkeklerde böyle bir ayrışma gözlenmemiştir.

Etkileşimin anlamlı olması nedeniyle ana etkiler tek başına yorumlanmamış, BKİ grubunun etkisi her cinsiyet için ayrı ayrı incelenmiştir (Tablo 3). Erkeklerde incelenen dört bağımlı değişkenden yalnızca birinde anlamlı fark saptanırken, kadınlarda dördünde de anlamlı fark bulunmuştur.

Tablo 3. BKİ grubunun ark indeksleri üzerindeki etkisinin cinsiyete göre incelenmesi

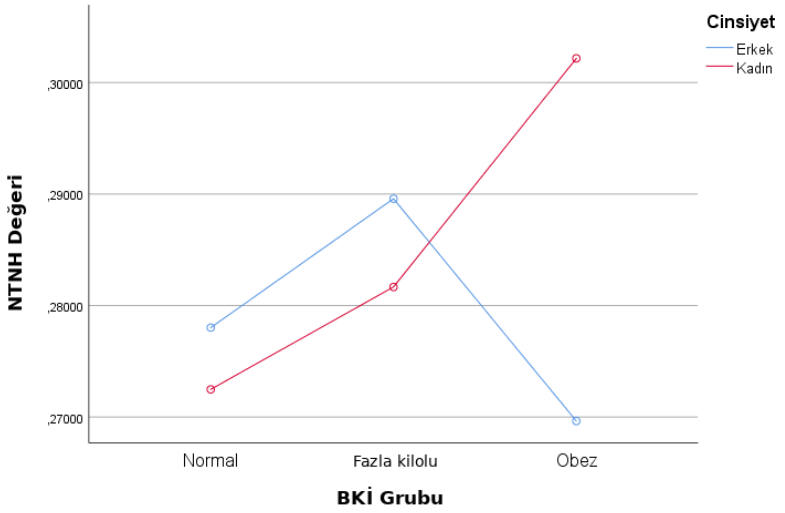
İndeks	Levene p	F	p	İkili karşılaştırma
Erkek (n = 60)				
Staheli – Baskın	0,452	4,076	0,022	N < O (p = 0,021)
Staheli – Bask. olm.	0,720	2,432	0,097	–
NTNH – Baskın	0,681	1,433	0,247	–
NTNH – Bask. olm.	0,426	1,451	0,243	–
Kadın (n = 60)				
Staheli – Baskın	< 0,001	5,711 [a]	0,007	N < O (0,006); FK < O (0,012)
Staheli – Bask. olm.	< 0,001	6,772 [a]	0,003	N < O (0,008); FK < O (0,003)
NTNH – Baskın	0,171	7,157	0,002	N < O (p = 0,001)
NTNH – Bask. olm.	0,006	5,440 [a]	0,009	FK < O (p = 0,008)

N: Normal; FK: Fazla kilolu; O: Obez. [a] Welch düzeltmeli F istatistiği; ikili karşılaştırmalarda Games-Howell testi kullanılmıştır. Diğer satırlarda klasik F istatistiği ve Tukey HSD testi uygulanmıştır. Levene testi medyan temellidir. Serbestlik dereceleri klasik F için (2; 57); Welch düzeltmeli F için sırasıyla (2; 34,85), (2; 33,33) ve (2; 36,15).



Şekil 5. Staheli indeksinin BKİ grubu ve cinsiyete göre dağılımı. Her iki cinsiyette de BKİ arttıkça indeks değerleri yükselmekte, artış obez kadınlarda belirginleşmektedir (cinsiyet × BKİ etkileşimi, p = 0,031).

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Şekil 6. NTNH değerinin BKİ grubu ve cinsiyete göre dağılımı. Şekil 5'ten farklı olarak, obez grupta erkek ve kadın eğrileri zıt yönde ayrışmaktadır (cinsiyet × BKİ etkileşimi, p = 0,009).

İndeksler Arası İlişki

Staheli indeksi ile NTNH arasındaki korelasyonlar beklenen yönde (negatif) ancak zayıf düzeyde saptanmıştır (baskın ayak r = −0,140, p = 0,128 — baskın olmayan ayak r = −0,195, p = 0,033). Buna karşılık aynı indeksin iki ayak arasındaki korelasyonu oldukça yüksektir (Staheli r = 0,881, NTNH r = 0,814; p < 0,001). Bu bulgu, her iki indeksin kendi içinde tutarlı ölçüm yapmakla birlikte birbirinden farklı anatomik özellikleri yansıttığını düşündürmektedir.

TARTIŞMA

Çalışmanın en dikkat çekici bulgusu, cinsiyet × BKİ grubu etkileşiminin her iki indekste de anlamlı olması ve bu etkileşimin kadınlarda BKİ arttıkça belirginleşmesidir. Obezitenin ayak yapısını etkilediği ve ayağın daha geniş, daha yassılaşmış ve arkının daha basık hâle geldiği, bunun hem MLA yüksekliğindeki azalmadan hem de orta ayak plantar yağ yastığının kalınlaşmasından kaynaklandığı bildirilmektedir (Wearing ve ark., 2012). Bu mekanizma, obez kadın grubunda gözlenen belirgin değişimi kısmen açıklayabilir. Öte yandan, kadınlarda MLA morfolojisinin erkeklere kıyasla farklı seyretmesi, kadınlarda görülen daha yüksek ligament laksitesi, daha geniş eklem hareket açıklığı ve göreceli olarak daha düşük kas kuvveti ile pelvis-alt ekstremite dizilimindeki cinsiyete özgü farklılıklarla ilişkilendirilmiştir (Fukano & Fukubayashi, 2012). Bu fizyolojik özellikler, kadınlarda artan vücut ağırlığının ark üzerindeki yük etkisine karşı yapısal direncin erkeklere göre daha sınırlı olabileceğini düşündürmektedir.

Bununla birlikte literatürde BKİ-ark ilişkisi konusunda tam bir fikir birliği yoktur. NTNH yöntemiyle 360 sağlıklı yetişkinde yürütülen bir çalışmada BKİ ile ark tipi arasında anlamlı bir ilişki bulunamamış, buna karşın ark tipi ile cinsiyet arasında güçlü bir ilişki saptanmıştır (Soni & Shah, 2025). Benzer şekilde, İspanya'da yürütülen geniş örneklemli bir çalışmada hem cinsiyetler arası hem de BKİ gruplarına göre ayak postür indeksi açısından anlamlı farklar bildirilmiştir (Rosende-Bautista ve ark., 2021). Bu çalışmalarla karşılaştırıldığında, bizim örneklemimizde cinsiyet × BKİ etkileşiminin anlamlı çıkması, etkinin ana etkiler düzeyinde değil, iki değişkenin birleşik etkisinde ortaya çıktığını göstermesi bakımından farklı bir bakış açısı sunmaktadır. Nitekim BKİ grubunun ana etkisi NTNH'de anlamlı değildir (p = 0,252); bu bulgu, etkileşim göz önüne alınmadan yorumlanırsa yanıltıcı sonuçlara yol açabilir.

Bulgularımızın dikkat gerektiren diğer bir yönü, obez kadın grubunda Staheli indeksinin yükselirken (düşük ark yönünde) NTNH'nin de yükselmesidir (yüksek ark yönünde); bu durum iki indeksin aynı anatomik yapıyı zıt yönde yansıttığı anlamına gelmektedir. Bu çelişki, tesadüfi bir bulgudan çok, iki yöntemin farklı doku bileşenlerine duyarlı olmasıyla açıklanabilir. Staheli indeksi, footprint temas

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alanına dayandığından, orta ayak plantar yağ yastığındaki kalınlaşmadan doğrudan etkilenir ve kemik yapısı değişmese dahi temas alanının artmasıyla "düşük ark" yönünde sapabilir. NTNH ise naviküler tüberkülünün yerden yüksekliğini temel aldığından, yumuşak doku kalınlaşmasından bağımsız olarak iskelet düzeyindeki konumu yansıtır. Nitekim obez bireylerde ayağın büyümesinin altında yatan mekanizmanın hem ark yüksekliğindeki azalma hem de plantar yağ yastığı kalınlaşması olduğu, ancak bu iki bileşenin birbirinden ayrıştırılması gerektiği vurgulanmıştır (Hande ve ark., 2025). Obez kadın grubunda Staheli indeksinin standart sapmasının diğer tüm hücrelerden belirgin biçimde yüksek bulunması da (0,384) iki farklı şekilde yorumlanabilir. Birincisi bu grupta footprint temelli ölçümün tutarlılığının azaldığına, olası ölçüm gürültüsünün arttığına işaret ediyor olabilir. İkincisi, obez kadın alt grubunun ark morfolojisi açısından gerçekten heterojen bir yapıya sahip olması, yani bazı bireylerde belirgin ark basıklığı gelişirken bazılarında bu değişimin sınırlı kalmasıdır. Mevcut verilerle bu iki olasılık birbirinden ayrıştırılamamaktadır; bu belirsizliğin giderilmesi için obez kadın alt grubuna odaklanan, tekrarlı ölçüm (test-retest) tasarımıyla yürütülecek ileri çalışmalara ihtiyaç vardır. Böyle bir tekrarlama, gözlenen geniş varyansın kişiler arası gerçek bir farklılığı mı yoksa yöntemin bu popülasyonda azalan güvenirliğini mi yansıttığını netleştirebilecektir.

Staheli indeksi ile NTNH arasında beklenen yönde ancak zayıf bir korelasyon bulunması (baskın ayak $r = -0{,}140$; baskın olmayan ayak $r = -0{,}195$), buna karşılık aynı indeksin iki ayağı arasındaki korelasyonun yüksek olması, iki yöntemin ölçüm tekrarlanabilirliği yüksek fakat birbirinden farklı yapıları yansıttığını düşündürmektedir. Zuil-Escobar ve ark. (2018) naviküler düşme testi ile Staheli indeksi arasında $r = 0{,}633$ düzeyinde korelasyon bildirmiştir; bizim örneklemimizde NTNH ile Staheli arasındaki ilişki belirgin biçimde daha zayıftır ($r = -0{,}140$). Bu farklılık, iki çalışmada kullanılan naviküler temelli ölçümlerin farklı olmasından (naviküler düşme testi dinamik bir ölçümdür, NTNH ise statik) kaynaklanıyor olabilir. Nitekim, NTNH yönteminin deneyimsiz ve deneyimli değerlendiriciler arasında mükemmele yakın güvenirlik göstermesi, bu zayıf korelasyonun ölçüm hatasından çok gerçek bir anatomik/metodolojik farkı yansıttığı yönündeki yorumumuzu desteklemektedir (Motantasut ve ark., 2019). Bu bulgular bir arada değerlendirildiğinde, Staheli indeksi ve NTNH'nin birbirinin yerine geçebilecek ölçümler olmadığı, aksine MLA'nın farklı boyutlarını (yumuşak doku/temas alanı karşısında iskelet yüksekliği) tamamlayıcı şekilde değerlendirdiği söylenebilir.

Bulgularımız, klinik uygulamada tek bir footprint tabanlı indeksle "düşük ark" veya "yüksek ark" tanısı konulmasının, özellikle obez kadın popülasyonunda yanıltıcı sonuçlara yol açabileceğini göstermektedir. Obezitenin ark morfolojisi üzerindeki etkisinin cinsiyete göre farklılaştığı ve tek başına BKİ artışının her indekste aynı yönde değişikliğe yol açmadığı göz önüne alındığında, klinik değerlendirmelerde mümkün olduğunca birden fazla yöntemin (footprint temelli ve iskelet temelli) birlikte kullanılması, özellikle kadın ve obez hastalarda önerilebilir.

Baskın ve baskın olmayan ayak arasında Staheli indeksi ve NTNH açısından anlamlı bir fark bulunmaması (sırasıyla $p = 0{,}311$ ve $p = 0{,}689$) ve iki ayak arasındaki güçlü korelasyon ($r = 0{,}881$ ve $r = 0{,}814$), bilateral simetrinin bu örneklemde korunduğuna işaret etmektedir. Nitekim Yu ve ark. (2020) da statik ayakta durma koşulunda sağ-sol ayak arasında ark indeksi açısından anlamlı bir fark bulunmadığını, bu simetrinin dinamik yürüme ve koşu sırasında da korunduğunu bildirmiştir. Benzer şekilde, Molitor ve ark. (2024) da yürüme ve koşu sırasında MLA hareket açıklığının baskın ve baskın olmayan ekstremite arasında grup düzeyinde anlamlı farklılık göstermediğini, ancak farkların bireysel düzeyde ortaya çıkabildiğini bildirmiştir. Bu bulguların bizim sonuçlarımızla birleşmesi, bilateral simetrinin farklı yük koşulları altında (statik ve dinamik) da sürdürülebildiğini düşündürmektedir. Bununla birlikte literatürde farklı yönde bulgular da mevcuttur; Hadoush ve ark. (2025) tarafından okul çağı çocuklarında yürütülen bir çalışmada anormal ark tiplerinin baskın olmayan ayakta daha sık görüldüğü rapor edilmiştir. Bu farklılık, örneklem özelliklerinden (çocuk-yetişkin), kullanılan ölçüm yönteminden veya statik-dinamik değerlendirme farkından kaynaklanıyor olabilir. Çalışmamızın statik ölçümlere (ayak izi ve naviküler yükseklik) dayanması ve yetişkin popülasyonu içermesi nedeniyle, bulgumuzun daha çok fonksiyonel simetrinin korunduğu yetişkin gruplarındaki literatürle örtüştüğü söylenebilir. Bununla birlikte, bu bulgunun tek taraflı spor branşlarıyla uğraşan bireylerde farklı sonuçlanabileceğini düşünmekteyiz. Örneklemimizdeki bireylerin sporcu olma durumu veya spor dalı kaydedilmediğinden, katılımcıların büyük çoğunluğunun günlük yaşamda her iki ayağını da benzer düzeyde kullandığı varsayılabilir. Hayatı boyunca bir ekstremiteyi tekrarlayan biçimde asimetrik

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yükleyen (örn. futbolda şut ayağı-destek ayağı ayrımı gibi tek taraflı gelişim gerektiren branşlar) sporcu popülasyonlarında, kronik ve yoğun tek taraflı yüklenmenin MLA üzerinde baskın ayak lehine veya aleyhine belirgin bir yapısal farklılaşmaya yol açabileceği düşünülmektedir. Bu nedenle mevcut bulgumuzun "ayak baskınlığının MLA'yı etkilemediği" şeklinde genellenmesi yerine, "günlük yaşam düzeyindeki asimetrik kullanımın, sporcu olmayan bireylerde MLA'yı belirgin biçimde farklılaştırmaya yetmediği" şeklinde yorumlanması daha isabetli olabilir. İleride bu konunun, tek taraflı baskın gelişim gerektiren spor dallarında (futbol, tenis vb.) uzun süredir aktif olarak yer alan sporcu örneklemlerinde incelenmesi, genetik/gelişimsel faktörlerin mi yoksa kümülatif mekanik yüklenmenin mi MLA simetrisini belirlediğini netleştirebilir.

Çalışmanın bazı sınırlılıkları belirtilmelidir. Öncelikle kesitsel tasarım, BKİ artışı ile ark morfolojisindeki değişim arasında nedensel bir ilişki kurulmasına izin vermemektedir. İkinci olarak, ayak baskınlığı öznel bir yöntemle (top tekmeleme testi) belirlenmiştir; bu durum sınıflamada yanlılığa yol açabilir. Üçüncü olarak, plantar yağ yastığı kalınlığı doğrudan ölçülmediğinden, obez kadınlardaki çelişkili bulgunun yumuşak doku kaynaklı olduğu yönündeki yorum dolaylı kanıta dayanmaktadır; ileride ultrasonografi veya benzeri görüntüleme yöntemleriyle yağ yastığı kalınlığının doğrudan ölçüldüğü çalışmalar bu yorumu doğrulayabilir. Dördüncü olarak NTNH yönteminin geçerlik kanıtları büyük ölçüde çocuk ve adolesan popülasyonlarından elde edilmiştir (Aboelnasr ve ark., 2018); yöntemin genç yetişkinlerdeki ölçüt geçerliği konusunda ek çalışmalara ihtiyaç vardır. Son olarak, örneklemin tek merkezli ve göreli olarak sınırlı sayıda (n=120) olması, bulguların genellenebilirliğini kısıtlamaktadır; obez kadın alt grubundaki geniş varyansın (SS=0,384) daha büyük örneklemlerde de tutarlı olup olmadığının doğrulanması gerekmektedir.

SONUÇ

Bu çalışmanın bulguları, medial longitudinal arkın ayak baskınlığından bağımsız, ancak cinsiyet ve BKİ'nin birleşik etkisinden etkilendiğini göstermektedir. Ayak baskınlığı MLA üzerinde anlamlı bir fark yaratmazken, cinsiyet × BKİ etkileşimi her iki indekste de anlamlı bulunmuş ve bu etkileşim özellikle obez kadınlarda belirginleşmiştir. Dikkat çekici biçimde, obez kadın grubunda Staheli indeksi ve NTNH'nin zıt yönlerde değişmesi, tek bir footprint tabanlı ölçümün ark morfolojisini değerlendirmek için tek başına yeterli olmayabileceğini ortaya koymaktadır. Bu bulgular, klinik değerlendirmelerde özellikle kadın ve obez bireylerde birden fazla ölçüm yönteminin bir arada kullanılmasının önemine işaret etmekte; gözlenen değişkenliğin kaynağını netleştirmek için tekrarlı ölçüm tasarımıyla yürütülecek ileri araştırmalara ihtiyaç bulunmaktadır.

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EK 1. Karma Desen Varyans Analizi Sonuçları

Etki	sd	F	p	η^2_p
Staheli indeksi				
Ayak (baskınlık)	1; 114	1,037	0,311	0,009
Cinsiyet	1; 114	2,884	0,092	0,025
BKİ grubu	2; 114	12,046	< 0,001	0,174
Cinsiyet × BKİ grubu	2; 114	3,579	0,031	0,059
Ayak × Cinsiyet	1; 114	3,700	0,057	0,031
Ayak × BKİ grubu	2; 114	1,703	0,187	0,029
Ayak × Cinsiyet × BKİ	2; 114	0,145	0,865	0,003
NTNH				
Ayak (baskınlık)	1; 114	0,161	0,689	0,001
Cinsiyet	1; 114	1,146	0,287	0,010
BKİ grubu	2; 114	1,393	0,252	0,024
Cinsiyet × BKİ grubu	2; 114	4,864	0,009	0,079
Ayak × Cinsiyet	1; 114	3,068	0,083	0,026
Ayak × BKİ grubu	2; 114	1,183	0,310	0,020
Ayak × Cinsiyet × BKİ	2; 114	3,473	0,034	0,057

sd: Serbestlik derecesi; η^2_p: Kısmi eta kare. Küresellik varsayımı iki düzeyli kişi içi faktör nedeniyle sağlanmıştır (Mauchly W = 1,000).

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EK 2. Ark İndeksleri Arasındaki Korelasyon Katsayıları

	Staheli-B	Staheli-BO	NTNH-B	NTNH-BO
Staheli – Baskın	1	0,881**	−0,140	−0,226*
Staheli – Bask. olmayan		1	−0,146	−0,195*
NTNH – Baskın			1	0,814**
NTNH – Bask. olmayan				1

* $p < 0,05$; ** $p < 0,01$. B: Baskın; BO: Baskın olmayan. Staheli indeksinde yüksek, NTNH'de düşük değerler daha düşük ark yüksekliğine işaret ettiğinden, iki indeks arasındaki korelasyonun negatif olması beklenen yöndedir.

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A MULTISYSTEM FRAMEWORK OF EMOTIONAL EXHAUSTION RECOVERY: EMOTION REGULATION FLEXIBILITY, AUTONOMIC AND ENDOCRINE LOAD, AND NETWORK-LEVEL NEUROPHYSIOLOGY

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ABSTRACT

Recovery from emotional exhaustion (EE) is usually inferred from a fall in self-reported symptom scores between two time points. This assumes that psychological, autonomic, endocrine and neurophysiological systems recover in step — an assumption that adjacent literatures on allostatic load and stress physiology suggest may not hold. We propose a conceptual model in which EE recovery is defined as a multisystem and potentially asynchronous trajectory across four domains: psychological (EE, perceived stress, anxiety, affect); autonomic (heart rate variability and electrodermal activity); endocrine (salivary cortisol); and neurophysiological (quantitative EEG). We deliberately avoid single-band markers, which are non-specific, and instead frame the neurophysiological domain at the level of network organisation — default mode, salience and central executive networks — evaluated jointly with the other three domains, so that each measure gains interpretive value only within a multivariate profile. Emotion-regulation flexibility is positioned as the modifiable process hypothesised to drive the transition from sustained activation towards recovery. The framework predicts discriminable recovery profiles (predominantly psychological, predominantly physiological, convergent, or delayed) and generates testable hypotheses for controlled longitudinal designs. It is offered as a hypothesis-generating model; no empirical claims are made here.

Keywords: emotional exhaustion; burnout; emotion regulation flexibility; allostatic load; heart rate variability; electrodermal activity; salivary cortisol; quantitative EEG; triple network model; psychophysiology; recovery trajectories

1. Introduction

Emotional exhaustion (EE) is widely regarded as the core component of burnout and describes the subjective experience of depleted emotional and energetic resources following sustained demands. (Lim & Lee, 2025) Burnout is typically conceptualized as a multidimensional occupational phenomenon that includes emotional exhaustion, cynicism or mental distancing, and reduced professional efficacy, but EE has consistently occupied the central position in both measurement and theory (Jiménez-Ortiz et al., 2019). Despite extensive research on the antecedents, correlates, and consequences of EE, considerably less attention has been given to a more fundamental question: what constitutes recovery from emotional exhaustion?

In intervention and longitudinal research, recovery is commonly operationalised as a reduction in self-reported symptom scores between two or more assessment points. (Nordhall et al., 2018; Zadow et al., 2017). This approach is clinically meaningful because subjective improvement is itself an important outcome and cannot be replaced by physiological measurement. However, a lower post-intervention score establishes only that the individual reports feeling less exhausted. It does not establish that biological systems recruited during prolonged stress exposure have changed to the same extent, in the same direction, or within the same temporal window.

This distinction becomes important when EE is placed within the physiology of chronic stress (Grossi et al., 2015). Allostasis refers to the active process through which physiological systems alter their activity to maintain stability under changing demands, whereas allostatic load refers to the cumulative biological cost of repeated or prolonged adaptation (McEwen & Akil, 2020). In healthy workers, higher

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allostatic-load scores have been associated with burnout symptoms and hypocortisolemic profiles, illustrating that burnout-related symptoms can coexist with multisystem biological alteration rather than a single endocrine signature (Jiménez-Ortiz et al., 2019; Traunmüller et al., 2019). Yet studies of the hypothalamic-pituitary-adrenal (HPA) axis and autonomic nervous system (ANS) in burnout remain inconsistent, with evidence for hyperactivity, hypoactivity, and apparently preserved function depending on severity, chronicity, design, and measurement context (García-León et al., 2019; Jönsson et al., 2015; Zuccarella-Hackl et al., 2024).

Importantly, inconsistency may contain theoretically relevant information rather than merely methodological noise. In a study of 105 workers under high-demand conditions, Traunmüller and colleagues identified physiologically distinct subgroups among individuals with elevated burnout symptoms: although the high-burnout group showed compromised HRV, higher cortisol, and higher blood pressure on average, discriminant analysis indicated that only one subgroup showed clear autonomic dysfunction. The authors concluded that burnout need not imply the same physiological disturbance in every individual (Traunmüller et al., 2019). This observation directly challenges the assumption that equivalent symptom scores index equivalent biological states.

Longitudinal evidence further supports a specific relationship between autonomic regulation and exhaustion. In the Dresden Burnout Study, lower vagally mediated HRV predicted subsequent overall burnout and EE over one year, and higher EE predicted later reductions in HRV (Wekenborg et al., 2019). A later four-wave analysis found that vagally mediated HRV predicted subsequent exhaustion symptoms, but not vice versa, and that the effect was specific to exhaustion rather than the other burnout dimensions or depressive symptoms (Wekenborg et al., 2022). These findings establish that the association between EE and autonomic regulation is temporally structured, but they do not imply that HRV alone defines the exhausted or recovered state.

The neurophysiological literature points in the same direction. Resting-state EEG studies have reported lower alpha power in employees with burnout relative to matched controls (Afek et al., 2025; Golonka et al., 2017). More recently (Afek et al., 2025) reported decreased frontal and midline functional connectivity in the alpha3 sub-band during eyes-open resting state in workers with burnout. Crucially, the effect was not a global shift across all frequencies, and it was condition-dependent. Such results support the relevance of resting-state brain organisation while simultaneously arguing against interpreting any single frequency band as a specific biomarker of EE.

The problem is therefore not simply that burnout lacks an objective biomarker. A more fundamental possibility is that emotional exhaustion is expressed through multiple partially coupled systems whose trajectories need not be synchronous. If equivalent EE scores can coexist with different autonomic, endocrine, and neurophysiological states, then equivalent reductions in EE cannot automatically be assumed to represent equivalent biological recovery. One individual may experience substantial symptomatic improvement while autonomic or endocrine alterations persist; another may show measurable physiological recovery before subjective improvement becomes evident; a third may recover coherently across systems. (Jönsson et al., 2015; Lim & Lee, 2025; Nordhall et al., 2018; Skau et al., 2021).

This paper proposes the Multisystem Emotional Exhaustion Recovery Framework (MEERF). The framework reframes the central empirical question from whether symptoms decreased to which systems changed and whether they changed together. It treats the degree of convergence or divergence among psychological, autonomic, endocrine, and neurophysiological change as a property of recovery itself. Emotion-regulation flexibility (ERF) is positioned as a candidate modifiable process capable of facilitating transitions away from sustained activation, while the resulting recovery trajectory is expected to remain heterogeneous across individuals and systems.

MEERF is a conceptual and hypothesis-generating framework, not an empirical validation study. No diagnostic threshold or validated biological definition of recovery is proposed. Instead, the framework specifies constructs, candidate recovery profiles, an operationalisation strategy, a prospective validation protocol, and explicit observations that would count against its central predictions.

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2. The Proposed Multisystem Emotional Exhaustion Recovery Framework

2.1 Theoretical grounding: allostasis, recovery, and regulatory flexibility

MEERF begins from a distinction between adaptation and recovery. Allostasis permits the organism to maintain function by changing physiological activity in response to demand. Such mobilisation is adaptive when it is context-sensitive and followed by sufficient disengagement or restoration. (de Kloet et al., 2019; Gavelin et al., 2020). The biological cost accumulates when demands remain sustained, regulatory responses are repeatedly recruited, or recovery opportunities are insufficient. In this sense, allostatic load offers a useful account of cumulative regulatory burden but does not by itself specify how recovery should be defined once symptoms begin to improve.

The framework therefore treats recovery as a trajectory rather than a state. A post-intervention value is one observation along that trajectory, not proof that all relevant systems have returned toward the same baseline or set point. This position is consistent with broader resilience scholarship, in which adaptation is defined over time and cannot be inferred from a single cross-sectional endpoint (Southward et al., 2018). It is also consistent with the neurovisceral integration model, which conceptualises emotion regulation as emerging from integrated central-autonomic circuitry rather than from a single physiological channel (Laborde et al., 2017; Thayer & Lane, 2009).

Emotion-regulation flexibility supplies the process-level component of the framework. Bonanno and Burton (Bonanno & Burton, 2013) argued against the assumption that a particular coping or emotion-regulation strategy is always adaptive or maladaptive. Their regulatory-flexibility model emphasises context sensitivity, access to a repertoire of strategies, and responsiveness to feedback. Aldao, Sheppes, and Gross (Aldao et al., 2015) similarly framed effective emotion regulation as flexible matching between regulatory strategy and situational demands. Recent work shows that ERF is associated with momentary affective functioning across contexts and cultures (M. S. Chen et al., 2024) and an experimental intervention designed specifically to enhance ERF improved flexibility, wellbeing, and psychological distress relative to comparison conditions (Sharma & Singh, 2025).

Within MEERF, ERF is not a fifth recovery domain. It is a modifiable regulatory process hypothesised to influence transitions from sustained stress-related activation toward recovery. The framework does not predict that increasing ERF must produce equal changes in EE, HRV, EDA, cortisol, and qEEG. Instead, improved flexibility may increase the probability that regulatory responses become more context-appropriate and less persistently costly, while the magnitude and timing of recovery remain dependent on the prior state and dynamics of each system.

2.2 The four recovery domains

MEERF defines four domains that should be assessed separately before they are integrated. The domains are deliberately non-redundant: each captures a different level of the recovery process and none is assumed to substitute for another.

Domain	Candidate measures	Primary construct	Interpretive boundary
Psychological	EE, perceived stress, anxiety, burnout-related symptoms, positive/negative affect	Subjective and symptomatic recovery	Clinically meaningful, but does not establish biological recovery
Autonomic	HRV (e.g., RMSSD; protocol-dependent frequency-domain measures), EDA	Parasympathetic regulatory capacity and sympathetic sudomotor arousal	Neither HRV nor EDA is specific to EE; both are context- and acquisition-sensitive

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Endocrine	Salivary cortisol sampled using a standardised protocol	HPA-axis activity and stress-related endocrine regulation	Single values are not equivalent to HPA "normalisation"; timing and sampling protocol are critical
Neurophysiological	Resting-state qEEG: spectral, connectivity, and source-informed network measures where technically valid	Distributed neural organisation relevant to self-referential processing, salience detection, and executive control	No isolated band or scalp location is treated as a diagnostic marker; network claims require appropriate methodology

2.2.1 Psychological recovery

Psychological recovery refers to change in the lived and reported manifestations of exhaustion. EE should remain the anchor construct when the framework is applied to burnout, while perceived stress, anxiety, affect, and the remaining burnout dimensions provide complementary information about the broader symptom context. The psychological domain is not treated as an inferior or noisy approximation of biology. It measures a different level of the phenomenon: distress as experienced and reported by the individual. (Grossi et al., 2015; Traunmüller et al., 2019) The framework's claim is not that biology is more "objective" and therefore superior, but that a symptom score alone cannot establish what has occurred in other systems.

2.2.2 Autonomic recovery

The autonomic domain captures regulation within the ANS. Vagally mediated HRV is a particularly relevant candidate measure because cross-sectional and longitudinal evidence links lower HRV specifically with exhaustion symptoms (Ardi et al., 2021; Khammissa et al., 2022). EDA provides a complementary measure of sympathetic sudomotor activation. (Zaehringer et al., 2020). These measures should not be collapsed into a single "autonomic balance" score without empirical justification. HRV and EDA reflect partly different regulatory processes and may themselves recover asynchronously. (Lima et al., n.d.).

Candidate operationalisation: Electrodermal Recovery Latency (ERL). One way of formalising autonomic recovery kinetics — illustrative rather than mandatory, and reported alongside, not collapsed into, HRV-based outcomes — treats tonic skin conductance level, SCL(t), as a continuous function of time following a stress probe or an ecologically identified high-demand event. Let t_peak denote the timestamp of the post-activation maximum, and let μ_base and σ_base denote the mean and standard deviation of the participant's own pre-exhaustion baseline, estimated over a stable resting epoch. The acceptance tolerance interval is then:

$$I\_base = [\, \mu\_base - \sigma\_base \,,\ \mu\_base + \sigma\_base \,]$$

Requiring the signal to remain within I_base for a minimum persistence window δ — so that transient fluctuations are not read as recovery — yields a tonic latency:

$$ERL\_tonic = inf\{\, t - t\_peak : \ SCL(t') \in I\_base \ \ \forall t' \in [t,\, t + \delta] \,\}$$

Phasic skin conductance responses (SCRs) can be characterised separately, following the same logic, as an exponential decay of event amplitude:

$$A(t) = A_0 \cdot exp(\, -\lambda\_SCR \cdot (t - t\_peak) \,)$$

with λ_SCR the clearance rate constant and $t_{½} = \ln(2) / \lambda\_SCR$ the half-life of phasic hyperexcitability. ERL is proposed here as one candidate pre-specified primary outcome for the autonomic domain (Section 2.6), not as a replacement for vagally mediated HRV.

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2.2.3 Endocrine recovery

The endocrine domain is initially represented by salivary cortisol because the HPA axis is central to stress physiology and because cortisol can be repeatedly sampled using relatively low-burden procedures. (García-León et al., 2019). The burnout literature, however, contains both hyper- and hypocortisolemic findings, and a major review concluded that there is no compelling evidence for one uniform HPA-axis pattern across burnout (Oosterholt et al., 2015; Zuccarella-Hackl et al., 2024). MEERF therefore treats cortisol as a trajectory-sensitive component of a profile rather than a unidirectional severity marker. Standardised time of collection, medication and health covariates, recent food/caffeine/exercise, and relevant time and frequency of collection context must be specified before change can be interpreted. (Saxbe, 2008)

It is suggested that at least two salivary cortisol samples are collected at standardised times of the day, preferably including a morning and an evening sample. This recommendation takes into consideration studies showing that diurnal cortisol is not always disrupted in individuals with stress-related symptoms (Adam et al., 2017; Knezevic et al., 2023). Assessing cortisol at different times of the day provides information about the diurnal cortisol pattern and may therefore better indicate whether an individual presents a regulated or dysregulated HPA-axis pattern than a single cortisol measurement (Dong et al., 2025).

2.2.4 Neurophysiological recovery

The neurophysiological domain is represented by resting-state qEEG. Existing burnout studies support resting-state EEG as a plausible source of complementary information, but they do not justify a single-band phenotype. Golonka (Golonka et al., 2017) found lower alpha power in burnout in the eyes-open condition and later identified reduced alpha3 functional connectivity in frontal and midline regions, again specifically in eyes-open rest (Afek et al., 2025). The condition dependence and frequency specificity of these findings argue for network-aware analysis rather than a search for a universal "burnout wave."

The framework is informed by the triple-network literature because the default mode network (DMN), salience network (SN), and central executive network (CEN) provide a coherent systems-level language for stress-related changes in self-referential processing, salience allocation, and executive control. A systematic review of human stress neuroimaging found stress-related changes within and between all three networks, with a particularly important coordinating role for the SN (Paltoglou et al., 2024). However, the canonical triple-network model is largely grounded in fMRI. qEEG does not directly "measure the DMN" merely because particular electrodes or bands are recorded. Network-level qEEG claims require validated source localisation, connectivity, or cross-modal mappings; a review of simultaneous EEG-fMRI studies concluded that several qEEG features relate to resting-state networks, but the mapping is complex and not reducible to one spectral feature (Nishida et al., 2015). MEERF therefore treats network interpretation as a methodological target, not an assumption.

2.3 Cross-domain convergence and divergence

The central theoretical contribution of MEERF is not additional biomarkers for EE research, but treating the relation among domains as information in itself. Two concepts are central: recovery convergence and recovery divergence.

Recovery convergence occurs when change across two or more domains is directionally and temporally compatible with the same recovery interpretation. For example, a substantial reduction in EE accompanied by increased vagally mediated HRV, lower resting EDA, a cortisol trajectory moving toward the participant's previously defined adaptive range, and neurophysiological changes consistent with more integrated resting-state organisation would constitute convergent evidence. Importantly, convergence does not require identical effect sizes, nor does it require every measure to change.

Recovery divergence occurs when domains show discordant change. Symptom scores may improve while physiological indices remain unchanged, a biological system may improve before the participant reports feeling better, or two physiological domains may move differently. MEERF treats such discordance as a candidate phenotype of recovery rather than automatically dismissing it as

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measurement error. The framework therefore predicts that individuals with similar EE change scores can occupy different multisystem recovery profiles.

This proposition is consistent with psychophysiological evidence for burnout subtypes (Traunmüller et al., 2019) and with the broader failure to identify one consistent HPA or autonomic signature across burnout samples (Skau et al., 2021). It also provides a direct reason to study multiple systems in the same individuals at the same assessment points.

2.4 Candidate recovery profiles

MEERF proposes four candidate profiles. These are hypotheses about patterns of change, not validated clinical categories. Their purpose is to make the framework testable and to prevent post-hoc storytelling after a multivariate dataset has been collected.

Profile	**Psychological change**	**Biological change**	**Interpretation to be tested**
Convergent multisystem recovery	Clear symptomatic improvement	Compatible improvement across multiple autonomic/endocrine/neurophysiological measures	Recovery is broadly coordinated across domains
Predominantly psychological recovery	Clear symptomatic improvement	Minimal or discordant biological change at the same assessment point	Subjective recovery precedes or exceeds measured biological recovery
Predominantly physiological recovery	Limited symptomatic change	Compatible biological improvement in two or more domains	Biological change precedes or exceeds subjective recovery
Delayed physiological recovery	Early psychological improvement	Biological change emerges at later follow-up	Systems recover on different timescales; two-point designs can misclassify this profile

A fifth logical outcome—minimal change across all domains—is a non-recovery pattern rather than a recovery profile and should be retained as an explicit comparator in empirical work. Likewise, mixed biological patterns that cannot be coherently classified should be reported as unresolved or heterogeneous rather than forced into one of the candidate profiles.

2.5 Emotion-regulation flexibility as a modifiable recovery process

ERF is positioned upstream of the recovery profiles. The theory does not require that one strategy be universally beneficial; rather, it predicts that improved sensitivity to context, broader strategic repertoire, and responsiveness to feedback should reduce the likelihood of rigidly maintaining ineffective regulation (Bonanno & Burton, 2013; S. Chen & Bonanno, 2021). In an exhaustion context, this includes both top-down and bottom-up strategies, with the relevant question being whether the strategy fits the current regulatory demand rather than whether it belongs to a privileged category.

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Recent intervention evidence provides proof of principle that ERF can be trained. Sharma and Singh randomised 153 participants with low ERF to an ERF-focused intervention, an active comparison, or a no-treatment group, and reported improvement in ERF and psychological outcomes in the intervention group (Sharma & Singh, 2025). MEERF extends this logic by proposing that future intervention studies should ask not only whether ERF training reduces symptoms, but whether greater gains in ERF predict broader and more durable cross-domain recovery.

This is intentionally a probabilistic claim. A participant may improve in ERF while cortisol or qEEG remains unchanged over the observation window. Such a result would not automatically refute the role of ERF; it would indicate that the affected biological system either did not change, changed outside the measured window, or was not coupled to ERF in the manner predicted. The framework therefore requires repeated and domain-specific measurement rather than a single omnibus definition of response.

2.6 Operational strategy for measuring recovery

MEERF does not introduce a composite score at this stage. The first validation task is to determine whether the domains show meaningful, reproducible patterns of convergence and divergence using established measures. Prematurely collapsing psychometrics, HRV, EDA, cortisol, and qEEG into a single weighted number would obscure the very dissociations the framework is designed to detect.

For empirical testing, each domain should therefore retain its own pre-specified primary outcome. Change can be represented using raw change, model-estimated marginal change, standardised change relative to the baseline distribution, or reliable-change methods where measurement properties justify them. The direction defining "recovery-compatible" change must be declared before outcome inspection and should be based on the relevant measure rather than imposed globally. For cortisol and qEEG in particular, a universal rule that "lower is better" is scientifically indefensible.

Cross-domain convergence can then be quantified at two levels. At the group level, multivariate or multilevel models can estimate the covariance among domain-specific slopes. At the individual level, pre-specified rules can classify whether each domain shows recovery-compatible, neutral, or discordant change, with uncertainty retained rather than hidden. Latent profile or mixture modelling may later be used to evaluate whether the proposed profiles emerge empirically, but such analyses require substantially larger samples than simple intervention-effect tests and should be labelled exploratory until replicated.

Candidate quantification of cross-domain asynchrony (linked to H6). One concrete instantiation of the individual-level classification rule described above is a time-lagged cross-correlation between domain-specific trajectories. For any two domains X and Y sampled repeatedly across the observation window, the lag τ at which the pair reaches maximal cross-correlation can be estimated as:

$$\rho max(X,Y) = max\tau \, [\, corr(\, X(t),\, Y(t+\tau)\,)\,]$$

A positive τ indicates that Y lags X — that is, recovers later. Under H6, systematic non-zero lags between the psychological trajectory and one or more physiological trajectories would constitute evidence for temporal asynchrony; a distribution of τ concentrated at zero across domains and participants would instead support synchronous, single-factor recovery and count against H6.

Domain-specific trajectories feeding this calculation can, in turn, be represented with a simple exponential recovery function — again illustrative rather than mandatory:

$$Y(t) = Y\_end + (Y\_0 - Y\_end) \cdot exp(-t / \tau)$$

where Y_0 is the value at intake, Y_end is the participant's asymptotic recovery value, and τ is a domain-specific recovery time constant. Vectors of τ across domains, one per participant, provide a natural input to the latent profile or mixture modelling already proposed above and to the Phase 4 profile-replication step of the validation programme (Section 3.3): candidate profiles would be expected to differ in the relative ordering and magnitude of their domain-specific τ, rather than in any single composite score.

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3. Methodology and Validation Protocol

3.1 Assessment protocol

Domain	T0 baseline	T1 post-intervention	Follow-up (recommended)
Psychological	EE + perceived stress + anxiety + affect + burnout dimensions; ERF measure	Repeat same battery	Repeat key outcomes to test durability
Autonomic	Standardised resting HRV and EDA	Repeat same acquisition	Repeat if feasible to test delayed change
Endocrine	Standardised salivary cortisol protocol	Same clock time and pre-analytic conditions	Repeat if endocrine lag is a target hypothesis
Neurophysiological	Resting-state qEEG; eyes-open and/or eyes-closed conditions pre-specified	Same montage, condition, duration, and preprocessing	Repeat if testing delayed neural reorganisation

Acquisition conditions must be standardised sufficiently that within-person change is interpretable. HRV analyses should specify posture, recording duration, respiration handling, artefact correction, and the pre-defined HRV metric. EDA should distinguish tonic measures from phasic event-related measures when no discrete stimulus is present. Salivary cortisol must be collected at the same clock time across longitudinal assessments and accompanied by standardised restrictions and relevant covariates. qEEG must use the same montage, sampling rate, reference, eyes-open/eyes-closed condition, artefact-processing pipeline, epoch definition, and connectivity/source methodology at each time point.

Resting-state qEEG should not be interpreted as direct measurement of canonical fMRI networks unless the analysis pipeline supports that inference. Where source localisation and validated connectivity mapping are available, hypotheses may be formulated around network organisation involving DMN-, SN-, and CEN-related cortical nodes. Where only sensor-level data are available, results should be reported as sensor-level spectral or connectivity findings and not renamed as network activity after the fact.

The following table gives one candidate measurement cadence consistent with the standardisation requirements above; acquisition cost and participant burden, rather than domain importance, justify the differing frequencies shown.

Domain	Candidate measure	Frequency	Total window
Psychological	EE, perceived stress, anxiety, affect (brief serial battery)	Weekly	Matched to intervention + follow-up
Autonomic	HRV recording; ambulatory EDA (tonic SCL, phasic SCRs)	Biweekly	Matched to intervention + follow-up
Endocrine	Salivary cortisol (CAR, diurnal slope, post-stressor reactivity)	Weekly	Matched to intervention + follow-up

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Neurophysiological	Resting-state qEEG (standardised montage and condition)	Baseline, mid-point, endpoint	3 sessions minimum

Candidate longitudinal measurement schedule (illustrative).

3.2 Emotion-Regulation Flexibility (ERF) Protocol

- The ERF protocol consists of training in emotion-regulation strategies, context sensitivity, and efficacy monitoring, following current literature. ERF training is intended to function as an intervention that moves participants towards more flexible, context-oriented, and adaptive regulation. It is suggested that individuals with elevated EE or stress be taught, on a regular basis, to use ERF strategies, monitor their reactions and wellbeing, and develop coping strategies fitted to their own life circumstances. An existing 5-session protocol can be used to train participants in these abilities, as can any comparable protocol grounded in ERF skills (Maftum & De Moura Sales, 2025).

3.3 Staged validation programme

Validation should proceed in stages rather than moving directly from association to clinical interpretation:

- Phase 1 — Measurement reliability: establish test-retest reliability and technical quality of each domain under the intended acquisition protocol.
- Phase 2 — Construct and change validity: determine whether each domain changes in theoretically coherent ways and whether cross-domain convergence/divergence is reproducible.
- Phase 3 — Predictive validity: test whether baseline multisystem configuration or early cross-domain change predicts subsequent EE recovery and durability better than symptoms alone.
- Phase 4 — Profile replication: determine whether the proposed recovery profiles emerge in independent cohorts and whether profile membership is stable or meaningfully transitions over time.
- Phase 5 — Clinical utility: only after prior phases should the field test whether profile-informed decisions improve outcomes relative to standard symptom-guided care.

The full prediction set, primary outcomes, preprocessing decisions, covariates, and profile-classification rules should be preregistered before outcome inspection. This is particularly important because a multisystem dataset creates many opportunities for post-hoc selection of whichever biomarker appears to "match" symptoms.

4. Falsifiable Hypotheses

A multisystem framework is useful only if its claims can fail. The hypotheses below therefore pair each central proposition with an observation that would count against it in an adequately powered, technically valid study. Failure of a peripheral hypothesis should revise that component; failure of the structural hypotheses concerning divergence and incremental cross-domain information would require revision of the framework itself.

H1 — Psychological-biological non-equivalence — Change in EE will not map one-to-one onto change in autonomic, endocrine, and neurophysiological measures. Moderate associations may occur, but no single biological domain will consistently explain the full variance in symptomatic recovery.

Falsified if: In adequately powered replicated studies, EE change is almost perfectly and consistently coupled to the same biological measure or common biological factor, leaving negligible independent information in the remaining domains.

H2 — Recovery heterogeneity — Individuals with comparable reductions in EE will exhibit heterogeneous biological recovery trajectories.

Falsified if: Participants matched on psychological improvement repeatedly show highly similar autonomic, endocrine, and neurophysiological change patterns, with little between-person heterogeneity beyond measurement error.

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H3 — Baseline-dependent recovery — Baseline EE and baseline physiological configuration will influence the magnitude or direction of subsequent biological change, such that the same intervention can produce different trajectories from different starting states.

Falsified if: Baseline state shows no reproducible association with subsequent change in any domain, and recovery trajectories are independent of starting configuration across adequately powered cohorts.

H4 — Regulatory flexibility as a process predictor — Greater improvement in ERF will be associated with broader psychological recovery and, in at least a subset of participants, greater cross-domain convergence.

Falsified if: ERF change shows no reproducible relation to EE change or to any measure of cross-domain recovery after controlling for baseline severity and treatment exposure.

H5 — Cross-domain convergence carries incremental information — A multisystem recovery profile will predict durability or later functioning beyond post-intervention EE score alone. This is the load-bearing translational hypothesis of MEERF.

Falsified if: Once post-intervention EE and baseline severity are included, cross-domain information adds no reproducible predictive value for later symptoms, functioning, relapse, or sustained recovery. If this occurs, multisystem profiling may remain descriptively interesting but would lose its proposed clinical relevance.

H6 — Temporal asynchrony — At least some recovery trajectories will show systematic lag between psychological and biological change; therefore the profile assigned at immediate post-intervention will differ from that observed at later follow-up in a non-trivial subset of participants.

Falsified if: Repeated longitudinal measurements show that domain changes occur synchronously within the temporal resolution of the protocol, with no reproducible evidence of lagged biological or psychological recovery.

H7 — No single qEEG marker is sufficient — Network-informed or multivariate qEEG features will provide a more stable account of neurophysiological change than any isolated band-power marker selected a priori as a universal signature of EE recovery.

Falsified if: A single pre-specified qEEG feature repeatedly demonstrates high specificity, reproducibility, and incremental predictive validity across independent cohorts, rendering the network-level multivariate approach unnecessary for the neurophysiological domain.

4.1 Criteria that would not constitute falsification

A null result in a severely underpowered sample does not rescue or refute the framework; it is simply uninformative. Likewise, technical failure of a sensor does not count against a theoretical prediction about recovery. Conversely, the framework should not be protected after the fact by changing band definitions, selecting a different cortisol time point, redefining a "responder," or constructing a new composite after viewing the results. Such modifications may generate new exploratory hypotheses but cannot be reported as confirmation of the pre-specified framework.

5. Discussion

MEERF proposes a change in the unit of analysis used to understand recovery from emotional exhaustion. Conventional intervention research asks whether symptom severity decreased. The present framework retains that question but adds a second: whether the systems implicated in stress adaptation changed together. The distinction matters because the existing literature already demonstrates that physiological disturbance is neither uniform nor specific across burnout, and because longitudinal HRV data suggest that exhaustion has a temporally structured relation with autonomic regulation.

5.1 Theoretical contribution: recovery is a relation among trajectories

The framework's primary theoretical contribution is to define recovery not as the value of one variable at one time point, but as the relation among trajectories. This is more specific than describing EE as "multifactorial." A multifactorial model can still treat each factor as an independent predictor of one

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outcome. MEERF instead predicts that convergence and divergence among domains have their own explanatory value.

This approach may also help reinterpret contradictory biomarker findings. Hypercortisolism and hypocortisolism, reduced HRV in some but not all highly exhausted individuals, and condition-specific EEG differences are difficult to reconcile if a biomarker is expected to track a single severity continuum. They become more intelligible if individuals can occupy different regulatory states and stages, and if those states change on different timescales. This does not prove the framework, but it converts heterogeneity from a nuisance into a measurable prediction.

5.2 Rationale and constraints of the neurophysiological domain

qEEG is included because recovery from chronic stress-related exhaustion plausibly involves changes in distributed neural organisation that cannot be inferred from peripheral physiology alone. Resting-state EEG is non-invasive, repeatable, temporally precise, and substantially more accessible than MRI for repeated longitudinal assessment. Burnout studies have already demonstrated group differences in resting-state power and connectivity (Golonka et al., 2017; Afek et al., 2025).

However, the framework explicitly rejects the use of an isolated frequency band as a diagnostic or recovery marker. Alpha, beta, theta, and other spectral features are context-dependent and transdiagnostic. Furthermore, the DMN, SN, and CEN are large-scale networks originally defined predominantly through fMRI and related imaging approaches. EEG can contribute to network-level inference through source localisation, coherence, phase-based connectivity, and validated EEG-fMRI correspondences, but a scalp power value cannot simply be renamed as “DMN activity.” The validity of the neurophysiological domain therefore depends as much on methodological discipline as on signal acquisition.

This constraint limits what can be claimed from qEEG data, but does not limit the testability of the framework. MEERF does not require qEEG to diagnose exhaustion. It requires neurophysiological measurements that can be repeatedly acquired and interpreted transparently alongside psychometric, autonomic, and endocrine data. If qEEG contributes no incremental information after rigorous validation, H7 and H5 allow that result to count against the proposed role of the neurophysiological domain.

5.3 Translational implications

The translational aim of MEERF is not to require qEEG, cortisol, HRV, EDA, and extensive psychometrics in every clinical consultation; the intended logic runs in the opposite direction. A research phase using richer multimodal phenotyping could identify which combinations of measures carry reproducible information about recovery. Subsequent studies could then test reduced models composed of measures that are more feasible in routine care, such as validated questionnaires, salivary cortisol collected under a standardised protocol, and wearable-derived autonomic indices.

Such a strategy would imply a staged path from discovery to implementation: comprehensive multimodal assessment, replication of cross-domain signatures, out-of-sample prediction, reduction to parsimonious measurement sets, and only then prospective testing of clinical utility. A reduced model should not be considered “precision” merely because it contains biomarkers; it must demonstrate that it improves prediction, stratification, or treatment monitoring beyond validated symptom measures and simpler alternatives.

If successful, this approach could eventually support repeated assessment in outpatient or occupational-health settings without requiring the full research battery. Importantly, that possibility is a future translational hypothesis, not an application validated by the present framework.

5.4 Clinical interpretation and ethical boundaries

MEERF does not propose that a biological profile override a person’s subjective report. A participant who reports meaningful improvement has experienced a clinically relevant change even if a biomarker does not move. Conversely, a physiological shift does not entitle a clinician or researcher to tell a person

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that they are “recovered” when distress remains substantial. Cross-domain divergence is precisely the phenomenon to be understood, not a reason to privilege one domain as the ground truth.

The framework also does not establish diagnosis, fitness for work, or an automated return-to-work decision. Biological and neurophysiological measures should be used as research variables or, in future validated applications, as decision support interpreted by qualified professionals. In occupational samples, individual data should remain inaccessible to employers unless the participant has explicitly consented to a clinically appropriate disclosure process; research reporting should use aggregated, non-identifiable results.

5.5 Limitations and boundaries of the framework

- EE is conceptually embedded in burnout but overlaps with general fatigue, stress, anxiety, and depressive symptoms. MEERF requires construct-specific psychometric assessment and cannot assume that all exhaustion is occupational burnout.
- The four domains are an initial pragmatic selection, not a complete model of allostatic physiology. Immune, inflammatory, metabolic, sleep, and behavioural measures may be important but are not necessary for the first test of the framework.
- HRV and EDA are sensitive to posture, respiration, medication, temperature, movement, and preprocessing. Their interpretation depends on protocol quality.
- Salivary cortisol is strongly time-dependent and influenced by medication, sleep, food intake, physical activity, and sampling adherence. A single afternoon sample can be useful for a standardised pre-post comparison but cannot represent the full diurnal HPA profile.
- qEEG network inference depends on montage density, source localisation, reference, artefact rejection, connectivity metric, and the validity of mapping EEG features to large-scale networks. Network labels should not exceed what the acquisition and analysis can support.
- The delayed-recovery hypothesis cannot be tested with a two-time-point design. At least one follow-up is required to distinguish persistent divergence from simple temporal lag.
- The proposed recovery profiles may not emerge as discrete clusters. The data may support continuous dimensions of convergence and lag rather than categorical profiles. The framework should follow the empirical structure rather than force categories.
- No causal claim follows from cross-domain correlation. Even when ERF change precedes biological change, mediation requires temporal and statistical assumptions that must be tested explicitly.
- Clinical utility remains unproven until a profile-informed approach prospectively outperforms symptom-guided care on meaningful patient outcomes.

5.6 Next steps

The immediate next step is a preregistered controlled longitudinal study that measures EE, ERF, HRV, EDA, salivary cortisol, and resting-state qEEG in the same participants under standardised conditions. The first study should prioritise the intervention effect on EE and the feasibility, reliability, and covariance of the biological measures. A larger replication sample should then test profile structure, moderation, and predictive validity. Only after these stages should reduced clinical measurement sets or profile-guided intervention decisions be evaluated.

The framework also invites independent testing. Because MEERF does not depend on a single composite score, different research groups could operationalise the same four-domain logic using comparable validated measures, provided that outcomes and recovery-compatible directions are specified in advance. Convergence across laboratories would be more informative than success of any single analytic pipeline.

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6. Conclusion

Recovery from emotional exhaustion should not be reduced to the disappearance of symptoms, nor should it be redefined as normalisation of a single biomarker. MEERF proposes that recovery is a dynamic relation among psychological, autonomic, endocrine, and neurophysiological trajectories. Its central empirical question is therefore not only whether a person improved, but which systems changed, whether they changed together, and whether the resulting pattern predicts durable recovery. Emotion-regulation flexibility is proposed as a modifiable process that may facilitate this transition, while cross-domain convergence and divergence provide the framework's principal testable outcomes. The model is deliberately falsifiable and clinically bounded: it makes no diagnostic claim, privileges no single physiological channel, and requires longitudinal validation before translational use. If supported, the framework could provide a path from rich multisystem phenotyping toward more parsimonious and accessible monitoring of recovery in research and, eventually, clinical practice.

Conflict of Interest

Viviane DaSilva is Director of Development at Neuromedtech UK Ltd, a company involved in the development of the qEEG-based framework and related technology discussed in this paper. This conflict of interest is disclosed in the interest of transparency; the authors report no other financial or non-financial competing interests related to this work.

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MERMER ATIKLARININ ÇİMENTO ESASLI HARÇLARDA İNCE AGREGA VE ÇİMENTO İKAMESİ OLARAK DEĞERLENDİRİLMESİ

UTILIZATION OF MARBLE WASTE AS FINE AGGREGATE AND CEMENT REPLACEMENT IN CEMENT-BASED MORTARS

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ÖZET

Mermer ve doğal taş endüstrisinde kesme, ebatlandırma ve yüzey işleme süreçleri sırasında önemli miktarda iri ve ince taneli atık oluşmaktadır. Bu atıkların ikincil hammadde olarak değerlendirilmesi, depolama yükünün azaltılması, doğal agrega tüketiminin sınırlandırılması ve çimento kullanımına bağlı çevresel etkilerin azaltılması açısından önem taşımaktadır. Bu çalışmada, bir mermer işleme tesisinden temin edilen mermer atıklarının çimento esaslı harçlarda iki farklı kullanım biçimi deneysel olarak incelenmiştir. Kaba mermer atıkları kırılarak ince agrega fraksiyonuna, bir kısmı ise kuru bilyalı öğütme ile mikronize toz fraksiyonuna dönüştürülmüştür. Kontrol karışımına ek olarak, standart CEN kumunun %10, %20, %30 ve %40 oranlarında kırılmış mermer agregasıyla; Portland çimentosunun ise aynı oranlarda mikronize mermer tozuyla ikame edildiği karışımlar hazırlanmıştır. 40×40×160 mm prizmatik numuneler 7, 28 ve 56 gün kürlenmiş ve üç noktalı eğilme ile basma dayanımı deneylerine tabi tutulmuştur. Karakterizasyon sonuçları mermer atığının karbonat esaslı ve dolomitik karakter taşıdığını; öğütülmüş fraksiyonun d10, d50 ve d90 değerlerinin sırasıyla 3,49, 26,33 ve 97,65 µm olduğunu göstermiştir. Agrega ikamesinde 28 günlük %40 ikame serisi 47,08 MPa basma ve 16,83 MPa eğilme dayanımına ulaşarak kontrol numunesine göre sırasıyla yaklaşık %10,5 ve %20,2 daha yüksek değerler vermiştir. Buna karşılık çimento ikamesinde mekanik kayıplar ikame oranı ve kür süresiyle belirginleşmiş; 56 günlük %40 ikame serisinde basma dayanımı 21,50 MPa'a gerilemiştir. Sonuçlar, kırılmış mermer atığının ince agrega ikamesinde yüksek oranlarda kullanılma potansiyeli bulunduğunu; mikronize mermer tozunun ise çimento ikamesinde özellikle düşük oranlarla sınırlandırılması gerektiğini ortaya koymuştur.

Anahtar Kelimeler: Mermer Atığı, İnce Agrega İkamesi, Çimento İkamesi, Basma Dayanımı, Eğilme Dayanımı, Döngüsel Ekonomi.

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ABSTRACT

Significant amounts of coarse- and fine-grained waste are generated during cutting, sizing, and surface-processing operations in the marble and natural stone industry. The utilization of these wastes as secondary raw materials is important for reducing the burden of waste disposal, limiting the consumption of natural aggregates, and mitigating the environmental impacts associated with cement use. In this study, two different utilization routes for marble waste obtained from a marble processing plant were experimentally investigated in cement-based mortars. Coarse marble waste was crushed to produce a fine aggregate fraction, while a portion of the material was micronized by dry ball milling to obtain a fine powder fraction. In addition to the control mixture, mortar mixtures were prepared by replacing standard CEN sand with crushed marble aggregate at replacement levels of 10%, 20%, 30%, and 40%, while Portland cement was replaced with micronized marble powder at the same replacement levels. Prismatic specimens measuring 40×40×160 mm were cured for 7, 28, and 56 days and subsequently subjected to three-point flexural and compressive strength tests. Characterization results indicated that the marble waste was carbonate-based and exhibited dolomitic characteristics, while the ground fraction had d10, d50, and d90 values of 3.49, 26.33, and 97.65 µm, respectively. For fine aggregate replacement, the mixture containing 40% marble waste achieved 28-day compressive and flexural strengths of 47.08 and 16.83 MPa, respectively, corresponding to increases of approximately 10.5% and 20.2% compared with the control mixture. In contrast, mechanical strength losses associated with cement replacement became more pronounced with increasing replacement level and curing age, with the 56-day compressive strength decreasing to 21.50 MPa at a 40% replacement level. The results demonstrate that crushed marble waste has considerable potential for use at relatively high replacement levels as a fine aggregate substitute, whereas the use of micronized marble powder as a cement replacement should preferably be limited to low replacement levels.

Keywords: Marble Waste, Fine Aggregate Replacement, Cement Replacement, Compressive Strength, Flexural Strength, Circular Economy.

1. GİRİŞ

Mermer ve doğal taş üretimi; ocaktan blok çıkarma, kesme, ebatlandırma ve yüzey işleme gibi çok sayıda aşama içermekte ve bu aşamalar boyunca farklı tane boyutlarında önemli miktarda atık oluşmaktadır. Literatürde, üretime giren mermerin yalnızca yaklaşık %20-30'luk bölümünün nihai ürüne dönüştüğü, kalan kısmın ise parça, kırıntı, toz veya çamur olarak atık hâline gelebildiği bildirilmektedir (Yılmaz ve Ark., 2009; Topçu ve Ark., 2009; Uygunoğlu ve Ark., 2014; Adıgüzel ve Ark., 2022). İnce mermer atıklarının kontrolsüz depolanması arazi kullanımı, yüzeysel akış ve partikül yayılımı gibi çevresel sorunlara neden olabildiğinden, bu malzemelerin ikincil hammadde olarak geri kazanılması döngüsel ekonomi açısından önem kazanmıştır (Omar ve Ark., 2012; Ashish, 2019).

Mermer atıklarının çimento esaslı sistemlerde değerlendirilmesinde iki temel yaklaşım öne çıkmaktadır. Birincisi, mikronize mermer tozunun Portland çimentosunun bir bölümünün yerine kullanılmasıdır. Bu durumda çok ince karbonat taneleri çimento taneleri arasındaki boşlukları doldurabilir ve hidratasyon ürünleri için çekirdeklenme yüzeyleri oluşturabilir. Bununla birlikte mermer tozunun esas olarak inert karbonat karakterinde olması nedeniyle yüksek ikame oranlarında bağlayıcı fazın azalması ve buna bağlı seyreltme etkisi mekanik dayanımı sınırlayabilmektedir (Ergün, 2011; Li ve Ark., 2018; Alyousef ve Ark., 2019).

İkinci yaklaşım, kırılmış mermer parçalarının doğal ince agrega yerine kullanılmasıdır. Bu kullanım biçiminde çimento miktarı korunurken doğal kum tüketimi azaltılmaktadır. Mermer agregasının tane şekli, yüzey özellikleri ve kalsit esaslı mineralojisi, çimento hamuru ile agrega arasındaki arayüzey geçiş bölgesini etkileyebilmekte ve uygun gradasyonda mekanik performans korunabilmektedir (Hebhoub ve Ark., 2011; Bentlemsan ve Ark., 2023). Bu nedenle aynı mermer atığının bağlayıcı ve agrega ikamesi olarak kullanımı, birbirinden farklı mekanizmalar ve optimum ikame aralıkları doğurabilir.

Bu çalışmanın amacı, bir mermer işleme tesisinden elde edilen atığın kırılmış ince agrega ve mikronize toz olarak iki farklı biçimde değerlendirilmesini karşılaştırmalı olarak incelemektir. Bu kapsamda

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fiziksel-kimyasal karakterizasyon yapılmış; %10-40 ikame aralığında hazırlanan harçların 7, 28 ve 56 günlük basma ve eğilme dayanımları belirlenmiş ve kullanım biçimine göre mekanik performans değişimi tartışılmıştır.

2. MALZEME VE YÖNTEM

2.1. Kullanılan Malzemeler ve Atık Hazırlama

Deneysel çalışmada bir mermer işleme tesisinden temin edilen kaba mermer atıkları kullanılmıştır. Atık malzeme, serbest nemin karışım suyu üzerindeki etkisini azaltmak amacıyla 105±5 °C'de sabit kütleye kadar kurutulmuştur. Kaba parçalar laboratuvar tipi çeneli kırıcı ile kademeli olarak küçültülmüş; ince agrega olarak kullanılacak bölüm uygun boyut aralığında ayrılırken, çimento ikamesinde kullanılacak bölüm laboratuvar tipi bilyalı değirmende yaklaşık 30 dakika kuru öğütülerek mikronize edilmiştir.

Bağlayıcı olarak TS EN 197-1'e uygun CEM I 42,5 R Portland çimentosu, kontrol agregası olarak TS EN 196-1'e uygun CEN referans kumu ve karışım suyu olarak içilebilir nitelikte şebeke suyu kullanılmıştır. Mikronize mermer tozunun özgül ağırlığı piknometre yöntemiyle; kimyasal bileşimi ICP-OES ile; aktif kil kirliliği TS EN 933-9 metilen mavisi deneyiyle ve tane boyutu dağılımı lazer kırınımı yöntemiyle değerlendirilmiştir.

Tablo 1. Mermer atığının seçilmiş fiziksel ve kimyasal karakterizasyon sonuçları.

Özellik	**Sonuç**	**Değerlendirme**
Özgül ağırlık ölçümleri	2,61 g/cm^3	Karbonat esaslı doğal taş aralığı
ICP-OES	Ca ≈ %24; Mg ≈ %11	Dolomitik-kalsitik karakter
d10	3,49 µm	İnce fraksiyon
d50	26,33 µm	Çimento tane boyutuyla karşılaştırılabilir
d90	97,65 µm	Kaba sınır

2.2. Karışım Tasarımı ve Kür Programı

Deneysel matris üç gruptan oluşturulmuştur: herhangi bir mermer atığı içermeyen kontrol serisi; Portland çimentosunun ağırlıkça %10, %20, %30 ve %40 oranlarında mikronize mermer tozu ile değiştirildiği çimento ikame serileri; CEN standart kumunun aynı oranlarda kırılmış mermer agregasıyla değiştirildiği agrega ikame serileri. Her karışım ve kür yaşı için tekrarlı numune üretimi yapılmıştır.

Taze harçlar TS EN 196-1 esaslarına uygun mekanik mikserde homojenleştirilmiş, 40×40×160 mm boyutlarında üç gözlü prizmatik çelik kalıplara yerleştirilmiş ve sarsma tablasında sıkıştırılmıştır. Numuneler 20±2 °C laboratuvar koşullarında 24 saat kalıp içinde tutulmuş, ardından kalıptan çıkarılarak 20±2 °C'deki kür havuzlarında 7, 28 ve 56 gün bekletilmiştir.

Tablo 2. Deneysel karışım matrisi ve kür programı.

Sistem	**İkame malzemesi**	**İkame oranları (%)**	**Kür süreleri (gün)**
Kontrol	Yok	0	7, 28, 56
Agrega serisi	Kırılmış mermer agregası	10, 20, 30, 40	7, 28, 56
Çimento serisi	Mikronize mermer tozu	10, 20, 30, 40	7, 28, 56

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2.3. Mekanik Deneyler ve Veri Değerlendirme

Kür süresi tamamlanan prizmatik numunelerde önce üç noktalı eğilme deneyi uygulanmış, kırılma sonrasında elde edilen prizma yarımları basma dayanımı deneyinde kullanılmıştır. Her karışım serisi ve kür yaşı için en az üç numunenin sonuçları değerlendirilerek ortalama dayanım değerleri esas alınmıştır. Agrega ve çimento ikame serileri, aynı kür yaşındaki kontrol numunesiyle ve kendi içlerinde ikame oranına göre karşılaştırılmıştır.

3. BULGULAR VE TARTIŞMA

3.1. Karakterizasyon Bulguları

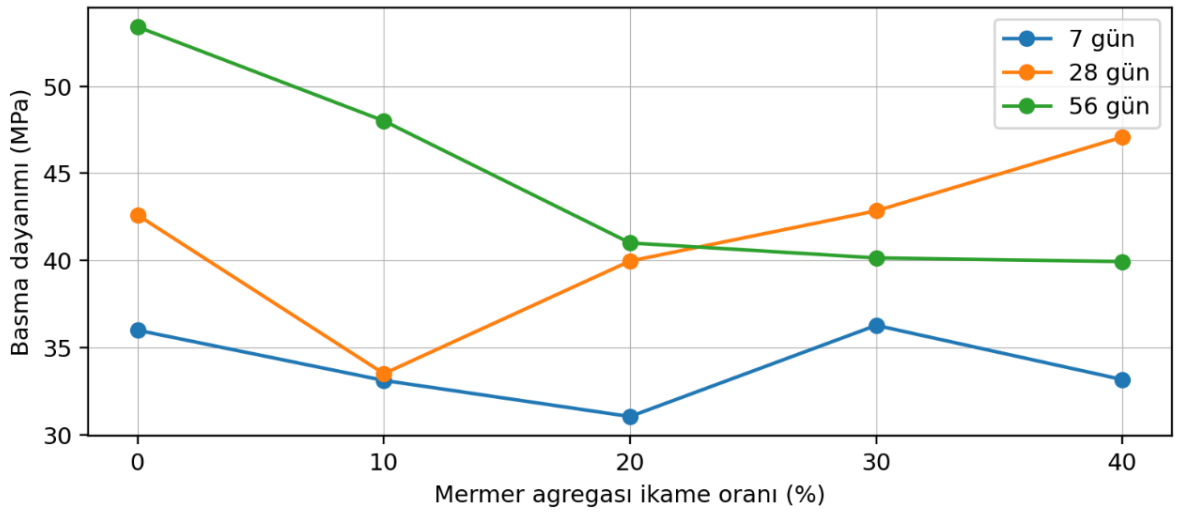
Mermer atık numunesinin piknometre ile yapılan yoğunluk ölçüm sonucu 2,61 g/cm^3 olarak bulunmuştur. ICP-OES analizinde yaklaşık %24 Ca ve %11 Mg belirlenmesi, numunenin karbonat esaslı ve dolomitik-kalsitik karakterini desteklemektedir. Silisyum, alüminyum ve demir bileşenlerinin düşük olması, malzemenin doğrudan puzolanik bir katkıdan çok fiziksel dolgu ve çekirdeklenme mekanizmalarıyla davranmasının daha olası olduğunu göstermektedir.

Lazer kırınımı analizinde d10=3,49 µm, d50=26,33 µm ve d90=97,65 µm olarak belirlenmiştir. Özellikle 26,33 µm'lik medyan tane boyutu, mikronize mermer tozunun çimento taneleri arasındaki boşlukları doldurabilecek fiziksel boyut aralığında olduğunu göstermektedir. Bununla birlikte, bu tane boyutu avantajının yüksek çimento ikame oranlarında bağlayıcı kaybını telafi edip edemediği mekanik sonuçlarla birlikte değerlendirilmelidir.

3.2. Agrega İkamesinin Mekanik Performansı

Mermer atığının ince agrega olarak kullanıldığı serilerde mekanik performans, kür süresi ve ikame oranına bağlı olarak değişmekle birlikte genel olarak kontrol seviyesine yakın kalmıştır. 7 günlük serilerde basma dayanımları 31,05-36,28 MPa aralığında iken eğilme dayanımları özellikle %30 ve %40 ikame seviyelerinde artarak sırasıyla 11,95 ve 13,49 MPa'a ulaşmıştır.

En belirgin olumlu sonuç 28 günlük %40 agrega ikame serisinde elde edilmiştir. Bu karışımda basma dayanımı 47,08 MPa'a çıkarak 42,60 MPa'lık kontrol değerinin yaklaşık %10,5 üzerine; eğilme dayanımı ise 16,83 MPa ile 14,00 MPa'lık kontrolün yaklaşık %20,2 üzerine çıkmıştır. Bu davranış, uygun tane paketlenmesi ve mermer agregası ile çimento hamuru arasındaki arayüzey geçiş bölgesinin mekanik katkısıyla ilişkilendirilebilir.



Şekil 1. Mermer agregası ikame oranının 7, 28 ve 56 günlük basma dayanımına etkisi.

56 günlük sonuçlarda tüm agrega ikame serilerinin basma dayanımı kontrol numunesinden düşük kalmıştır; ancak %10 ikamede 48,01 MPa ile dayanımın önemli bir bölümü korunmuştur. Eğilme dayanımında ise %10 ve %30 agrega ikamelerinde sırasıyla 18,15 ve 18,14 MPa değerleri elde edilmiş

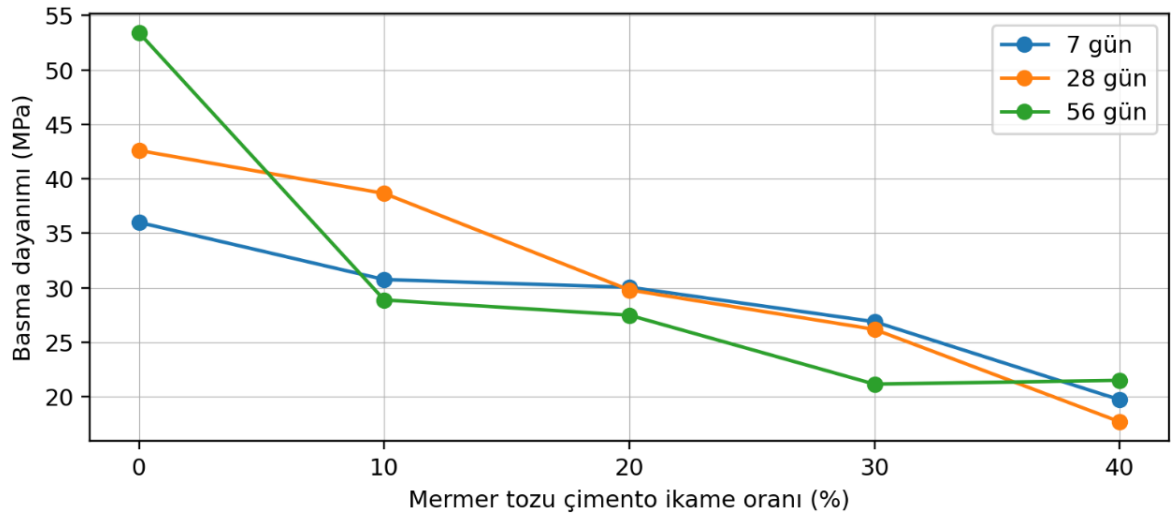
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ve 17,20 MPa'lık kontrol değerinin yaklaşık %5,5 üzerine çıkılmıştır. Bu sonuçlar, mermer agregasının özellikle eğilme performansını koruyabildiğini, ancak ileri yaş basma dayanımında optimum ikame oranının ayrıca değerlendirilmesi gerektiğini göstermektedir.

3.3. Çimento İkamesinin Mekanik Performansı

Çimento yerine mikronize mermer tozu kullanılan serilerde ikame oranı arttıkça basma dayanımındaki düşüş daha belirgin olmuştur. 7 günlük kontrol numunesi 36,00 MPa iken %10 ve %20 ikame serileri 30,75 ve 30,05 MPa seviyelerinde kalmış; %40 ikamede dayanım 19,72 MPa'a gerilemiştir. Erken yaş eğilme dayanımında %10 ikame serisinin 11,54 MPa ile kontrolün hafif üzerinde olması, düşük ikame oranında mikro-dolgu ve çekirdeklenme etkisinin sınırlı olumlu katkısına işaret etmektedir.

28 günlük basma dayanımı %10 ikamede 38,66 MPa olarak ölçülmüş ve kontrolün yaklaşık %9,2 altında kalmıştır. %20, %30 ve %40 ikamelerde değerler sırasıyla 29,80, 26,18 ve 17,70 MPa'a düşmüştür. 56 günlük kürde ise kontrol dayanımı 53,40 MPa'a yükselmesine karşın %10-40 çimento ikame serileri 28,88-21,50 MPa aralığında kalmıştır. Uzun kür süresinin bu kaybı telafi etmemesi, mikronize mermer tozunun bağlayıcı faz oluşturmadığını ve yüksek ikame oranlarında seyreltme etkisinin baskınlaştığını göstermektedir.

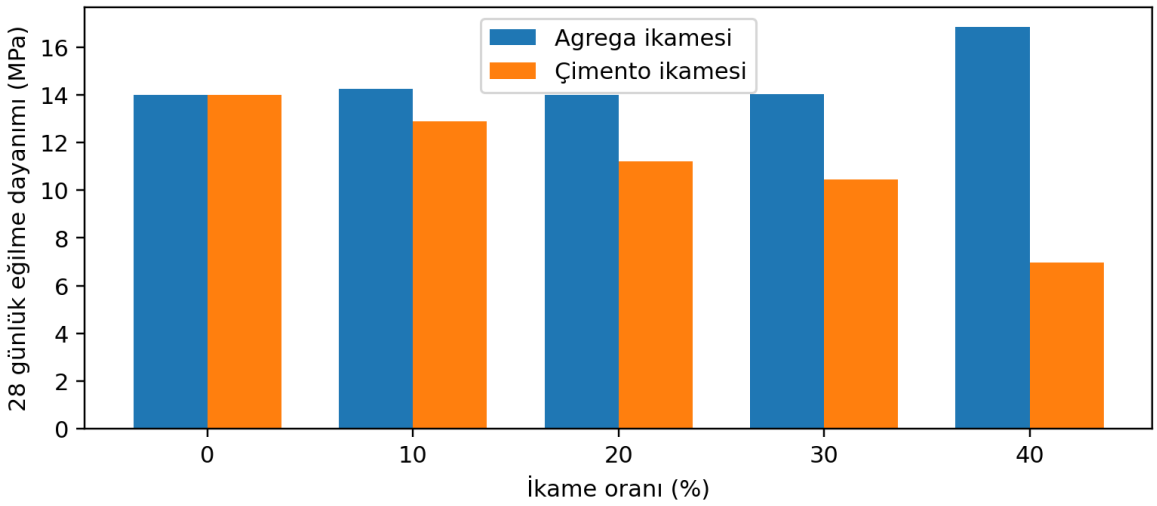


Şekil 2. Mikronize mermer tozu çimento ikame oranının 7, 28 ve 56 günlük basma dayanımına etkisi.

3.4. İkame Türlerinin Karşılaştırılması

Agrega ve çimento ikame serileri birlikte değerlendirildiğinde temel fark, agrega ikamesinde bağlayıcı miktarının korunmasına karşın çimento ikamesinde hidratasyona katılan çimento miktarının doğrudan azalmasıdır. Bu nedenle kırılmış mermer agregası yüksek ikame oranlarında dahi kabul edilebilir mekanik performans gösterebilirken, mikronize mermer tozunun yüksek oranlarda çimento yerine kullanılması belirgin dayanım kaybı yaratmaktadır.

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Şekil 3. 28 günlük eğilme dayanımının agrega ve çimento ikame türlerine göre karşılaştırılması.

28 günlük eğilme verileri bu farkı açık biçimde göstermektedir. %40 agrega ikamesi 16,83 MPa'a ulaşırken aynı orandaki çimento ikamesi 6,98 MPa'da kalmıştır. Benzer eğilim basma dayanımında da görülmektedir. Bu nedenle çalışmada incelenen mermer atığı için ince agrega ikamesi, çimento ikamesine göre daha geniş bir teknik kullanım aralığı sunmaktadır.

Çimento ikamesi açısından sonuçlar, %10 seviyesinin yüksek ikame oranlarına göre daha uygun olduğunu göstermektedir; ancak 56 günlük basma dayanımında bu seviyede dahi kontrol numunesine göre belirgin kayıp bulunduğundan, %10 oranının 'optimum' olarak genellenebilmesi için dayanıklılık, işlenebilirlik ve mikro yapı testleriyle desteklenen ek çalışmalar gereklidir. Bu nedenle bildiride düşük oranlı çimento ikamesi bir kullanım potansiyeli olarak değerlendirilmiş, yüksek ikameler ise mekanik açıdan sınırlı bulunmuştur.

4. SONUÇLAR

Mermer işleme atıklarının çimento esaslı harçlarda ince agrega ve çimento ikamesi olarak değerlendirildiği bu deneysel çalışmadan aşağıdaki temel sonuçlar elde edilmiştir:

• Mermer atığının Ca ve Mg bakımından zengin karbonat esaslı yapısı ve d50=26,33 µm düzeyindeki mikronize tane boyutu, malzemenin fiziksel dolgu amaçlı kullanımına uygun bir karakter göstermektedir.

• Kırılmış mermer agregası, doğal ince agrega yerine kullanıldığında mekanik performansı genel olarak çimento ikamesine göre daha iyi korumuştur.

• 28 günlük %40 agrega ikamesi 47,08 MPa basma ve 16,83 MPa eğilme dayanımı ile kontrol serisine göre sırasıyla yaklaşık %10,5 ve %20,2 artış sağlamıştır.

• 56 günlük agrega serilerinde basma dayanımı kontrolün altında kalmakla birlikte, %10 ve %30 ikame serilerinin eğilme dayanımı kontrolün yaklaşık %5,5 üzerinde gerçekleşmiştir.

• Mikronize mermer tozunun çimento ikamesinde kullanılmasıyla ikame oranı yükseldikçe basma ve eğilme dayanımları azalmış; özellikle %20 ve üzerindeki oranlarda seyreltme etkisi belirginleşmiştir.

• Sonuçlar, bu mermer atığının ince agrega ikamesinde yüksek oranlarda değerlendirilmesinin teknik açıdan umut verici olduğunu; çimento ikamesinin ise düşük oranlarda ve ilave dayanıklılık/mikroyapı doğrulamasıyla ele alınması gerektiğini göstermektedir.

Atığın agrega ikamesi olarak kullanılması doğal kum tüketiminin azaltılmasına ve mermer işleme atıklarının ikincil hammaddeye dönüştürülmesine katkı sağlayabilir. Çimento ikamesinde ise çevresel kazanım ile mekanik performans arasındaki denge birlikte değerlendirilmelidir. Gelecek çalışmalarda su emme, porozite, sülfat ve donma-çözülme dayanıklılığı, SEM/XRD analizleri ve yaşam döngüsü değerlendirmesi ile optimum ikame aralıklarının daha kapsamlı biçimde doğrulanması önerilmektedir.

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KONSANTRİK KANALLARDA İÇTEKİ SİLİNDİRİN DÖNMESİ DURUMUNDA AKIŞ KARAKTERİSTİKLERİNİN NÜMERİK OLARAK İNCELENMESİ

NUMERICAL INVESTIGATION OF FLOW CHARACTERISTICS IN CONCENTRIC CHANNELS WITH ROTATION OF THE INNER CYLINDER

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ÖZET

Eş merkezli ve ayrı merkezli döner silindirler arasındaki akışlar; petrol çıkarma ve işleme tesisleri, hidrodinamik yağlama, makine elemanları ve turbo makineler gibi çok çeşitli mühendislik uygulamalarında görülmektedir. Bu çalışmada, dış çapı 40 mm, iç çapı 20 mm ve uzunluğu 2 m olan konsantrik bir kanalda, içteki silindirin dönmesi durumunda eksenel ve çevresel akış karakteristikleri hesaplamalı akışkanlar dinamiği (HAD) yöntemiyle nümerik olarak incelenmiş ve deneysel sonuçlarla karşılaştırılmıştır. Reynolds sayısının 9.000, 30.000 ve 60.000 değerleri için ANSYS Fluent yazılımında sayısal analizler gerçekleştirilmiştir. İç silindir rotasyonunun akış alanına etkisini belirlemek amacıyla 0 ve 300 dev/dk dönme hızları karşılaştırılmıştır. Eksenel ve çevresel yöndeki hız profilleri, türbülans yoğunlukları, Reynolds gerilmeleri, sürtünme katsayıları ve logaritmik hız profilleri hesaplanmış ve deneysel sonuçlarla karşılaştırılmıştır. Reynolds sayısının artmasıyla boyutsuz eksenel hız profilinin genel yapısının korunduğu, buna karşılık sürtünme katsayısının % 42,57 azaldığı belirlenmiştir. İç silindirin dönmesiyle çevresel bir hız alanının oluştuğu ve rotasyon etkisinin özellikle iç cidara yakın bölgede belirginleştiği görülmüştür.

Anahtar Kelimeler: Konsantrik annülüs, türbülanslı akış, iç silindir rotasyonu, hesaplamalı akışkanlar dinamiği, Reynolds gerilmeleri.

ABSTRACT

Flows between concentric and eccentric rotating cylinders are encountered in a wide range of engineering applications, including petroleum extraction and processing facilities, hydrodynamic lubrication, machine elements, and turbomachinery. In this study, the axial and circumferential flow characteristics in a concentric channel with an outer diameter of 40 mm, an inner diameter of 20 mm, and a length of 2 m were numerically investigated using the computational fluid dynamics (CFD) method for the case of inner cylinder rotation and compared with experimental results. Numerical analyses were performed in ANSYS Fluent for Reynolds numbers of 9,000, 30,000, and 60,000. To determine the effect of inner cylinder rotation on the flow field, rotational speeds of 0 and 300 rpm were compared. Axial and circumferential velocity profiles, turbulence intensities, Reynolds stresses, friction coefficients, and logarithmic velocity profiles were calculated and compared with experimental results. It was determined that the general form of the dimensionless axial velocity profile was preserved as the Reynolds number increased, whereas the friction coefficient decreased by 42.57%. Rotation of the inner cylinder generated a circumferential velocity field, and the effect of rotation became particularly pronounced near the inner wall.

Keywords: Axial and circumferential flow, Concentric channels, CFD, ANSYS Fluent

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1. GİRİŞ

Eş merkezli silindirik kanallarda akış; petrol ve doğal gaz kuyularındaki sondaj işlemleri, yataklar, döner borulu ısı değiştiricileri, elektrik motorları ve çeşitli türbomakine uygulamalarında yaygın olarak karşılaşılan önemli bir mühendislik problemidir. Özellikle sondaj uygulamalarında akışkan, içteki sondaj dizisi ile kuyu cidarı arasındaki halkasal boşluktan geçerek kırıntıların yüzeye taşınmasını ve sürtünme sonucu oluşan ısının uzaklaştırılmasını sağlamaktadır. Bu sistemlerde akış alanının doğru belirlenmesi; basınç kayıplarının, pompalama gereksinimlerinin ve akışın taşıma kapasitesinin tahmin edilmesi açısından önem taşımaktadır (Nouri vd., 1993; Nouri ve Whitelaw, 1994).

İç silindirin dönmediği eş merkezli silindirik kanallarda akış temel olarak eksenel basınç gradyanı tarafından oluşturulurken, iç silindirin dönmesiyle akışa teğetsel bir hız bileşeni de eklenmektedir. Eksenel Poiseuille akışı ile dönmeden kaynaklanan Taylor–Couette akışının birlikte bulunması, Taylor–Couette–Poiseuille akışı olarak tanımlanan daha karmaşık bir akış yapısı meydana getirmektedir. İç silindirin dönüşü; eksenel ve teğetsel hız profillerini, türbülans şiddetlerini, Reynolds kayma gerilmelerini, duvar kayma gerilmesini ve basınç kaybını doğrudan etkileyebilmektedir. Bu etkilerin büyüklüğü Reynolds sayısı, dönüş hızı, çap oranı ve halkasal boşluk genişliği gibi geometrik ve işletme parametrelerine bağlıdır (Nouri ve Whitelaw, 1994; Abdelhafiz vd., 2023).

Nouri vd. (1993), çap oranı 0,5 olan eş merkezli ve eksantrik halkasal kanallarda Newtonian akışkanın tam gelişmiş türbülanslı akışını deneysel olarak incelemiştir. Reynolds sayısının 8900 ve 26600 olduğu koşullarda üç ortalama hız bileşeni ile Reynolds kayma gerilmeleri ölçülmüş; eş merkezli kanalda iç ve dış duvar bölgelerindeki hız dağılımlarının duvar kanunuyla uyumlu olduğu belirlenmiştir. Ayrıca eş merkezli halkasal kanaldaki sürtünme katsayısının düzgün dairesel borudaki değerden yaklaşık %8 daha yüksek olduğu bildirilmiştir.

İç silindir dönüşünün etkisi Nouri ve Whitelaw (1994) tarafından, aynı çap oranına sahip eş merkezli silindirik kanalda 300 rpm dönüş hızı için araştırılmıştır. Çalışmada, düşük ve orta Reynolds sayılarında dönüşün eksenel hız profilini daha düz hâle getirdiği ve özellikle iç duvar yakınındaki türbülans dalgalanmalarını artırdığı görülmüştür. Reynolds sayısı arttıkça eksenel akışın atalet etkisinin güçlendiği, buna bağlı olarak dönüşün eksenel hız profili ve sürtünme katsayısı üzerindeki etkisinin azaldığı belirlenmiştir. Nouri ve Whitelaw (1997), çalışmayı eksantrik silindirik kanallara genişleterek iç silindir dönüşünün akışın çevresel dağılımını ve ikincil akış yapılarını önemli ölçüde değiştirebildiğini göstermiştir.

Arslan (2025), Newtonian ve non-Newtonian akışkanların konsantrik ve eksantrik kanallardaki tam gelişmiş türbülanslı akışını ANSYS Fluent ve Reynolds Gerilme Modeli kullanarak sayısal olarak incelemiş ve elde edilen sonuçları literatürdeki deneysel verilerle karşılaştırmıştır. Çalışmada iç silindir dönüşünün akış karakteristikleri üzerindeki etkisi de değerlendirilmiş; dönmeli ve dönmesiz durumlar arasındaki maksimum hız farkının konsantrik kanallarda yaklaşık %6–7, eksantrik kanallarda ise en fazla %12 düzeyinde olduğu bildirilmiştir.

İç silindir rotasyonundan kaynaklanan akım eğriliği ve dönme etkilerinin modellenebilmesi amacıyla, Reynolds gerilmelerini ayrı taşınım denklemleriyle çözen Reynolds Stress–Stress Omega türbülans modeli kullanılmıştır (ANSYS, 2023).

Deneysel çalışmaların yanında Hesaplamalı Akışkanlar Dinamiği (HAD), halkasal kanallardaki üç boyutlu akış yapısının ve deneysel olarak ölçülmesi güç türbülans büyüklüklerinin belirlenmesinde etkili bir yöntemdir. Ofei vd. (2015), iç borunun döndüğü dar silindirik kanallarda üç boyutlu HAD analizleri gerçekleştirerek dönüş hızı ve geometrik parametrelerin hız dağılımları ile basınç kayıpları üzerindeki etkilerini incelemiştir. Abdelhafiz vd. (2023), eş merkezli silindirik kanaldaki türbülanslı Taylor–Couette–Poiseuille akışını ANSYS Fluent ile modellemiş ve sayısal hız alanlarını literatürdeki deneysel verilerle karşılaştırmıştır. Basso ve Franco (2024) ise iç silindir dönüşünün türbülans istatistiklerinin büyüklüğünü ve kanal içerisindeki dağılımını değiştirdiğini göstermiştir. Bununla birlikte, Newtonian akışkanın farklı Reynolds sayılarındaki tam gelişmiş türbülanslı akışında iç silindir dönüşünün ortalama hızlar, türbülans büyüklükleri, Reynolds gerilmeleri ve sürtünme karakteristikleri üzerindeki etkilerinin birlikte değerlendirilmesine ihtiyaç bulunmaktadır.

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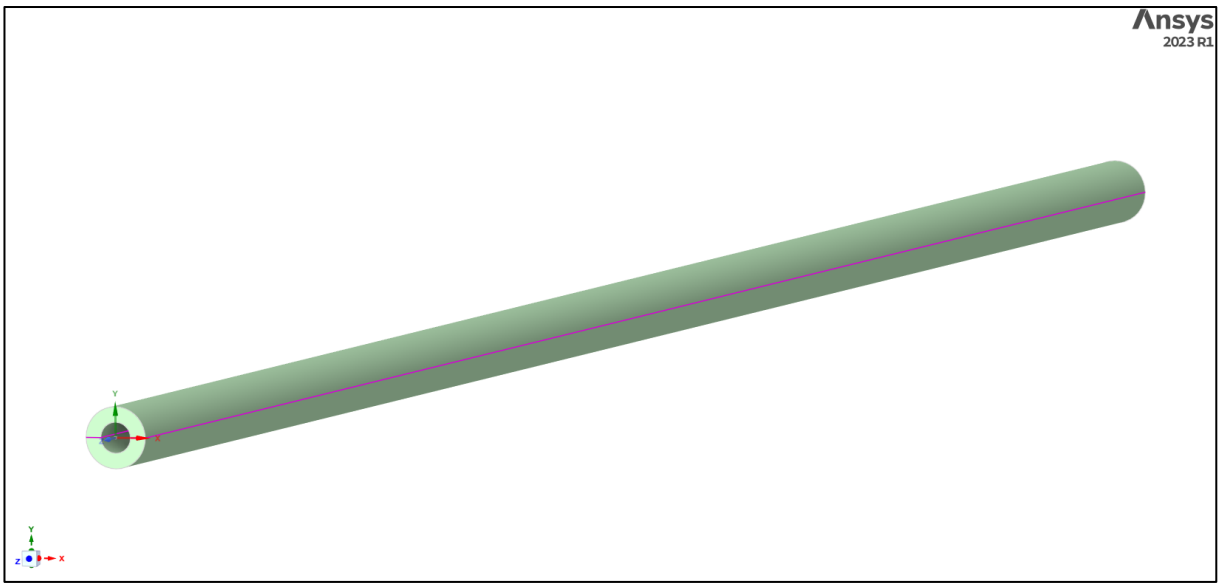
Bu çalışmada, eş merkezli halkasal kanalda Newtonian akışkanın türbülanslı akış karakteristikleri, iç silindirin dönmediği ve 300 rpm hızla döndüğü koşullar için sayısal olarak incelenmiştir. ANSYS Fluent kullanılarak gerçekleştirilen analizlerde eksenel ve teğetsel ortalama hız profilleri, türbülans hız dalgalanmaları, Reynolds kayma gerilmeleri, duvar kanunu davranışı, sürtünme katsayısı ve basınç değişimi değerlendirilmiş; elde edilen sayısal sonuçlar literatürde bulunan deneysel verilerle karşılaştırılmıştır.

2. ARAŞTIRMA VE BULGULAR

Bu bölümde oluşturulan sayısal model, çözüm üzerine yaklaşım, deneysel doğrulama ve elde edilen bulgular sunulmuştur.

2.1. Geometri ve Akışkan Koşulları

Geometrik model, dış yarıçapı R_o = 0,020 m olan ve iç yarıçapı R_i = 0,010 m olan eş merkezli silindirik bir kanaldan oluşmaktadır. Kanal uzunluğu L = 2 m, halkasal boşluk S = Ro – Ri = 0,010 m ve hidrolik çap $D_h = D_o - D_i$= 0,020 m'dir. Buna değerlere göre çap oranı D_i/D_o = 0,5'tir. Geometrik çizimdeki eksenel yön z, radyal yön r ve teğetsel yön θ ile gösterilmiştir. Sonuçların alındığı düzlem, giriş etkilerinin büyük ölçüde sönümlendiği z = -1,8 m kesitindeki radyal hat üzerinden alınmıştır.

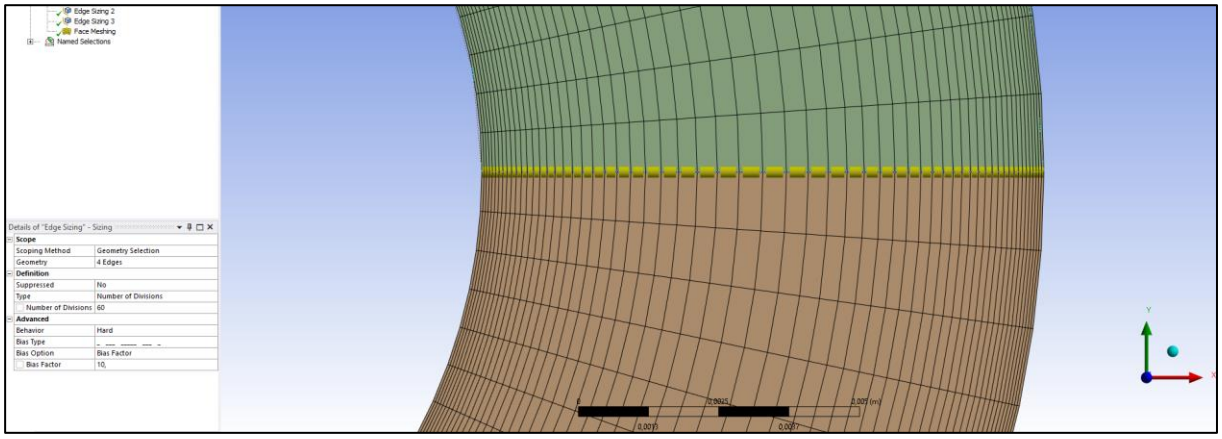


Şekil 1. 2 metre uzunluğundaki eş merkezli kanal

Geometri için ağ oluşturma aşamasında, geometri ANSYS SpaceClaim ortamında Share Topology komutu kullanılarak iki hacme ayrılmıştır. Bu sayede temas eden bölgelerde ortak node oluşturularak uyumlu (conformal) ağ yapısı elde edilmiştir.

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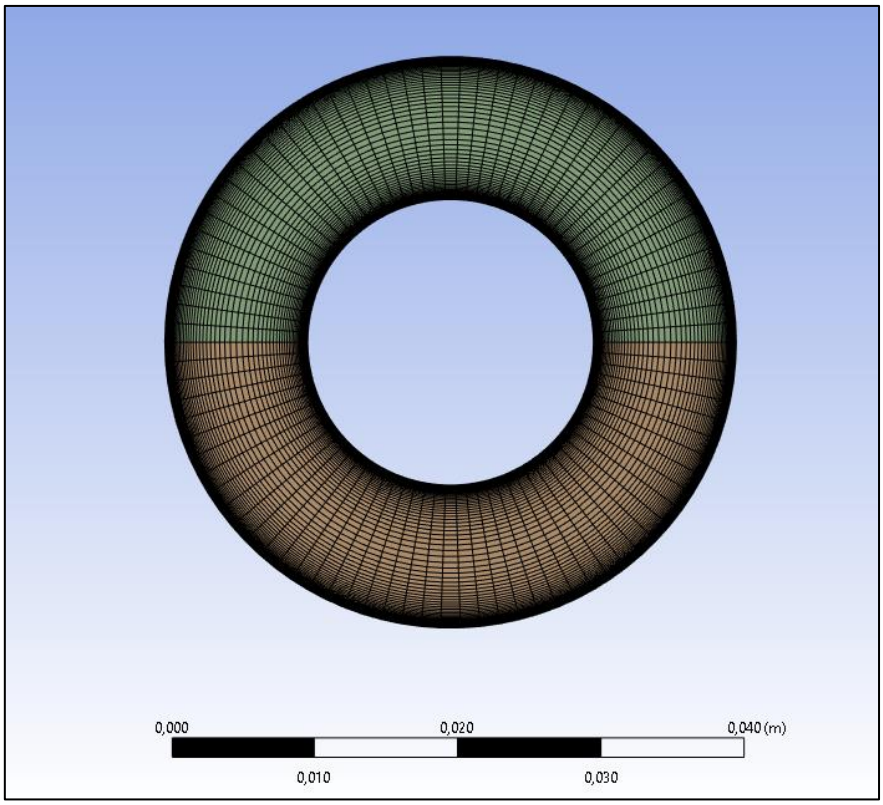
Ağ yapısı, halkasal boşluktaki hız değişimlerini ve iki duvarın yakınındaki sınır tabakayı çözebilecek biçimde hazırlanmıştır. Cidar etrafında bulunacak sık ağ elemanları katmanlı olarak kullanılmış ve seçilen yaklaşık 2,052 milyon elemanlı hücreden oluşup, ortalama y+ değerinin yaklaşık 1,7 olduğu belirlenmiştir.



Şekil 2. Cidara bölgesi için kullanılan "kenar boyutlandırma" mesh metodu

Duvar yakınında hız ve basınç gradyanlarının belirginleşmesi, akış özelliklerinin bu bölgelerde hassas biçimde çözümlenmesini gerektirmektedir. Duvar fonksiyonlarının uygun olmayan ağ yapısıyla kullanılması, sayısal sonuçların doğruluğunu olumsuz etkileyebilmektedir. Bu nedenle sınır tabaka davranışını daha iyi yakalayabilmek amacıyla cidara yaklaştıkça sıklaşan bir ağ yapısı oluşturulmuş ve Şekil 2'de gösterilen boyutlandırma yöntemi uygulanmıştır.

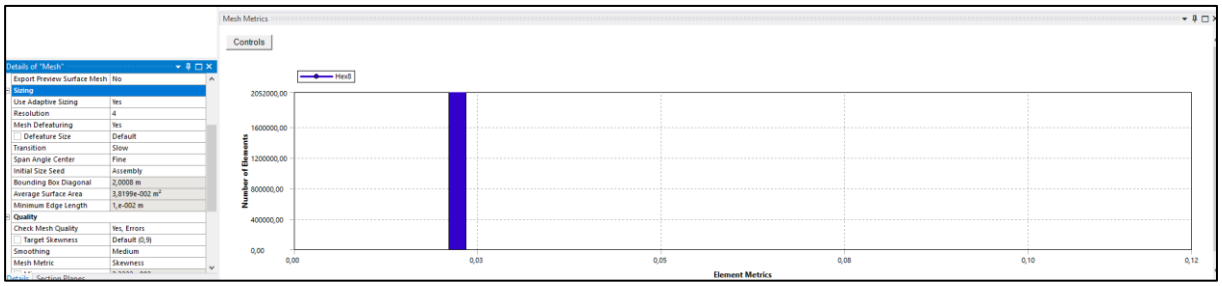
Şekil 3'de eş merkezli kanal için oluşturulan ağ (mesh) yapısı gösterilmektedir. Duvar bölgelerinde akış alanındaki hız gradyenlerinin ve duvar etkilerinin daha doğru çözülebilmesi amacıyla daha ince ağ elemanları kullanılmıştır.



Şekil 3. Eş merkezli geometri mesh atılmış önden görünüşü

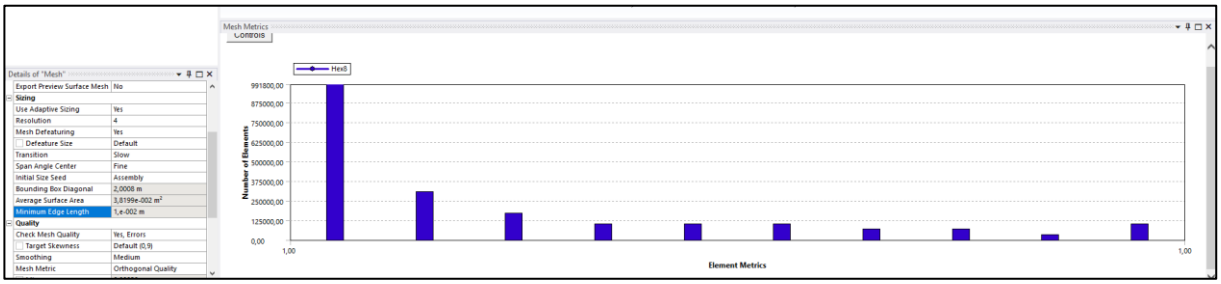
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Ağ yapısının kalitesi, ortogonal kalite (Orthogonal Quality) ve çarpıklık (Skewness) kriterleri kullanılarak değerlendirilmiştir. Şekil 4'te ortogonal kalite dağılımı gösterilmektedir. Elde edilen minimum ortogonal kalite değeri 0,99939 olup, bu değerin 1'e oldukça yakın olması oluşturulan ağın yüksek kaliteye sahip olduğunu göstermektedir.



Şekil 4. Mesh metrik Orthogonal Quality değerleri (Ortogonal kalitesi)

Şekil 5'te verilen çarpıklık (Skewness) dağılımı incelendiğinde ise maksimum çarpıklık değerinin yaklaşık 0,022 olduğu görülmektedir. Çarpıklık değerinin 0'a oldukça yakın olması, oluşturulan hegzagonal ağ yapısının sayısal analizler için uygun olduğunu ve yüksek çözüm doğruluğu sağlayacağını göstermektedir.



Şekil 5. Mesh metrik Skewness değerleri (çarpıklık)

Analizde kullanılan eş merkezli silindirik kanal geometrisine ve akışkana ait temel özellikler Tablo 1'de sunulmuştur.

Tablo 1. Geometri ve akışkan özellikleri

Büyüklük	Sembol	Değer
Dış çap	D_o	0,040 m
İç çap	D_i	0,020 m
Kanal uzunluğu	L	2 m
Halkasal boşluk	S	0,010 m
Hidrolik çap	D_h	0,020 m
Çap oranı	D_i/D_o	0,50
Akışkan	-	Su, 20 °C
Yoğunluk	P	1000 kg/m³
Kinematik viskozite	ν	$1{,}001 \times 10^{-6}$ m²/s

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2.2. Temel Denklemler ve Boyutsuz Parametreler

Akışkan sıkıştırılamaz ve Newtonian kabul edilmiştir. Süreklilik ve momentum denklemleri sırasıyla aşağıdaki biçimde ifade edilir:

$$\nabla \cdot \vec{u} = 0 \tag{2.1}$$

Silindirik koordinarlarda tanımlanan momentum denkleminin üç yöndeki tanımları,

$$\rho\left(\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_r}{\partial \theta} - \frac{v_\theta^2}{r} + v_z\frac{\partial v_r}{\partial z}\right) = -\frac{\partial P}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r v_r)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_r}{\partial \theta^2} - \frac{2}{r^2}\frac{\partial v_\theta}{\partial \theta} + \frac{\partial^2 v_r}{\partial z^2}\right] + \rho g_r \tag{2.2}$$

$$\rho\left(\frac{\partial v_\theta}{\partial t} + v_r\frac{\partial v_\theta}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_\theta}{\partial \theta} + \frac{v_r v_\theta}{r} + v_z\frac{\partial v_\theta}{\partial z}\right) = -\frac{1}{r}\frac{\partial P}{\partial \theta} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r v_\theta)}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_\theta}{\partial \theta^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \theta} + \frac{\partial^2 v_\theta}{\partial z^2}\right] + \rho g_\theta \tag{2.3}$$

$$\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + \frac{v_\theta}{r}\frac{\partial v_z}{\partial \theta} + v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial P}{\partial z} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 v_z}{\partial \theta^2} + \frac{\partial^2 v_z}{\partial z^2}\right] + \rho g_z \tag{2.4}$$

Akışkan Reynolds sayısı, kütlesel ortalama hız U_b ve D_h hidrolik çap kullanılarak tanımlanmıştır:

$$Re = \frac{U \times D_h}{\nu} \tag{2.5}$$

Radyal konum, iç duvardan dış duvara 0 ile 1 arasında değişecek biçimde boyutsuzlaştırılmıştır.

İç silindirin 300 rpm, dönme hızı ω = 31,416 rad/s ve iç duvar çevresel hızı $U_{inner} = \omega R_i$ = 0,314159 m/s'dir. Teğetsel hız profili $V_\theta/(\omega R_i)$ ile boyutsuzlaştırılmıştır. Böylece ideal no-slip koşulunda iç duvarda $V_\theta/(\omega R_i)$ = 1, sabit dış duvarda ise 0 elde edilir.

$$u^* = \sqrt{\frac{\tau}{\rho}} \tag{2.6}$$

$$y^+ = \frac{y u^*}{\nu} \tag{2.7}$$

$$u^+ = \frac{u}{u^*} \tag{2.8}$$

2.3. Sınır Şartları ve Çözüm Ayarları

Giriş sınırında her Reynolds sayısına karşılık gelen üniform ortalama hız tanımlanmış, çıkışta gösterge basıncı sıfır olan şbasınç çıkışı kullanılmıştır. İç ve dış silindir yüzeylerinde no-slip koşulu

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uygulanmıştır. Rotasyonsuz durumlarda her iki duvar sabit, rotasyonlu durumlarda ise iç silindir 300 rpm açısal hızla dönen duvar olarak tanımlanmıştır. Akışkan özellikleri sabit kabul edilmiş ve yerçekimi etkisi ihmal edilmiştir.

Tablo 2. İncelenen sayısal çalışma koşulları

Re	İç silindir	U_b (m/s)	ω (rad/s)	Amaç
9.000	0 rpm	0,45	0	Reynolds etkisi
9.000	300 rpm	0,45	31,416	Rotasyon karşılaştırması
26.600	0 rpm	1,33	0	Reynolds etkisi / doğrulama
26.600	300 rpm	1,33	31,416	Deneysel karşılaştırma
30.000	0 rpm	1,50	0	Rotasyon karşılaştırması
30.000	300 rpm	1,50	31,416	Rotasyon karşılaştırması
40.000	0 rpm	2,00	0	Reynolds etkisi
40.000	300 rpm	2,00	31,416	Rotasyon karşılaştırması
60.000	0 rpm	3,00	0	Reynolds etkisi
60.000	300 rpm	3,00	31,416	Rotasyon karşılaştırması

Denklemler sonlu hacimler yöntemiyle ANSYS Fluent ortamında çözülmüştür. Basınç-hız bağlaştırması ve yakınsama ölçütleri Tablo 3'te özetlenmiştir.

Tablo 3. Sayısal çözüm ayarları

Ayar	Kullanılan seçenek
Çözücü	Pressure-Based / Steady
Türbülans modeli	Reynolds Stress – Stress Omega
Basınç-hız bağlaştırması	SIMPLE
Basınç ayrıklaştırması	Second Order
Momentum ayrıklaştırması	Second Order Upwind
Türbülans denklemleri	First Order Upwind
Yakınsama ölçütü	10^{-6}
ANSYS Fluent sürümü	2023/R1

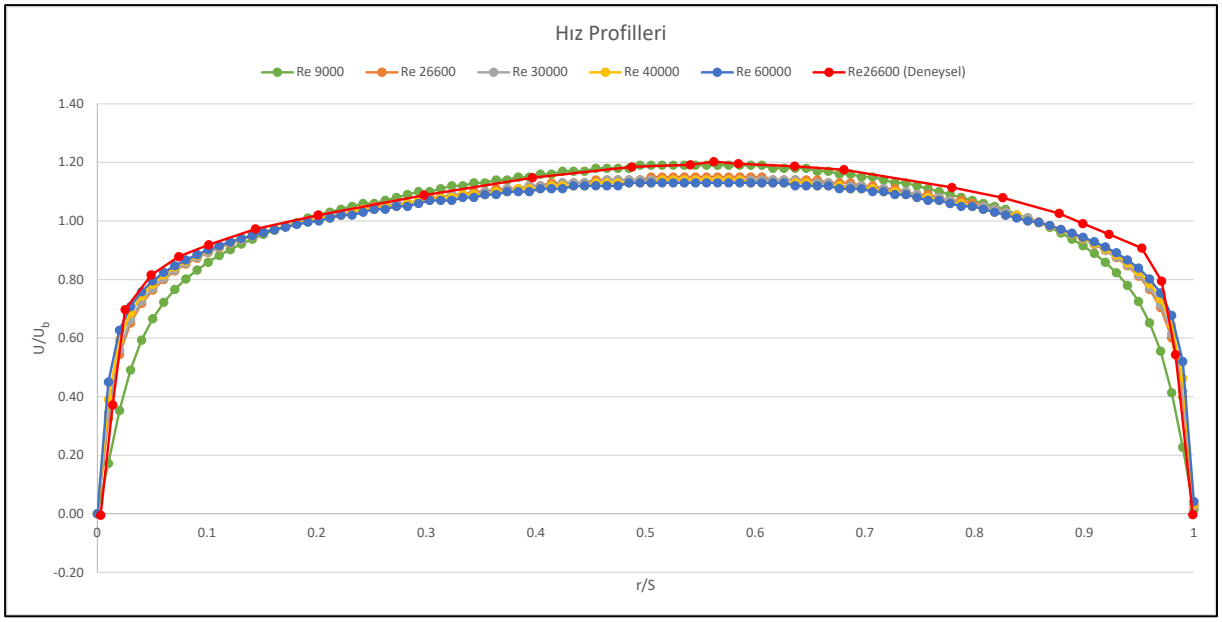
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2.4. Bulgular ve Tartışma

2.4.1. Reynolds Sayısının Eksenel Hız Profiline Etkisi

Rotasyonsuz analizlerde Re = 9.000-60.000 aralığında elde edilen U_z/U_b profilleri Şekil 6'da karşılaştırılmaktadır. Bütün profiller iç ve dış duvarlarda no-slip koşulunu sağlamakta ve halkasal boşluk içinde tek bir maksimum değer oluşturmaktadır. Maksimum hız konumunun r/S ≈ 0,45 civarında bulunması, iç ve dış duvar eğriliklerinin farklı olmasından kaynaklanan asimetrik silindirik kanal davranışıyla uyumludur.

Re = 9.000 değerinde profil daha sivri bir yapı göstermekte, bu Re sayısındaki maksimum hız da diğerlerine göre daha yüksek seviyede gerçekleşmektedir. Reynolds sayısı arttıkça profiller birbirine benzer bir görünüm kazanmakta. Merkezdeki tepe değer düşerek profil daha dolgun bir şekle bürünmektedir. Bu davranışın sebei, Reynolds sayısı arttıkça türbülanslı bölgenin kuvvetlenmesi ve bunun sonucunda momentumun kesit üzerinde daha homojen biçimde dağılmasıyla açıklanabilir. Öte yandan, Re = 26.600 ve üzerindeki eğrilerin birbirine oldukça yakın seyretmesi, akışın bu Re aralığında Reynolds sayısından büyük ölçüde bağımsız bir karaktere ulaştığına işaret etmektedir.



Şekil 6. Konsantrik kanalda Newtonian akışkanda nümerik analiz ve deneysel verilere göre rotasyonsuz durumda hız profilleri.

2.4.2. Basınç Değişimi ve Sürtünme Katsayısı

Reynolds sayısındaki artış, kütlesel ortalama hızda yükselmeye ve bunun sonucunda hem duvar kayma gerilmesinde hem de birim uzunluk başına düşen basınç kaybında artışa neden olmuştur. Buna karşılık, dinamik basınca göre normalize edilmiş sürtünme katsayısı Reynolds sayısı yükseldikçe azalma eğilimi göstermiştir. Elde edilen bu sonuç, tam gelişmiş türbülanslı iç akışlarda beklenen davranışla örtüşmektedir.

Tablo 4. Basınç gradyeni, sürtünme katsayısı sonuçları

Re	U_b [m/s]	P_1 [Pa]	P_2 [Pa]	ΔP/L [kg m^-2 s^-2]	C_f
9.000	0,45045	275,065	91,8532	183,211	0,00902941
26.600	1,33133	1.664,14	556,371	1.107,77	0,00624998
30.000	1,5015	2.038,26	681,015	1.357,25	0,00602017
40.000	2,002	3.366,06	1.125,6	2.240,45	0,00558995
60.000	3,003	7.030,99	2.354,98	4.676,01	0,00518519

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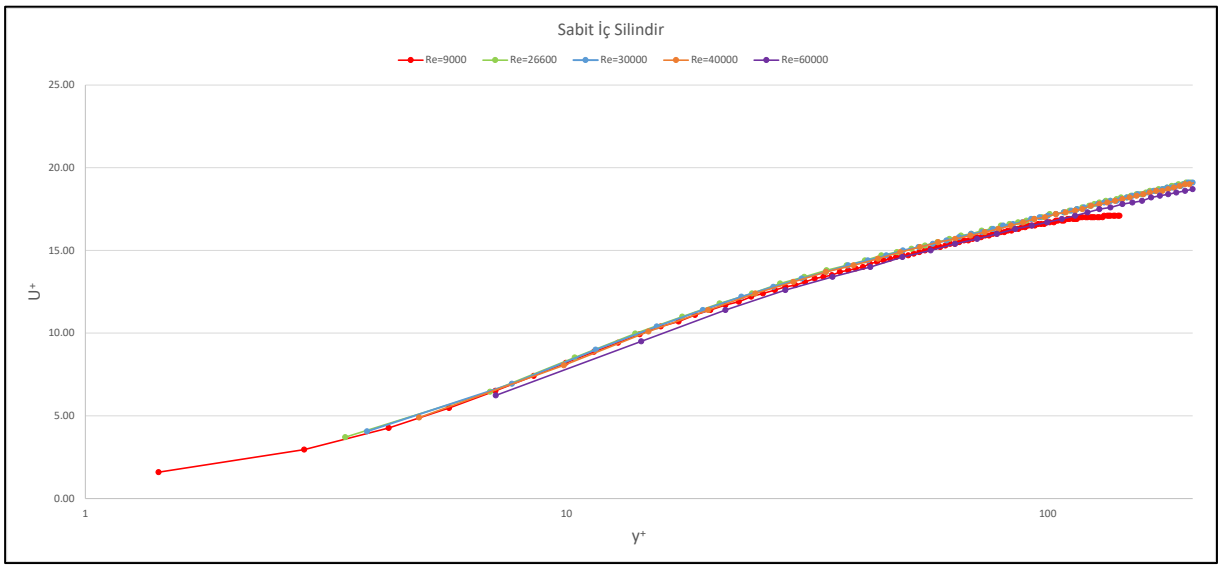
2.4.3. İç ve Dış Duvar Kanunu Profilleri

İç ve dış duvarlar için sürtünme hızlarının farklı olması nedeniyle u^+ - y^+ profilleri ayrı ayrı değerlendirilmiştir. İç duvar profili R_i'den r = 0,0145 m konumuna, dış duvar profili ise R_o'dan aynı ayrım noktasına kadar alınmıştır. Her Reynolds sayısı için ilgili duvara ait τw ve uτ değerleri kullanılmıştır. Logaritmik x ekseninde y+ = 0 noktaları gösterime dahil edilmemiştir.

Şekil 7 ve Şekil 8'de Reynolds sayısı arttıkça eğrilerin daha yüksek y+ değerlerine ulaştığı, buna karşın duvar değişkenleriyle ölçeklenen profillerin özellikle duvar yakınında birbirine yaklaştığı görülmektedir.



Şekil 7. 300 dev/dk için iç silindir duvarında farklı Reynolds sayıları için u^+ - y^+ profilleri

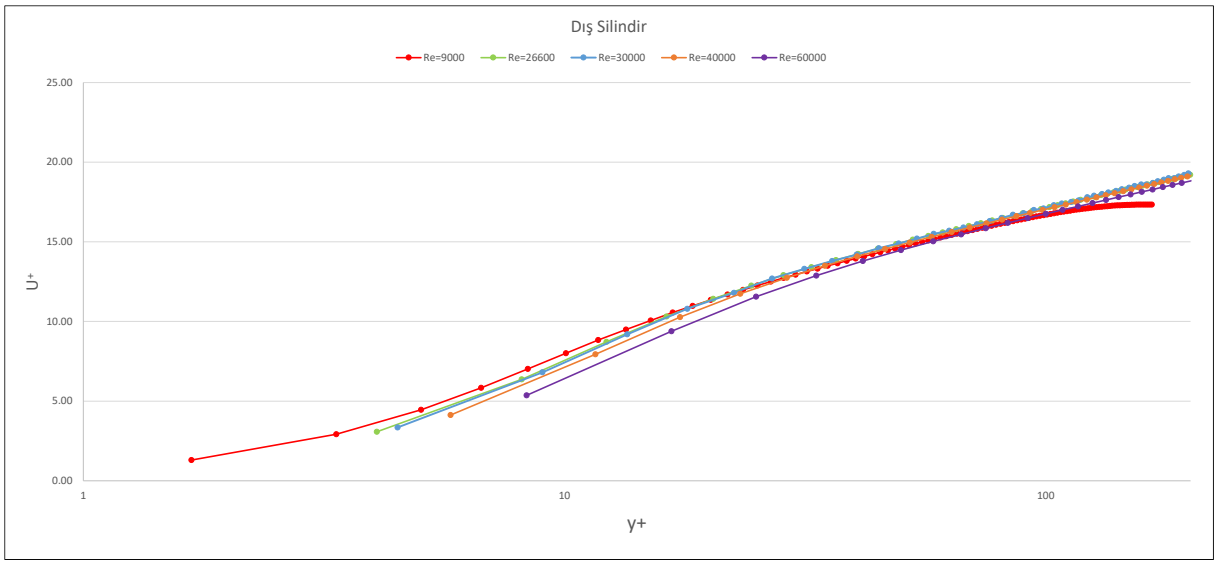


Şekil 8. 0 dev/dk için iç silindir duvarında farklı Reynolds sayıları için u^+ - y^+ profilleri

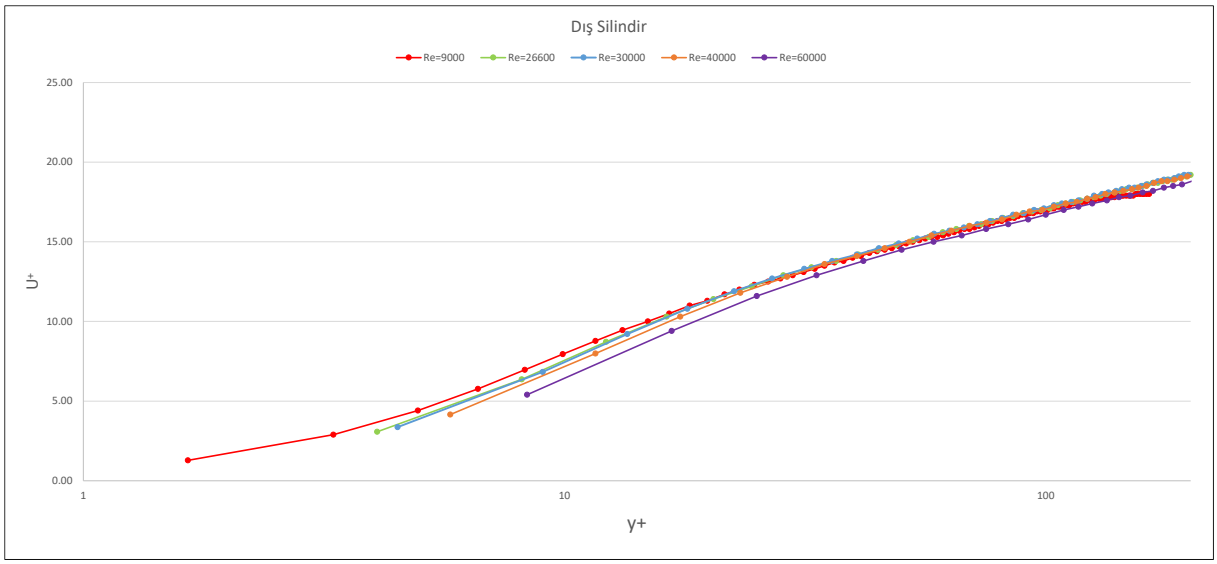
Sabit iç silindir konfigürasyonunda, farklı Reynolds sayılarına karşılık gelen u^+–y^+ profilleri özellikle logaritmik bölgede birbirine yakın bir seyir izlemekte ve klasik duvar kanunuyla uyumlu, ortak bir eğri etrafında toplanan bir eğilim göstermektedir. Buna karşılık döner iç silindir durumunda eğriler arasındaki bu örtüşme zayıflamakta, yüksek y^+ değerlerinde profiller arasında belirgin bir ayrışma ortaya çıkmaktadır. Bu farklılık, iç silindirin dönmesiyle akışa katılan teğetsel momentumun sınır tabaka yapısını değiştirdiğini ve Reynolds gerilmelerinin dağılımını etkileyerek klasik duvar kanunundan

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sapmaya neden olduğunu göstermektedir. Öte yandan her iki durumda da Re=9.000 eğrisi diğer Reynolds sayılarından ayrılarak viskoz alt tabaka–geçiş bölgesi davranışının daha erken başladığı bir profil sergilemekte; ancak bu eğrinin ulaştığı maksimum u^+ değeri sabit silindir durumunda döner silindire kıyasla daha yüksek kalmaktadır. Sonuç olarak, dönen iç silindirde ortaya çıkan merkezkaç etkileri ve ilave türbülans üretim mekanizmaları, akış yapısını sabit silindir durumuna göre daha karmaşık bir hâle getirmektedir.



Şekil 9. 300 dev/dk için dış silindir duvarında farklı Reynolds sayıları için u^+ - y^+ profilleri



Şekil 10. 0 dev/dk için dış silindir duvarında farklı Reynolds sayıları için u^+ - y^+ profilleri

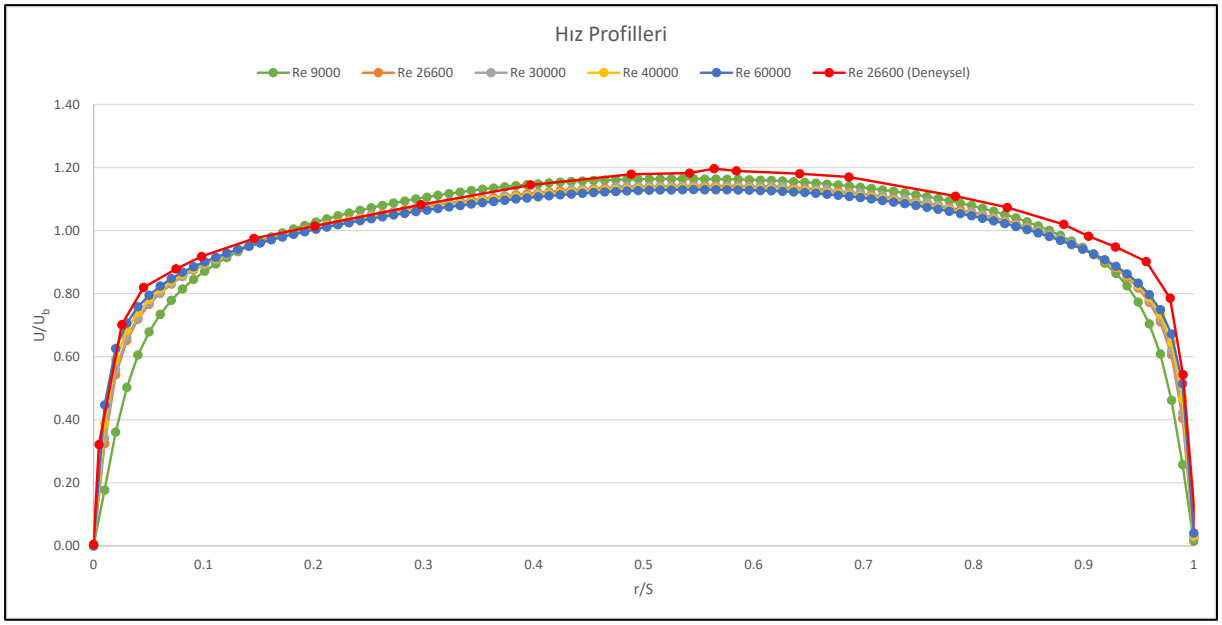
Dış silindire ait u^+–y^+ profilleri, rotasyonlu ve rotasyonsuz durumlarda birbirine oldukça yakın seyretmekte ve iç silindirdeki gibi belirgin bir ayrışma göstermemektedir. Farklı Reynolds sayılarına ait eğriler her iki durumda da düşük ve orta y^+ bölgesinde büyük ölçüde çakışmakta; yalnızca Re=9.000 eğrisi diğerlerinden ayrılarak daha erken bir viskoz alt tabaka–geçiş davranışı sergilemektedir. Bu benzerlik, iç silindirin dönmesinden kaynaklanan teğetsel momentum ve merkezkaç etkilerinin dış duvar bölgesindeki sınır tabaka yapısı üzerinde iç silindire kıyasla oldukça sınırlı bir etkiye sahip olduğunu göstermektedir.

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2.4.4. İç Silindir Rotasyonunun Ortalama Akışa Etkisi

İç silindir rotasyonunun etkisi Re = 9.000-26.600-30.000-40.000-60.000 için 0 ve 300 rpm sonuçları karşılaştırılarak incelenmiştir. Rotasyon, iç duvarda U_{inner} = 0,314 m/s teğetsel hız koşulu oluşturarak halkasal boşluğa açısal momentum aktarmaktadır. Boyutsuz teğetsel hız iç duvarda 1'den başlayıp dış duvara doğru azalarak 0'a ulaşmaktadır. En yüksek teğetsel hız gradyeni ve buna bağlı kayma etkisi iç duvar yakınında görülmektedir.

Eksenel ortalama hız profillerinin karşılaştırılması, Nouri ve Whitelaw'ın yüksek Rossby sayılarında rotasyon etkisinin eksenel ortalama hız ve sürtünme üzerinde azaldığı yönündeki deneysel bulgularıyla nitel olarak uyumludur.



Şekil 11. İç silindir rotasyonunun boyutsuz eksenel hız profiline etkisi

2.4.5. Türbülans Şiddetleri ve Reynolds Kayma Gerilmeleri

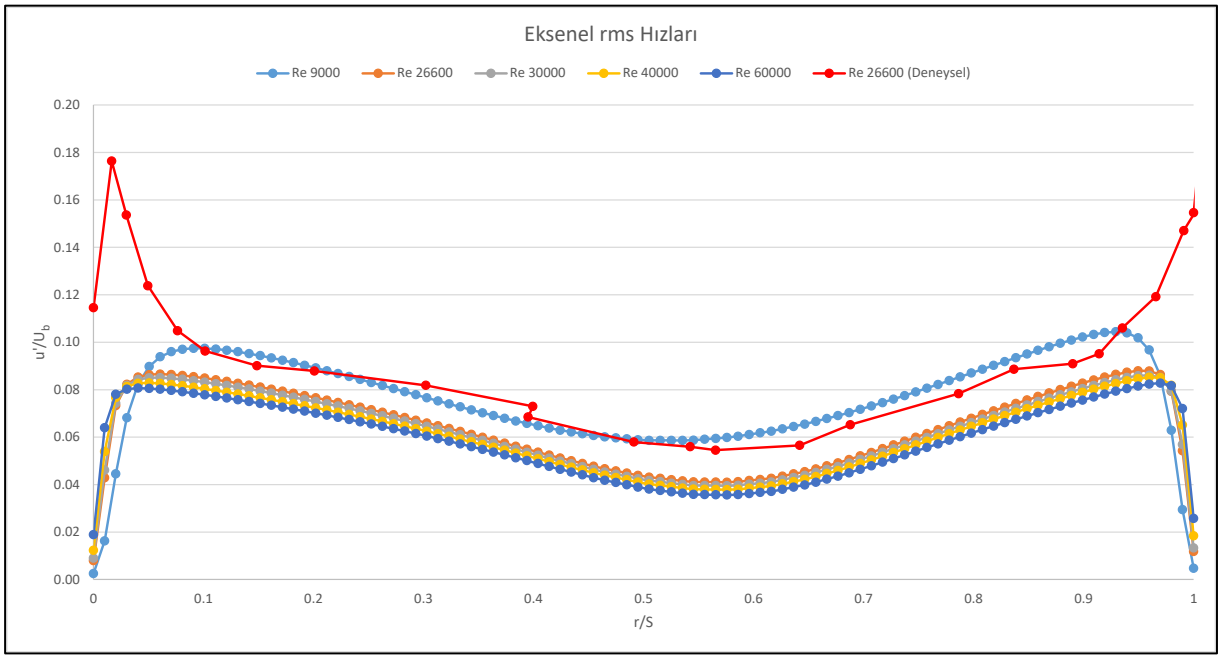
Türbülans yapısı; eksenel, radyal ve teğetsel hız dalgalanmalarının rms değerleri ile Reynolds kayma gerilmesi bileşenleri üzerinden değerlendirilmiştir. rms hızlar U_b ile, kayma gerilmeleri U_b^2 ile boyutsuzlaştırılmıştır.

u′v′ davranışı Boussinesq girdap viskozite hipotezi dikkate alınarak analiz edilebilir.Tam gelişmiş akış olduğu düşünüldüğünde Reynolds gerilimi şu şekilde ifade edilebilir:

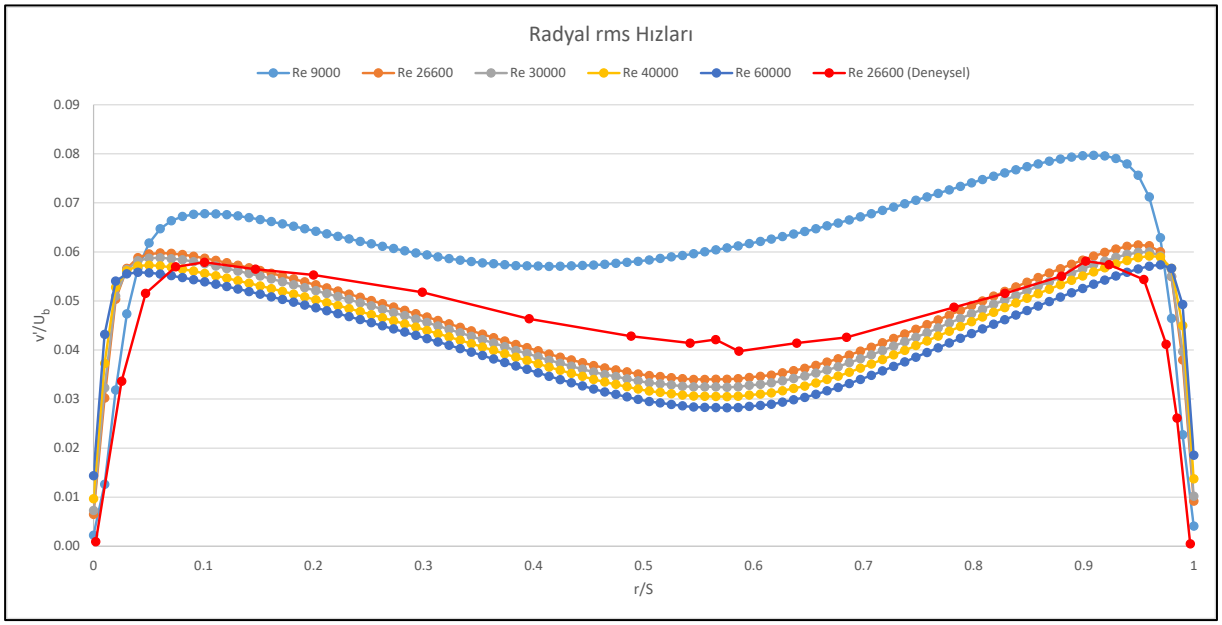
$$\rho\overline{u'v'} = -\mu_T\left(\frac{\partial U}{\partial y}\right) \tag{2.9}$$

Rotasyonun Reynolds gerilmesi üzerindeki etkisi çoğunlukla iç duvar yakınında görülmektedir. Ancak Reynolds sayısı arttıkça türbülans oranı güçlendiğinden, rotasyonun eksenel hız profili üzerindeki etkisi azalmaktadır.

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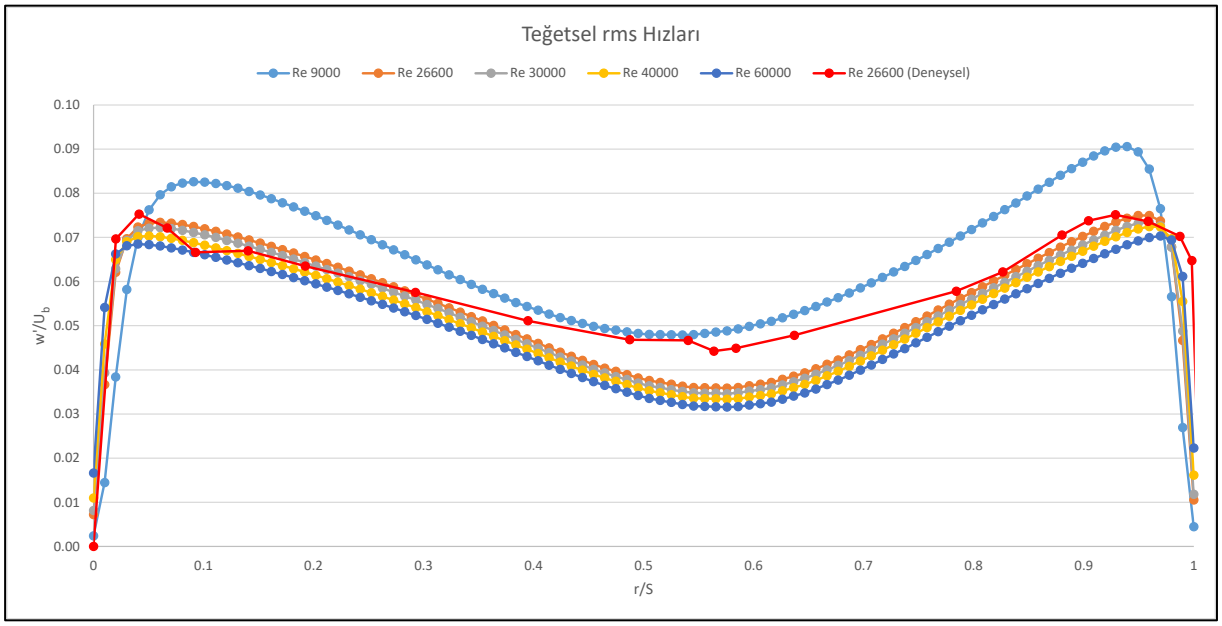


Şekil 12. Farklı Reynolds sayılarında boyutsuz Eksenel rms hız profilleri 300rpm

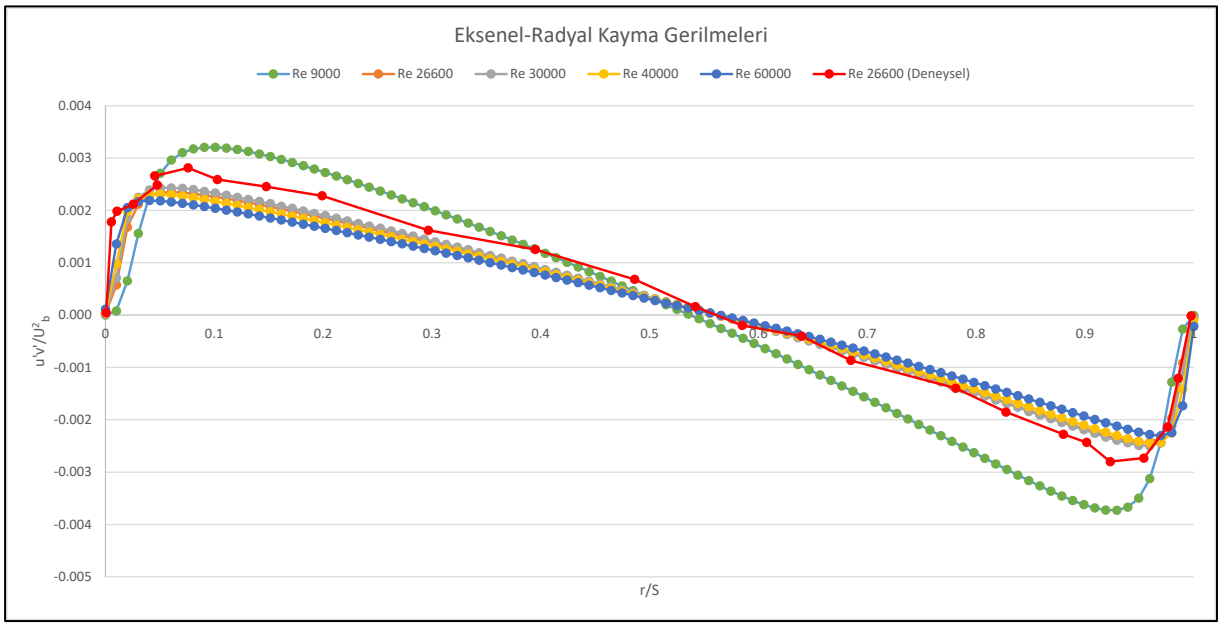


Şekil 13. Farklı Reynolds sayılarında boyutsuz Radyal rms hız profilleri 300rpm

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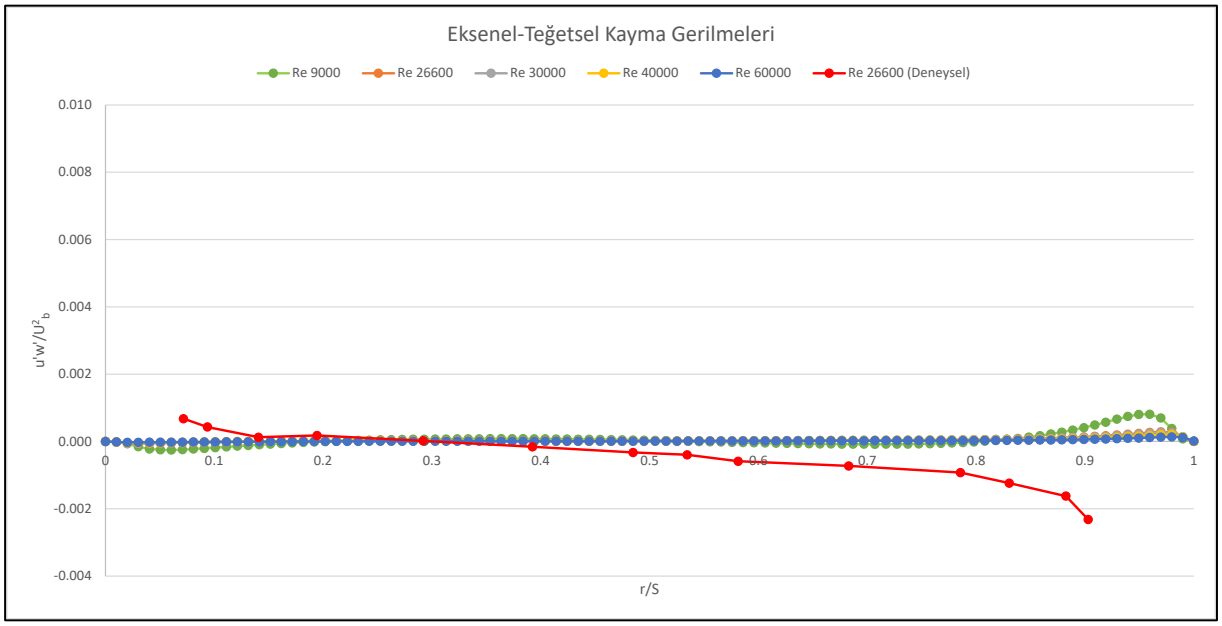


Şekil 14. Farklı Reynolds sayılarında boyutsuz Teğetsel rms hız profilleri 300rpm



Şekil 15. Farklı Reynolds sayılarında boyutsuz Eksenel–Radyal Reynolds kayma gerilmesi dağılımları 300 rpm

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Şekil 16. Farklı Reynolds sayılarında boyutsuz Eksenel–Teğetsel Reynolds kayma gerilmesi dağılımları 300 rpm

3. SONUÇ

Bu çalışmada, çap oranı 0,5 olan eş merkezli bir kanalda Newtonian su akışının türbülanslı karakteristikleri Re = 9.000-60.000 aralığında sayısal olarak incelenmiş ve seçili koşullarda 300 rpm iç silindir rotasyonunun etkisi değerlendirilmiştir. Elde edilen başlıca sonuçlar aşağıda özetlenmiştir.

Boyutsuz eksenel hız profilleri, incelenen Reynolds sayısı aralığında benzer bir dağılım göstermiş; maksimum hız konumu halkasal boşluğun geometrik ortasından sınırlı ölçüde iç duvar tarafına kaymıştır. Reynolds sayısının artmasıyla mutlak basınç gradyeni ve duvar kayma gerilmesi artarken, dinamik basınca göre tanımlanan sürtünme katsayısı azalmıştır.

İç ve dış duvar için ayrı sürtünme hızlarıyla oluşturulan u^+ - y^+ profilleri, duvara yakın bölgede viskoz alt tabaka ve daha yüksek y^+ değerlerinde elde edilen nümerik veriler deneysel değerlerle uygun olduğu gözlemlenmiştir.

İç silindirin 300 rpm dönmesi halkasal boşlukta teğetsel hız bileşeni oluşturmuş ve etkisini en belirgin biçimde iç duvar yakınında göstermiştir. Re = 30.000 koşulunda eksenel ortalama hız profilindeki değişim sınırlı kalırken, teğetsel türbülans büyüklükleri ve ilgili Reynolds kayma gerilmeleri rotasyona daha duyarlı olmuştur.

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TREATMENT OF A COMPLEX GLIOBLASTOMA USING THREE-DIMENSIONAL CONFORMAL RADIOTHERAPY: A CASE REPORT

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ABSTRACT

This case report presents the treatment planning and long-term clinical follow-up of a patient with bifocal glioblastoma infiltrating the optic pathways and brainstem, treated with three-dimensional conformal radiotherapy (3D-CRT) at the X-Knife Unit, Department of Neurosurgery, "Mother Teresa" University Hospital Centre. The case is of particular clinical interest because of the tumor's close anatomical relationship with critical structures, specifically the optic chiasm and brainstem, which posed a significant challenge for radiotherapy planning. The tumor was treated with a total dose of 57 Gy in 30 fractions. To achieve adequate lesion coverage while maintaining low radiation doses to the optic pathways and brainstem, a three-field treatment arrangement with different beam entry points was used. Dose differentiation was performed, with 57 Gy delivered to the target volume outside the organs at risk (OARs) and 50 Gy to the region involving the OARs. Plan evaluation shows that dose constraints for the OARs remained within the accepted levels required by the treatment protocol. During regular clinical follow-up over a 10-year period, including periodic brain magnetic resonance imaging (MRI) examinations, the patient's condition remained stable, and no significant adverse effects involving the OARs were observed. This case demonstrates that 3D-CRT can provide adequate target-volume coverage while effectively limiting radiation exposure to critical anatomical structures, even in anatomically challenging cases involving the optic chiasm and brainstem. Despite the availability of more advanced radiotherapy technologies, 3D-CRT remains a valuable and feasible treatment option for selected patients with glioblastoma when careful treatment planning and appropriate dose constraints are applied.

Keywords: Glioblastoma, Survival, Brain tumors, Three-dimensional conformal radiotherapy, Radiotherapy, Organs at risk, Treatment planning.

Case report

Clinical case presentation – Bifocal glioblastoma

INTRODUCTION

Glioblastoma (GBM) is an aggressive high-grade primary brain tumor with a poor prognosis despite multimodal treatment. Postoperative radiotherapy with concomitant and adjuvant temozolomide is an important standard treatment approach for newly diagnosed GBM (Klonowicz et al., 2007), while long-term survival remains uncommon although it is documented in a small proportion of patients (Stupp et al., 2005; Mirimanoff et al., 2007). Prognostic analyses have also shown that age, performance status, tumor location, and extent of surgical resection are associated with survival outcomes (Simpson et al., 1993). From a radiotherapy perspective, treatment planning requires a balance between adequate target coverage and sparing of normal tissues and critical organs. Several studies show that 3D-CRT can provide acceptable target and OAR dose distributions in selected glioblastoma patients, while intensity-

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modulated radiotherapy (IMRT) may offer improved target coverage or reduced dose to some normal tissues in particular anatomical situations (Lorentini et al., 2013; Kumar et al., 2020; Zach et al., 2009). Importantly, comparative planning studies do not identify a single technique as universally superior and support individualized treatment selection according to target geometry and OAR–PTV relationships (Lorentini et al., 2013; Zach et al., 2009). These considerations are directly relevant to the present case, in which the bifocal tumor location required careful individualized beam arrangement and dose planning.

RESEARCH AND FINDINGS

Case Presentation

The patient, an 18-year-old female, presented to the service after the onset of progressive left-sided deficit, headache of intensity 7/10, blurred vision, and morning vomiting. Family history was significant for the patient's mother, who died in 2012 from colorectal cancer, and the patient's aunt, who died from a malignant brain tumor (GBM).

Neurological evaluation showed that she was active and oriented in time and space, with left facial paralysis, grade I, and left hemiparesis more pronounced in the upper limb.

In February 2015, contrast-enhanced MRI showed bifocal cerebral lesions localized in the right basal ganglia and sellar region. In March 2015, a stereotactic biopsy was performed in the Neurosurgery Service, which resulted in Grade IV glioblastoma.

Visual field testing showed HLH (homonymous lateral hemianopia). The multidisciplinary team recommended combined radiotherapy and chemotherapy.

Results

Pre-treatment imaging confirmed the bifocal nature of the disease, with contrast-enhancing lesions in the right basal ganglia and sellar region corresponding to the histologically confirmed Grade IV glioblastoma (Fig. 1).

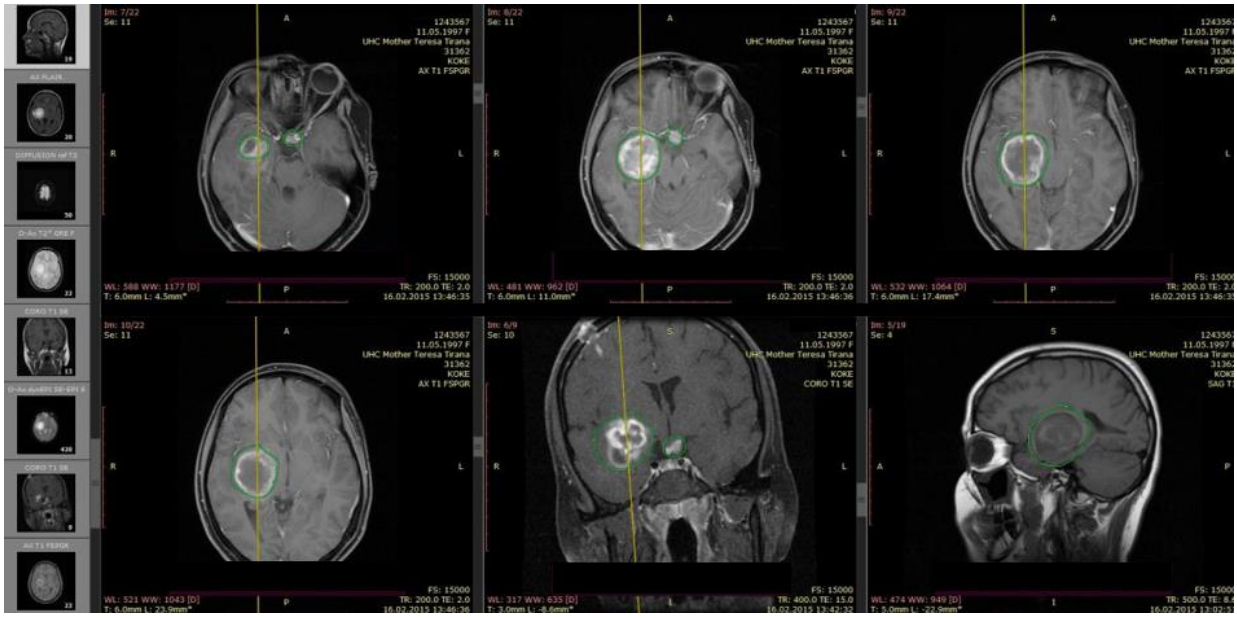


Fig. 1. MRI imaging appearance of the bifocal tumor before treatment with 3D-CRT in 2015.

The treatment volumes were contoured in the Eclipse Treatment Planning System (TPS). The gross tumor volume (GTV), clinical target volume (CTV), planning target volume (PTV), and organs at risk (OARs) were identified for treatment planning. The CTV was defined as the GTV plus a 2 cm margin.

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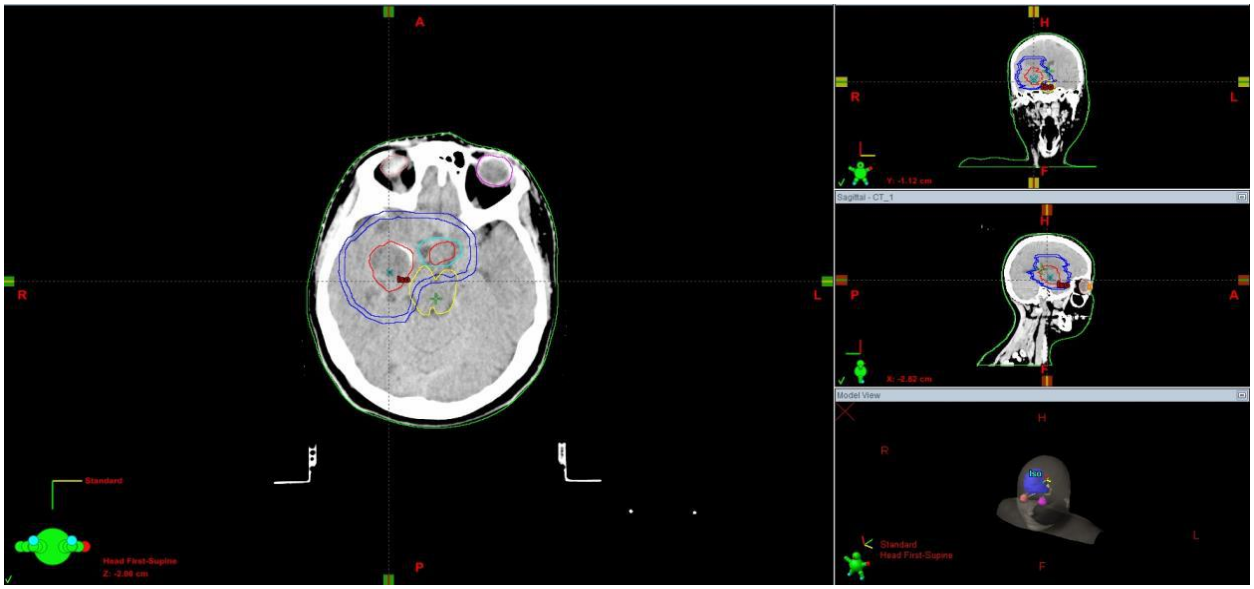


Fig. 2. Graphical representation of tumor volumes and organs at risk.

The prescribed treatment dose was 57 Gy in 30 daily fractions of 1.9 Gy. Three beam entry points were selected and three planar fields with different gantry angles were used. The field sizes ranged from 8 to 11 cm. Wedge dose modifiers were used for all three fields because of the treatment geometry. The plan was evaluated with respect to target coverage and dose to the OARs; according to the treatment record, the OAR dose constraints remained within the accepted protocol limits.

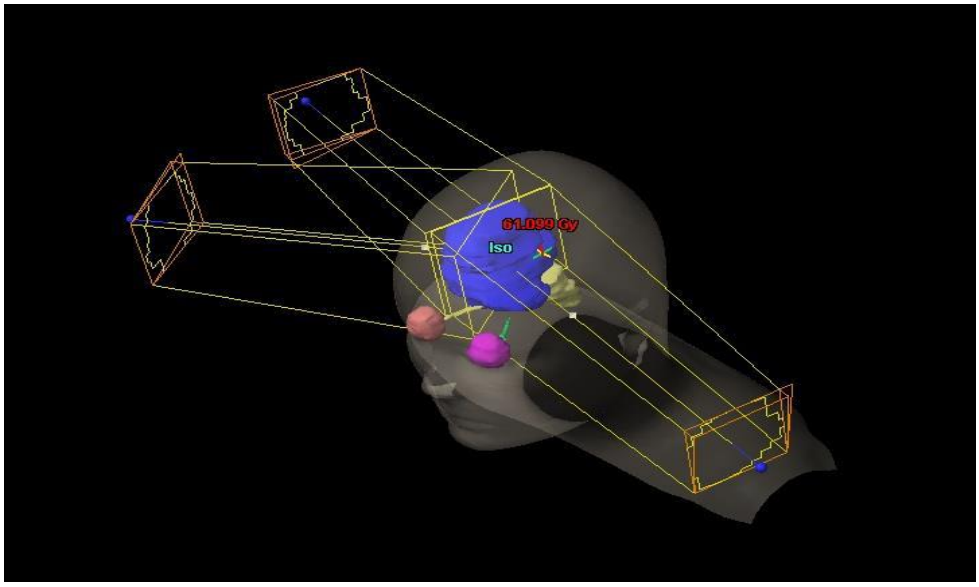


Fig. 3. 3D representation of the treatment fields.

The graphical representation of the dose distribution is shown in Fig. 4.

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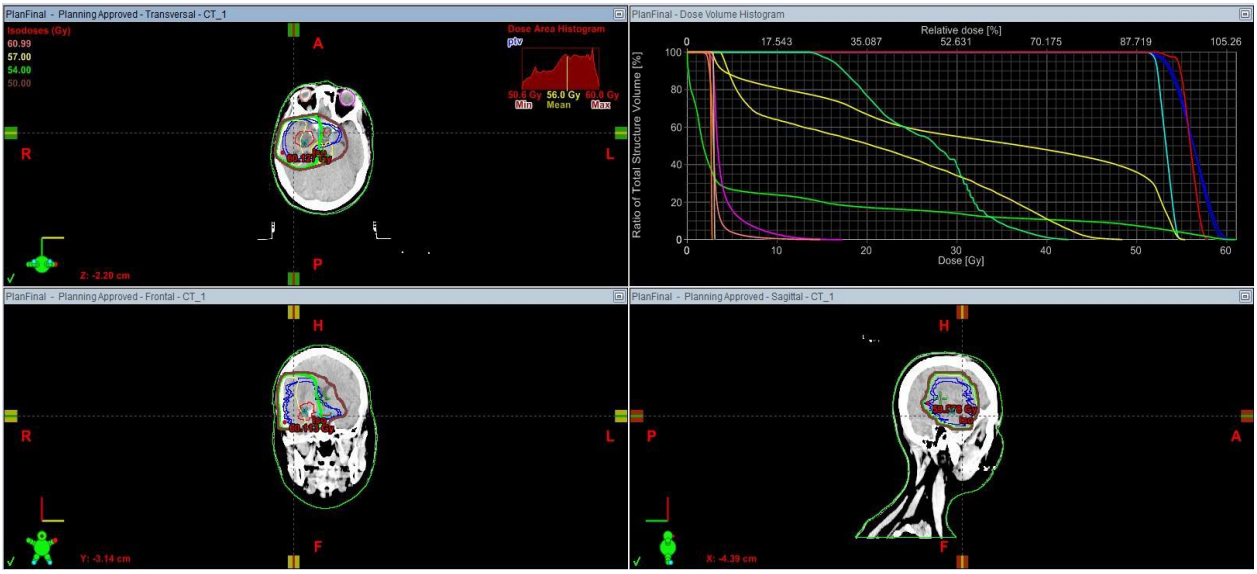


Fig. 4. Graphical representation of the dose distribution.

The dose values in the tumor volumes and organs at risk are presented graphically in Fig. 5.

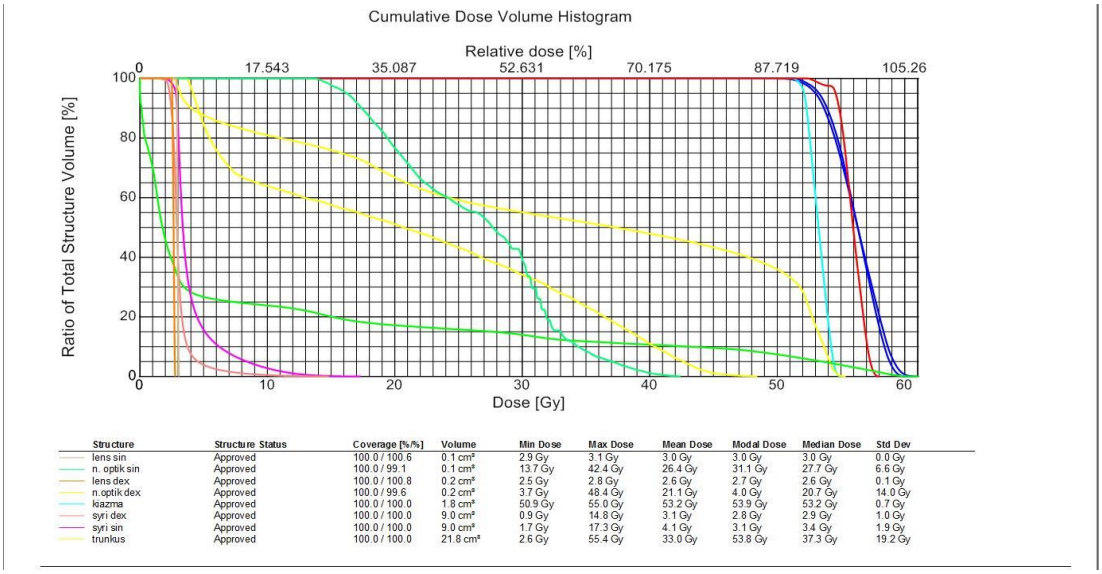


Fig. 5. Dose–Volume Histogram.

The significant dose values received by the tumor volumes and organs at risk are presented numerically in Table 1.

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Organ / target volume	Volume (cm³)	Min dose (Gy)	Max dose (Gy)	Mean dose (Gy)
GTV	22.7	52.3	58	55.9
CTV	133.7	50.5	60.5	57.2
PTV		50.6	60.0	56.0
Optic chiasm	1.8	50.9	55.0	53.2
Brainstem	21.8	2.6	55.4	33.0
Optic nerve, right	0.2	3.7	48.4	21.1
Optic nerve, left	0.1	13.7	42.4	26.4
Eye (globe), right	9.0	0.9	14.8	3.1
Eye (globe), left	9.0	1.7	17.3	4.1
Lens, right	0.2	2.5	2.8	2.6
Lens, left	0.1	2.9	3.1	3.0

Table 1. Dose–volume statistics for the target volumes and organs at risk (OARs), derived from the treatment planning system's dose data).

During radiotherapy treatment, the patient simultaneously received chemotherapy with CCNU (Lomustine).

At the end of treatment, the patient's condition was good, with no complaints.

After completing radiotherapy, the patient continued chemotherapy with temozolomide.

During continuous clinical and radiological follow-up, the patient's condition remained stable.

Follow-up imaging obtained in 2021 continued to show radiological stability of the treated lesions, consistent with the patient's stable clinical course (Fig. 6).

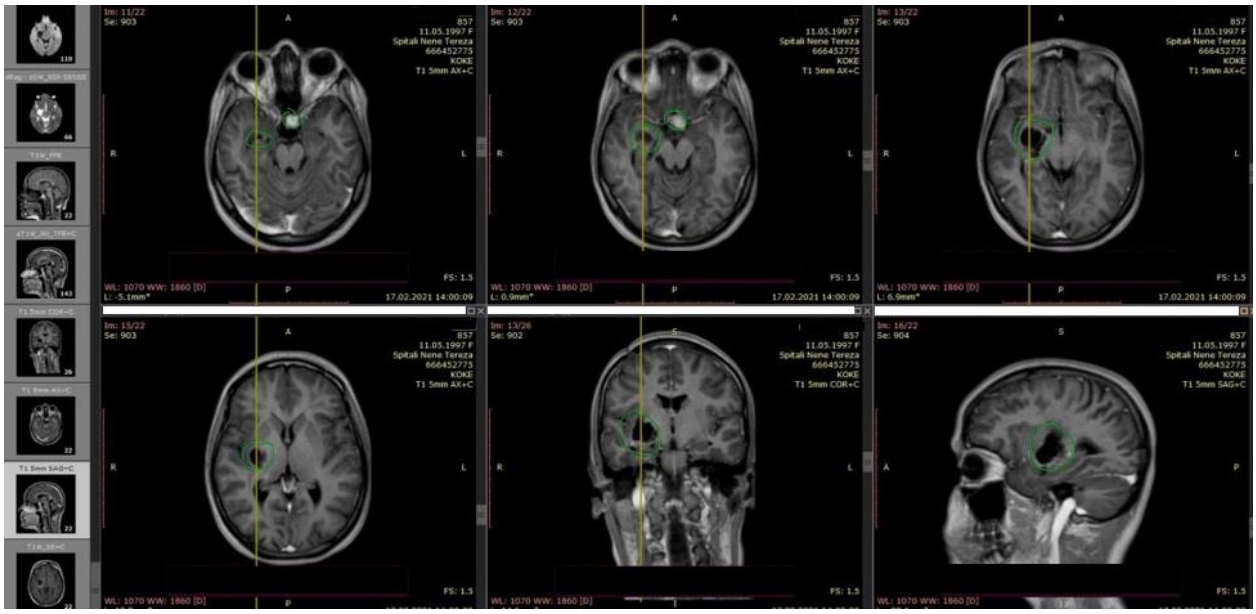


Fig. 6. MRI imaging appearance of the tumor in 2021.

Imaging performed in 2025, ten years after the initial diagnosis, confirmed the persistence of this long-term radiological stability (Fig. 7).

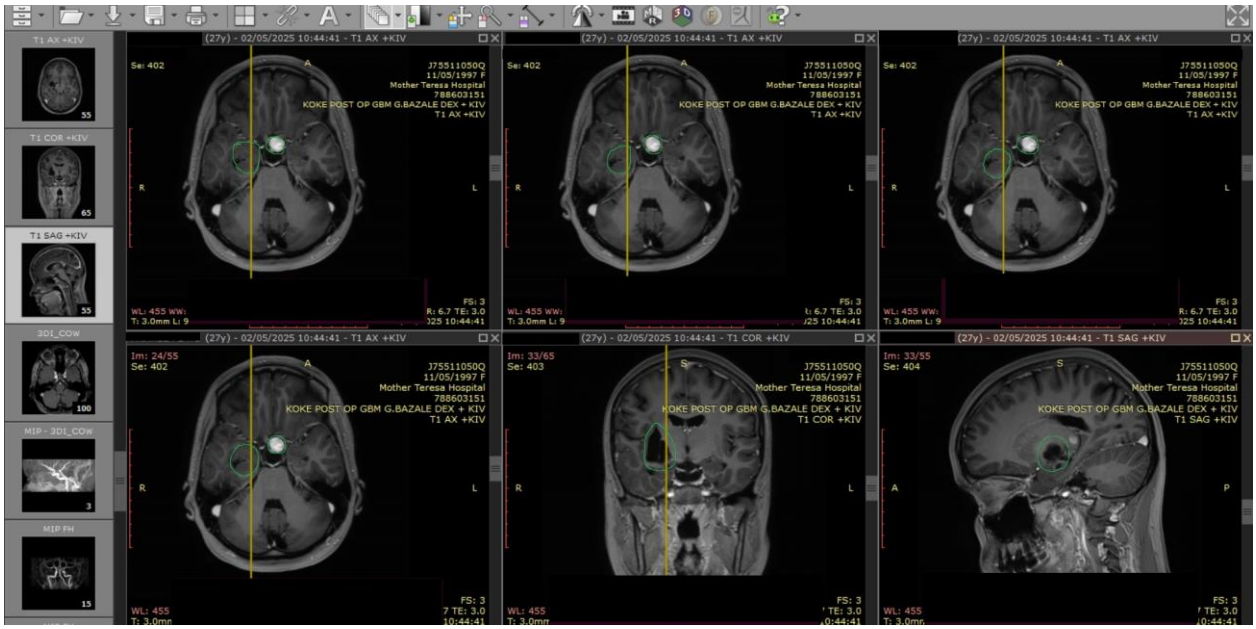


Fig. 7. MRI imaging appearance of the tumor in 2025.

Discussion

The main radiotherapy challenge in this case was to obtain adequate target-volume coverage while limiting radiation exposure to critical structures. The selected three-field arrangement provided different beam entry directions, allowing the treatment geometry to be adapted to the complex anatomy. Wedge modifiers were used to improve dose distribution within the selected field arrangement.

A dose differentiation strategy was used, with 57 Gy prescribed to the target region outside the OARs and 50 Gy to the region in which the OARs were involved. The treatment plan was considered acceptable according to the protocol constraints used at the time of treatment.

The long-term stability observed in this patient is notable, particularly because long-term survival after GBM remains uncommon (Mirimanoff et al., 2007). However, a single case cannot establish a causal relationship between 3D-CRT and prolonged survival. The value of the present case is therefore primarily in illustrating the feasibility of individualized 3D-CRT planning in an anatomically complex situation, rather than demonstrating superiority of one radiotherapy technique over another.

CONCLUSION

This case illustrates a complex bifocal glioblastoma treated with 3D-CRT using a three-field arrangement designed to balance target coverage with protection of critical structures. The treatment plan used 57 Gy in 30 fractions, with dose differentiation in the region involving OARs. The unusually long-term clinical and radiological stability is notable, although this single case does not allow attribution of the outcome to 3D-CRT alone.

The findings are consistent with the literature cited in this paper, which supports individualized selection of 3D-CRT or more conformal techniques according to tumor geometry, OAR–PTV relationships, and dosimetric objectives.

For anatomically challenging high-grade glioma cases, careful target delineation, beam arrangement, dose distribution, and OAR constraints remain essential. This case supports the consideration of 3D-CRT as a feasible treatment-planning approach when its geometry provides an acceptable balance between target coverage and OAR protection.

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ETHICS STATEMENT

Informed consent for publication of this case report and the accompanying clinical images was obtained from the patient.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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PREVOTELLA COPRİ VE KISA ZİNCİRLİ YAĞ ASİTLERİ: MİKROBİYAL METABOLİTLER ÜZERİNDEN METABOLİK VE NÖROİMMÜN DÜZENLEME

PREVOTELLA COPRI AND SHORT-CHAIN FATTY ACIDS: METABOLIC AND NEUROIMMUNE REGULATION VIA MICROBIAL METABOLITES

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ÖZET

Giriş ve Amaç: Bağırsak mikrobiyotası, konağın enerji metabolizması, bağışıklık yanıtı ve merkezi sinir sistemi işlevleriyle çift yönlü iletişim kuran metabolik bir ekosistemdir. Bu ekosistemde yer alan Prevotella copri, özellikle kompleks karbonhidratların kullanımındaki kapasitesi ve suşlar arasındaki genomik çeşitliliği nedeniyle metabolik sağlık açısından dikkat çekmektedir. Kısa zincirli yağ asitleri (KZYA) ise lif fermentasyonunun başlıca ürünleri olarak bağırsak bariyeri, immün sistem ve bağırsak-beyin aksı üzerinde etkili olmaktadır. Bu derlemenin amacı, *P. copri* ile KZYA arasındaki ilişkinin metabolik ve nöroimmün düzenleme bakımından güncel kanıtlar ışığında değerlendirilmesidir.

Kapsam ve Yöntem: Çalışmada *P. copri*'nin merkezi karbon metabolizması, klad ve suş farklılıkları, diyetle ilişkisi, süksinat-asetat-format üretimi, mikrobiyal topluluk içindeki metabolit dönüşümleri ve KZYA'nın bağırsak-beyin aksındaki etkileri ele alınmıştır. İn vivo, in vitro ve derleme niteliğindeki güncel çalışmalar karşılaştırmalı olarak incelenmiştir. *P. copri*'nin doğrudan propiyonat üretimi ile topluluk düzeyinde süksinatın propiyonata dönüştürülmesi birbirinden ayrılmıştır.

Bulgular: *P. copri*'nin glikoliz ve fumarat solunumuna dayalı metabolizması sonucunda başlıca süksinat, asetat ve format oluştuğu; bakterinin süksinattan propiyonat üretimi için gerekli bazı enzimleri taşımadığı görülmektedir. Bu nedenle *P. copri* etkisi yalnızca toplam KZYA miktarıyla değil, metabolit profilinin niteliği ve diğer mikroorganizmalarla olan trofik etkileşimleriyle değerlendirilmelidir. Dört ana kladın farklı karbonhidrat kullanım profillerine sahip olması, literatürdeki olumlu ve olumsuz ilişkilerin önemli bir açıklamasını sunmaktadır. KZYA'lar bağırsak epitel bütünlüğü, G proteinine bağlı reseptörler, histon deasetilaz inhibisyonu, mikroglial olgunlaşma ve nöroinflamatuvar yanıt üzerinde etkili olabilir.

Sonuç: *P. copri* –KZYA ilişkisi, diyet, konak metabolizması ve mikrobiyal topluluk bileşimi tarafından belirlenen dinamik bir eksendir. *P. copri*, bazı bağlamlarda metabolik iyileşme ve beslenme tedavisine katkı sağlayabilse de bu etkilerin suş ve diyet bağımlı olduğu unutulmamalıdır. Klinik uygulamaya geçiş için klad düzeyinde metagenomik tanımlama, metabolomik doğrulama ve kontrollü insan çalışmalarına ihtiyaç vardır.

Anahtar Kelimeler: Prevotella copri; kısa zincirli yağ asitleri; süksinat; bağırsak-beyin aksı; mikroglia; nöroimmün düzenleme; mikrobiyal metabolitler.

ABSTRACT

Background and Objective: The gut microbiota is a metabolic ecosystem that communicates bidirectionally with the host's energy metabolism, immune response, and central nervous system functions. *Prevotella copri*, a member of this ecosystem, has attracted attention in relation to metabolic health because of its capacity to utilize complex carbohydrates and its genomic diversity among strains.

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Short-chain fatty acids (SCFAs), which are major products of dietary fiber fermentation, influence intestinal barrier integrity, the immune system, and the gut–brain axis. The aim of this review is to evaluate the relationship between *P. copri* and SCFAs in terms of metabolic and neuroimmune regulation in light of current evidence.

Scope and Methods: This study addresses the central carbon metabolism of *P. copri*, its clade- and strain-level differences, its relationship with diet, the production of succinate, acetate, and formate, metabolite transformations within the microbial community, and the effects of SCFAs on the gut–brain axis. Current in vivo, in vitro, and review studies were comparatively examined. The direct production of propionate by *P. copri* was distinguished from the community-level conversion of succinate into propionate by other microorganisms.

Results: The metabolism of *P. copri*, based on glycolysis and fumarate respiration, primarily results in the production of succinate, acetate, and formate. The bacterium lacks some of the enzymes required for the conversion of succinate into propionate. Therefore, the effects of *P. copri* should be evaluated not only according to the total amount of SCFAs produced but also according to the quality of the metabolite profile and the trophic interactions with other microorganisms. The presence of four major clades with distinct carbohydrate-utilization profiles provides an important explanation for the positive and negative associations reported in the literature. SCFAs may influence intestinal epithelial integrity, G protein-coupled receptors, histone deacetylase inhibition, microglial maturation, and neuroinflammatory responses.

Conclusion: The relationship between *P. copri* and SCFAs is a dynamic axis shaped by diet, host metabolism, and microbial community composition. Although *P. copri* may contribute to metabolic improvement and nutritional therapy in certain contexts, its effects are strain- and diet-dependent. Clade-level metagenomic characterization, metabolomic validation, and controlled human studies are required before clinical applications can be developed.

Keywords: *Prevotella copri*; short-chain fatty acids; succinate; gut–brain axis; microglia; neuroimmune regulation; microbial metabolites.

GİRİŞ

Bağırsak mikrobiyotası, yalnızca sindirim kanalında bulunan mikroorganizmaların toplamı değildir; konağın enerji kullanımı, epitel bütünlüğü, immün toleransı ve sinir sistemi işlevleriyle sürekli etkileşim içinde olan biyokimyasal bir ortak sistemdir. Mikrobiyal topluluklar, konak tarafından sindirilemeyen polisakkaritleri fermente ederek asetat, propiyonat ve bütirat gibi kısa zincirli yağ asitleri üretir. Bu metabolitler enerji substratı olmanın ötesinde, reseptör aracılı ve epigenetik mekanizmalar yoluyla hücresel yanıtları düzenler. Bu nedenle mikrobiyota bileşiminin değerlendirilmesi, yalnızca hangi bakterilerin bulunduğuna değil, bu bakterilerin hangi metabolitleri hangi koşullarda ürettiğine de odaklanmalıdır [1], [2].

Prevotella copri, özellikle lif ve bitkisel polisakkaritlerden zengin beslenme örüntülerinde öne çıkabilen, anaerobik ve sakkarolitik bir bağırsak bakterisidir.. Geniş genomik çalışmalar, *P. copri* kompleksinin birbirinden belirgin biçimde ayrılan dört kladı içerdiğini ve bu kladların karbonhidrat metabolizması bakımından farklı işlevsel repertuarlara sahip olduğunu göstermiştir [3]. Dolayısıyla bir çalışmada *P. copri* bolluğunun yararlı bir metabolik sonuçla, başka bir çalışmada ise inflamatuvar veya metabolik bozuklukla ilişkilendirilmesi, tek başına çelişki olarak yorumlanmamalıdır.

Bu derlemenin temel sorusu, *P. copri*'nin mikrobiyal metabolitler aracılığıyla konak metabolizmasını ve nöroimmün homeostazı nasıl etkileyebileceğidir. Bu soruyu yanıtlamak için üç düzey birlikte ele alınmıştır: bakterinin kendi merkezi karbon metabolizması, bağırsak mikrobiyal topluluğu içinde gerçekleşen metabolit paylaşımı ve KZYA'ların bağırsak-beyin aksı üzerindeki etkileri. Çalışmanın önemli bir sınırlılığı, *P. copri*'ye özgü insan klinik kanıtlarının hâlen sınırlı olmasıdır. Bu nedenle aşağıdaki değerlendirmeler, mekanistik deneyler ve hayvan modelleri ile insan gözlemsel çalışmalarının birlikte yorumlanmasına dayanmaktadır.

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ARAŞTIRMA VE BULGULAR

Bu derleme çalışması için kaynak doğrulamasında PubMed, PubMed Central, DOI kayıtları, hakemli dergi sayfaları ve resmi güvenlilik bilgi kaynakları kullanılmıştır. Belirtilen kapsam doğrultusunda *P. copri*'nin metabolizması, klad çeşitliliği, diyet ilişkisi, KZYA biyolojisi ve bağırsak-beyin aksı üzerine yayımlanmış araştırmalar değerlendirilmiştir. Kaynak seçiminde öncelik birincil araştırmalara, genomik ve metabolomik çalışmalara ve mekanizma açıklayan güncel derlemelere verilmiştir. Bulgular, "bakterinin doğrudan metabolizması", "topluluk düzeyindeki dönüşümler" ve "konak yanıtı" başlıkları altında toplanmıştır.

P. COPRI'NİN METABOLİK ÖZELLİKLERİ

P. copri'nin karbon metabolizması, glikoliz ile fumarat solunumunun birlikte çalışmasına dayanır. Karbonhidratlardan oluşan fosfoenolpirüvat, bir yandan pirüvata yönelerek asetil-CoA, asetat ve format oluşumuna katkı sağlarken diğer yandan oksaloasetat, malat ve fumarat üzerinden süksinat oluşumuna yönlenebilir. Fumaratın elektron alıcısı olarak kullanılması, bakterinin anaerobik enerji korunumu açısından önemlidir. Deneysel kültür çalışmalarında glikoz metabolizmasının başlıca ürünleri süksinat, asetat ve format olarak belirlenmiştir [4].

Bu nokta, *P. copri* ile propiyonat arasındaki ilişkinin doğru kurulması bakımından önemlidir. *P. copri*'nin süksinatı doğrudan propiyonata dönüştürmesi için gerekli metilmalonil-CoA mutaz, metilmalonil-CoA epimeraz ve süksinat:metilmalonil-CoA transferaz enzimlerini kodlayan genlerden yoksun olduğu bildirilmiştir [4]. Buna karşılık bağırsak ekosistemindeki bazı diğer bakteriler süksinatı propiyonata dönüştürebilir. Bu nedenle *P. copri*, topluluk düzeyinde propiyonat oluşumunun başlangıç substratını sağlayan bir bakteri olarak işlev görebilir; ancak ortaya çıkan propiyonatın tümünü doğrudan üreten organizma olarak tanımlanması bilimsel açıdan doğru bir yaklaşım değildir.

P. copri metabolizmasının bir başka özelliği karbondioksit veya bikarbonat gereksinimidir. Bu gereksinim, PEP'in oksaloasetata yönlenmesi ve fumarat-süksinat kolunun çalışmasıyla ilişkilidir. Böylece bakterinin büyüme kapasitesi, yalnızca diyetle alınan karbonhidrat miktarına değil, bağırsak ortamındaki redoks koşullarına, karbon dioksit kullanılabilirliğine ve diğer mikroorganizmaların oluşturduğu metabolik nişlere de bağlanır.

KLAD VE SUŞ ÇEŞİTLİLİĞİ

P. copri kompleksinin dört farklı kladdan oluştuğu, 6.500'den fazla metagenomun ve 1.000'den fazla genomun incelendiği çalışma ile gösterilmiştir. Kladlar arasında yüzde 10'un üzerinde genetik uzaklık ve karbonhidrat metabolizmasıyla ilişkili işlevsel farklılıklar bildirilmiştir. Kladların Batılılaşmış popülasyonlarda daha düşük oranda bulunması, çok kuşaklı diyet değişikliklerinin bu bakterinin ekolojik başarısını etkilemiş olabileceğini düşündürmektedir [3].

Kladlar arasındaki farklılıklar, karbonhidrat-aktif enzimlerin ve polisakkarit kullanım lokuslarının dağılımında belirgindir. İzolatların farklı polisakkaritleri kullanabilmesi, aynı "*P. copri* bolluğu" ölçümünün farklı bireylerde farklı metabolik sonuçlar doğurabileceği anlamına gelir [5]. Ayrıca standart 16S rRNA tabanlı profilleme yöntemleri, çoğu durumda klad düzeyindeki ayrımı yeterince yapamaz. Bu durum, *P. copri*'nin sağlık üzerindeki rolünü araştıran çalışmalar arasında gözlenen sonuç farklılıklarının metodolojik bir kaynağıdır.

Bu nedenle gelecekteki çalışmaların üç özelliği taşıması gerekir. İlk olarak *P. copri*'nin yalnızca tür düzeyinde değil, suş veya klad düzeyinde tanımlanması gerekir. İkinci olarak mikrobiyal bolluk ile metabolik aktivite birbirinden ayrılmalıdır; yüksek bolluk her zaman yüksek metabolit üretimi anlamına gelmez. Üçüncü olarak diyet bileşimi, konak metabolik durumu ve birlikte bulunan mikroorganizmalar analiz modeline dâhil edilmelidir. Bu çerçeve, *P. copri*'nin bazı çalışmalarda yararlı, bazı çalışmalarda ise inflamasyonla ilişkili bulunmasını açıklamaya yardımcı olur.

DİYET–*P. COPRI*–METABOLİT EKSENİ

Diyet tarzı, *P. copri*'nin ekolojik nişini belirleyen temel çevresel faktörlerden biridir. Bitkisel lifler ve kompleks polisakkaritler, *P. copri*'nin sakkarolitik kapasitesini destekleyebilir. Ancak bu ilişkinin yönü, lifin kimyasal yapısına, diğer bakterilerle rekabete ve konağın bağırsak geçiş özelliklerine bağlıdır.

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MDCF-2 adı verilen mikrobiyota yönlendirmeli tamamlayıcı gıda üzerine yapılan çalışma, diyet ile mikrobiyal işlev arasındaki ilişkiyi açıklayan önemli bir örnektir. Klinik çalışmada MDCF-2 ile beslenen malnütrisyonlu çocuklarda kilo alımı daha iyi olmuş; metagenomik veriler *P. copri* suşlarının MDCF-2 glikanlarını kullanma yollarının ponderal büyüme ile ilişkili olduğunu göstermiştir. Gnotobiyotik farelerde yürütülen ters translasyon deneylerinde *P. copri* içeren mikrobiyal konsorsiyumların MDCF-2 glikan metabolizmasına ve bağırsak epitel hücrelerinin enerji metabolizmasına katkı sağladığı bildirilmiştir ([6]).

Bu çalışma iki önemli sonucu ortaya koymaktadır. Birincisi, *P. copri*'nin etkisi belirli bir diyet bağlamında ortaya çıkmıştır; aynı bakteri farklı bir diyetle aynı sonucu vermeyebilir. İkincisi, gözlenen etki *P. copri*'nin tek başına faaliyetinden ziyade Bifidobacterium infantis gibi diğer bakterilerle etkileşim içinde oluşmuştur. Araştırmacılar *P. copri*'nin doğrudan ürünleri ile toplulukta daha sonra oluşan metabolit veya sinyal olaylarını birbirinden ayırmak için ek çalışmalara ihtiyaç olduğunu da vurgulamıştır [6].

Tablo 1. *P. copri* –KZYA ekseninde temel mekanizmaların özeti

Düzey	Temel bulgu	Yorum
Bakteriyel metabolizma	Süksinat, asetat ve format oluşumu	*P. copri*'nin doğrudan propiyonat üretimi için gerekli enzimleri taşımadığı bildirilmiştir.
Mikrobiyal topluluk	Süksinatın diğer bakterilerce propiyonata dönüştürülmesi	Net KZYA profili topluluk bileşimine bağlıdır.
Diyet bağlamı	Lif ve özgül glikanların kullanımı	Metabolik etki, substratın kimyasal yapısına ve diyet bağlamına bağlıdır.
Konak yanıtı	Bariyer, reseptör ve epigenetik etkiler	KZYA'lar metabolik ve nöroimmün sinyalleşmeyi birlikte etkileyebilir.

KZYA'LARIN METABOLİK ETKİLERİ

Asetat, propiyonat ve bütirat bağırsak mikrobiyotasının en çok incelenen fermentasyon ürünleridir. Bütirat, kolon epitel hücreleri için enerji kaynağı olarak işlev görürken asetat ve propiyonat portal dolaşıma geçerek karaciğer ve periferik dokulara ulaşabilir. KZYA'lar GPR41/FFAR3, GPR43/FFAR2 ve GPR109A gibi reseptörler üzerinden sinyal iletebilir; ayrıca özellikle bütirat ve propiyonat histon deasetilaz aktivitesini baskılayarak gen ekspresyonunu değiştirebilir [1], [7].

Metabolik etkiler arasında glukoz homeostazının, iştah sinyallerinin, adipokin yanıtının ve insülin duyarlılığının düzenlenmesi yer alır. Bununla birlikte KZYA etkileri doz, uygulama yolu, beslenme modeli ve mikrobiyota kompozisyonuna göre değişebilir. Bu nedenle bir metabolitin plazma veya dışkı düzeyindeki artışı, tek başına terapötik yarar kanıtı olarak kabul edilmemelidir.

Araştırılan deneysel çalışmalar, *P. copri* uygulamasının diyabetik db/db farelerde glukoz metabolizması bozukluklarını hafifletebildiğini bildirmiştir. Bu etkilerin bağırsak mikrobiyota kompozisyonu, metabolit profili ve bağırsak endokrin sinyalleşmesiyle ilişkili olabileceği öne sürülmüştür [8]. Ayrıca 2025 yılında yayımlanan bir hayvan çalışmasında *P. copri* uygulamasının yüksek yağlı diyetle beslenen farelerde yağ birikimini azaltabildiği ve inguinal beyaz adipoz dokuda kahverengileşmeyi desteklediği bildirilmiştir [9].

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Süksinatın da konak metabolizmasında bağımsız bir sinyal molekülü olarak değerlendirilmesi gerekir. Süksinat reseptörü 1 (SUCNR1) aracılığıyla immün ve metabolik hücrelerde yanıt oluşturabilir.

KZYA'LAR, BAĞIRSAK BARİYERİ VE NÖROİMMÜN DÜZENLEME

Bağırsak-beyin aksı; vagus siniri, dolaşımdaki hormonlar, immün aracılar, mikrobiyal metabolitler ve enterik sinir sistemi üzerinden iki yönlü iletişim sağlayan bir ağdır. KZYA'lar bu ağın önemli kimyasal aracılarındandır. Bağırsak epitelinin sıkı bağlantı proteinlerini, mukus üretimini ve lokal immün yanıtı etkileyerek bağırsak geçirgenliğinin düzenlenmesine katkıda bulunabilirler. Bağırsak bariyerindeki bozulmanın azalması, dolaşıma geçen mikrobiyal ürünlerin ve inflamatuvar sinyallerin sınırlanmasına yardımcı olabilir [7].

Kan-beyin bariyeri de mikrobiyota kaynaklı sinyallerden etkilenebilen dinamik bir yapıdır. KZYA'ların bir bölümü dolaşıma geçerek endotel hücreleri, perisitler ve astrositler üzerinden bariyer işlevini etkileyebilir. Hayvan modellerinde KZYA üreten mikrobiyal toplulukların bariyer bütünlüğüyle ilişkili olduğu bildirilmiş olsa da bu etkinin insanlardaki boyutu ve *P. copri*'ye özgü katkısı henüz kesin değildir. Bu nedenle *P. copri*'nin nöroimmün etkisi doğrudan gösterilmiş bir klinik gerçeklikten çok, mikrobiyal metabolitler ve topluluk ekolojisi üzerinden araştırılmakta olan bir mekanizma olarak görülmelidir.

Mikroglia, merkezi sinir sisteminin yerleşik bağışıklık hücreleridir ve sinaptik düzenleme, nörogenez, hasar yanıtı ve nöroinflamasyon süreçlerinde görev alır. Germ-free hayvanlarda mikroglial gelişim ve olgunlaşmanın bozulması, bağırsak mikrobiyotası ile mikroglia arasındaki ilişkinin erken dönemden itibaren kurulabildiğini göstermiştir. KZYA–mikroglia yolaklarında öne çıkan mekanizmalar arasında FFAR2/FFAR3 gibi reseptörler, GPR109A sinyali ve histon deasetilaz inhibisyonu bulunmaktadır [10], [11].

KZYA'ların mikroglial aktivasyonu her koşulda baskıladığı düşünülmemelidir. Metabolitin türü, konsantrasyonu, uygulama zamanı ve hastalık modeli sonucu değiştirebilir. Güncel derlemeler, SCFA–mikroglia yolunun nöroinflamasyon, kan-beyin bariyeri, sinaptik işlev ve davranışsal çıktılarla ilişkili olduğunu; ancak kesin mekanizmaların birçok noktada henüz tam olarak açıklanmadığını bildirmektedir [11]. Bu nedenle *P. copri* veya KZYA takviyelerinin nörodejeneratif ve nöropsikiyatrik hastalıklarda rutin tedavi olarak önerilmesi için daha güçlü klinik kanıt gereklidir.

P. COPRİ'NİN ÇİFT YÖNLÜ BİYOLOJİK ROLÜ

P. copri'nin konağa etkisi bağlama duyarlıdır. Bir yandan liften zengin diyetlerde karbonhidrat kullanımına katkı sağlayabilir, malnütrisyon için tasarlanmış özgül bir tamamlayıcı gıdanın etkisini destekleyebilir ve bazı hayvan modellerinde glukoz metabolizması ile adipoz doku üzerinde olumlu sonuçlar oluşturabilir [6], [8], [9]. Diğer yandan *P. copri*'nin bazı suşları romatoid artrit gibi inflamatuvar durumlarla ilişkilendirilmiş, belirli metabolik ortamlarda insülin direnci veya düşük dereceli inflamasyonla birlikte bulunmuştur. Bu ilişkiler çoğunlukla gözlemsel veya suş-spesifik olduğundan, türün tüm üyelerine genellenmemelidir.

Bu çift yönlülüğün temelinde üç unsur bulunmaktadır. İlk unsur klad ve suş çeşitliliğidir. İkinci unsur diyetin sağladığı substratlardır. Üçüncü unsur ise *P. copri*'nin birlikte yaşadığı mikroorganizmaların, onun ürettiği süksinat ve diğer ara ürünleri nasıl dönüştürdüğüdür.

KLİNİK VE TERAPÖTİK PERSPEKTİFLER

P. copri ve KZYA ekseni, üç olası müdahale alanı sunmaktadır. İlk alan diyet düzenlemesidir. Lif türü ve miktarı, P. copri'nin metabolik aktivitesini ve topluluk içindeki metabolit akışını değiştirebilir. İkinci alan, suş seçimine dayalı yeni nesil probiyotik veya tanımlı mikrobiyal konsorsiyum yaklaşımlarıdır. Üçüncü alan ise doğrudan metabolit, reseptör veya epigenetik yolak hedeflemesidir.

MDCF-2 çalışması, mikrobiyota yönlendirmeli beslenme tedavisinin genel bir probiyotik yaklaşımından daha kontrollü olabileceğini göstermektedir. Burada amaç yalnızca bakterinin sayısını artırmak değil, belirli bir gıdanın glikanlarını kullanabilen mikrobiyal işlevleri desteklemektir. Ancak bu yaklaşımın farklı yaş gruplarında, farklı coğrafyalarda ve farklı beslenme örüntülerinde aynı sonucu verip vermeyeceği ayrıca araştırılmalıdır [6].

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Klinik araştırmalarda dışkı *P. copri* bolluğunun yanı sıra metagenomik klad profili, kısa zincirli yağ asitleri, süksinat, inflamatuvar belirteçler, glukoz metabolizması ve bağırsak geçirgenliği birlikte ölçülmelidir. Nöroimmün çalışmalar buna mikroglial aktiviteyi doğrudan veya dolaylı olarak yansıtan nörogörüntüleme, nörofilament, sitokin ve bilişsel değerlendirmeleri eklemelidir.

SINIRLILIKLAR

Bu derlemenin ilk sınırlılığı, *P. copri* ile KZYA arasındaki ilişkinin çoğu zaman doğrudan bir insan müdahale çalışmasıyla değil, hayvan modelleri, in vitro kültürler veya metagenomik korelasyonlarla incelenmiş olmasıdır. İkinci sınırlılık, çalışmaların *P. copri*'yi tek bir biyolojik canlı gibi ele alabilmesidir. Oysa kladlar ve suşlar karbonhidrat kullanımı, metabolit üretimi ve konakla etkileşim bakımından farklılaşabilir. Üçüncü sınırlılık, dışkı metabolitlerinin bağırsak mukozası, portal dolaşım veya beyin dokusundaki gerçek konsantrasyonları her zaman yansıtmamasıdır.

Ayrıca KZYA'ların koruyucu veya zararlı etkileri doğrusal değildir. KZYA düzeyindeki artış, üretici topluluğun çeşitliliği, metabolitin dokuya ulaşımı, reseptör ekspresyonu ve konak inflamasyonunun evresi birlikte değerlendirilmeden yorumlanmamalıdır. Bu sınırlılıklar, *P. copri*'nin klinik uygulamalarda doğrudan "yararlı" veya "zararlı" olarak sınıflandırılmasını engeller.

SONUÇ

Prevotella copri, bağırsak mikrobiyotasında kompleks karbonhidrat metabolizması ve mikrobiyal metabolit akışları açısından önemli bir bakteridir. Bununla birlikte bakterinin merkezi metabolizması, doğrudan propiyonat üretiminden çok süksinat, asetat ve format oluşumunu desteklemektedir. Propiyonatın ortaya çıkışı çoğu durumda diğer bakterilerin katıldığı topluluk düzeyinde bir dönüşüm olarak değerlendirilmelidir. Bu ayrım, *P. copri*–KZYA ilişkisinin doğru anlaşılması için temel noktadır.

P. copri'nin metabolik ve nöroimmün etkileri, tür düzeyindeki bolluktan ziyade klad veya suş özellikleri, diyet substratları ve mikrobiyal topluluk etkileşimleri tarafından belirlenir. KZYA'lar bağırsak bariyerini, glukoz ve enerji metabolizmasını, immün yanıtı, mikroglial olgunlaşmayı ve kan-beyin bariyerini etkileyebilen çok işlevli sinyallerdir. Bu nedenle diyet– *P. copri* –mikrobiyal metabolit–nöroimmün yanıt ekseni, gelecekteki araştırmalar için bütüncül bir çerçeve sunmaktadır.

Klinik uygulama açısından en gerçekçi yaklaşım, *P. copri*'yi koşulsuz biçimde artırmak değil; yararlı metabolik işlevleri taşıyan suşları tanımlamak, bunları uygun diyet substratlarıyla eşleştirmek ve ortaya çıkan metabolitleri metabolomik yöntemlerle doğrulamaktır. İnsanlarda yürütülecek kontrollü, uzun süreli ve klad düzeyinde karakterizasyon yapan çalışmalar tamamlanmadan *P. copri* veya KZYA takviyelerinin nörolojik ve metabolik hastalıkların tedavisi için standart uygulama olarak önerilmesi henüz mümkün değildir.

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PERCEIVED NEED FOR SCHOOL PSYCHOLOGICAL SERVICES IN PRE-UNIVERSITY EDUCATION: AN EXPLORATORY STUDY OF SCHOOL-BASED PROFESSIONALS IN ONE MUNICIPALITY IN KOSOVO

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ABSTRACT

Schools are important settings for promoting mental health, preventing psychosocial difficulties, and supporting students' educational development. This exploratory study examined perceived need for school psychological services among school-based professionals in one municipality in Kosovo during 2020–2021. A descriptive exploratory design was used with 25 participants, including primary- and secondary-school principals, pedagogical personnel, secretaries, and administrators. Data were collected using an anonymous 16-item questionnaire containing open-ended and closed-ended questions concerning school challenges, perceived need for psychological services, potential support to teachers, collaboration, and awareness of institutional provisions. Closed-ended responses were intended for descriptive analysis, while open-ended responses were examined thematically. Because the original respondent-level response sheet is no longer available, the manuscript reports only numerical findings that can be verified from surviving study documentation and does not reconstruct missing item-level percentages. The documented responses identified recurring concerns involving student motivation, absenteeism, interpersonal conflict, behavioral and emotional difficulties, family-related problems, and organizational constraints. Participants also perceived school psychologists as potentially valuable for prevention, early identification, consultation, psychoeducation, teacher and family support, crisis response, and referral. The findings provide context-specific exploratory evidence from an under-researched educational setting. They should not be interpreted as nationally representative or causal evidence. The study supports further research and systematic development of school psychological services in Kosovo and offers lessons relevant to other educational systems in which school-based psychological services are developing.

Keywords: school psychology; school psychological services; school mental health; pre-university education; Kosovo; prevention; psychological services

1. Introduction

The school is not only an institution responsible for academic instruction but also an important developmental environment in which children and adolescents spend a substantial part of their formative years. Academic achievement, psychological well-being, social relationships, emotional development, behavioral adjustment, and family-school interaction are closely interconnected. Consequently, educational systems increasingly recognize that effective schooling requires attention not only to cognitive development but also to students' social, emotional, and psychological needs.

The importance of schools as settings for mental health promotion has been emphasized internationally. The World Health Organization (WHO) and UNESCO have argued that education and health are interdependent and that schools should function as environments that promote the health and well-being of students, staff, families, and communities. Their global framework for health-promoting schools emphasizes safe and supportive social-emotional environments, collaboration with communities, and access to school-based or school-linked health services addressing students' physical, emotional, psychosocial, and educational needs.

Childhood and adolescence represent particularly important periods for psychological development. During these stages, young people encounter significant developmental transitions and may experience

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difficulties related to academic performance, peer relationships, family changes, identity development, emotional regulation, behavioral adjustment, bullying, substance use, anxiety, depression, and other psychosocial stressors. The global burden of mental health difficulties among children and adolescents has consequently become an important public health and educational concern (Kieling et al., 2011).

Schools are uniquely positioned to respond to these difficulties because they provide sustained access to large populations of children and adolescents. School-based interventions can support universal prevention, selective intervention for students at elevated risk, and targeted assistance for students experiencing significant difficulties. Reviews of school-based mental health interventions indicate that schools can be effective settings for mental health promotion and prevention, although the effectiveness of interventions depends on program quality, implementation, contextual factors, and appropriate professional support (Fazel et al., 2014; Weare & Nind, 2011).

The role of the school psychologist has consequently expanded beyond traditional psychological assessment. Contemporary school psychology includes prevention, consultation, counseling, psychoeducation, behavioral intervention, crisis response, family collaboration, teacher consultation, mental health promotion, and participation in multidisciplinary educational planning.

School psychologists can therefore serve as a bridge between psychological knowledge and educational practice. Their work can help schools identify students who require additional support, assist teachers in understanding behavioral and learning difficulties, support parents in responding to developmental challenges, and facilitate referral to specialized services when needs exceed the school's capacity.

Evidence also suggests that interventions targeting social-emotional competencies can produce meaningful educational and psychosocial benefits. A major meta-analysis by Durlak et al. (2011), involving 213 school-based universal programs and 270,034 students, found improvements in students' social and emotional skills, attitudes, behavior, and academic performance.

These findings are relevant for educational systems in which school psychological services are still developing. Kosovo represents such a context, where the organization, accessibility, and systematic integration of psychological services into schools have developed progressively but remain areas requiring further institutional strengthening.

The present study therefore revisits the issue of school psychological services from the perspective of professionals working within schools. Rather than attempting to estimate the prevalence of psychological problems among students, the study focuses on the perceived need for professional psychological support and the potential functions of school psychologists within the school system.

These national indicators are important for interpreting the present study, but they should not be confused with the study's primary data. The present research was conducted in one municipality during 2020–2021 and involved 25 school-based participants. Its purpose was to explore professional perceptions of need and the potential functions of school psychologists, not to estimate national prevalence, staffing ratios, or national service coverage. The national statistics are therefore used as contextual secondary evidence that situates the local exploratory findings within the broader development of Kosovo's education system.

Policy developments provide further evidence that psychological and pedagogical support has become part of the institutional development agenda. The Government of Kosovo's assessment of the Education Strategy 2022–2026 reports that 223 professional positions had been filled by the reporting period, including 76 pedagogues and psychologists employed during 2022–2023. The same assessment states that 520 positions were planned through specific grants and continued municipal employment and identifies the limited number of professional staff as a continuing challenge. The implementation status for this activity was assessed at 20–39%, indicating that institutional development was underway but remained incomplete (Government of Kosovo, 2024).

The national figures also indicate a continuing decline in school enrolment. Compared with 2024/2025, primary and lower-secondary enrolment decreased from 208,515 to 198,639 pupils, a reduction of 9,876 pupils (4.7%), while upper-secondary enrolment decreased from 63,551 to 62,085 pupils, a reduction of 1,466 pupils (2.3%). These demographic changes should not be interpreted as evidence of a reduced

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need for psychological services. Rather, they underline the importance of planning services according to the changing psychosocial and educational needs of pupils and schools, rather than enrolment numbers alone (Kosovo Agency of Statistics [KAS], 2025, 2026).

The scale of Kosovo's pre-university education system provides an important contextual basis for considering the organization and accessibility of school psychological services. According to the Kosovo Agency of Statistics (KAS), in the 2025/2026 school year there were 198,639 pupils enrolled in primary and lower-secondary education and 62,085 pupils enrolled in upper-secondary education, for a combined total of 260,724 pupils across these levels. The large majority were enrolled in the public sector: 97.8% of pupils in primary/lower-secondary education and 91.6% of pupils in upper-secondary education.

1.1. National educational context and the scale of need

National indicator	2024/2025	2025/2026
Primary + lower-secondary pupils	208,515	198,639
Upper-secondary pupils	63,551	62,085
Combined pupils	272,066	260,724
Public-sector share, primary/lower-secondary	95.5%	97.8%
Public-sector share, upper-secondary	91.8%	91.6%

2. Theoretical and empirical background

2.1. Schools as settings for mental health promotion

The concept of school mental health has evolved considerably. Earlier models often focused primarily on identifying students with psychological or learning difficulties and referring them for specialized assessment. Contemporary approaches emphasize a broader continuum that includes promotion of well-being, universal prevention, early identification, targeted intervention, and collaboration across educational, health, and social systems.

WHO and UNESCO's framework for health-promoting schools reflects this broader perspective. It emphasizes that schools should provide safe and supportive environments and that health and well-being should be integrated into school governance, curriculum, social-emotional environments, and access to health services.

This whole-school approach is particularly relevant to school psychology because many student difficulties cannot be adequately understood in isolation from classroom practices, peer relationships, family circumstances, school climate, and broader social conditions.

2.2. The role of the school psychologist

The school psychologist is a specialist who applies psychological knowledge to educational and developmental contexts. The role may include:

- psychological assessment;
- early identification of emotional, behavioral, and learning difficulties;
- individual and group counseling;
- consultation with teachers;

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- consultation with parents;
- psychoeducation;
- behavioral intervention;
- prevention programs;
- social-emotional learning;
- crisis intervention;
- support for students with special educational needs;
- referral and coordination with external services;
- school-wide mental health promotion;
- participation in multidisciplinary teams;
- evaluation of intervention outcomes; and
- professional consultation with school leadership.

Consequently, the school psychologist should not be conceptualized merely as a professional who works with students who already have psychological problems. A contemporary model emphasizes prevention and promotion alongside assessment and intervention.

2.3. Evidence for school-based psychological and mental health interventions

The empirical literature provides considerable support for school-based mental health promotion and prevention. Weare and Nind (2011), in a systematic review of reviews, examined 52 systematic reviews and meta-analyses and concluded that school-based interventions can have beneficial effects across mental health, social, emotional, and educational outcomes.

Fazel et al. (2014a, 2014b) similarly argued that schools represent important settings for mental health promotion, prevention, and treatment, particularly when interventions are integrated into a broader whole-school approach. Their review also emphasized the need for implementation research to determine how effective interventions can be sustainably incorporated into educational systems.

The evidence is not limited to mental health symptoms. Social and emotional learning programs have demonstrated benefits across multiple domains. Durlak et al. (2011) reported positive effects on social-emotional skills, attitudes, behavior, and academic performance across 213 universal school-based programs.

These findings support the conceptualization of psychological services as an integral component of educational quality rather than as an isolated clinical service.

3. Problem statement

Despite the recognized importance of students' psychological well-being, access to school-based psychological services may remain limited in educational systems where such services are not systematically established.

The absence or limited availability of school psychologists may result in psychological and behavioral difficulties being addressed primarily by teachers, school administrators, parents, or other personnel who may not have specialized psychological training.

This may be particularly problematic when students experience complex difficulties involving emotional distress, behavioral dysregulation, family conflict, peer difficulties, school refusal, academic disengagement, bullying, substance use, or other psychosocial problems.

The central problem addressed by this study is therefore the extent to which school-based professionals perceive a need for dedicated psychological services within pre-university education in Kosovo.

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4. Aim of the study

The primary aim of the study was:

To assess perceived need for school psychological services in the participating educational setting, within the broader context of pre-university education in Kosovo.

The study additionally sought to explore:

1. the main educational and psychosocial challenges encountered in schools;
2. the extent to which existing school personnel perceive themselves as able to respond to these challenges;
3. perceptions regarding the potential contribution of school psychologists;
4. areas in which psychological services are considered most necessary;
5. the potential contribution of psychologists to students' educational success;
6. the need for collaboration among psychologists, teachers, parents, school leadership, and external services; and
7. awareness regarding the institutional provision of school psychological services.

5. Research questions

The study was guided by the following research questions:

RQ1: What educational, behavioral, emotional, and psychosocial challenges are perceived as most important in the participating schools?

RQ2: Do school leaders and support personnel perceive a need for professional psychological services in schools?

RQ3: What functions are considered most important for a school psychologist?

RQ4: How do participants perceive the potential contribution of school psychologists to students' academic and psychosocial functioning?

RQ5: With whom should school psychologists collaborate to maximize the effectiveness of their work?

6. Methods

6.1. Study design

A descriptive exploratory study design was used. The study adopted a predominantly qualitative orientation because the purpose was to explore professional perceptions, experiences, and recommendations regarding the need for school psychological services.

Closed-ended questionnaire responses were used descriptively, while responses to open-ended questions were analyzed thematically.

Because the study involved a small, non-probability sample from one municipality, the findings should be interpreted as exploratory rather than representative of Kosovo's entire education system.

6.2. Setting and study period

The study was conducted in one municipality in Kosovo during 2020–2021.

The study period is particularly relevant because it coincided with the COVID-19 pandemic, a period characterized internationally by substantial disruption to education and increased attention to the psychological well-being of children and adolescents. WHO and UNESCO emphasized during this period that school closures and educational disruption had important implications for students' health and well-being.

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However, because the questionnaire did not specifically measure COVID-19-related psychological outcomes, the pandemic is treated in this article as contextual background rather than as an explanatory variable.

6.3. Participants and sampling

The final sample consisted of 25 participants occupying leadership, professional, and administrative positions in schools.

Professional position	**n**	**%**
Primary school principals	12	48.0
Secondary school principals	3	12.0
Pedagogues	2	8.0
Secretaries	3	12.0
Administrators	5	20.0
Total	**25**	**100.0**

The sample therefore consisted predominantly of school principals (15; 60.0%), while the remaining 10 participants (40.0%) were pedagogical or administrative personnel.

Participants were selected from schools within the municipality included in the study. Given the exploratory nature of the investigation and the absence of a probability sampling procedure, the sample should not be interpreted as statistically representative of all school personnel in Kosovo.

6.4. Instrument

The closed-ended items addressed perceived usefulness of a school psychologist (Question 6), the perceived relationship between psychological support and academic success (Question 8), the extent of potential support to teachers (Question 9), and awareness of existing school psychological services and institutional/legal provisions (Questions 11–15). Open-ended items (Questions 1–5, 7, 10, and 16) were used to elicit descriptive and thematic information.

Data were collected using an anonymous structured questionnaire consisting of 16 questions.

The questionnaire included both closed-ended and open-ended questions. The items addressed:

- school size and staffing;
- major challenges experienced by schools;
- difficulties reported by teachers and students;
- existing capacity to respond to student difficulties;
- perceived usefulness of a school psychologist;
- areas requiring professional psychological support;
- perceived relationship between psychological support and academic success;
- potential assistance to teachers;
- professional collaboration;
- awareness of school psychologists in Kosovo;

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- awareness of legal/institutional provisions;
- perceived staffing requirements;
- previous requests for school psychologist positions; and
- participants' comments regarding the questionnaire.

The questionnaire was designed specifically for the exploratory purposes of the study.

6.5. Data collection procedure

Participants were informed about the purpose of the study and were asked to provide responses anonymously. No identifying information was required beyond basic professional and demographic characteristics relevant to the research objectives.

The anonymity of responses was intended to reduce social desirability and encourage participants to provide candid perceptions regarding the functioning of their schools and the need for psychological services.

Quantitative responses to the closed-ended questionnaire items were intended to be summarized using frequencies and percentages. Because the original item-level response sheet is no longer available, the present manuscript reports only numerical results that can be directly verified from the surviving study documentation; no missing response frequencies or percentages have been reconstructed. Open-ended responses were examined thematically and grouped according to recurring themes concerning student-related difficulties, school-level challenges, limitations of existing support, perceived functions of the school psychologist, collaboration with teachers and parents, and institutional development of psychological services. No inferential statistical analysis was conducted because of the small sample size, non-probability sampling, and exploratory design.

Open-ended responses were examined using a thematic approach. Responses were reviewed and grouped according to recurring themes concerning:

1. student-related difficulties;
2. school-level challenges;
3. limitations of existing support;
4. perceived functions of the school psychologist;
5. collaboration with teachers and parents; and
6. institutional development of psychological services.

No inferential statistical analysis was conducted because of the small sample size and exploratory study design.

7. Results

Important reporting limitation: The original respondent-level dataset is no longer available. Accordingly, this section does not reconstruct percentages for Questions 6, 8, 9, and 11–15 from memory or inference. The results below preserve the findings that remain documented in the study materials and present the open-ended responses as a qualitative thematic synthesis.

7.1. Characteristics of the sample

The sample included 25 school-based professionals. Nearly half of the participants were principals of primary schools (48.0%), while principals of secondary schools accounted for 12.0%. Pedagogues represented 8.0%, secretaries 12.0%, and administrators 20.0%.

Overall, 60.0% of participants held school leadership positions, while 40.0% represented pedagogical or administrative support positions.

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This composition provided perspectives from individuals who are directly involved in school management, student-related decision-making, educational coordination, and administrative functioning.

7.2. Perceived challenges in schools

The qualitative responses indicated that participating personnel encountered multiple categories of school-related challenges.

The most prominent themes included:

- declining student motivation toward learning;
- absenteeism;
- interpersonal conflicts among students;
- behavioral difficulties;
- developmental and emotional challenges associated with adolescence;
- difficulties in teacher-student relationships;
- family-related problems affecting students;
- difficulties in parental management and communication;
- challenges associated with students' emotional instability; and
- broader organizational and resource-related difficulties within schools.

The findings suggest that the difficulties experienced by schools cannot be reduced to academic achievement alone. Rather, academic functioning appears to be interconnected with students' emotional, behavioral, family, interpersonal, and developmental circumstances.

7.3. Perceived need for school psychological services

A central theme in the documented responses was the perceived need for professional psychological services within schools.

The documented responses identified the school psychologist as a potentially valuable professional resource capable of assisting schools with problems that exceed the traditional responsibilities or capacities of teachers and administrative personnel.

The perceived need extended beyond individual counseling. Participants associated school psychological services with prevention, early identification, consultation, behavioral support, family collaboration, teacher support, and the improvement of the school environment.

This finding is consistent with contemporary international approaches that conceptualize school mental health as a whole-school responsibility requiring coordinated professional services. WHO and UNESCO explicitly emphasize access to comprehensive school-based or school-linked services addressing emotional, psychosocial, and educational needs.

7.4. Areas in which psychological services were considered necessary

The responses identified several domains in which a school psychologist could provide professional assistance.

These included:

Students

- emotional difficulties;
- behavioral problems;
- school adjustment;

- academic disengagement;
- interpersonal conflicts;
- low motivation;
- developmental difficulties;
- family-related distress;
- social skills;
- crisis situations; and
- prevention of school dropout.

Teachers

- classroom behavior management;
- understanding students' developmental needs;
- responding to difficult behaviors;
- managing stressful situations;
- improving teacher-student communication; and
- developing preventive interventions.

Parents

- understanding children's developmental needs;
- improving parent-child communication;
- responding to behavioral difficulties;
- managing conflict;
- strengthening cooperation with the school; and
- receiving psychoeducation.

School system

- prevention programs;
- mental health promotion;
- crisis response;
- school climate improvement;
- multidisciplinary collaboration;
- referral to specialized services; and
- program evaluation.

8. Discussion

The present exploratory study indicates a clear perceived need for school psychological services among school leaders and support personnel in the participating municipality.

The finding is consistent with the broader international literature demonstrating that schools constitute an important setting for mental health promotion and prevention. Weare and Nind (2011), based on a systematic review of reviews, identified substantial evidence for school-based interventions producing benefits across mental health, social, emotional, and educational outcomes.

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Similarly, Fazel et al. (2014a, 2014b) concluded that schools have an important role in promoting positive mental health and implementing prevention and treatment interventions, particularly when these are embedded within a broader whole-school framework.

The present findings are also compatible with evidence concerning social-emotional learning. Durlak et al. (2011) found that universal school-based SEL programs improved social-emotional skills, attitudes, behavior, and academic achievement across a very large sample of students.

This evidence has an important implication for the role of school psychologists. If schools are expected to promote not only academic achievement but also students' social-emotional development and psychological well-being, specialized psychological expertise becomes an important component of a comprehensive educational system.

8.1. Beyond the traditional counseling model

One important implication of the study is that school psychology should not be reduced to individual counseling.

Participants identified needs that require intervention at multiple levels. Some difficulties are individual, while others emerge from classroom relationships, family circumstances, peer interactions, school climate, or organizational factors.

Therefore, the school psychologist should operate across multiple levels:

student → classroom → teacher → family → school → community.

This ecological orientation is consistent with contemporary school mental health models, in which psychological services are integrated into educational systems rather than operating as isolated clinical activities.

8.2. Prevention and early intervention

Another important implication concerns prevention.

School-based mental health services allow professionals to identify emerging difficulties before they develop into more severe and persistent problems. This is particularly important during childhood and adolescence, when emotional and behavioral difficulties may affect educational trajectories, peer relationships, family functioning, and later psychosocial adjustment.

The evidence reviewed by Fazel et al. (2014a, 2014b) supports the use of schools as settings for promotion and prevention, while also emphasizing the importance of effective implementation.

Taken together, the documented responses support a broad conception of the school psychologist's role. Within the limits of this exploratory study, the role can reasonably be framed as including prevention, psychoeducation, early identification, consultation, parent education, and early intervention, rather than being limited to individual counseling.

8.3. Collaboration with teachers and parents

The study also highlights the importance of collaboration.

Teachers are frequently the first professionals to observe changes in students' behavior, academic engagement, social relationships, or emotional functioning. Parents, meanwhile, possess essential information about children's developmental and family contexts.

The school psychologist can connect these perspectives and help develop coordinated intervention plans.

This collaborative role is particularly important because many school-related difficulties cannot be adequately addressed through individual counseling alone.

8.4. Relevance for Kosovo

The findings have particular significance for Kosovo because the development of school psychological services must take place within the specific social, institutional, and educational context of the country.

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The original study was motivated by the observation that school personnel often had to respond to student difficulties without access to dedicated psychological expertise. The current findings indicate that this concern remains conceptually important.

However, the results should not be interpreted as evidence that every school in Kosovo experiences exactly the same problems. Rather, they provide an exploratory indication that professionals working in schools perceive psychological support as an important component of an effective educational system.

The WHO/UNESCO health-promoting school framework is particularly relevant because it emphasizes adaptation to local contexts rather than the implementation of a single universal model. (WHO & UNESCO, 2021).

Nationally, the later development of pedagogical-psychological staffing supports the direction identified by the present study. The Government's 2024 assessment documents both progress and an ongoing staffing gap: 223 professional positions had been filled, 76 pedagogues/psychologists had been hired during 2022–2023, and 520 positions were planned overall. This is consistent with interpreting the 2020–2021 findings as an early exploratory contribution to a process that subsequently moved further toward institutionalization, rather than as a description of the current national level of service provision (Government of Kosovo, 2024).

Current KAS data further show that Kosovo's pre-university education system still serves more than 260,000 pupils in primary/lower-secondary and upper-secondary education combined. At the same time, enrolment is declining. This combination suggests that future planning should focus not only on the number of pupils served but also on the accessibility, continuity, quality, prevention orientation, and multidisciplinary integration of psychological services. In this context, the study's emphasis on prevention, early identification, consultation, family collaboration, and referral remains relevant to contemporary service development (KAS, 2026).

8.5. The COVID-19 context

The study period of 2020–2021 coincided with the COVID-19 pandemic, which significantly disrupted educational systems worldwide.

WHO and UNESCO highlighted increased concerns regarding stress, anxiety, and other mental health difficulties during the period of school disruption and emphasized the need for schools to support health and well-being alongside education. (WHO & UNESCO, 2021).

The pandemic therefore provides an important contextual backdrop for interpreting the study period. Nevertheless, the present study did not specifically assess COVID-19-related psychological symptoms, school closures, remote learning, or pandemic-specific stressors. Therefore, no causal conclusions concerning COVID-19 can be drawn from the present data.

9. Implications for practice

Based on the findings and the existing evidence, several practical implications can be proposed.

9.1. Establish sustainable school psychological services

School psychological services should be integrated into the organizational structure of pre-university education rather than being dependent on temporary projects or individual initiatives.

9.2. Define the professional role clearly

The role of the school psychologist should include:

- prevention;
- assessment;
- counseling;
- psychoeducation;
- consultation;

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- behavioral intervention;
- crisis response;
- family collaboration;
- teacher support;
- referral;
- multidisciplinary teamwork; and
- evaluation of interventions.

9.3. Develop prevention programs

Schools should implement structured programs addressing:

- social-emotional learning;
- bullying prevention;
- conflict resolution;
- emotional regulation;
- stress management;
- substance-use prevention;
- school dropout;
- resilience; and
- help-seeking behavior.

The evidence supporting school-based SEL is particularly strong, with large-scale meta-analytic evidence demonstrating improvements across social-emotional and academic outcomes. (Durlak et al., 2011).

9.4. Strengthen family-school collaboration

Psychologists should facilitate structured communication between schools and families and provide parents with psychoeducation regarding child development, behavior, emotional regulation, and communication.

9.5. Strengthen referral pathways

Schools should establish clear referral pathways connecting school psychologists with:

- primary health care;
- mental health services;
- social services;
- child protection services;
- specialized clinical services; and
- relevant community organizations.

9.6. Continuous professional development

School psychologists should receive continuing professional development in:

- evidence-based assessment;
- child and adolescent mental health;
- trauma-informed practice;

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- behavioral intervention;
- crisis management;
- suicide prevention;
- safeguarding;
- bullying prevention;
- family systems;
- inclusive education; and
- culturally responsive practice.

The national statistics introduced in the Introduction and Discussion are secondary contextual data from official sources and were not part of the original 2020–2021 dataset. They are therefore not used to calculate new inferential statistics or to modify the original study sample.

8.6. International implications and lessons learned

Although the study is limited to one municipality, its findings address a broader implementation question relevant to educational systems in which school psychological services are emerging: how school-based professionals understand the need, functions, and institutional integration of psychological support. Three transferable lessons emerge. First, the perceived need for school psychology extends beyond individual counseling to prevention, early identification, consultation, family collaboration, and referral. Second, implementation requires clear links between psychologists, teachers, school leadership, families, and external services. Third, service development should be evaluated not only by the number of psychologists employed but also by accessibility, continuity, professional role clarity, prevention capacity, and quality of multidisciplinary collaboration. These lessons are context-dependent and should be tested through comparative research rather than treated as universal findings.

10. Limitations

Several limitations should be considered when interpreting the findings.

First, the study included only 25 participants, which substantially limits statistical generalizability.

Second, participants were recruited from one municipality in Kosovo. Consequently, the findings cannot be assumed to represent all municipalities, schools, or educational professionals in Kosovo.

Third, the sampling procedure was non-probabilistic. Selection bias may therefore have influenced the findings.

Fourth, the study relied on participants' perceptions rather than direct measurements of students' mental health, academic outcomes, or intervention effectiveness.

Fifth, the questionnaire was developed specifically for this exploratory study and was not presented as a standardized psychometric instrument. Consequently, psychometric reliability and validity cannot be assumed.

Sixth, although the study took place during 2020–2021, COVID-19-related variables were not systematically measured. The pandemic should therefore be understood as contextual background rather than as a measured explanatory factor.

These limitations do not eliminate the value of the study; rather, they define its appropriate contribution. The study should be understood as an exploratory investigation capable of generating hypotheses and informing future, larger-scale research.

11. Recommendations for future research

Future research in Kosovo should expand this investigation using larger and more representative samples.

A national study could include:

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- students;
- teachers;
- school psychologists;
- principals;
- parents;
- pedagogues;
- municipal education officials; and
- health and social service professionals.

Future research should also use validated instruments to assess:

1. perceived need for school psychological services;
2. student mental health;
3. school climate;
4. teacher stress and burnout;
5. bullying;
6. academic engagement;
7. absenteeism;
8. help-seeking attitudes;
9. access to psychological services; and
10. satisfaction with existing services.

Mixed-methods designs combining quantitative surveys with qualitative interviews and focus groups would provide a stronger understanding of the needs of schools across Kosovo.

Longitudinal studies would also be valuable for examining whether the introduction of school psychological services is associated with improvements in academic engagement, attendance, school climate, behavioral outcomes, and students' psychological well-being.

12. Conclusion

The present exploratory study examined the perceived need for school psychological services in pre-university education in one municipality in Kosovo during 2020–2021.

The findings indicate that school leaders and support personnel perceive a substantial need for professional psychological expertise within schools. The perceived need extends beyond individual counseling and includes prevention, early identification, psychological assessment, consultation, psychoeducation, behavioral support, family collaboration, teacher support, crisis intervention, and coordination with external services.

The findings are consistent with international evidence demonstrating that schools represent strategic environments for promoting mental health and supporting children and adolescents.

School psychological services should therefore be conceptualized not as an optional supplementary service but as an integral component of a comprehensive educational and health-promoting school system.

For Kosovo, the systematic development of school psychological services has the potential to strengthen early identification and intervention, improve collaboration between schools and families, support teachers, reduce barriers to help-seeking, and contribute to safer and more supportive educational environments.

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At the same time, the limited sample size and single-municipality design require caution in generalizing the findings. The study should consequently be regarded as an exploratory contribution that supports the need for broader national research and evidence-informed policy development.

Ultimately, a school system that seeks to educate the whole child must also address the psychological and social conditions that make learning possible. Establishing accessible, professionally regulated, and sustainable psychological services within schools represents an important step toward such a system.

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PHYTOGENIC FEED ADDITIVES AS ALTERNATIVES TO ANTIBIOTICS: A PATHWAY TOWARDS SUSTAINABLE, SAFE AND RESILIENT ANIMAL PRODUCTION

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ABSTRACT

Growing concerns about antimicrobial resistance, antibiotic residues, environmental pollution, and sustainability of animal agriculture have prompted the search by nutritionists for alternatives to antibiotics as growth promoters in livestock production. Phytogenic feed additives are natural feed ingredients with biological functions that can enhance animal productivity and health. They include herbal and spice plants, extracts, essential oils, and isolated pure bioactive substances. Their beneficial effects are often attributed to phenols, flavonoids, terpenoids, alkaloids, tannins, saponins and other metabolites that exhibit antimicrobial, antioxidant, anti-inflammatory, immunomodulatory, digestion enhancing, and gut microbial regulating activities. Supplementation with phytochemicals can improve the host's nutrient utilization and digestion, intestinal function, growth performance, egg and meat quality, and resistance to environmental and microbial challenges. Meta-analyses of broiler studies have revealed that phytogenic additives can improve the average daily weight gain and feed conversion ratio. The combination of different phytogenic feed additives may elicit better performance due to synergism among their bioactive components. Recent studies show that the antimicrobial, antioxidant, immunomodulatory and microbiota regulating properties of phytogenic feed additives can contribute towards improving production performance and promoting sustainable animal husbandry. It is concluded that while phytogenic feed additives offer multiple benefits and opportunities for sustainable animal production, its effectiveness depends on future phytomedicine research directed towards standardization of botanical preparations, determination of optimum dosage rates and establishment of good production practices.

Keywords: antibiotic alternatives, antimicrobial resistance, gut health, phytobiotic, plant extract, and poultry

Introduction

Animal agriculture is an important pillar of food security, employment creation, and rural development. However, livestock and poultry production face challenges such as infectious diseases, high feed costs, environmental stress, antimicrobial resistance, and food safety issues. Antibiotics have been used in animal feed for therapeutic purposes and to promote growth and improve feed efficiency in various livestock and poultry species (Khine, et al., 2025; Aminullah et al., 2025). However, the extensive and inappropriate use of antibiotics in animal husbandry has contributed to the development of antimicrobial resistance. Antimicrobial resistance is considered a One Health issue due to the potential for resistant organisms and resistance genes to spread in animals, humans, and the environment. According to the Food and Agriculture Organization (2024), decreasing unnecessary antimicrobial use in animal agriculture requires improving biosecurity and hygienic practices, vaccination, disease control and management, and using nutritional and alternative compounds such as probiotics, prebiotics, acidifiers, enzymes, and phytochemicals to prevent and control diseases.

Therefore, there has been a drive to find alternatives to antibiotic growth promoters. Phytogenic feed additives have attracted considerable attention from researchers and the animal feed industry (Polycarpo,

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et al., 2022). Phytogenic feed additives are plant-derived materials added to animal diets to improve feed attributes, animal productivity, health, and product quality (Agbetuyi, et al., 2025). They contained a wide range of bioactive compounds that can be derived from leaves, roots, and stems, plants, whole herbs and spices, their powders or extracts, essential oils, oleoresins, or isolated compounds (Ren, et al., 2025). Most plants possess secondary metabolites that play an essential role in plant defense against pathogens, pests, and environmental stress. Researchers have reported the potential of phytochemicals in regulating microbial populations, improving productivity, and modifying the gut environment (Agbetuyi et al., 2025). Recent studies have demonstrated that phytochemicals can modulate harmful bacteria and the intestinal microbiota, reduce oxidative stress, inflammation, and improve the immune response and intestinal morphology in animals (Song, et al., 2023; Biswas, et al., 2024; Wang, et al., 2024). The increased interest in phytochemicals is also due to their potential to contribute to creating economically viable, eco-friendly, and consumer-friendly animal production systems.

Concept of phytogenic feed additives

Phytogenic feed additives, also referred to as phytobiotics or botanicals, are feed ingredients derived from plants and used in animal nutrition due to their biological and functional properties (Ren, et al., 2025; Agbetuyi, 2026). They includes leaves, roots, and stems, plants, whole herbs and spices, their powders or extracts, essential oils, oleoresins, or isolated compounds. Common phytogenic additives include Garlic (*Allium sativum*), Ginger (*Zingiber officinale*), Turmeric (*Curcuma longa*), Oregano (*Origanum vulgare*), Thyme (*Thymus vulgaris*), Rosemary (*Rosmarinus officinalis*), Cinnamon (*Cinnamomum species*), and Clove (*Syzygium aromaticum*). Others are Black pepper (*Piper nigrum*), Neem (*Azadirachta indica*), Moringa (*Moringa oleifera*), Papaya (*Carica papaya*), Moring-glory (*Ipomoea asarifolia*), Hog plum (*Spondias mombin*), and various tropical medicinal plants and agroforestry species. The phytochemical content of phytobiotics is influenced by plant taxonomy, geography, botanical part, maturity at harvest, processing technique and storage conditions. Consequently, different extracts obtained from the same plant can have varying biological activities. According to Wang et al. (2024), phytobiotics are complex phytochemical mixtures, and batch-to-batch variations are a primary limitation to their use in animal production.

Major bioactive components of phytogenic feed additives

The biological activity of phytochemicals in feed additives is attributed to secondary metabolites that play an essential role in plant defense against pathogens, pests, and environmental stress (Biswas, et al., 2024). The major classes of phytochemicals in phytogenic feed additives were presented in Table 1. A single plant generally contains mixtures of phytochemicals, and the combination of two or more compounds can enhance the demonstrated biological activity (Agbetuyi et al., 2023)

Table 1: Major phytogenic compounds and their potential functions

Phytogenic compound/class	Examples	Major biological functions
Phenolic compounds	Phenolic acids, catechins	Antioxidant and antimicrobial activities
Flavonoids	Quercetin, rutin, catechin	Antioxidant, anti-inflammatory activities and immunomodulation
Terpenoids	Carvacrol, thymol, limonene	Antimicrobial, antioxidant activity
Essential oils	Oregano, thyme, clove oil	Antimicrobial, digestive activity
Alkaloids	Piperine and related compounds	Antimicrobial and metabolic effects
Tannins	Condensed and hydrolysable tannins	Antimicrobial and antioxidant activities
Saponins	Steroidal/triterpenoid saponins	Antimicrobial and immunomodulatory activity
Organosulfur compounds	Allicin and related compounds	Antimicrobial and antioxidant activity
Gingerols	Ginger	Antioxidant, anti-inflammatory, and digestive activities

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Curcuminoids	Curcumin	Antioxidant, anti-inflammatory activities

The needs for alternative to antibiotics in animal production

The extensive use of antibiotics in animal production has led to the development and proliferation of resistant microorganisms. Transmission of antimicrobial resistance can occur through animals and their products, direct and indirect contact with animals, farm environments, manure, water, and the food chain (FAO, 2024). In addition, improper use and administration of antimicrobial drugs can lead to undesirable residues in food animals, affecting the quality and safety of animal products. Antibiotics, resistant bacteria, and antimicrobial residues can enter the environment through livestock waste and affect environmental health (Khine, et al., 2025). Increasing consumer demand for animal products with minimal antimicrobial residues has also necessitated the need for alternatives to antibiotics. Sustainable livestock production requires addressing multiple issues, including animal health, productivity, food safety, and environmental protection while considering economic profitability (Mnisi, et al., 2024). Phytogenic feed additives can be part of a comprehensive strategy to minimize the use of antibiotics in animal production instead of a complete replacement of antibiotics for the control of infectious diseases.

Mechanisms of action of phytogenic feed additives

The primary advantage of phytogenic feed additives is their multi-functionality. In contrast to synthetic antibiotics, which mainly target susceptible microorganisms, phytogenic compounds can affect several physiological processes. Most phytochemicals have antimicrobial activity that interferes with the cell membrane and metabolic processes of pathogenic organisms (Ogbuewu, et al., 2024). For instance, essential-oil components such as thymol and carvacrol can disrupt cellular membranes of target microorganisms, while allyl sulfur compounds from garlic can inhibit microbial enzymes. Similarly, phenolic compounds can affect microbial enzymes and cell membranes. Therefore, phytogenic feed additives can help modulate the composition of the intestinal microbiota by reducing the population of undesirable species such as *Escherichia coli*, *Salmonella*, and *Clostridium species*. However, in vivo evaluations of the antimicrobial activity of phytogenic feed additives are complicated by the fact that the final concentration of active compounds reaching the intestines is influenced by several factors (Agbetuyi, et al., 2025). The composition and activity of the intestinal microbiota are critical in determining the effectiveness of phytogenic feed additives since they can impact digestion and nutrient utilization, host metabolism, immunity, and microbial balance. Phytogenic feed additives can reduce intestinal inflammation and oxidative stress and promote intestinal health by altering the microbial composition and enhancing the integrity of the mucosal layer, villus morphology, and enzyme activities (Ren, et al., 2025). These effects can then impact the host's immunity and productivity. Intestinal microbiota modulation is, therefore, a significant mechanism by which phytogenic feed additives can enhance animal health and production.

Application of phytogenic feed additives in poultry production

A considerable number of studies have demonstrated the ability of phytogenic feed additives to modulate different aspects of poultry physiology and production, including growth performance, intestinal health and morphology, immunity, antioxidant status, meat and egg quality, and productivity. A recent review on the application of phytogenic feed additives in poultry concluded that their antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory properties make them promising alternatives to conventional antibiotic growth promoters (Agbetuyi, et al., 2025), although the inconsistent results reported in various studies limit their current application. The review by Polycarpo et al. (2022) reports that a meta-analysis of trials conducted in broilers showed that phytogenic additives improved average daily gain and feed conversion, although their effectiveness in the face of high disease challenges was limited. A similar observation was reported in a study conducted by (Agbetuyi, 2026) on the effect of antioxidants derived from *Ipomoea asarifolia* on the performance of broilers challenged with heat stress. The results indicated that dietary supplementation with *Ipomoea asarifolia* antioxidants improved performance by reducing oxidative cell damaging; promote intestinal health, and overall productivity of the birds. Study by Song et al. (2023) explained that phytogenic rich-antioxidants also promote immune response in birds. The study thus demonstrates the importance of combining different phytogenic feed

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additives since the combination of selected phytobiotics was more effective than the individual use of each additive.

Application of phytogenic feed additives in pig production

There is considerable potential for the use of phytogenic feed additives in pig production. Similar to poultry, the benefits of using phytobiotics in pigs include improvements in intestinal health, reduced incidence of diarrhea and other gastrointestinal diseases, improved feed conversion and nutrient utilization, modulation of the gut microbiota, improved immune function, reduced oxidative stress, and improved meat quality and carcass characteristics. Dietary supplementation with phytogenic feed additives can be especially important in pigs during the post-weaning period when the animals experience stress that affects gastrointestinal function and immunity (Biswas, et al., 2024). Recent reviews on the application of phytogenic feed additives in swine production highlight the potential of these feed additives to increase production efficiency and sustainability while improving health status, especially in non-ruminant livestock species such as pigs and poultry (Biswas, et al., 2024).

Application of phytogenic feed additives in ruminant production

Although much of the discussion on phytogenic feed additives has focused on their application in poultry and pigs, these feed additives can also benefit from their use in ruminant production. According to Ali, et al. (2025), the potential benefits of using phytogenic feed additives in cattle, sheep, and goat production include improvement of rumen fermentation and utilization of feed nutrients, reduction in methane emissions, modulation of undesirable microorganisms, and improvement of antioxidant status and immune function. Phytochemicals can affect various physiological processes in ruminants, including digestion and absorption of nutrients, reduction of inflammation, and improvement of milk quality and production. Some secondary metabolites affect the rumen microbiota by inhibiting the growth of undesirable microorganisms and protozoa (Kapp-Bitter, et al., 2021). Therefore, phytogenic additives can be used to manipulate rumen fermentation to improve animal production while reducing environmental pollution by methane gas. However, it is important to recognize that the use of certain phytobiotics may cause adverse effects, such as reduced feed intake and nutrient utilization, due to unfavorable interactions with the rumen microbiota (Ali, et al., 2025).

Phytogenic additives and sustainable animal production

Sustainable animal production entails balancing economic, environmental, and social factors to ensure long-term viability and food security. Phytogenic feed additives can contribute to sustainable animal production in several ways. Recent studies have shown that phytogenic products can improve various aspects of poultry production (Figure 1), making them a promising functional feed additive for use in the sustainable production of poultry in Africa (Mnisi, et al., 2024; Agbetuyi, et al., 2024).

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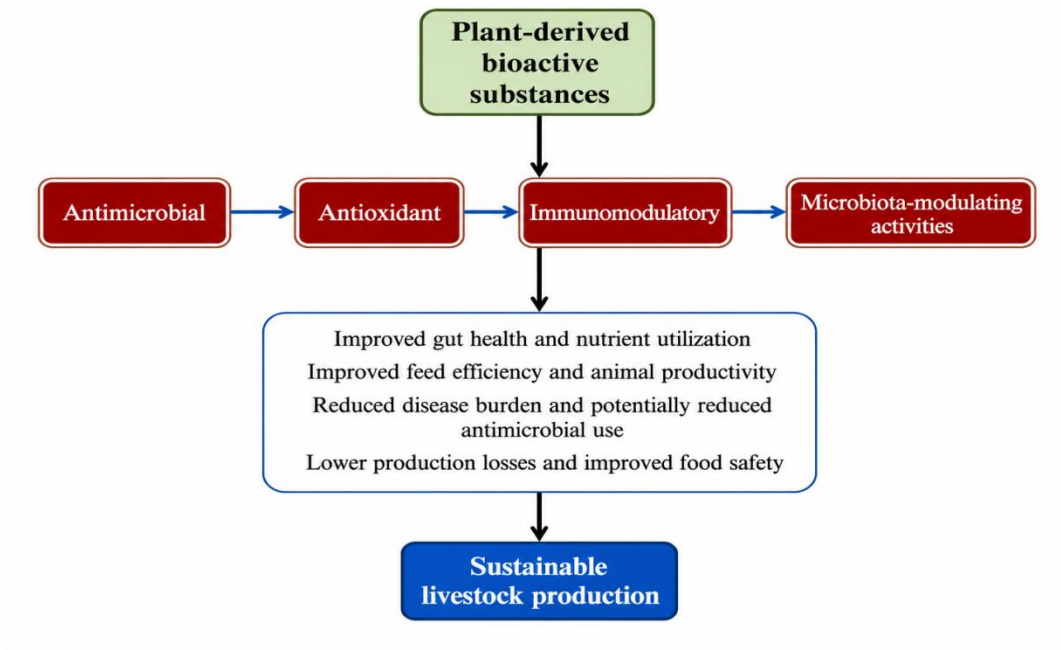


Figure 1: Conceptual pathway linking phytogenic feed additives with sustainable animal production

Phytogenic feed additives, feed efficiency and product quality

Feed accounts for the largest proportion of costs in animal production. Therefore, improving feed efficiency is often the most effective way to reduce production costs and increase profits. Moreover, improvements in feed conversion can reduce feed use per unit of animal product, lower the cost of production, reduce waste and emissions from livestock farms, and conserve natural resources such as land and water. Phytogenic feed additives can improve feed efficiency by increasing the digestibility and absorption of nutrients, reducing the presence of harmful organisms, and reducing the occurrence of inflammation and oxidative stress (Agbetuyi, 2026). However, the use of phytogenic feed additives should be evaluated based on their economic feasibility rather than their physiological effects. Phytogenic feed additives can improve the technological and nutritional quality of meat, milk, and eggs due to their anti-oxidative properties (Song, et al., 2023). In poultry, for instance, phytochemicals such as flavonoids and carotenoids can improve the color and flavor of meat while reducing lipid oxidation. Moreover, phytochemicals can improve the quality of eggs by enhancing the yolk color, eggshell thickness, and egg freshness (Agbetuyi, et al., 2024). Therefore, phytogenic feed additives can be used to improve the technological properties of animal products, which are critical for ensuring consistent food quality and prolonged shelf life.

Phytogenic feed additives and antimicrobial resistance

One of the most compelling reasons for promoting the use of phytogenic feed additives is their potential to reduce the excessive and inappropriate use of conventional antibiotics. Unlike synthetic antibiotics, phytogenic feed additives contain multiple bioactive compounds that can target different aspects of microbial physiology, which reduces the likelihood of resistance development (Wang, et al., 2024). However, it would be wrong to dismiss the possibility that phytogenic feed additives can contribute to antimicrobial resistance. As with conventional antibiotics, the use of phytogenic feed additives can lead to the emergence and dissemination of resistance, especially when they are used inappropriately or excessively. Therefore, the most effective way of reducing antimicrobial resistance is to ensure prudent use of all antimicrobial compounds. In this context, phytogenic feed additives can be used to promote the health and productivity of food animals while reducing the use of conventional antibiotics in the treatment and control of bacterial infections (Agbetuyi, et al., 2024).

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Major challenges limiting commercial application of phytogenic feed additives

Despite the many benefits of using phytogenic feed additives, these feed additives are not without challenges. A major limitation of phytogenic feed additives is the complexity of their phytochemical composition, which varies depending on the plant species, geographic location, botanical part, stage of maturity at harvest, processing and storage conditions, and other factors (Anaso, 2026). Consequently, the concentration and efficacy of bioactive compounds in commercial preparations may vary considerably, which limits their practical use. Another challenge is the optimum dosage required to attain the desired effects. The efficacy of phytogenic feed additives is often dose-dependent, and there is a narrow margin between an ineffective and overly high dose that may decrease animal performance (Agbetuyi, 2026). In addition, most phytogenic compounds are not standardized, which complicates the interpretation of research results and the application of phytogenic feed additives in practice. According to a study by Wang et al. (2024), who report that poor standardization and batch-to-batch variation significantly impact the effectiveness of phytogenic feed additives. Not all phytogenic compounds are proven to be effective and safe for use in animal husbandry. The reported inconsistency in the observed effects of phytogenic feed additives is partially attributed to differences in the experimental designs used in various studies. The variation in the results may be due to differences in the animal species and their physiological status, dietary treatments, phytocompounds used, phytochemical concentrations, and environmental conditions, among other factors (Anaso, 2026). Therefore, phytogenic feed additives should not be considered as a universal remedy, and the observed effects should be evaluated based on the specific study conditions. Natural phytochemicals may also be harmful if they are used inappropriately or in high doses. For instance, excessive levels of tannins, alkaloids, saponins, and essential oils can have adverse effects on animal health and productivity. Therefore, the safety of phytochemicals should be evaluated based on their toxicity, physiological effects, and potential for causing adverse effects before they are used in animal feed.

Role of technology in improving phytogenic feed additives

Recent advances in biotechnology offer new opportunities for improving the production and application of phytogenic feed additives. Encapsulation technology can help stabilize phytochemicals and improve their bioavailability (Nantapo and Marume, 2025). Metabolomic studies can be used to identify biomarkers of phytobiotic efficacy, while metagenomic approaches can provide invaluable insights into the effects of various phytochemicals on the gut microbiota. In transcriptomics, gene expression profiling can help identify the molecular mechanisms by which phytochemicals affect animal health and production. With the application of these emerging technologies, researchers can reveal the physiological effects and molecular mechanisms of phytogenic feed additives. Wang et al. (2024) highlight the role of metagenomics, transcriptomics, proteomics, and network pharmacology in elucidating the multifaceted properties of phytogenic feed additives. A better understanding of phytogenic compounds and the development of effective phytobiotic formulations require an integrated multidisciplinary approach (Table 2).

Table 2: Integrated multidisciplinary approach for successful application

Strategy	Purpose
Microbiome analysis	Determines effects on gut microorganisms
Combination of compatible phytogenics	Exploits synergistic effects
Dose-response trials	Establishes effective dose
Safety assessment	Prevents toxic effects
Encapsulation	Improves stability and delivery
Standardized extraction	Improves consistency
Field validation	Confirms laboratory findings under practical conditions
Botanical identification	Ensures correct plant species
Phytochemical profiling	Identifies active compounds
Economic analysis	Determines commercial feasibility

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Integrated model for sustainable antibiotic reduction

Phytogenic additives should be part of a comprehensive strategy that promotes sustainable animal production while reducing the reliance on antibiotics. This strategy is based on the principle of One health that shows that prophylactics and adequate production practices can reduce antimicrobial usage in animal production (Khine, et al., 2025).

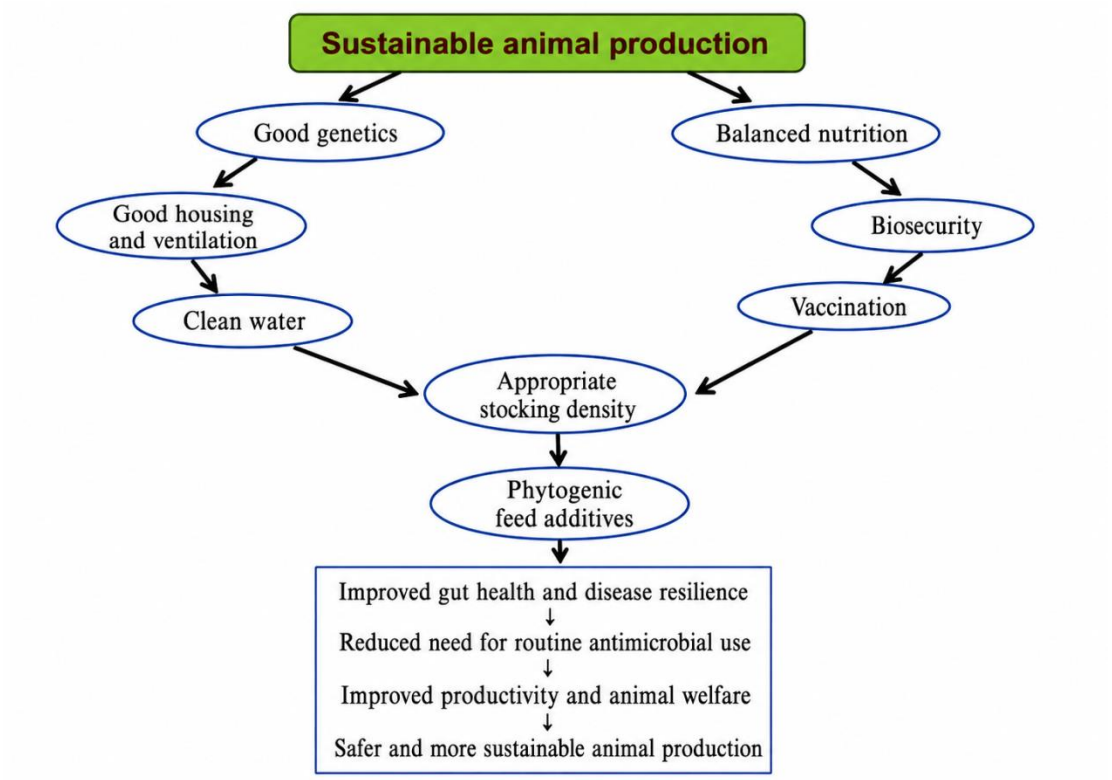


Figure 2: Integrated antibiotic-reduction strategy

Conclusion

Phytogenic feed additives are a promising component of sustainable animal production systems. They contain various phytochemicals that can modulate multiple physiological processes in animals, including antimicrobial, antioxidant, anti-inflammatory, immunomodulatory, and digestive activities, as well as intestinal microbiota regulation. Evidence from poultry, pigs, and ruminants indicates that phytogenic feed additives can improve several production parameters, although their effects are often inconsistent. For instance, while the meta-analysis shows that phytogenic feed additives can improve the growth performance of broilers; their ability to replace the antimicrobial effects of conventional antibiotics in the face of high disease challenges is limited. Therefore, phytogenic feed additives should be used as a component of a comprehensive strategy that improves animal production while reducing antimicrobial use. Effective application of phytogenic feed additives requires proper identification and characterization of phytochemicals, determination of appropriate dosing, and evaluation of their beneficial and detrimental effects. The standardization of phytogenic feed additives is critical for their successful application in animal production. In the context of African countries, which experience high feed costs and antimicrobial-resistance challenges while relying on imported feed additives, the development of standardized feed additives from local plants could be a valuable endeavor.

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"DARIJA 2.0": WHEN TIKTOK AND INSTAGRAM REINVENT THE LINGUISTIC COMMUNITY OF YOUNG MOROCCANS

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ABSTRACT

Over the past decade, darija — vernacular Moroccan Arabic long confined to orality — has undergone a profound transformation under the influence of digital platforms. On TikTok and Instagram, young Moroccans do not merely transcribe their spoken language: they reinvent it, mix it, and stage it in short, viral, and highly interactive formats. This paper examines the emergence of a "Darija 2.0," a hybrid digital variety drawing on dialectal Arabic, French, English, arabizi (Latin transliteration mixed with numerals), and a semiotic repertoire specific to social networks. By combining the sociolinguistics of digital media (Androutsopoulos), translanguaging (García & Wei), and communities of practice (Wenger) with foundational research on darija (Caubet, Miller, Ziamari), the article shows that this connected writing reflects not linguistic impoverishment but a creative plurilingual competence. It concludes by examining the issues this mutation raises: the relationship to linguistic norms, the legitimacy of written darija, generational tensions, and the redefinition of the boundaries between orality and writing.

Keywords: Darija 2.0; social media; TikTok & Instagram; translanguaging; linguistic community; Moroccan youth; arabizi; digital identity

1. Introduction

Morocco is a plurilingual and pluriglossic space where Modern Standard Arabic, Moroccan Arabic (darija), Amazigh in its regional varieties, French, Spanish in certain areas, and, increasingly, English coexist (Youssi, 1986; Caubet, 1993). Within this tangle of languages and statuses, darija occupies a paradoxical position: the mother tongue and vehicular language of the overwhelming majority of Moroccans, it has long remained confined to speech and excluded from "legitimate" written uses — administration, school, formal media — in favor of Standard Arabic and French (Caubet, 1993; Miller, 2013). This hierarchy began to shift in the 2000s with the emergence of new information and communication technologies: SMS, forums, instant messaging, and later social media (Caubet, 2005, cited in Boukaddour, 2026: 6).

Since the mid-2010s, a second shift has occurred with the spread of short-video platforms — TikTok, Instagram (stories, reels) — which have profoundly transformed the conditions under which youth discourse is produced and circulated. These platforms do not simply host spontaneous writing the way Facebook or MSN once did; they articulate image, sound, text, and real-time interaction (comments, live streams) within brief, highly viral formats. It is this mutation that the present paper proposes to call "Darija 2.0": a hybrid digital variety drawing on dialectal Arabic, French, English, arabizi (Latin transliteration mixed with numerals), and a semiotic repertoire specific to social networks — emojis, memes, hashtags, viral sounds.

This article has a twofold aim. On the one hand, it documents, drawing on the available sociolinguistic literature on the language practices of Moroccan youth and on an illustrative corpus built as an extension of earlier work (Belaouissi, 2017), the salient features of this connected writing. On the other hand, it discusses the theoretical scope of this "Darija 2.0" in light of three complementary notions: the sociolinguistics of digital media (Androutsopoulos, 2006), translanguaging (García & Wei, 2014), and

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communities of practice (Wenger, 1998). We argue that this writing does not reflect the simple linguistic impoverishment so often denounced in Moroccan public debate, but rather a creative plurilingual competence that plays on code-switching, humor, and the subversion of the graphic norms of Standard Arabic and French.

The article unfolds in five stages. We first set out the theoretical framework used (§2), then retrace the Moroccan context of darija's shift from orality to digital writing (§3). We then clarify our methodological approach and the limits of the corpus used (§4), before presenting the analysis of the scriptural practices and identity markers of Darija 2.0 (§5) and discussing the sociolinguistic issues this mutation raises (§6).

2. Theoretical and Conceptual Framework

2.1. The Sociolinguistics of Digital Media

Jannis Androutsopoulos (2006) showed that computer-mediated communication should not be treated as a mere degraded avatar of speech or standard writing, but as a domain of language practice in its own right, with its own emerging norms, genres, and styles. This perspective calls for moving away from a normative reading — one that would judge young people's digital writing against the yardstick of school orthography — toward a descriptive reading attentive to the social and identity functions of these practices. Androutsopoulos also emphasizes the situated nature of digital practices: each platform, through its technical architecture (message length, presence or absence of video, synchronous or asynchronous temporality), shapes specific language uses. TikTok and Instagram, with their short formats, their logic of algorithmic virality, and their multimodal writing (text overlaid on image or video, captions, hashtags, comments), thus constitute a terrain distinct from the one occupied a decade earlier by forums or Facebook.

2.2. Translanguaging and Communities of Practice

The notion of *translanguaging*, developed by Ofelia García and Li Wei (2014), designates the practices through which plurilingual speakers fluidly and without compartmentalization draw on their entire linguistic repertoire to construct meaning, without the boundaries between named "languages" (darija, French, English) constituting watertight partitions in their subjective experience. This approach departs from the more classical concept of code-switching, which presupposes alternation between distinct linguistic systems, in favor of the idea of a single, integrated repertoire that the speaker deploys strategically. Applied to the Moroccan context, this notion helps explain why young internet users do not necessarily perceive the shift from darija to French and then to English, within a single caption or comment, as a "mixing" of languages foreign to one another, but rather as the natural expression of a unified plurilingual repertoire, shaped by darija itself (Ziamari, 2008).

The notion of *community of practice*, coined by Etienne Wenger (1998), designates a group of people collectively engaged in a shared enterprise, who develop through their interactions a shared repertoire — vocabulary, ways of doing things, objects, narratives, but also tacit norms of participation. The communities of TikTok and Instagram users built around accounts popular with 15-25-year-old Moroccans display several features of a digital community of practice: mutual engagement (commenting, reacting, duplicating a format), a joint enterprise (producing and circulating content recognized as funny, authentic, or "stylish"), and a shared repertoire of linguistic and semiotic resources (set phrases, viral sounds, hashtags, neologisms) that functions as a marker of belonging. It is this shared, constantly evolving repertoire that we propose to call Darija 2.0.

2.3. Darija: Status, Vitality, and Writing

The foundational work of Dominique Caubet (1993, 2005, 2013) and Catherine Miller (2005, 2013) established that darija, long considered a "low" language in Morocco's diglossic hierarchy, has experienced an unprecedented functional expansion since the 2000s, driven notably by the cultural industries (radio, advertising, cinema, urban music) and by digital uses (Caubet & Miller, 2013; Leporcq, Miller & Tamer, 2013). The work of Karima Ziamari (2008) and of Ziamari and Barontini (2013, 2016) on code-switching and on the mediatization of youth speech — notably through the analysis of the television series "Bouzebbal" — shows that this expansion is accompanied by an aesthetic and identity-based valorization of hybrid darija, sometimes at the expense of French, which is associated

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with the affluent classes. This body of work, together with Belaouissi's (2017) research on the language practices of Moroccan youth on Facebook, forms the empirical foundation on which the present reflection builds, extending it to the TikTok and Instagram platforms.

3. From Vernacular Orality to Connected Writing: The Moroccan Context

Historically, darija has remained an essentially oral language, with writing falling within the domain of Standard Arabic (institutional, educational, religious) and, to a lesser extent, French (administration, elites, French-language press) (Youssi, 1986; Caubet, 1993). Darija's shift into writing has proceeded along two distinct paths. On the one hand, in the Arabic-language press and certain literary currents, a mixed style close to Middle Arabic developed, using darija to reinforce the expressiveness and social grounding of a text without, however, breaking with standard Arabic script (Belaouissi, 2017). On the other hand — and it is this second movement that concerns us most directly here — new information and communication technologies gave rise, from the 2000s onward, to a more spontaneous and informal form of writing: e-darija, an adaptation of the Latin script to the phonology of Moroccan Arabic, in which numerals (3, 7, 9, among others) stand in for Arabic phonemes with no Latin equivalent (Belaouissi, 2017, drawing on Caubet, 2012). This connected writing, owing to its spontaneous and loosely regulated character, is marked by considerable orthographic instability — an absence of stabilized norms that some linguists and advocates of codifying Moroccan Arabic regard as a shortcoming, but one that has not prevented darija from gaining considerable ground in the public sphere, particularly in the audiovisual media and on social networks (Belaouissi, 2017).

As early as 2005, Dominique Caubet observed that darija "managed [...] to take the path of the internet, in forums, emails, or chats; but also that of SMS written in 'e-darija,'" with millions of messages exchanged daily in Morocco in this variety (Caubet, 2005: 242, cited in Boukaddour, 2026). A decade later, the analysis of Facebook interactions conducted by Belaouissi (2017) confirmed this dynamic: on a network then used by 90% of Moroccans aged 13 to 34, greetings, terms of address, and set phrases in darija showed intense scriptural creativity — expressive vowel lengthening rendered through letter repetition (*sda3 raaaaaas*, *kolchi tayer l3ezzzzz*), borrowings from Algerian youth speech via France (*wesh*, *khu*/*kho*), alternation between darija, French, and English within a single utterance (*Merci, Bonne Année à tous et dima Peace and smo 3lih*), and the coining of gendered terms of address (*sat*/*sata*) carrying strong social connotations (Belaouissi, 2017, citing notably Caubet, 2013).

Mohamed Boukaddour (2026) further shows that this digital dynamic is part of a broader set of mutually reinforcing factors — Moroccan plurilingualism, urbanization, the rise of urban music (rap, hip-hop), mediatization — noting that new technologies offer young people "a space for expressing their discontent and frustration, in a language specific to them" (Boukaddour, 2026: 5), a space where activism combines with linguistic creativity (the February 20 Movement, boycott campaigns, online political humor). It is in this fertile ground that Darija 2.0, as displayed on TikTok and Instagram since the mid-2010s, takes root.

4. Corpus and Methodological Approach

Studying Darija 2.0 on TikTok and Instagram calls for the constitution of a corpus of posts, captions, comments, and video transcriptions drawn from accounts popular with 15-25-year-old Moroccans, comparable in principle to the Facebook corpus used by Belaouissi (2017), but broadened to encompass the multimodal dimension specific to these platforms (image, sound, overlaid text). The approach favored here is a qualitative analysis of scriptural practices and identity markers — nicknames, set phrases, neologisms, code play — in line with the work of Caubet and Miller on Moroccan youth speech and with conversation analysis as applied to digital writing (Androutsopoulos, 2006).

An important methodological limitation should be noted at this stage of the research: the systematic and ethical archiving of TikTok and Instagram content — platforms whose data-retention policies are more restrictive than those of the forums or Facebook at the time of the 2017 study — requires a gradual collection process, currently under way, and anonymized handling of the accounts observed. The examples used in the following section therefore rely, for the attested forms of code-switching, greetings, and neography, on the corpus already validated in the literature (Belaouissi, 2017; Caubet, 2013; Ziamari & Barontini, 2016), which we show continues, for the most part, to structure the practices

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observable on TikTok and Instagram, while flagging the extensions specific to these platforms (multimodality, viral sounds, hashtags, brevity constraints) that call for complementary data collection, currently under way, to establish their quantitative scope.

5. Darija 2.0 in Practice

5.1. Code-Mixing and Creative Translanguaging

The most salient feature of Darija 2.0 is the continuity — and intensification — of the translanguaging already observed on Facebook and forums (Belaouissi, 2017; Ziamari, 2008). A reel caption or a comment reply frequently strings together darija, French, English, and arabizi without any explicit marking of the language switch, as in the example noted by Caubet (2013: 78) and taken up by Belaouissi (2017): *"Merci, Bonne Année à tous et dima Peace and smo 3lih"* — where French (*Merci, Bonne Année à tous*), darija (*dima*, "always"), and English (*Peace*) follow one another, sealed by a set phrase specific to the speaking group (*smo 3lih*). This functioning illustrates precisely what García and Wei (2014) describe as translanguaging: the boundaries between named languages fade in favor of a single repertoire mobilized according to expressive purposes (reinforcing humor, marking belonging, stylizing the utterance) rather than according to a logic of translation or controlled alternation.

On TikTok and Instagram, this translanguaging finds a renewed field of expression in bilingual or trilingual hashtags, in captions that comment on a video filmed in darija with an English catchphrase, or in comments where users reply to a content creator by mixing all three languages within a single sentence, with heightened lexical creativity driven by the format's brevity constraints (character limits on captions, the pace of real-time comments during a livestream).

5.2. Neography and Arabizi: Between 3, 7, and 9

Writing darija in Latin characters — arabizi — remains a central marker of Darija 2.0, in direct continuity with the e-darija described by Caubet as early as the mid-2000s. The numerals 3 (for /ʕ/), 7 (for /ħ/), and 9 (for /q/) compensate for the absence of Latin equivalents to these Arabic phonemes (Belaouissi, 2017). To these graphic conventions are added expressive neographic devices already identified on Facebook — vowel lengthening through letter repetition to convey intensity or enthusiasm (*raaaaaaaaaaaaaasss*, *l3ezzzzz*) — which are found amplified on TikTok and Instagram, where they now combine with multimodal resources: emojis reinforcing or nuancing the written utterance, stickers and graphic filters, audio clips ("sounds") reused and repurposed from one video to the next, which constitute a form of viral quotation that is both linguistic and musical. This combination of writing, image, and sound configures what may be described as an expanded semiotic repertoire, in which meaning is no longer constructed solely through spelling but through the interplay of text, voice, music, and image — a configuration that the strictly textual framework of early research on electronic writing (SMS, forums) could not fully anticipate.

5.3. Identity Markers and Community of Practice

Belaouissi's (2017) analysis of terms of address and greetings on Facebook reveals a repertoire of identity markers that continues to structure the digital exchanges of Moroccan youth: the term of address *sat* ("dude," with a feminine form *sata* considered more vulgar), the Algerian borrowing *wesh* / *wach* ("what," which became a term of address and greeting), and *khu* / *kho* ("brother"), borrowed from Algiers slang via French youth speech and readily Moroccanized through the addition of the article (*al-kho*). These terms function as community shifters: their use signals membership in an age group and in a shared set of cultural references (urban music, humor, dress codes), in the sense in which Wenger (1998) defines the shared repertoire of a community of practice. On TikTok and Instagram, this repertoire continues to expand at an accelerated pace through the viral circulation of new expressions, often launched by a popular content creator and then picked up and reworked, within days, across thousands of comments and reels — a dynamic reminiscent of Ziamari and Barontini's (2016) observations on the rapid mediatization of Moroccan youth speech through fiction (the series *Bouzebbal*), but at a diffusion speed multiplied many times over by the algorithmic logic of short-form platforms.

Humor plays a central role in this dynamic: the subversion of proverbs, bilingual wordplay, deliberately exaggerated spelling mistakes to signal irony or complicity, self-deprecation about regional accents or

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French proficiency — all practices that, far from betraying ignorance of the norm, in fact presuppose its implicit mastery, since the game requires awareness of the very norm it transgresses (Androutsopoulos, 2006). In this sense, Darija 2.0 resembles what the literature on youth speech describes as a playful "anti-language," mobilized to mark generational distinction and group complicity rather than to communicate information in the strict sense (Boukaddour, 2026).

6. Discussion: Sociolinguistic Issues Raised by Darija 2.0

6.1. Relationship to Norms and the Legitimacy of Dialectal Writing

The question of linguistic norms remains central to the social reception of these practices. On the one hand, part of Morocco's intellectual and institutional establishment continues to regard the digital writing of darija as a sign of linguistic impoverishment, or even a threat to younger generations' mastery of Standard Arabic and French (Belaouissi, 2017). On the other hand, a discourse of valorization — carried by the cultural industries, advertising, and part of the sociolinguistic research community — emphasizes the creativity and vitality of this writing, echoing the observation made, in an altogether different French-speaking context, that "some praise the 'inventiveness' and 'creativity' of these new forms of expression, [while] others decry the spelling and grammatical laxity of younger generations" (Leporcq, Miller & Tamer, 2013, cited in Boukaddour, 2026: 7). Following Androutsopoulos (2006) and García and Wei (2014), our analysis leans toward the latter reading: the absence of a stabilized orthographic norm in arabizi does not signal incompetence, but rather the existence of a norm of a different order — endogenous, tacit, specific to each community of practice — one that allows for variation while excluding certain forms deemed too formal or too artificial by peers.

6.2. Generational Tensions and the Relationship to Identity

Darija 2.0 also crystallizes generational tensions. Adults, whether less connected or connected through different uses, sometimes perceive this writing as opaque, which heightens the sense, already documented by Belaouissi (2017), of a "digital divide" between youth and adults — here compounded by a linguistic divide. For young people themselves, by contrast, mastery of this hybrid repertoire functions as social capital within the peer group, on a par with mastery of dress or musical codes — and its absence can be experienced as a factor of exclusion from the digital network (Belaouissi, 2017). Darija 2.0 thus participates in a reshaping of identity boundaries: it asserts a strong Moroccan anchoring (through the use of darija rather than French or Standard Arabic) while simultaneously claiming a cosmopolitan openness (through borrowings from English and the circulation of globalized cultural references) — a configuration that aligns with Ziamari and Barontini's (2016) analyses of the valorization of darija vis-à-vis French, which is associated with the affluent classes.

6.3. Shifting Boundaries Between Orality and Writing

Finally, Darija 2.0 calls into question the classic distinction between orality and writing. Neographic devices (letter repetition for vowel lengthening, the use of arabizi, the insertion of sounds and emojis) give digital writing a texture close to spontaneous speech, to the point that some researchers describe this writing as "oralized" or as cyberlanguage — a linguistic and iconic sign at the crossroads of both codes, driven by the instantaneity and ephemeral character of online exchanges. On TikTok and Instagram, this hybridization is compounded by the audiovisual nature of the medium: video literally restores the speaker's voice and body, while overlaid text, captions, and comments function as a stylized, unregulated transcription of this staged orality. Darija 2.0 thus appears less as a new language than as a new articulation, specific to the digital medium, between the available linguistic resources (darija, French, English) and the semiotic resources of the medium (image, sound, interaction).

7. Conclusion

This paper has proposed to describe as "Darija 2.0" the hybrid digital variety deployed by young Moroccans on TikTok and Instagram, drawing on the theoretical framework of the sociolinguistics of digital media (Androutsopoulos, 2006), translanguaging (García & Wei, 2014), and communities of practice (Wenger, 1998), and placing it in dialogue with foundational research on youth speech and digital darija (Caubet, Miller, Ziamari, Belaouissi). The analysis shows that this connected writing extends and intensifies dynamics already at work on earlier platforms — Facebook, forums, SMS —

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while enriching them with an expanded semiotic repertoire specific to short, multimodal formats: code-mixing, arabizi neography, identity markers (terms of address, set phrases), humor, and the subversion of norms.

Far from the linguistic impoverishment so often denounced in Moroccan public debate, Darija 2.0 reflects a creative plurilingual competence, one that presupposes implicit mastery of the very norms it transgresses and that functions as a powerful marker of community and generational identity. In doing so, it contributes to a de facto legitimation of written darija, even though this legitimation does not translate into institutional codification of the variety — hence a persistent tension between social recognition and the absence of official status.

These conclusions call for further consolidation through the constitution of a systematic TikTok and Instagram corpus, currently under way, which will make it possible to quantify the scope and spread of these practices and to refine the typology of identity markers mobilized across accounts, regions, and age groups. A complementary avenue would be to compare Moroccan Darija 2.0 with the dynamics observed in other Maghreb countries and in Maghrebi diasporas in Europe (Belhaiba, 2014), in order to gauge the extent of national specificity versus transnational circulation in this new digital vernacular.

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PLASTİK ENJEKTÖR KAYNAKLI PİROLİZ SIVISININ DİZEL MOTOR PERFORMANS VE EMİSYONLARINA ETKİSİ

EFFECT OF PLASTIC SYRINGE-DERIVED PYROLYSIS LIQUID ON DIESEL ENGINE PERFORMANCE AND EMISSIONS

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ÖZET

Bu çalışmada, Türkiye'nin önemli yerleşim merkezlerinden biri olan Malatya ilinde sağlık hizmetleri sonucunda ortaya çıkan ve kullanım ömrünü tamamlayan plastik enjektörlerin enerji kaynağı olarak yeniden değerlendirilmesi araştırılmıştır. Sağlık kuruluşlarında yaygın olarak kullanılan tek kullanımlık enjektörlerin önemli bir kısmı plastik esaslı malzemelerden oluşmakta ve kullanım sonrasında atık haline gelmektedir. Bu atıkların doğrudan bertaraf edilmesi yerine, içerdikleri yüksek enerji potansiyelinden yararlanılması amacıyla piroliz yöntemiyle sıvı yakıta dönüştürülmesi hedeflenmiştir. Bu kapsamda, kullanılmış plastik enjektörler öncelikle metal ve plastik bileşenlerine ayrılmış, ardından plastik kısımlar daha küçük boyutlara getirilerek piroliz işlemine uygun hale getirilmiştir. Hazırlanan plastik malzeme, farklı sıcaklık koşullarında çalışan bir reaktörde 160–360 °C sıcaklık aralığında termal bozunmaya tabi tutulmuş ve bunun sonucunda atık plastik kaynaklı piroliz sıvısı (APPS) elde edilmiştir. Elde edilen piroliz sıvısının fiziksel ve yakıt özelliklerinin standart dizel yakıta yakın olduğu belirlenmiş ve motor yakıtı olarak kullanılabilirliği değerlendirilmiştir. Çalışmanın deneysel aşamasında, elde edilen piroliz sıvısı standart dizel yakıt ile hacimsel olarak %20 piroliz sıvısı ve %80 dizel içerecek şekilde harmanlanarak APPS20 olarak adlandırılan karışım yakıt hazırlanmıştır. Hazırlanan bu yakıt, tek silindirli bir dizel motorda farklı çalışma koşullarında kullanılarak motor performansı ve egzoz emisyonları üzerindeki etkileri deneysel olarak incelenmiştir. Elde edilen sonuçlar, saf dizel yakıtla gerçekleştirilen motor testleriyle karşılaştırılmıştır. Deneysel bulgular, piroliz sıvısının dizel yakıta belirli oranlarda ilave edilmesinin motorun tork ve güç değerlerinde bir miktar düşüşe, özgül yakıt tüketiminde ise artışa neden olduğunu göstermiştir. Emisyon sonuçları değerlendirildiğinde, karışım yakıt kullanımıyla CO, HC ve CO_2 emisyonlarında artış eğilimi gözlenirken, NOx emisyonlarında ise dizel yakıta kıyasla azalma meydana geldiği belirlenmiştir. Genel olarak çalışma, sağlık kuruluşlarında ortaya çıkan plastik enjektör atıklarının yalnızca bertaraf edilmesi gereken bir atık olarak değil, uygun termokimyasal dönüşüm yöntemleri kullanılarak alternatif bir enerji kaynağına dönüştürülebilecek potansiyel bir hammadde olarak değerlendirilebileceğini ortaya koymaktadır.

Anahtar Kelimeler: Atık plastik, enjektör, piroliz, Dizel motor, performans, egzoz emisyonu

ABSTRACT

This study investigates the reuse of disposable plastic syringes, generated in healthcare facilities in Malatya, a major urban center in Turkey, as an energy source. A significant portion of these disposable syringes, commonly used in healthcare, are made of plastic and become waste after use. Instead of directly disposing of this waste, the aim was to convert it into liquid fuel using pyrolysis, leveraging its high energy potential. In this context, used plastic syringes were first separated into their metal and plastic components, and then the plastic parts were reduced to smaller sizes to make them suitable for the pyrolysis process. The prepared plastic material was subjected to thermal decomposition in a reactor operating at different temperatures, ranging from 160 to 360 °C, resulting in the production of waste plastic pyrolysis liquid (WPPL). The physical and fuel properties of the resulting pyrolysis liquid were determined to be close to those of standard diesel fuel, and its usability as engine fuel was evaluated. In the experimental phase of the study, the obtained pyrolysis liquid was blended with standard diesel fuel

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to prepare a mixed fuel called APPS20, containing 20% pyrolysis liquid and 80% diesel by volume. This prepared fuel was used in a single-cylinder diesel engine under different operating conditions, and its effects on engine performance and exhaust emissions were experimentally investigated. The results obtained were compared with engine tests performed with pure diesel fuel. Experimental findings showed that adding pyrolysis liquid to diesel fuel in certain proportions caused a slight decrease in engine torque and power values, while increasing specific fuel consumption. When the emission results were evaluated, an increase in CO, HC, and CO_2 emissions was observed with the use of the mixed fuel, while a decrease in NOx emissions occurred compared to diesel fuel. Overall, the study demonstrates that plastic injector waste generated in healthcare facilities can be considered not only as waste to be disposed of, but also as a potential raw material that can be converted into an alternative energy source using appropriate thermochemical conversion methods.

Keywords: Waste plastic, injector, pyrolysis, Diesel engine, performance, exhaust emission

1. GİRİŞ

Nüfus artışı, sanayileşme ve tüketim alışkanlıklarının değişmesi, farklı niteliklerdeki atık miktarının giderek artmasına neden olmaktadır. Atıkların çevreye kontrolsüz biçimde bırakılması veya uygun olmayan yöntemlerle bertaraf edilmesi, çevresel kirlilik açısından önemli sorunlar oluşturabilmektedir. Bu nedenle atıkların yalnızca bertaraf edilmesi yerine, yeniden değerlendirilerek ekonomik ve enerji açısından kullanılabilir ürünlere dönüştürülmesi son yıllarda önemli bir araştırma alanı haline gelmiştir. Özellikle enerji ihtiyacının sürekli artması ve geleneksel fosil yakıtların kullanımına bağlı çevresel etkiler, atıkların alternatif enerji kaynağı olarak değerlendirilmesine yönelik çalışmaları hızlandırmıştır. Bu kapsamda bitkisel ve hayvansal kökenli atık yağlar, kullanılmış lastikler ve plastik atıklar, alternatif yakıt üretiminde değerlendirilen başlıca atık grupları arasında yer almaktadır.

Atıkların içten yanmalı motorlarda alternatif yakıt olarak değerlendirilmesine yönelik çalışmaların önemli bir bölümü bitkisel ve hayvansal kökenli yağlara odaklanmıştır. Özellikle atık yağların biyodizel üretiminde hammadde olarak kullanılması, hem atıkların değerlendirilmesi hem de dizel yakıta alternatif oluşturulması açısından dikkat çekmektedir. Lin ve Li (2009), deniz balıklarının atık kısımlarından elde edilen balık yağından biyodizel üretmiş ve elde edilen yakıtın özelliklerini incelemiştir. Aynı araştırmacılar, balık yağı biyodizelinin dizel motordaki performans ve egzoz emisyonlarına etkisini de değerlendirmiştir. Benzer şekilde Alptekin ve Canakci (2010), tavuk yağından biyodizel üretiminde ön işlem ve transesterifikasyon koşullarının optimizasyonunu araştırmıştır. Bu çalışmalar, atık yağların uygun kimyasal işlemler sonucunda dizel motorlarında kullanılabilecek alternatif yakıtlara dönüştürülebileceğini göstermektedir.

Atık yağlardan elde edilen biyodizellerin motor uygulamalarına yönelik araştırmalarda, yakıtın türü ve dizel yakıtla karışım oranının motor performansı ve egzoz emisyonları üzerinde etkili olduğu görülmektedir. Behçet vd. (2014), balık yağı ve yemeklik yağlardan üretilen yakıtların dizel motor performansı ve emisyonları üzerindeki etkilerini incelemiştir. Behçet (2015) ise farklı yağ kaynaklarından elde edilen biyodizellerin dizel motorlarındaki performans ve emisyon davranışlarını değerlendirmiştir. Benzer şekilde Behçet ve Oral (2014), biyodizel-dizel karışım yakıtların dizel motor performansı ve emisyonları üzerindeki etkilerini araştırmıştır. Bu çalışmalar, atık kaynaklı yakıtların motorlarda kullanılabilirliğinin yalnızca yakıtın üretilebilmesine değil, aynı zamanda yakıt özellikleri ile motor çalışma koşullarının uyumuna bağlı olduğunu ortaya koymaktadır.

Atık yağların yanı sıra, karbon ve hidrokarbon içeriği yüksek olan lastik ve plastik atıkların da termokimyasal yöntemlerle yakıta dönüştürülmesi mümkündür. Bu yöntemler içerisinde piroliz, atıkların oksijenin bulunmadığı veya sınırlı olduğu ortamda ısıl olarak parçalanmasına dayanan ve sıvı, gaz ve katı ürünlerin elde edilebildiği bir süreçtir. Özellikle plastik atıkların pirolizi sonucunda elde edilen sıvı ürünler, sahip oldukları hidrokarbon yapıları nedeniyle alternatif motor yakıtı olarak değerlendirilmektedir. Bu yaklaşım, bir yandan plastik atıkların yeniden değerlendirilmesine olanak sağlarken diğer yandan elde edilen sıvı ürünün enerji kaynağı olarak kullanılmasına imkân vermektedir.

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Atık lastiklerin piroliz yoluyla değerlendirilmesi de alternatif yakıt araştırmalarının önemli konularından biridir. İlkılıç ve Aydın (2011), atık araç lastiklerinden piroliz yöntemiyle yakıt üretmiş ve elde edilen yakıtı dizel motorda test etmiştir. Araştırmada, atık lastiklerden elde edilen yakıtın motor performansı ve egzoz emisyonları üzerindeki etkileri dizel yakıtla karşılaştırılmıştır. Bu çalışma, hidrokarbon esaslı katı atıkların piroliz yoluyla sıvı yakıta dönüştürülerek içten yanmalı motorlarda değerlendirilebileceğini göstermesi açısından önemlidir.

Plastik atıkların piroliz yoluyla yakıta dönüştürülmesi ise son yıllarda daha fazla araştırılan konulardan biri haline gelmiştir. Plastiklerden elde edilen piroliz yağlarının fiziksel ve kimyasal özellikleri, kullanılan plastik türüne ve üretim koşullarına bağlı olarak değişebilmekte ve bu durum motor performansı ile emisyon sonuçlarına doğrudan yansıyabilmektedir. Mani vd. (2011), atık plastik yağı ile dizel yakıt karışımlarının sıkıştırmalı ateşlemeli motorlardaki kullanımını incelemiş ve yakıt karışımlarının motor performansı ile emisyon özelliklerini değerlendirmiştir. Çalışmada atık plastik yağının dizel yakıtla birlikte kullanılmasının motor çalışma karakteristikleri üzerinde belirgin değişiklikler oluşturabildiği ortaya konulmuştur.

Kaimal ve Vijayabalan (2016), atık plastiklerden enerji yakıtı üretimini ve elde edilen ürünün dizel motorları için alternatif yakıt olarak kullanım potansiyelini araştırmıştır. Aynı araştırmacılar başka bir çalışmalarında, atık plastik yağının doğrudan püskürtmeli dizel motorda dietil eter (DEE) katkısıyla kullanımını incelemiş ve katkı maddesinin motor performansı ile emisyonlar üzerindeki etkisini değerlendirmiştir (Kaimal & Vijayabalan, 2016). Bu çalışmalar, plastik piroliz yağının motor yakıtı olarak değerlendirilmesinde yalnızca dizel yakıtla karıştırma oranının değil, yakıtın özelliklerini değiştirebilecek katkı maddelerinin de önemli olduğunu göstermektedir.

Plastik piroliz yağının dizel motorlarında kullanılmasına yönelik çalışmalar farklı yakıt karışım oranları ve farklı motor çalışma koşulları üzerinden de gerçekleştirilmiştir. Devaraj vd. (2015), atık plastik piroliz yağını dietil eter ile birlikte dizel motorunda kullanarak performans, emisyon ve yanma karakteristiklerini araştırmıştır. Elde edilen sonuçlar, plastik piroliz yağının oksijen içeren bir katkı maddesiyle birlikte kullanılmasının yanma süreci ve egzoz emisyonları üzerinde etkili olabileceğini göstermiştir. Singh vd. (2020) ise atık plastiklerin piroliziyle elde edilen yağın sıkıştırmalı ateşlemeli motorda kullanımını inceleyerek motor performansı ve yanma karakteristiklerini değerlendirmiştir. Bu çalışma, plastik atıkların pirolitik sıvı yakıta dönüştürülmesinin ardından içten yanmalı motorlarda değerlendirilebileceğine ilişkin deneysel literatürü güçlendirmiştir.

Plastik piroliz yağlarının motor yakıtı olarak kullanımında önemli konulardan biri, elde edilen yakıtın özelliklerinin standart dizel yakıt özelliklerinden farklı olmasıdır. Bu nedenle plastik piroliz yağının dizel yakıtla belirli oranlarda harmanlanması, motorun mevcut yakıt sistemiyle uyumunun artırılması açısından tercih edilen yöntemlerden biridir. Bununla birlikte karışım oranının artırılması her zaman performans ve emisyonlar açısından olumlu sonuç vermeyebilmektedir. Saha vd. (2021), plastik piroliz yağının sıkıştırmalı ateşlemeli motorlarda kullanımının performans ve emisyon karakteristikleri üzerindeki etkilerini kapsamlı biçimde değerlendirmiş ve plastik piroliz yağının motor yakıtı olarak kullanımında yakıt özellikleri ile motor çalışma koşullarının birlikte ele alınması gerektiğini ortaya koymuştur. Bu nedenle plastik piroliz yağlarının motor uygulamalarında değerlendirilmesinde uygun karışım oranının belirlenmesi önemli bir araştırma parametresidir.

Plastik piroliz yakıtlarının özelliklerinin iyileştirilmesi amacıyla oksijen içeren yakıt katkılarının kullanılması da literatürde önemli bir araştırma alanıdır. Oksijenli katkıların yanma bölgesinde oksijen miktarını artırarak yanma sürecini etkileyebilmesi, özellikle eksik yanma sonucu oluşan CO ve HC gibi emisyonların azaltılması açısından önem taşımaktadır. Damodharan vd. (2017), atık plastik yağı/dizel karışımlarına n-bütanol ilave ederek doğrudan püskürtmeli dizel motorda performans ve emisyon değişimlerini araştırmıştır. Damodharan vd. (2018) ise atık plastik yağının yüksek karbonlu alkollerle birlikte kullanımını incelemiş ve oksijenli katkıların plastik kökenli yakıtların daha temiz yanma karakteristiği elde edilmesindeki potansiyelini değerlendirmiştir. Bu sonuçlar, plastik piroliz yakıtlarının tek başına kullanılmasının yanında uygun oksijenli katkılarla birlikte değerlendirilmesinin de önemli olduğunu göstermektedir.

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Alkol katkıları içerisinde etanol, fiziksel ve kimyasal özellikleri nedeniyle alternatif motor yakıtlarıyla birlikte değerlendirilen önemli bir oksijenli katkıdır. Etanolün plastik piroliz yakıtı içeren karışımlara ilave edilmesiyle yakıtın yanma karakteristiklerinin ve egzoz emisyonlarının değiştirilmesi mümkün olabilmektedir. Padmanabhan vd. (2022), etanol içeren plastik yakıt karışımlarını inceleyerek yakıt bileşiminin çevresel etkiler ve motor performansı açısından değerlendirilmesini gerçekleştirmiştir. Aynı yıl yayımlanan başka bir çalışmalarında Padmanabhan vd. (2022), atık plastiklerden dizel yakıt elde edilmesi ve bu yakıtın etanol ile etoksi etil asetat katkılarıyla birlikte kullanılması üzerine çalışmıştır. Araştırmacılar, bu yaklaşımı atıkların enerjiye dönüştürülmesi ve döngüsel ekonomi açısından değerlendirmiştir. Böylece etanol katkısının plastik kaynaklı alternatif yakıtların motor uygulamalarındaki kullanımında araştırılması gereken önemli bir parametre olduğu görülmektedir.

Plastik piroliz yağlarının özelliklerinin belirlenmesi ve uygun motor yakıtının seçilmesi de araştırmaların önemli bir bölümünü oluşturmaktadır. Mangesh vd. (2020), farklı plastik türlerinden elde edilen piroliz yağlarının özelliklerini deneysel olarak inceleyerek bunlar arasından dizel motor yakıtına dönüştürülmeye uygun olan türün belirlenmesini amaçlamıştır. Bu yaklaşım, plastik türünün piroliz sonucunda elde edilen sıvı ürünün özellikleri üzerindeki önemini ortaya koymaktadır. Dolayısıyla atık plastiklerden elde edilen her piroliz sıvısının aynı motor performansını ve emisyon karakteristiğini vermesi beklenmemelidir. Yakıtın elde edildiği plastik türü, piroliz koşulları ve motor çalışma şartları birlikte değerlendirilmelidir.

Mevcut literatür genel olarak değerlendirildiğinde, atık plastiklerden elde edilen piroliz yağlarının dizel yakıtla karıştırılması, farklı oksijenli katkılarla özelliklerinin geliştirilmesi ve dizel motorlarındaki performans ve emisyon davranışlarının belirlenmesi üzerine çok sayıda çalışma gerçekleştirildiği görülmektedir. Bununla birlikte çalışmaların önemli bir bölümü genel plastik atıklara, belirli polimer türlerine veya endüstriyel plastik atıklarına odaklanmaktadır. Özellikle kullanım sonrasında atık haline gelen plastik enjektörlerin doğrudan piroliz hammaddesi olarak değerlendirilmesi ve elde edilen piroliz sıvısının dizel motorunda test edilmesi konusunda literatürde önemli bir araştırma boşluğu bulunmaktadır. Bu nedenle plastik enjektörlerin alternatif yakıt üretiminde hammadde olarak değerlendirilmesi, mevcut plastik piroliz çalışmalarının farklı ve özgün bir uygulama alanına taşınmasını sağlayabilir.

Bu çalışmanın temel amacı, kullanım sonrasında atık haline gelen plastik enjektörlerin piroliz yöntemiyle değerlendirilmesi ve elde edilen sıvı ürünün dizel motorlarında alternatif yakıt olarak kullanılabilirliğinin deneysel olarak araştırılmasıdır. Bu amaç doğrultusunda, plastik enjektörlerden piroliz yöntemiyle elde edilen sıvı yakıtın standart dizel yakıtla belirli oranlarda karıştırılması ve hazırlanan yakıtın tek silindirli bir dizel motorda test edilmesi planlanmıştır. Bunun yanında, oksijenli bir yakıt katkısı olarak etanolün karışıma ilave edilmesiyle motor performansı ve egzoz emisyonlarında meydana gelen değişimlerin belirlenmesi amaçlanmıştır. Böylece atık plastik enjektörlerin çevresel bir atık olmaktan çıkarılarak enerji taşıyıcısı niteliğinde bir ürüne dönüştürülmesi ve elde edilen ürünün gerçek motor çalışma şartlarında değerlendirilmesi hedeflenmiştir.

2. MATERYAL VE YÖNTEM

2.1. Materyal

Bu çalışmanın ana hammaddesini, kullanım sonrasında atık hâline gelen tek kullanımlık plastik enjektörler oluşturmaktadır. Çalışmada, kullanım ömrünü tamamlamış bu plastik atıkların yalnızca bertaraf edilmesi veya geleneksel geri dönüşüm yöntemleriyle değerlendirilmesi yerine, termokimyasal bir dönüşüm yöntemi olan piroliz yoluyla sıvı ürüne dönüştürülmesi ve elde edilen piroliz sıvısının dizel motorunda alternatif yakıt olarak kullanılabilirliğinin araştırılması amaçlanmıştır. Bu kapsamda deneysel çalışma; atık plastik enjektörlerin hazırlanması, piroliz yoluyla sıvı ürünün elde edilmesi, piroliz sıvısının yakıt özelliklerinin belirlenmesi, test yakıtının hazırlanması, motor deneylerinin gerçekleştirilmesi ve elde edilen verilerin değerlendirilmesi aşamalarından oluşmaktadır.

Plastikler; düşük yoğunlukları, yüksek mekanik dayanımları, kimyasal dirençleri, kolay şekillendirilebilmeleri ve nispeten düşük üretim maliyetleri gibi özellikleri nedeniyle günlük yaşamda ve endüstriyel uygulamalarda yaygın olarak kullanılmaktadır. Enjektörler de tek kullanımlık tıbbi ürünler içerisinde önemli miktarda plastik içeren malzemeler arasında yer almaktadır. Özellikle

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kullanım süresinin kısa olması ve kullanım sonrasında atık hâline gelmeleri, bu tür plastiklerin etkin bir atık yönetimi yaklaşımıyla değerlendirilmesini gerekli kılmaktadır.

Türkiye'de plastik üretim ve tüketim miktarlarının yüksek olması, kullanım ömrünü tamamlayan plastiklerin yeniden değerlendirilmesini önemli bir çevresel ve ekonomik konu hâline getirmektedir. PAGEV'in 2026 yılı ilk çeyrek verilerine göre Türkiye'de plastik mamul üretimi yaklaşık 2,4 milyon ton olarak gerçekleşmiş ve mevcut üretim eğiliminin yıllıklandırılmasıyla 2026 yılı toplam plastik mamul üretiminin yaklaşık 9,6 milyon ton seviyesinde gerçekleşeceği tahmin edilmiştir (PAGEV, 2026). Bu yüksek üretim hacmi, plastik atıkların çevresel etkilerinin azaltılması ve enerji geri kazanımı potansiyelinden yararlanılması açısından alternatif değerlendirme yöntemlerinin önemini ortaya koymaktadır.

Çalışmada kullanılan atık plastik enjektörler, kullanım sonrasında atık hâline gelen tek kullanımlık plastik enjektörlerden seçilmiştir. Numunelerin üzerinde bulunabilecek yabancı maddeler, etiketler, ambalaj kalıntıları ve piroliz işlemine dâhil edilmesi istenmeyen plastik dışı parçalar deney öncesinde uzaklaştırılmıştır. Böylece kullanılan hammaddenin mümkün olduğunca homojen bir plastik yapıya sahip olması ve deney sonuçlarını etkileyebilecek istenmeyen bileşenlerin sisteme girmesinin önlenmesi amaçlanmıştır.

Atık plastik enjektörlerin enerji amaçlı değerlendirilmesinde piroliz yöntemi tercih edilmiştir. Piroliz, organik yapıdaki malzemelerin oksijensiz veya oksijenin sınırlı olduğu ortamda ısı etkisiyle daha küçük moleküler yapılara ayrıştırılması esasına dayanan bir termokimyasal dönüşüm yöntemidir. Plastik atıkların pirolizi sonucunda sıvı, gaz ve katı ürünler elde edilebilmekte; elde edilen sıvı ürün, uygun yakıt özelliklerine sahip olması durumunda enerji üretimi ve motor yakıtı uygulamalarında değerlendirilebilmektedir. Önceki çalışmalarda farklı plastik atıklardan elde edilen piroliz yağlarının dizel yakıtla belirli oranlarda harmanlanarak sıkıştırmalı ateşlemeli motorlarda kullanılabileceği ve motor performansı ile egzoz emisyonları açısından değerlendirilebileceği bildirilmiştir (Mani et al., 2011; Devaraj et al., 2015; Saha et al., 2021).

Piroliz sonucunda elde edilen sıvı ürün toplama kabında biriktirilmiş ve uygun koşullarda muhafaza edilmiştir. Sıvı ürün içerisinde bulunabilecek katı partiküllerin ve çözünmeyen kalıntıların uzaklaştırılması amacıyla filtrasyon işlemi uygulanmıştır. Filtrasyon sonrasında elde edilen piroliz sıvısı, yakıt özelliklerinin belirlenmesi ve motor deneylerinde kullanılması amacıyla uygun koşullarda depolanmıştır.

Bu çalışmada ana hammaddeye ek olarak, motor deneylerinde ticari dizel yakıtı referans yakıt olarak kullanılmıştır. Atık plastik enjektörlerden elde edilen piroliz sıvısı ise dizel yakıt ile belirlenen oranda harmanlanarak alternatif test yakıtı olarak değerlendirilmiştir. Bu kapsamda hazırlanan APPS20 test yakıtı, hacimsel olarak %20 piroliz sıvısı ve %80 ticari dizel yakıtından oluşturulmuştur. Ticari dizel yakıtı ile APPS20 yakıtının aynı motor çalışma koşullarında test edilmesiyle piroliz sıvısının motor performansı ve egzoz emisyonları üzerindeki etkisinin karşılaştırmalı olarak belirlenmesi amaçlanmıştır.

Deneysel çalışmanın genel akışı; atık plastik enjektörlerin temini, temizlenmesi ve hazırlanması, piroliz işlemi, piroliz sıvısının elde edilmesi, sıvı ürünün hazırlanması ve yakıt özelliklerinin belirlenmesi, APPS20 test yakıtının hazırlanması, motor deneylerinin gerçekleştirilmesi ve deneysel verilerin değerlendirilmesi aşamalarını kapsamaktadır.

Deneysel sürecin başlangıcında atık plastik enjektörlerin temini ve piroliz sıvısına dönüştürülmesi ile ilgili temel aşamalar Şekil 1 de verilmiştir. çalışma şartlarına uygun hâle getirilmiş, ardından piroliz işlemine tabi tutulmuştur. Piroliz sırasında oluşan yoğuşabilir ürünler yoğuşturularak sıvı piroliz ürünü elde edilmiş, yoğuşmayan gazlar ve reaktörde kalan katı ürünler ise ayrı ürün grupları olarak değerlendirilmiştir.

Elde edilen piroliz sıvısı gerekli hazırlama işlemlerinden geçirildikten sonra temel yakıt özellikleri belirlenmiş ve motor deneylerinde kullanılmak üzere ticari dizel yakıtı ile hacimsel olarak %20 piroliz sıvısı ve %80 dizel oranında harmanlanarak APPS20 test yakıtı hazırlanmıştır. Hazırlanan test yakıtları dizel motorunda aynı deneysel koşullar altında test edilmiş; motor momenti, motor gücü, fren özgül

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yakıt tüketimi ve fren termik verimi gibi performans parametreleri ile CO, HC, CO2 ve NOx gibi egzoz emisyonları ölçülmüştür. Son aşamada elde edilen deneysel veriler referans dizel yakıtı ile karşılaştırılarak piroliz sıvısının alternatif motor yakıtı olarak kullanılabilirliği değerlendirilmiştir. Deneysel çalışmanın genel akış şeması Şekil 1'de verilmiş olup bu şema, atık plastik enjektörlerin hammadde olarak sisteme alınmasından başlayarak ön hazırlama, piroliz, piroliz sıvısının elde edilmesi ve hazırlanması, yakıt karışımının oluşturulması, motor performans ve emisyon deneylerinin gerçekleştirilmesi ve sonuçların değerlendirilmesine kadar uzanan deneysel metodolojiyi bütüncül olarak göstermektedir. Deneysel çalışmanın her bir aşamasına ilişkin uygulama koşulları ve ölçüm yöntemleri takip eden bölümlerde ayrıntılı olarak açıklanmıştır.



Şekil 1. Atık plastik enjektörlerin piroliz yoluyla alternatif motor yakıtına dönüştürülmesine ilişkin deneysel çalışma akış şeması

2.2. Atık plastik enjektörlerin piroliz sıvısına dönüştürülmesi ve özelliklerinin belirlenmesi

Deneysel çalışmanın bu aşamasında, kullanım sonrasında atık hâline gelen tek kullanımlık plastik enjektörler piroliz işleminde hammadde olarak kullanılmış ve elde edilen sıvı ürünün dizel motorunda alternatif yakıt olarak kullanılabilirliği araştırılmıştır. Piroliz işlemi öncesinde numunelerin deneysel sonuçları etkileyebilecek yabancı maddelerden arındırılması ve reaktöre uygun hâle getirilmesi işlemi Şekil 2 de verilen dönüşüm aşamaları takip edilerek gerçekleştirilmiştir. Atık plastik enjektörler öncelikle fiziksel olarak incelenmiş ve üzerlerinde bulunabilecek etiket, ambalaj kalıntıları, toz, kir ve diğer yabancı maddeler uzaklaştırılmıştır. Piroliz işlemine dâhil edilmesi istenmeyen plastik dışı parçalar da mümkün olduğunca ayrılmıştır. Temizleme işleminin ardından numuneler kurutularak bünyelerinde bulunabilecek nemin uzaklaştırılması sağlanmıştır. Kurutulan numuneler hassas terazi ile tartılarak başlangıç hammadde miktarı belirlenmiştir. Büyük boyutlu parçalar ise reaktöre daha uygun şekilde beslenebilmeleri amacıyla küçültülmüştür. Bu ön işlemlerle hammadde bileşiminin mümkün olduğunca homojen hâle getirilmesi ve piroliz işleminin kontrollü şekilde gerçekleştirilmesi amaçlanmıştır.

Hazırlanan plastik enjektörler piroliz reaktörüne beslenmiş ve sistem kontrollü olarak ısıtılmıştır. Piroliz işlemi, plastik malzemenin oksijenin bulunmadığı veya sınırlı olduğu ortamda yüksek sıcaklığın etkisiyle termal olarak parçalanması esasına dayanmaktadır. Isıtma sonucunda plastik yapıyı oluşturan büyük moleküller daha küçük moleküler yapılara ayrışmış ve uçucu ürünler meydana gelmiştir. Oluşan sıcak buharlar reaktörden alınarak yoğuşturma sistemine yönlendirilmiştir.

Yoğuşturucuda soğutulan buharların yoğunlaştırılması sonucunda sıvı piroliz ürünü elde edilmiştir. Yoğuşmayan gaz ürünler sistemin gaz çıkış hattından uzaklaştırılırken, reaktörde kalan katı ürün ayrıca toplanmıştır. Böylece piroliz işlemi sonucunda sıvı, gaz ve katı ürünlerin oluşması sağlanmıştır. İşlem sırasında reaktör sıcaklığı izlenmiş ve deney süresince sıcaklık değerleri kayıt altına alınmıştır. Piroliz

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sıcaklığı, işlem süresi, ısıtma hızı ve hammadde özelliklerinin elde edilen ürünlerin miktarı ve özellikleri üzerinde etkili olduğu daha önceki çalışmalarda bildirilmiştir (Kaimal & Vijayabalan, 2016; Mangesh et al., 2020).



Şekil 2. Atık plastik enjektörlerin piroliz sıvısına dönüşüm aşamaları

Piroliz sonucunda elde edilen sıvı ürün toplama kabında biriktirilmiş ve uygun koşullarda muhafaza edilmiştir. Sıvı ürün içerisinde bulunabilecek katı partiküllerin ve çözünmeyen kalıntıların uzaklaştırılması amacıyla filtrasyon işlemi uygulanmıştır. Filtrasyon sonrasında elde edilen piroliz sıvısı, yakıt özelliklerinin belirlenmesi ve motor deneylerinde kullanılması amacıyla uygun koşullarda depolanmıştır.

Piroliz sıvısının alternatif motor yakıtı olarak kullanılabilirliğinin değerlendirilmesi amacıyla temel yakıt özellikleri belirlenmiştir. Bu kapsamda yoğunluk, kinematik viskozite, alt ısıl değer ve parlama noktası gibi temel yakıt özellikleri incelenmiştir. Elde edilen değerler ticari dizel yakıtının özellikleriyle karşılaştırılarak piroliz sıvısının dizel motorlarında kullanım açısından uygunluğu değerlendirilmiştir. Plastik piroliz sıvılarının fiziksel ve kimyasal özelliklerinin kullanılan plastik türüne ve piroliz koşullarına bağlı olarak değişebildiği daha önceki çalışmalarda belirtilmiştir (Mani et al., 2011; Singh et al., 2020; Saha et al., 2021).

Motor deneylerinde referans yakıt olarak ticari dizel yakıtı kullanılmıştır. Alternatif test yakıtının hazırlanması amacıyla elde edilen piroliz sıvısı ticari dizel yakıtı ile hacimsel olarak %20 piroliz sıvısı ve %80 dizel oranında karıştırılmıştır. Hazırlanan bu test yakıtı APPS20 olarak kodlanmıştır. Karışımın homojenliğinin sağlanması amacıyla bileşenler mekanik olarak karıştırılmış ve motor deneylerinde kullanılmak üzere uygun koşullarda muhafaza edilmiştir.

Elde edilen piroliz sıvısının ve hazırlanan APPS20 yakıtının motor deneylerinde kullanılmasından önce yakıtların fiziksel özellikleri dikkate alınmış ve referans dizel yakıtı ile karşılaştırılmıştır. Böylece atık plastik enjektörlerden elde edilen piroliz sıvısının yalnızca üretim verimi açısından değil, aynı zamanda motor yakıtı olarak kullanılabilirliği açısından da değerlendirilmesi sağlanmıştır.

2.3 Motor Test Deneyleri

Motor test yakıtlarının analizi İnönü Üniversitesi Akaryakıt/Petrol Analiz Laboratuvarı'nda yapılmış olup analiz sonuçları tablo 1' de ve test motorunun teknik özellikleri de tablo 2'te verilmiştir. Motor test deneyleri Bitlis Eren Üniversitesi Teknik Bilimler Meslek Yüksekokulu otomotiv atölyesinde yapılmıştır. Motor deneyleri için tek silindirli, dört zamanlı, hız değişimli, hava soğutmalı ve direkt enjeksiyonlu ve 9 kW güce sahip Antor 3LD 510 marka bir dizel motor kullanılmıştır. Deney test düzeneğinin şematik görünümü Şekil 3.'de gösterilmiştir.

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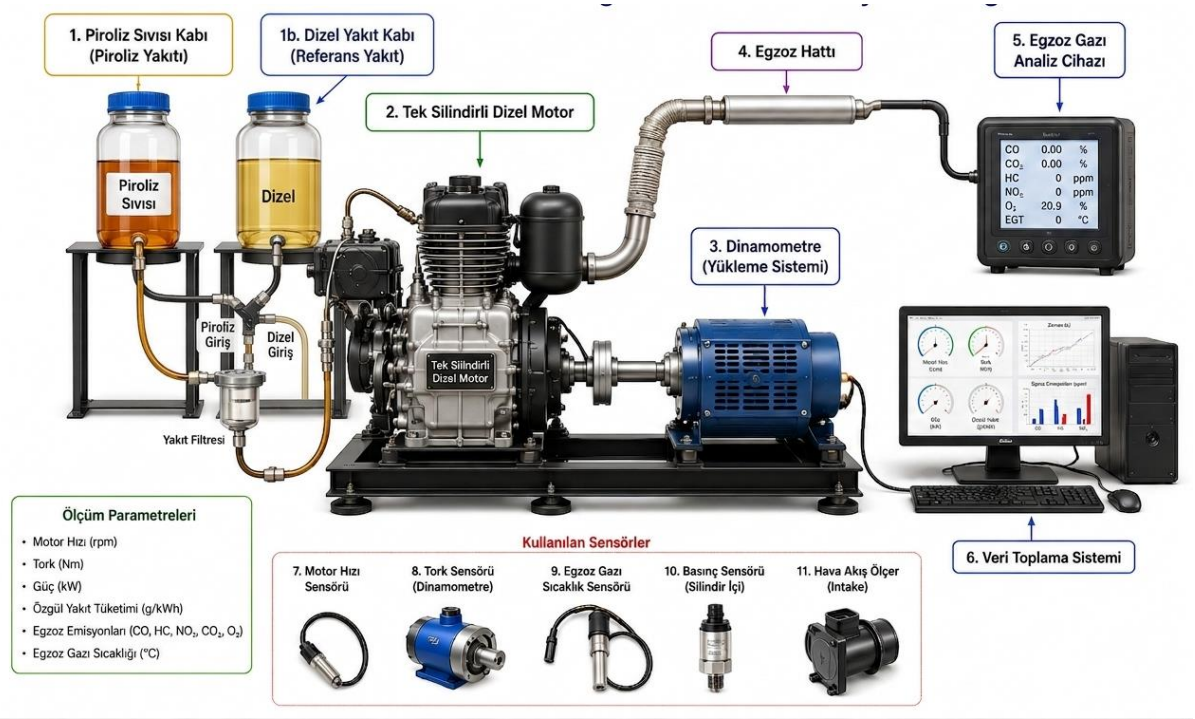
Tablo 1. Test yakıtlarının bazı özellikleri

Yakıt Özellikleri	APPS	Dizel Yakıt
Yoğunluk (kg/m3)	871,9	834,5
Viskozite 40 °C (mm2/sn)	2,78	2,45
Isıl Değer (kJ/kg)	41,8	45,142
Yanma (°C)	10	15
Görünüş	Koyu sarı, al	Sarı

Tablo 2. Test motorunun teknik özellikleri

Motor tipi	Antor 3LD510
Silindir sayısı	1
Silindir hacmi	510 cm3
Silindir çapı x strok	85 x 90 mm
Sıkıştırma oranı	17:1
Max. motor gücü	12 Hp
Max. motor devri	3200 dev/dk
Max. motor torku	3,5 kg.m 1800 dev/dk

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Şekil 3. Deney test düzeneğinin şematik görünümü

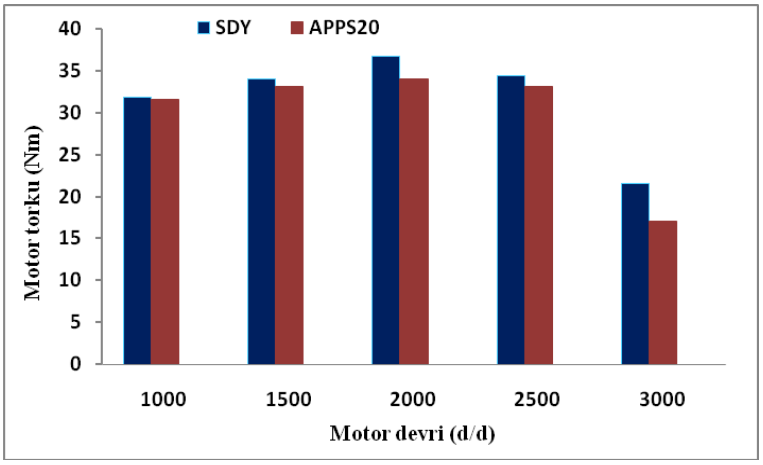
3. SONUÇLAR ve TARTIRŞMA

3.1. Motor Performansı

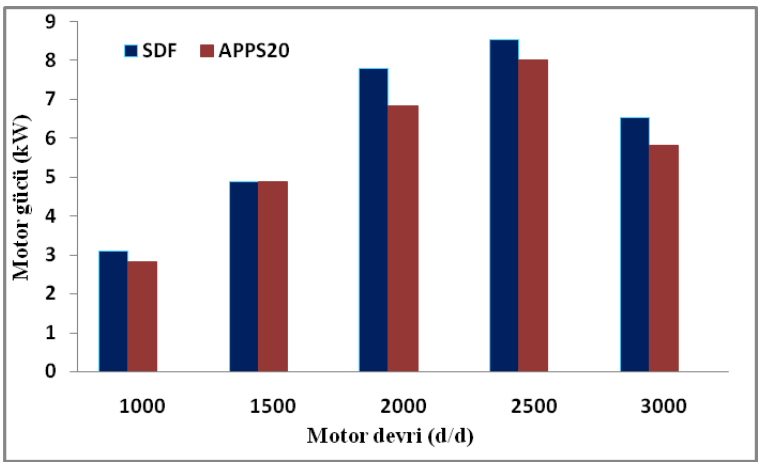
İçten yanmalı motorlarda motor performansı; yakıtın kimyasal enerjisinin ne kadar verimli bir şekilde mekanik işe dönüştürüldüğünü gösteren ve temel olarak motor torku, motor gücü ile özgül yakıt tüketimi parametreleriyle değerlendirilen dinamik bir süreçtir. Tork aracın çekiş gücünü, motor gücü birim zamanda üretilen işi, özgül yakıt tüketimi ise verimliliği temsil eder. Dizel yakıt ile atık plastik enjektör esaslı karışım yakıtın motor performans eğrileri Şekil 4, 5 ve 6'da verilmiştir. Bu grafikler genel olarak incelendiğinde; atık plastik enjektör türevli yakıtın alt ısıl değerinin dizele kıyasla hafif düşük olması tork ve güçte sınırlı bir azalmaya yol açarken, yüksek devirlerde iyileşen yanma verimi sayesinde özgül yakıt tüketiminde kayda değer avantajlar sağlandığı görülmektedir.

Motor torku, motorun ürettiği döndürme kuvvetinin bir ölçüsü olup aracın çekiş gücünü, ivmelenmesini ve yük taşıma kapasitesini doğrudan belirleyen temel bir performans parametresidir. Şekil 4'de, 1000 - 3000 d/d devir aralığında standart dizel yakıtı (SDY) ile plastik atık türevli yakıt karışımının (APPS20) motor torku üzerindeki etkileri incelenmektedir. Her iki yakıtta da motor devrinin artışıyla birlikte tork değerleri 2000 d/d seviyesine kadar yükselerek tepe noktasına ulaşmış, daha yüksek devirlerde ise dolgu veriminin düşmesi ve sürtünme kayıpları nedeniyle azalmıştır. APPS20 karışımı, plastik esaslı yakıtların alt ısıl değerinin konvansiyonel dizele göre bir miktar düşük olması sebebiyle SDY'ye kıyasla torkta çok hafif bir düşüş gösterse de genel tork eğrisini başarıyla takip etmekte ve motor performansını kabul edilebilir düzeyde tutmaktadır. Performanstaki bu ihmal edilebilir kayba karşılık, plastik atıkların termo-kimyasal yöntemlerle işlenerek motorda kullanılabilir bir yakıta dönüştürülmesi çevre ve şehir temizliği adına kritik bir kazançtır. Doğaya rastgele atılan veya depolama alanlarında biriken plastik polimerlerinin toplanması toprak ve su kirliliğini engellerken, bu atıkların yerel imkanlarla işlenip alternatif enerjiye dönüştürülmesi ithal ham petrole olan bağımlılığı azaltmaktadır. Sonuç olarak APPS20, motor torkunda kayda değer bir kayba yol açmadan sunduğu kabul edilebilir performans, yerli kaynak kullanımı ve küresel ekonomiye sağladığı katı atık bertarafı katkısıyla sürdürülebilir bir alternatif yakıt adayı olduğunu kanıtlamaktadır.

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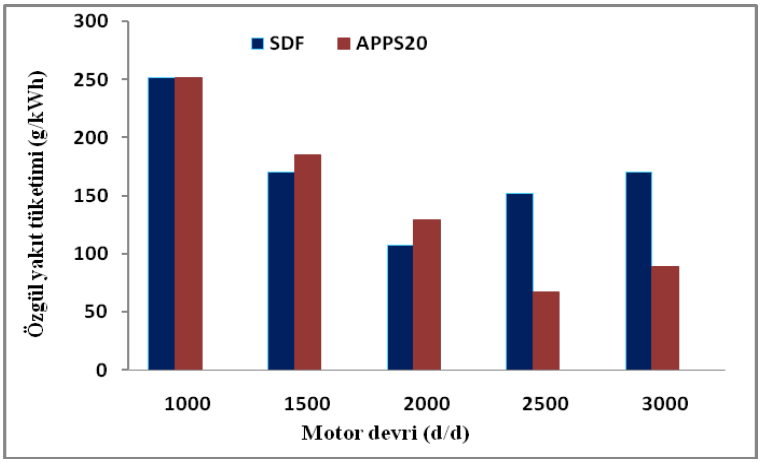
Şekil 4. Farklı devir sayılarındaki test yakıtlarının motor torku değişimleri



Şekil 5. Farklı devir sayılarındaki test yakıtlarının motor gücü değişimleri

Motor gücü, motorun birim zamanda ürettiği iş miktarını ifade eden ve aracın maksimum hızını, tırmanma kabiliyetini ile genel çalışma verimliliğini doğrudan belirleyen en temel performans parametresidir. Şekil 5 incelendiğinde, 1000 - 3000 d/d motor devri aralığında standart dizel yakıtı (SDY) ile plastik atıklardan elde edilen alternatif yakıt karışımının (APPS20) motor gücü değişimleri görülmektedir. Şekilde de açıkça takip edilebildiği üzere, 1000 d/d'de SDY ile yaklaşık 3,1 kW olan motor gücü APPS20 ile 2,8 kW seviyesindeyken, 1500 d/d'de her iki yakıtta da eşitlenerek yaklaşık 4,9 kW değerine ulaşmıştır. Motor gücü devrin artmasıyla yükselmeye devam etmiş; en yüksek güç değerlerine 2500 d/d'de ulaşılarak SDY için yaklaşık 8,5 kW, APPS20 için ise yaklaşık 8,0 kW olarak ölçülmüş, 3000 d/d'de ise sırasıyla 6,5 kW ve 5,8 kW seviyelerine gerilemiştir. APPS20'nin sunduğu motor gücünün SDY'ye göre bir miktar düşük kalması, atık plastik enjektör ten elde edilen yakıtın alt ısıl değerinin dizele kıyasla az da olsa düşük olmasından kaynaklanmaktadır. Ancak bu sınırlı güç farkına rağmen, doğada yüzyıllarca bozulmadan kalan katı plastik atıkların toplanıp dairesel ekonomiye kazandırılması çevre kirliliğini kaynağında önlemektedir. Yerel imkanlarla üretilen bu alternatif yakıt, ithal ham petrole olan bağımlılığı azaltıp enerji arz güvenliğini desteklerken, Şekil üzerindeki verilerin de kanıtladığı gibi motor gücünden büyük tavizler vermeden kabul edilebilir performans seviyelerinde sürdürülebilir bir enerji çözümü sunmaktadır.

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Şekil 6. Farklı devir sayılarında motor test yakıtlarının özgül yakıt tüketimi değişimleri

Özgül yakıt tüketimi (ÖYT), motorun birim güç (1 kW) elde etmek için saatte tükettiği yakıt kütlesini gösteren ve motorun termodinamik ile ekonomik verimliliğini doğrudan ortaya koyan kritik bir parametredir. Şekil 6incelendiğinde, farklı motor devirlerindeki standart dizel yakıtı ile plastik atıklardan elde edilen alternatif yakıt karışımının özgül yakıt tüketimindeki değişimler görülmektedir. Şekilde de belirgin şekilde takip edilebildiği üzere, en düşük motor devrinde her iki yakıt türü de oldukça yakın ve yüksek bir tüketim sergilemektedir. Düşük ve orta devir bantlarında APPS20'nin özgül yakıt tüketimi, alternatif yakıtın alt ısıl değerinin dizele kıyasla hafif düşük olmasına bağlı olarak SDY'nin bir miktar üzerinde kalmaktadır. Ancak daha yüksek çalışma devirlerine geçildiğinde eğilim tam tersine dönmekte; APPS20'nin özgül yakıt tüketimi SDY'ye göre belirgin bir şekilde gerileyerek yüksek devirlerde üstün bir tüketim avantajı ve verimlilik artışı sağlamaktadır. Yüksek devir bantlarında sağlanan bu yakıt tasarrufunun yanı sıra, çevreye zararlı katı plastik atıkların geri dönüştürülerek ekosistemden temizlenmesi dairesel ekonomiyi doğrudan desteklemektedir. Yerel olanaklarla elde edilen bu tür atık türevli sentetik yakıtlar, ithal petrole olan ihtiyacı azaltarak enerji bağımsızlığına katkı sağlamakta ve Şekil üzerindeki değişimlerin de kanıtladığı gibi özellikle yüksek devir koşullarında hem verimli hem de sürdürülebilir bir alternatif yakıt seçeneği sunmaktadır.

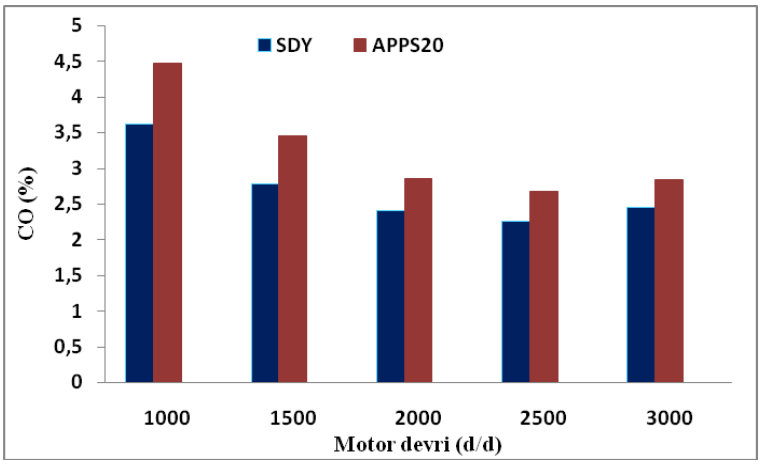
3.2. Egzoz Emisyonları

İçten yanmalı motorlarda CO (karbonmonoksit), yetersiz oksijen nedeniyle yakıtın tam yanamaması sonucu ortaya çıkan, kanda oksijen taşınmasını engelleyen renksiz ve son derece zehirli bir gazdır; HC (hidrokarbon) emisyonları ise yine silindir içinde eksik yanma sonucu dışarı atılan işlenmemiş yakıt moleküllerinden oluşarak hava kirliliğine ve solunum yolu rahatsızlıklarına yol açar. Öte yandan karbondioksit, CO ve HC'nin aksine yakıttaki karbonun tam yanmasıyla meydana gelen verimli yanmanın bir göstergesidir; toksik olmasa da küresel ısınmayı tetikleyen temel sera gazlarından biridir. NOx'lerde, yanma odasında ulaşılan aşırı yüksek sıcaklıklarda havadaki azot ve oksijenin reaksiyona girmesiyle şekillenerek asit yağmurlarına, kent içi sis oluşumuna ve ciddi çevresel tahribata neden olabilmektedir.

Şekil 7, standart dizel yakıt (SDY) ile hacimsel olarak %20 oranında atık plastik enjektör piroliz sıvısı içeren APPS20 (Atık plastik enjektör Piroliz Sıvısı) yakıtının farklı motor devirlerindeki CO emisyonlarını göstermektedir. APPS20 için CO emisyonu 1000 rpm'de yaklaşık %4,48 seviyesinde iken motor devrinin artırılmasıyla belirgin biçimde azalarak 1500 rpm'de %3,45, 2000 rpm'de %2,84 ve 2500 rpm'de %2,67 seviyesine ulaşmış, 3000 rpm'de ise küçük bir artışla %2,83 olarak gerçekleşmiştir. Buna göre APPS20 yakıtında 1000–2500 rpm aralığında CO emisyonunda yaklaşık %40 oranında azalma meydana gelmesi, motor devrinin artmasıyla yanma koşullarının iyileştiğini göstermektedir. APPS20'nin CO emisyonları tüm çalışma noktalarında SDY'den bir miktar yüksek olmakla birlikte, özellikle motor devrinin artmasıyla SDY'ye olan farkın azalması, yakıtın dizel motorlarında kullanım potansiyeli açısından olumlu değerlendirilebilir. Bunun yanında APPS20 kullanımı, yalnızca egzoz emisyonları açısından değil, atık plastik enjektör lerin çevreden uzaklaştırılması, kullanım ömrünü tamamlamış plastiklerin geri kazanılarak enerji taşıyan bir ürüne dönüştürülmesi ve fosil kökenli dizel

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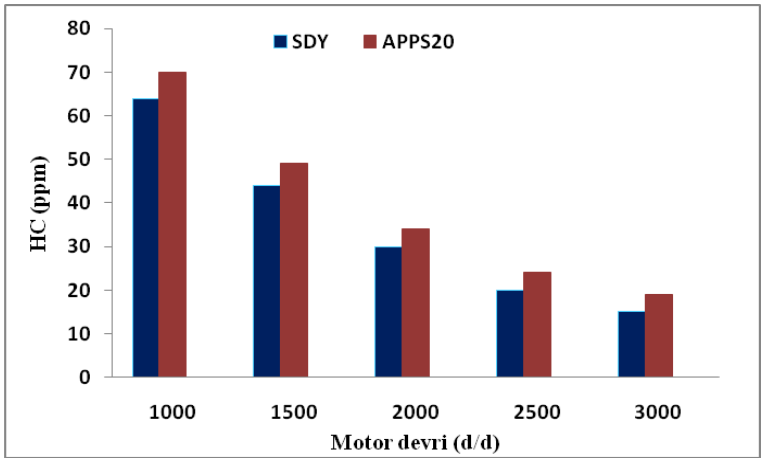
yakıtın %20 oranında alternatif bir yakıtla ikame edilmesi bakımından önemli avantajlar sunmaktadır. Özellikle piroliz için kullanılan plastik atıkların yerel kaynaklardan temin edilmesi durumunda, atıkların bölgesel olarak değerlendirilmesi ve elde edilen yakıtın yine yerel enerji üretiminde kullanılması mümkün olabileceğinden, APPS20 uygulaması atık yönetimi, kaynak geri kazanımı, alternatif yakıt kullanımı ve yerel enerji üretimini bir araya getiren sürdürülebilir bir yaklaşım olarak değerlendirilebilir.



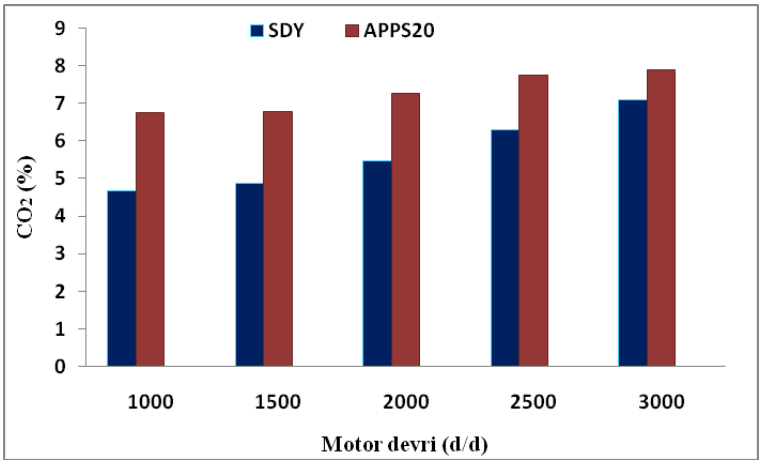
Şekil 7. Motor test yakıtlarının motor devrine bağlı olarak CO emisyonu değişimleri

Yanmamış hidrokarbon emisyon değerleri, silindir içerisindeki yakıtın tamamen yanmamasıyla oluşmakta olup ve ayrıca yakıtın uçuculuğu, viskozitesi ve içerdiği oksijenli bileşiklerle ilgilidir. Ayrca yanmamış hidrokarbonlar verimsiz yanmanın etkili bir ölçümü olarak da tanımlanabilir. Şekil 8 de farklı motor devirlerinde (1000 - 3000 d/d) standart dizel yakıtı (SDY) ile plastik atıklardan elde edilen alternatif yakıt karışımının (APPS20) Hidrokarbon (HC) emisyon değerleri karşılaştırılmaktadır. Motor devrinin artmasıyla birlikte silindir içi sıcaklık ve karışım homojenliğinin gelişmesine bağlı olarak yanma verimi artmakta, bu durum her iki yakıtta da HC emisyonlarının kademeli bir şekilde düşmesini sağlamaktadır. APPS20 karışımı, standart dizel yakıtına kıyasla hafif düzeyde daha yüksek HC emisyonu sergilese de aradaki fark kabul edilebilir sınırlar içerisindedir. Emisyon profilindeki bu nispi artışa karşın, plastik atıkların piroliz veya gazlaştırma gibi termo-kimyasal yöntemlerle dairesel ekonomiye kazandırılması çevre, enerji ve ekonomi boyutlarında çok yönlü avantajlar sunmaktadır. Doğada uzun süre bozunmadan kalan plastik kütlelerinin yakıta dönüştürülmesi depolama alanlarındaki kirliliği kaynağında engellerken, konvansiyonel fosil yakıtlara olan bağımlılığı azaltan yerel ve sürdürülebilir bir alternatif enerji kaynağı yaratmaktadır. Sonuç olarak, yerel imkanlarla toplanan atıkların enerji portföyüne dahil edilmesi hem dışa bağımlılığı azaltma hem de entegre atık yönetimi sağlama açısından kritik bir potansiyel taşımakta ve APPS20 gibi atık türevli yakıtların içten yanmalı motorlarda kullanılabilirliğini bilimsel olarak desteklemektedir.

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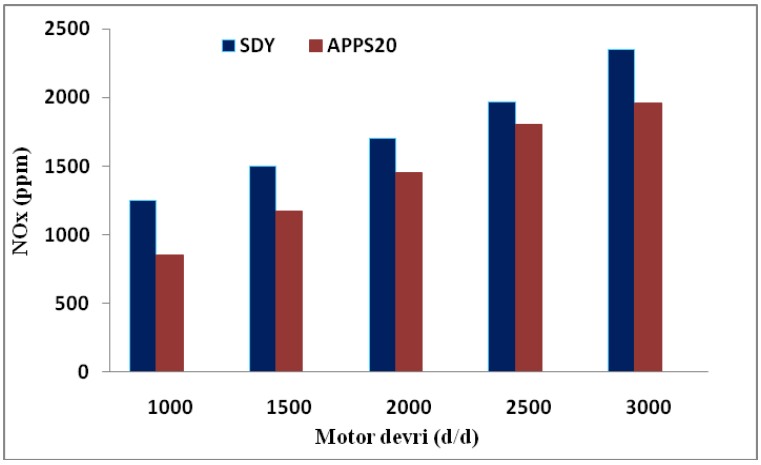
Şekil 8. Farklı devir sayılarındaki test yakıtlarının HC emisyonu değişimleri



Şekil 9. Farklı devir sayılarındaki test yakıtlarının CO2 emisyonu değişimleri

Şekil 9'da, farklı motor devirleri aralığında standart dizel yakıtı (SDY) ve plastik atık türevli alternatif yakıt karışımının (APPS20) Karbondioksit CO2 emisyon oranları karşılaştırılmaktadır. Motor devri arttıkça artan silindir içi sıcaklık, türbülans ve birim zamandaki yakıt tüketimi nedeniyle yanma reaksiyonu tamamlanma eğilimi göstermekte, bu durum her iki yakıtta da CO2 yüzdesini artırmaktadır. APPS20 karışımının SDY'ye kıyasla daha yüksek CO2 değerleri sergilemesi, plastiğin yapısındaki karbon bağlarının ve yakıtın yüksek sıcaklıktaki yanma karakteristiğinin tam yanmayı teşvik ettiğini göstermektedir; zira yüksek CO2 emisyonu, eksik yanma ürünü olan karbonmonoksitin CO2 aksine yakıtın enerjisini daha verimli açığa çıkardığının bilimsel bir göstergesidir. Doğada bozunmayan plastik polimerlerinin termo-kimyasal dönüşümle yakıt portföyüne kazandırılması, çevre kirliliğini kaynağında ortadan kaldırırken döngüsel ekonomi ilkesine hizmet etmektedir. Arazide veya depolama alanlarında biriken atıkların yerel imkanlarla toplanarak enerjiye dönüştürülmesi, fosil kökenli ham petrol bağımlılığını azaltmakta ve yerli yakıt arz güvenliğini desteklemektedir. Sonuç olarak APPS20, doğrudan bir sera gazı emisyon artışı gösterse de tam yanma verimliliği, katı atık yönetimine sunduğu katkı ve yerel alternatif yakıt potansiyeli bakımından sürdürülebilir bir enerji çözümü olarak öne çıkmaktadır.

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Şekil 10. Farklı devir sayılarındaki test yakıtlarının CO2 emisyonu değişimleri

Şekil 10'da, 1000 ile 3000 d/d arasında değişen motor devirlerinde standart dizel yakıtı (SDY) ile plastik atıklardan elde edilen alternatif yakıt karışımının (APPS20) Azot Oksit NOx emisyon değerleri karşılaştırılmaktadır. Motor devri yükseldikçe artan silindir içi sıcaklıklara bağlı olarak termal NOx oluşum mekanizması tetiklenmekte ve her iki yakıt türünde de NOx salınımı belirgin bir artış göstermektedir. Bir önceki grafikte görülen NOx artışının aksine bu grafikte APPS20 karışımı, tüm devir bantlarında standart dizel yakıtına kıyasla hissedilir derecede daha düşük NOx emisyonu sergilemektedir. Bu durum, plastik türevli yakıtın silindir içi tepe sıcaklıklarını bir miktar baskıladığını veya yanma sürecini NOx oluşumunu sınırlayacak şekilde modüle ettiğini gösteren kritik bir ekolojik avantajdır. Çevresel açıdan bakıldığında, asit yağmurlarına ve hava kirliliğine doğrudan sebep olan NOx emisyonlarının azalması, plastik atıkların yakıta dönüştürülmesini sadece bir katı atık bertaraf yöntemi olmaktan çıkarıp emisyon kalitesini iyileştiren teknik bir çözüme dönüştürmektedir. Doğada biriken plastik kütlelerinin yerel imkanlarla toplanarak bu şekilde yüksek katma değerli bir enerji kaynağına çevrilmesi, hem şehirlerdeki plastik kirliliğini engellemekte hem de ithal fosil yakıtlara olan bağımlılığı azaltmaktadır. Sonuç olarak APPS20, emisyon profilinde sunduğu bu somut NOx düşüşü, küresel ekonomiye sağladığı entegrasyon ve yerli alternatif yakıt potansiyeli sayesinde çevre dostu ve sürdürülebilir bir enerji seçeneği olarak öne çıkmaktadır.

SONUÇ

Tek silindirli, dört zamanlı bir dizel motorda, plastik atık enjektör esaslı yakıtın %20 oranında dizelle harmanlanmasıyla elde edilen APPS20 karışımı ve referans yakıt olan standart dizel (SDY) ile gerçekleştirilen performans ve emisyon testlerinden elde edilen temel bulgular aşağıda sıralanmıştır:

1. Alternatif yakıtın alt ısıl değerinin düşüklüğü nedeniyle APPS20'nin motor torku tüm devirlerde SDY'ye göre biraz düşük çıkmış, her iki yakıtta da 2000 d/d'de tepe noktasına ulaşmıştır.

2. APPS20'nin motor gücü SDY'nin biraz gerisinde kalmış; maksimum güç 2500 d/d'de SDY için ~8,5 kW, APPS20 için ~8,0 kW olarak ölçülmüştür.

3. Düşük ve orta devirlerde yüksek viskozite nedeniyle APPS20'nin ÖYT'i daha yüksek iken, yüksek devirlerde (2500-3000 d/d) artan yanma verimiyle SDY'nin belirgin şekilde altına inmiştir.

4. Sınırlı oksijenli bileşikler ve viskozite kaynaklı damlacık yapısı yüzünden APPS20'nin CO emisyonlarında SDY'ye göre hafif bir artış gözlenmiştir.

5. Yüksek viskozite ve düşük oksijen eksik yanmayı tetiklediği için APPS20'nin HC değerleri SDY'den yüksek çıkmış, ancak devir arttıkça her iki yakıtta da azalmıştır.

6. Yüksek sıcaklıklarda karbon bağlarının tam yanmaya dönüşmesiyle APPS20'nin CO2 değerleri tüm devirlerde SDY'den yüksek gerçekleşmiştir.

7. APPS20 karışım yakıtı tepe yanma sıcaklıklarını dengelediği için tüm devirlerde SDY'ye kıyasla belirgin derecede daha düşük NOx emisyonu sergilemiştir.

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Netice olarak, APPS20 karışım yakıtı tork, güç, CO ve HC'de küçük kayıplara yol açsa da yüksek devirdeki yakıt tasarrufu, düşük NOx emisyonu, çevre temizliği, yerel kaynak kullanımı ve fosil yakıta alternatif olması bakımından sürdürülebilir bir seçenektir.

TEŞEKKÜR

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BİNALARDA ENERJİ VERİMLİLİĞİNİN SAĞLANMASINDA YAPI MALZEMELERİNİN ROLÜ

THE ROLE OF BUILDING MATERIALS IN ACHIEVING ENERGY EFFICIENCY IN BUILDINGS

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ÖZET

Binalarda enerji tüketiminin azaltılması, enerji maliyetlerinin düşürülmesi, sera gazı emisyonlarının sınırlandırılması ve sürdürülebilir yapılaşmanın sağlanması açısından enerji verimli yapı malzemelerinin kullanımı giderek önem kazanmaktadır. Yapıların enerji performansında özellikle dış cephe, çatı, döşeme ve pencere sistemlerinin ısıl özellikleri belirleyici olmakta; uygun malzeme seçimi ile ısıtma ve soğutma yükleri azaltılabilmektedir. Bu çalışmada, enerji tasarrufu sağlayan yapı malzemeleri literatür temelinde incelenmiş; geleneksel ısı yalıtım malzemeleri, yüksek performanslı aerogel(gözenekli) yalıtım malzemeleri, biyobazlı yalıtım malzemeleri, faz değiştiren malzemeler (FDM), düşük yayınınlı camlar, elektrokromik akıllı camlar ve bina entegre güneş enerji sistemleri değerlendirilmiştir. Ayrıca malzemelerin yalnızca kullanım aşamasındaki enerji tasarrufu değil, üretim, taşıma, bakım ve kullanım ömrü sonundaki çevresel etkilerinin de dikkate alınması gerektiği ortaya konulmuştur. Literatür değerlendirmesi sonucunda, yüksek performanslı yapı malzemelerinin tek başına değerlendirilmesinden ziyade bina kabuğu, iklim koşulları, yönlenme, havalandırma, ısıtma-soğutma sistemleri ve yenilenebilir enerji teknolojileri ile birlikte ele alınmasının daha doğru olduğu belirlenmiştir. Türkiye açısından ise 2024 revizyonlu TS 825 standardının 2025 yılında zorunlu uygulamaya alınması, yapıların ısıtma ve soğutma enerji ihtiyaçlarının azaltılmasına yönelik malzeme seçiminin önemini daha da artırmıştır. Çalışma, enerji tasarrufu yapı malzemelerinin seçiminde ısıl performans, dayanıklılık, ekonomik geri ödeme, gömülü enerji, yaşam döngüsü karbon emisyonları ve geri dönüştürülebilirlik kriterlerinin birlikte değerlendirilmesi gerektiğini ortaya koymaktadır.

Anahtar Kelimeler: Enerji verimliliği, yapı malzemeleri, ısı yalıtımı, faz değiştiren malzemeler, akıllı camlar,

ABSTRACT

The use of energy-efficient building materials is becoming increasingly important in terms of reducing energy consumption in buildings, lowering energy costs, limiting greenhouse gas emissions, and ensuring sustainable construction. The thermal properties of the exterior facade, roof, floor, and window systems are particularly decisive in the energy performance of buildings; heating and cooling loads can be reduced with appropriate material selection. In this study, energy-saving building materials were examined based on the literature; traditional thermal insulation materials, high-performance aerogel-based materials, bio-based insulation materials, phase change materials (PCM), low-emission glass, electrochromic smart glass, and building-integrated photovoltaic (BIPV) systems were evaluated. Furthermore, it was revealed that not only the energy savings during the use phase of the materials but also their environmental impacts during production, transportation, maintenance, and at the end of their service life should be considered. As a result of the literature review, it was determined that it is more accurate to consider high-performance building materials together with the building envelope, climate conditions, orientation, ventilation, heating-cooling systems, and renewable energy technologies, rather than evaluating them in isolation. For Turkey, the mandatory implementation of the TS 825 standard, revised in 2024, in 2025 has further increased the importance of material selection aimed at reducing the heating and cooling energy needs of buildings. This study reveals that thermal performance,

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durability, economic payback, embodied energy, life cycle carbon emissions, and recyclability criteria should be evaluated together in the selection of energy-saving building materials.

Keywords: Energy efficiency, building materials, thermal insulation, phase change materials, smart glass

GİRİŞ

Binalar, küresel ölçekte enerji tüketiminin ve sera gazı emisyonlarının önemli bir bölümünden sorumlu olan temel sektörlerden biridir. Dünya nüfusunun artması, hızlı kentleşme, yaşam standartlarının yükselmesi, bina kullanım sürelerinin uzaması ve özellikle sıcak iklim bölgelerinde soğutma talebinin giderek artması, bina sektöründeki enerji tüketiminin gelecekte de önemli bir sorun olmaya devam edeceğini göstermektedir. Birleşmiş Milletler Çevre Programı (UNEP) ve Global Alliance for Buildings and Construction (GlobalABC) tarafından yayımlanan güncel değerlendirmelerde, bina ve inşaat sektörünün küresel enerji tüketimi, sera gazı emisyonları ve doğal kaynak kullanımı açısından önemli bir paya sahip olduğu belirtilmektedir (United Nations Environment Programme [UNEP] & Global Alliance for Buildings and Construction [GlobalABC], 2026). Bu nedenle enerji tüketiminin azaltılması ve karbon emisyonlarının sınırlandırılması açısından binaların enerji performansının iyileştirilmesi, küresel sürdürülebilirlik hedeflerinin önemli bileşenlerinden biri haline gelmiştir.

Binalarda enerji tüketiminin önemli bir kısmı ısıtma, soğutma, havalandırma, sıcak su hazırlama ve aydınlatma sistemlerinden kaynaklanmaktadır. Bununla birlikte, söz konusu enerji ihtiyacının oluşmasında bina kabuğunun özellikleri de belirleyici bir rol oynamaktadır. Dış duvarlar, çatılar, döşemeler, pencereler ve kapılar; iç ortam ile dış çevre arasında gerçekleşen ısı, ışınım ve hava hareketlerini kontrol eden temel yapı elemanlarıdır. Bina kabuğunun yeterli düzeyde yalıtılmaması veya iklim koşullarına uygun olmayan yapı malzemelerinin kullanılması durumunda kış döneminde önemli miktarda ısı kaybı, yaz döneminde ise yüksek miktarda ısı kazancı meydana gelebilmektedir. Bu durum, iç ortam koşullarının istenilen düzeyde tutulabilmesi için daha fazla ısıtma ve soğutma enerjisi kullanılmasına neden olmaktadır (International Energy Agency [IEA], 2024).

Enerji verimliliği açısından yapıların tasarımında yalnızca aktif mekanik sistemlerin verimliliğinin artırılması yeterli değildir. Enerji ihtiyacının öncelikle pasif tasarım ve uygun yapı malzemeleri aracılığıyla azaltılması, daha sonra gerekli enerjinin yüksek verimli aktif sistemlerle karşılanması daha bütüncül bir yaklaşım oluşturmaktadır. IEA (2024), bina enerji performansının iyileştirilmesinde enerji verimliliği standartlarının güçlendirilmesi, mevcut bina stokunun enerji açısından yenilenmesi ve bina kabuğunun performansının artırılmasını temel stratejiler arasında değerlendirmektedir. Bu bağlamda yapı malzemelerinin seçimi, yalnızca mimari veya statik bir karar olmaktan çıkmakta; binanın yaşam döngüsü boyunca enerji tüketimini etkileyen temel tasarım parametrelerinden biri haline gelmektedir.

Yapı malzemelerinin enerji performansı üzerinde etkili olan en önemli özelliklerden biri ısıl iletkenlik katsayısıdır. Isıl iletkenlik katsayısı düşük olan malzemeler, birim kalınlık başına daha yüksek ısıl direnç sağlayarak yapı elemanlarından gerçekleşen ısı transferinin azaltılmasına katkıda bulunmaktadır. Bununla birlikte gerçek bina performansı yalnızca malzemenin ısıl iletkenlik katsayısına bağlı değildir. Malzemenin kalınlığı, yoğunluğu, nem içeriği, sıcaklık bağımlılığı, uygulama koşulları, yapı elemanlarının birleşim detayları ve ısı köprüleri de toplam enerji performansını önemli ölçüde etkileyebilmektedir. Bu nedenle enerji tasarrufu sağlayan yapı malzemelerinin değerlendirilmesinde malzemenin tek başına laboratuvar koşullarındaki performansından ziyade, yapı kabuğu içerisindeki gerçek çalışma koşullarının dikkate alınması gerekmektedir (International Organization for Standardization [ISO], 2017).

Geleneksel ısı yalıtım malzemelerinin yanı sıra son yıllarda yüksek performanslı ve işlevsel özelliklere sahip yeni nesil yapı malzemeleri de geliştirilmiştir. Aerogel esaslı yalıtım malzemeleri, çok düşük ısıl iletkenlik değerleri nedeniyle düşük kalınlıkla yüksek ısıl direnç elde edilmesine olanak sağlayabilmektedir (Baetens et al., 2011). Faz değiştiren malzemeler (FDM) ise klasik yalıtım malzemelerinden farklı olarak belirli bir sıcaklık aralığında faz değiştirerek ısı enerjisini gizli ısı biçiminde depolamakta ve daha sonra çevre şartlarına bağlı olarak bu enerjiyi serbest bırakabilmektedir

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(Kalnæs & Jelle, 2015; Kurdi et al., 2021). Böylece bina kabuğunun yalnızca ısı transferine karşı direnç göstermesi değil, aynı zamanda termal enerji depolaması mümkün hale gelmektedir.

Bunun yanında, sürdürülebilir yapılaşma yaklaşımının gelişmesiyle birlikte biyobazlı yapı malzemelerine yönelik araştırmalar da hız kazanmıştır. Ahşap lifi, selüloz, kenevir, mantar, saman ve çeşitli tarımsal atıklar gibi yenilenebilir kaynaklardan üretilebilen biyobazlı malzemeler, uygun tasarım koşullarında ısı yalıtımı sağlamalarının yanında düşük gömülü karbon potansiyelleri nedeniyle de dikkat çekmektedir (Ye et al., 2025). Bu malzemelerin kullanılması, fosil kaynaklara dayalı hammaddelerin azaltılmasına ve bazı durumlarda yapı sektöründe döngüsel ekonomi yaklaşımının geliştirilmesine katkı sağlayabilmektedir. Ancak nem davranışı, yangın dayanımı, biyolojik bozunma, mekanik özellikler ve uzun dönemli performans gibi parametrelerin de malzeme seçiminde dikkate alınması gerekmektedir.

Bina enerji performansında yalnızca opak yapı elemanları değil, pencere ve diğer şeffaf yapı elemanları da büyük önem taşımaktadır. Pencereler, duvarlara göre genellikle daha yüksek ısı transferine izin vermekte ve aynı zamanda güneş ışınımının bina içerisine ulaşmasını sağlamaktadır. Bu nedenle pencere sistemlerinin seçimi, özellikle yüksek cam oranına sahip modern yapılarda ısıtma ve soğutma yüklerinin belirlenmesinde önemli bir parametredir. Düşük emissiviteli (Low-e) camlar, yüzeylerinde bulunan özel kaplamalar sayesinde uzun dalga boylu termal ışınım yoluyla gerçekleşen ısı transferini azaltarak pencere sistemlerinin ısıl performansını artırabilmektedir. Çift ve üçlü cam sistemleri, seçici güneş kontrol kaplamaları ve gelişmiş cam teknolojileri de enerji verimli bina tasarımında önemli seçenekler sunmaktadır (Li & Wu, 2025).

Akıllı ve elektrokromik cam teknolojileri, geleneksel sabit özellikli pencere sistemlerinden farklı olarak ışık ve güneş enerjisi geçirgenliğinin çevresel koşullara veya kullanıcı gereksinimlerine bağlı olarak değiştirilebilmesine olanak sağlamaktadır. Bu tür sistemler özellikle yaz aylarında aşırı güneş kazançlarının sınırlandırılması ve buna bağlı soğutma yüklerinin azaltılması açısından önemli bir potansiyel taşımaktadır (Zhao et al., 2025). Dolayısıyla geleceğin bina kabuklarının yalnızca pasif yalıtım sağlayan elemanlardan değil, çevresel koşullara tepki verebilen dinamik ve akıllı malzemelerden oluşması beklenmektedir.

İklim değişikliği ile mücadele açısından yapı malzemelerinin seçimi yalnızca kullanım aşamasındaki enerji tüketimi ile sınırlandırılmamalıdır. Bir yapı malzemesinin üretimi için gerekli hammadde miktarı, üretim sırasında tüketilen enerji, taşıma, montaj, bakım, kullanım ömrü ve kullanım ömrü sonunda geri dönüşüm veya bertaraf işlemleri malzemenin toplam çevresel etkisini belirlemektedir. IPCC tarafından yapılan değerlendirmelerde, binaların kullanım aşamasındaki enerji tüketimi azaltıldıkça yapı malzemelerinden kaynaklanan gömülü enerji ve gömülü karbonun toplam çevresel performans içerisindeki göreli öneminin arttığı vurgulanmaktadır (Intergovernmental Panel on Climate Change [IPCC], 2022). Bu nedenle geleceğin enerji verimli yapılarında yalnızca kullanım sırasında ne kadar enerji tasarrufu sağlandığı değil, malzemenin üretiminden kullanım ömrünün sonuna kadar meydana getirdiği toplam çevresel etkinin de dikkate alınması gerekmektedir (Lützkendorf, 2022).

Bu yaklaşım, yapı malzemelerinin yaşam döngüsü değerlendirmesi (Life Cycle Assessment, LCA) yöntemiyle incelenmesini gerekli hale getirmektedir. LCA yaklaşımında hammadde temini, malzeme üretimi, taşıma, yapı uygulaması, kullanım, bakım ve kullanım ömrü sonu aşamaları birlikte değerlendirilmektedir. Böylece bir malzemenin kullanım aşamasında sağladığı enerji tasarrufunun, üretim aşamasındaki yüksek enerji tüketimini veya yüksek karbon emisyonunu telafi edip etmediği daha sağlıklı biçimde ortaya konulabilmektedir (Asdrubali et al., 2024). Özellikle yüksek performanslı yalıtım malzemelerinin değerlendirilmesinde, üretim aşamasında kullanılan enerji ile bina kullanım süresince sağlanan enerji tasarrufu arasındaki ilişkinin incelenmesi önem taşımaktadır.

Enerji tasarrufu sağlayan yapı malzemelerinin geliştirilmesindeki bir diğer önemli eğilim, yapı kabuğunun enerji tüketen bir sistem olmaktan çıkarılarak enerji depolayan veya enerji üreten aktif bir sisteme dönüştürülmesidir. Bu kapsamda bina bütünleşik fotovoltaik (Building Integrated Photovoltaics, BIPV) sistemleri önemli bir örnek oluşturmaktadır. BIPV uygulamalarında fotovoltaik modüller çatı, cephe, güneş kırıcı veya cam sistemleriyle bütünleştirilerek yapı elemanının aynı zamanda elektrik üretmesi sağlanmaktadır (Faes et al., 2025; International Energy Agency Photovoltaic Power Systems Programme [IEA PVPS], 2025). Böylece yapı kabuğu, yalnızca binanın iç ortamını dış

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çevreden ayıran pasif bir eleman olmaktan çıkarak enerji üretimine katkıda bulunan aktif bir sisteme dönüşmektedir.

Türkiye açısından değerlendirildiğinde, bina enerji performansının iyileştirilmesi son yıllarda daha önemli bir politika ve mevzuat konusu haline gelmiştir. Türkiye'nin farklı iklim bölgelerine sahip olması, yapı malzemesi seçiminde bölgesel iklim koşullarının dikkate alınmasını gerekli kılmaktadır. Soğuk iklim bölgelerinde ısı kayıplarının azaltılması öncelikli olurken, sıcak iklim bölgelerinde güneş kazançlarının ve soğutma yüklerinin kontrol edilmesi daha önemli hale gelmektedir. Bu nedenle aynı yapı malzemesinin veya aynı yapı kabuğu çözümünün Türkiye'nin tüm bölgelerinde aynı enerji performansını sağlayacağı düşünülmemelidir.

Türkiye'de binaların ısı yalıtım performansına yönelik temel düzenlemelerden biri olan TS 825 Binalarda Isı Yalıtım Kuralları Standardı**,** 2024 yılında kapsamlı biçimde revize edilmiş ve yeni düzenleme 2025 yılında zorunlu uygulamaya alınmıştır. Güncellenen yaklaşımda yalnızca ısıtma ihtiyacının değil, soğutma ihtiyacının da dikkate alınması, farklı iklim koşullarındaki yapıların enerji performansının daha bütüncül biçimde değerlendirilmesine olanak sağlamaktadır (Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2025). Bu gelişme, Türkiye'de yapı malzemelerinin seçiminde yalnızca kış koşullarındaki ısı kayıplarının değil, yaz koşullarındaki ısı kazançlarının da dikkate alınmasının önemini artırmıştır.

Enerji tasarrufu sağlayan yapı malzemelerinin değerlendirilmesinde ayrıca ekonomik faktörler de göz önünde bulundurulmalıdır. Yüksek performanslı bir malzemenin teknik açıdan üstün olması, ekonomik açıdan her bina için optimum çözüm olduğu anlamına gelmemektedir. İlk yatırım maliyeti, enerji tasarrufu miktarı, enerji fiyatları, bakım maliyetleri, malzemenin kullanım ömrü ve yatırımın geri ödeme süresi birlikte değerlendirilmelidir. Bu nedenle enerji tasarrufu sağlayan yapı malzemelerinin seçiminde teknik performans–ekonomik performans–çevresel performans üçlüsünün birlikte ele alınması gerekmektedir (Asdrubali et al., 2024; Lützkendorf, 2022).

Sonuç olarak, enerji tasarrufu sağlayan yapı malzemeleri günümüzde yalnızca ısı yalıtımı sağlayan geleneksel ürünlerle sınırlı değildir. Geleneksel yalıtım malzemelerinin yanı sıra aerogeller, biyobazlı malzemeler, faz değiştiren malzemeler, Low-e camlar, akıllı camlar ve bina bütünleşik fotovoltaik sistemler, bina enerji performansının geliştirilmesinde farklı mekanizmalarla katkı sağlayabilmektedir (Baetens et al., 2011; Faes et al., 2025; Kalnæs & Jelle, 2015; Ye et al., 2025; Zhao et al., 2025). Bununla birlikte herhangi bir malzemenin enerji tasarrufu açısından başarısı, yalnızca malzemenin fiziksel özellikleriyle değil, binanın bulunduğu iklim, yapı geometrisi, yönlenme, kullanım amacı, mekanik sistemler ve kullanıcı davranışları ile birlikte değerlendirilmelidir.

Bu çalışmanın amacı; enerji tasarrufu sağlayan yapı malzemelerini teknik özellikleri, ısıl performansları, enerji tüketimine etkileri, kullanım alanları, ekonomik özellikleri ve sürdürülebilirlik kriterleri açısından sistematik olarak değerlendirmek ve farklı malzeme gruplarının enerji verimli bina tasarımındaki rolünü ortaya koymaktır. Bu kapsamda çalışmanın ilerleyen bölümlerinde geleneksel ve yeni nesil ısı yalıtım malzemeleri, aerogel ve biyobazlı malzemeler, faz değiştiren malzemeler, enerji verimli cam sistemleri, akıllı yapı malzemeleri ve enerji üreten yapı elemanları ayrı başlıklar altında incelenecek; malzemelerin enerji tasarrufu potansiyelleri yaşam döngüsü ve sürdürülebilirlik perspektifinden karşılaştırılacaktır.

2. BİNALARDA ENERJİ TÜKETİMİ VE ENERJİ VERİMLİLİĞİ

Binalar, yaşam ve çalışma faaliyetlerinin sürdürülebilmesi için ısıtma, soğutma, havalandırma, aydınlatma, sıcak su ve elektrikli cihazlar gibi çok sayıda enerji kullanım alanına sahiptir. Bu nedenle bina sektörü, küresel enerji tüketimi ve sera gazı emisyonları açısından önemli bir paya sahiptir. Uluslararası Enerji Ajansı'na göre binalar 2024 yılında küresel nihai enerji talebinin yaklaşık %30'unu oluşturmuş, konutlar bina enerji talebinin yaklaşık %70'ini meydana getirmiştir (IEA, 2025). Birleşmiş Milletler Çevre Programı ve GlobalABC tarafından yayımlanan güncel raporda ise binalar ve inşaat sektörünün küresel CO_2 emisyonlarının yaklaşık %37'sinden sorumlu olduğu belirtilmektedir (UNEP & GlobalABC, 2026). Bu durum, binalarda enerji tüketiminin azaltılmasını enerji güvenliği, ekonomik sürdürülebilirlik ve iklim değişikliğiyle mücadele açısından önemli bir hedef hâline getirmektedir.

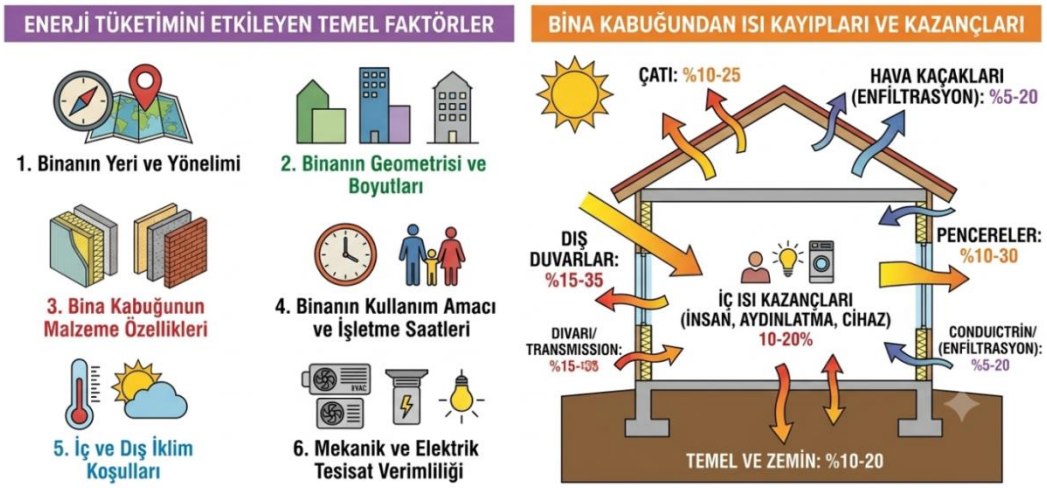
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2.1. Binalarda Enerji Tüketimini Etkileyen Faktörler

Binalardaki enerji tüketimi; binanın bulunduğu iklim bölgesi, yönelimi, kullanım amacı, bina yaşı, kullanıcı davranışları, ısıtma-soğutma sistemlerinin verimliliği, havalandırma ve aydınlatma sistemleri ile bina kabuğunun termal özellikleri gibi çok sayıda faktöre bağlıdır. Özellikle iklim koşulları, ısıtma ve soğutma ihtiyacının belirlenmesinde temel etkenlerden biridir. Bunun yanında bina kabuğunda kullanılan malzemelerin ısıl iletkenliği, yalıtım kalınlığı, pencere özellikleri ve hava sızdırmazlık düzeyi, iç ortam ile dış ortam arasındaki ısı transferini doğrudan etkiler. IEA (2025), özellikle yetersiz yalıtılmış binalarda ısıtma ve soğutma ihtiyacının azaltılmasının enerji verimliliğinin geliştirilmesinde temel önceliklerden biri olduğunu belirtmektedir.

2.2. Binalarda Isı Kayıpları ve Isı Kazançları

Binalarda enerji tüketiminin önemli bir bölümü, iç ortamın istenilen sıcaklıkta tutulması amacıyla gerçekleştirilen ısıtma ve soğutma faaliyetlerinden kaynaklanmaktadır. Kış aylarında iç ortam ile dış ortam arasındaki sıcaklık farkı nedeniyle duvar, çatı, döşeme, pencere ve kapılar üzerinden dış ortama doğru ısı kayıpları meydana gelir. Yaz aylarında ise güneş ışınımı, dış hava sıcaklığı ve bina kabuğundan gerçekleşen ısı geçişleri nedeniyle soğutma yükü artmaktadır. Özellikle bina kabuğundaki yetersiz yalıtım, ısı köprüleri ve hava sızıntıları enerji kayıplarını artırmaktadır. Bina kabuğu; dış duvarlar, çatı, döşeme, pencereler ve kapılardan oluşan ve iç ortam ile dış çevre arasındaki sınırı oluşturan temel yapı sistemidir. Bu elemanların termal performansının iyileştirilmesi, ısıtma ve soğutma için gerekli enerji miktarının azaltılmasına katkı sağlar (IEA, 2013; U.S. Department of Energy, 2024).



Şekil 1. Bina enerji tüketimini ve ısı geçişini etkileyen temel faktörler.

Şekil 1'de; dış ortam sıcaklığı, güneş ışınımı, duvar, çatı, pencere, döşeme, hava sızıntısı ve ısıtma-soğutma sistemi arasındaki ilişki gösterilerek, yapı malzemelerinin bina enerji performansındaki konumu görsel olarak açıklanabilir. Şeklin hemen ardından yapı malzemeleri ile enerji tüketimi arasındaki ilişkiye geçilmesi, çalışmanın ilerleyen bölümlerinde ele alınacak malzeme karşılaştırmalarına geçişi kolaylaştıracaktır.

2.3. Bina Kabuğunun Enerji Performansındaki Önemi

Bina kabuğu, enerji verimliliğinin sağlanmasında en önemli fiziksel bileşenlerden biridir. Dış duvarlar, çatılar, döşemeler, pencereler ve kapılar aracılığıyla gerçekleşen ısı transferinin kontrol edilmesi, binanın ısıtma ve soğutma yüklerinin azaltılmasını sağlar. IEA'ya göre bina kabuğunun enerji performansı, bir yapının ısıtma ve soğutma amacıyla ihtiyaç duyduğu enerji miktarının belirlenmesinde kritik öneme sahiptir (IEA, 2013). Bu nedenle düşük ısıl iletkenliğe sahip yalıtım malzemelerinin kullanılması, uygun yalıtım kalınlığının belirlenmesi ve ısı köprülerinin azaltılması bina enerji performansının geliştirilmesinde temel uygulamalardır. Ayrıca pencere ve kapı sistemlerinde kullanılan malzemelerin ısıl özellikleri ile hava sızdırmazlık düzeyleri de enerji kayıplarını önemli ölçüde etkileyebilmektedir (U.S. Department of Energy, 2024). Dolayısıyla bina kabuğunun tasarımı yalnızca yapısal dayanım açısından değil, enerji verimliliği ve iç ortam konforu açısından da değerlendirilmelidir.

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2.4. Binalarda Enerji Verimliliğinin Ekonomik ve Çevresel Boyutu

Binalarda enerji verimliliğinin artırılması, enerji tüketiminin ve buna bağlı işletme maliyetlerinin azaltılmasının yanı sıra sera gazı emisyonlarının düşürülmesine de katkı sağlamaktadır. Enerji verimli bir bina için başlangıçta daha yüksek yalıtım, yüksek performanslı pencere veya enerji verimli sistem yatırımları gerekebilse de, işletme süresince sağlanan enerji tasarrufu bu ilk yatırım maliyetlerinin geri kazanılmasına olanak sağlayabilir. Ayrıca enerji tüketiminin azaltılması, fosil yakıtlara olan bağımlılığın ve enerji fiyatlarındaki dalgalanmaların bina kullanıcıları üzerindeki etkisinin azaltılmasına katkıda bulunmaktadır. IEA (2026), bina enerji verimliliğinin geliştirilmesinde bina enerji kodları, mevcut yapıların iyileştirilmesi, yalıtım uygulamaları ve enerji performansının artırılmasına yönelik politikaların önemli araçlar olduğunu vurgulamaktadır. UNEP ve GlobalABC (2026) ise bina sektöründe enerji verimliliği yatırımlarının hızlandırılmasının iklim hedeflerine ulaşılması açısından kritik olduğunu belirtmektedir. Bu nedenle yapı malzemelerinin seçiminde yalnızca ilk yatırım maliyetinin değil, malzemenin kullanım ömrü boyunca sağlayacağı enerji tasarrufu, karbon azaltımı, dayanıklılık ve yaşam döngüsü etkilerinin birlikte değerlendirilmesi gerekmektedir.

3. ENERJİ TASARRUFLU YAPI MALZEMELERİ

3.1. Geleneksel Isı Yalıtım Malzemeleri

Enerji tasarrufu sağlayan yapı malzemeleri içerisinde en yaygın kullanılan malzeme gruplarından biri ısı yalıtım malzemeleridir. Bu malzemelerin temel amacı, bina kabuğundan gerçekleşen ısı transferini sınırlandırarak kış döneminde iç ortamdan dış ortama gerçekleşen ısı kayıplarını, yaz döneminde ise dış ortamdan iç ortama gerçekleşen ısı kazançlarını azaltmaktır. Mineral yün, cam yünü, genleştirilmiş polistiren (EPS), ekstrüde polistiren (XPS), poliüretan (PUR) ve poliizosiyanürat (PIR) esaslı malzemeler; bina duvarları, çatılar, döşemeler ve çeşitli cephe sistemlerinde yaygın olarak kullanılmaktadır. Şekil 2'de geleneksel ısı yalıtım malzemelerine ait örnekler gösterilmektedir. Bu malzemelerin enerji performansının değerlendirilmesinde temel parametrelerden biri ısıl iletkenlik katsayısı (λ) olmakla birlikte, gerçek bina performansı yalnızca bu parametreye bağlı değildir. Malzemenin yoğunluğu, gözeneklilik yapısı, nem içeriği, sıcaklık, kalınlık, mekanik özellikleri ve uygulama kalitesi de yalıtım performansını doğrudan etkileyebilmektedir (Asdrubali et al., 2024).Bu malzemelerin enerji performansının değerlendirilmesinde temel parametrelerden biri ısıl iletkenlik katsayısı (λ) olmakla birlikte, gerçek bina performansı yalnızca bu parametreye bağlı değildir. Malzemenin yoğunluğu, gözeneklilik yapısı, nem içeriği, sıcaklık, kalınlık, mekanik özellikleri ve uygulama kalitesi de yalıtım performansını doğrudan etkileyebilmektedir (Asdrubali et al., 2024).



Şekil 2. Geleneksel ısı yalıtım malzemelerine örnekler

Isı yalıtım tabakasının kalınlığının artırılması genel olarak yapı elemanının ısıl direncini yükseltmekte ve U değerini azaltmaktadır. Bununla birlikte yalıtım kalınlığının sürekli olarak artırılması, belirli bir noktadan sonra sağlanan enerji tasarrufunun ekonomik karşılığının azalmasına neden olabilmektedir.

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Bu nedenle optimum yalıtım kalınlığının belirlenmesinde yalnızca ısıl performans değil, malzemenin ilk yatırım maliyeti, enerji fiyatları, iklim koşulları, bina kullanım süresi ve yatırımın geri ödeme süresi birlikte değerlendirilmelidir. Ayrıca yalıtım malzemelerinin bina ömrü boyunca nem, yangın, mekanik yük, sıcaklık değişimleri ve yaşlanma etkileri altında performansını koruyabilmesi gerekmektedir. Özellikle uygulama sırasında oluşabilecek boşluklar, süreksizlikler ve ısı köprüleri, teorik olarak hesaplanan ısıl performansın gerçek bina performansından farklılaşmasına neden olabilmektedir (Asdrubali et al., 2024).

3.2. Aerogel Esaslı Yüksek Performanslı Yalıtım Malzemeleri

Geleneksel ısı yalıtım malzemelerine alternatif olarak geliştirilen yüksek performanslı malzemeler arasında aerogeller önemli bir yere sahiptir. Aerogeller, yüksek gözeneklilik oranına ve düşük yoğunluğa sahip, katı iskelet içerisinde büyük miktarda hava veya gaz içeren ileri mühendislik malzemeleridir. Özellikle silika aerogeller, ısı iletimini sınırlandıran nanogözenekli yapıları sayesinde çok düşük ısıl iletkenlik değerlerine ulaşabilmektedir. elle, Baetens ve Gustavsen (2015) tarafından gerçekleştirilen değerlendirmede, aerogel esaslı malzemelerin düşük ısıl iletkenlikleri sayesinde geleneksel yalıtım malzemelerine göre daha ince kesitlerde yüksek ısıl direnç sağlayabildiği belirtilmektedir. Şekil 3'te aerogel esaslı yüksek performanslı yapı malzemelerine örnekler gösterilmektedir.



Şekil 3. Aerogel esaslı yüksek performanslı yapı malzemeleri

Aerogellerin düşük ısıl iletkenliklerinin yanı sıra bazı türlerinin ışık geçirgenliği özelliklerine sahip olması, bu malzemelerin şeffaf veya yarı saydam yapı elemanlarında da kullanılabilmesine olanak sağlamaktadır (Jelle et al., 2015). Bu nedenle aerogel esaslı malzemeler; tarihi yapıların enerji performansının iyileştirilmesi, ince yalıtım panelleri, pencere sistemleri, cephe elemanları ve yüksek performans gerektiren özel yapı uygulamalarında değerlendirilebilmektedir. Bununla birlikte yüksek üretim maliyeti, üretim süreçlerinin karmaşıklığı, mekanik dayanım, kırılganlık ve uzun dönemli performansın belirlenmesine yönelik gereksinimler, aerogellerin geleneksel yalıtım malzemeleri kadar yaygınlaşmasını sınırlayan temel faktörlerdir. Bu nedenle aerogellerin ekonomik açıdan uygulanabilirliği değerlendirilirken sağladıkları enerji tasarrufunun malzeme maliyeti ve kullanım ömrü boyunca elde edilen enerji kazancı ile birlikte ele alınması gerekmektedir.

3.3. Biyobazlı Isı Yalıtım Malzemeleri

Sürdürülebilir yapılaşma ve düşük karbonlu bina tasarımı hedeflerinin önem kazanmasıyla birlikte yenilenebilir kaynaklardan elde edilen biyobazlı yalıtım malzemelerine yönelik araştırmalar da hızlanmıştır. Selüloz, ahşap lifi, kenevir, saman, mantar, çeşitli doğal lifler ve tarımsal atıklardan elde edilen malzemeler bu kapsamda değerlendirilmektedir. Biyobazlı yalıtım malzemeleri, uygun gözenekli yapıları sayesinde ısı transferini sınırlandırırken aynı zamanda yenilenebilir hammadde kullanımı, düşük gömülü karbon potansiyeli ve bazı malzemelerde karbonun kullanım süresince bünyede tutulabilmesi gibi çevresel avantajlar sağlayabilmektedir. Ye ve arkadaşlarının (2025) kapsamlı literatür değerlendirmesinde, biyobazlı yalıtım malzemelerinin ısıl, akustik, mekanik, dayanıklılık ve çevresel

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performanslarının birlikte değerlendirilmesi gerektiği ve bu malzemelerin sürdürülebilir yapılaşma açısından önemli bir potansiyel taşıdığı belirtilmiştir. Şekil 4'te biyobazlı ısı yalıtım malzemelerine ait örnekler gösterilmektedir.



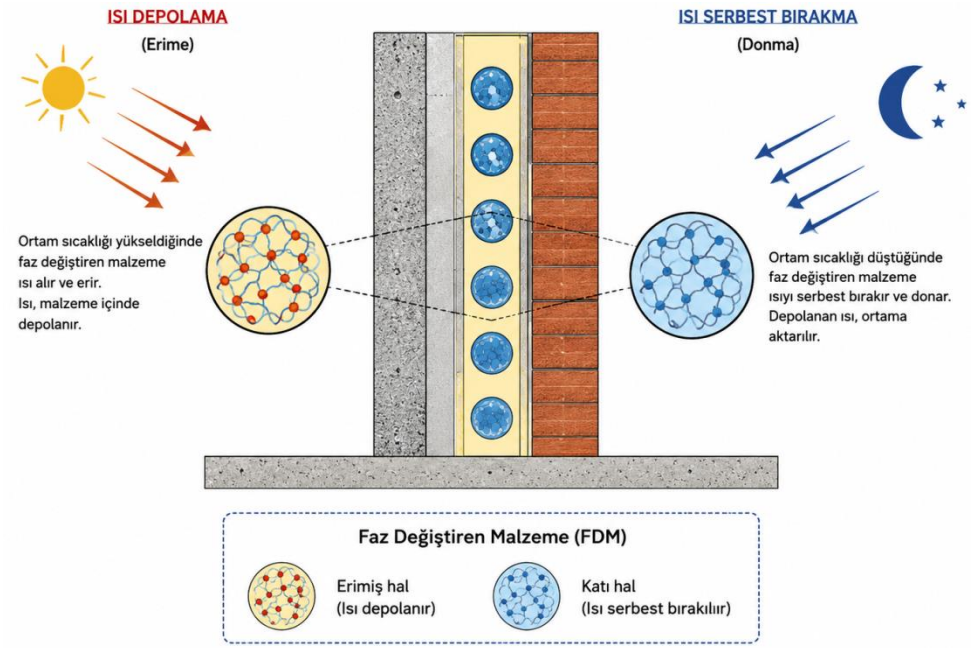
Şekil 4. Biyobazlı ısı yalıtım malzemeleri.

Biyobazlı malzemelerin enerji tasarrufu açısından önemli bir avantajı, ısı yalıtımı işlevi ile çevresel sürdürülebilirlik hedeflerini aynı yapı elemanında birleştirebilmesidir. Bununla birlikte doğal kökenli malzemelerin nem alma kapasitesi, yangın davranışı, biyolojik bozunma riski, boyutsal kararlılığı ve hammaddenin doğal özelliklerindeki değişkenlikler tasarım sürecinde dikkate alınmalıdır. Özellikle nem içeriğindeki artış, birçok gözenekli yalıtım malzemesinde ısıl iletkenliğin yükselmesine ve dolayısıyla yalıtım performansının azalmasına neden olabilmektedir. Bu nedenle biyobazlı malzemelerin yalnızca düşük ısıl iletkenlik değerleri üzerinden değerlendirilmesi yerine, malzemenin tüm kullanım ömrü boyunca göstereceği ısıl, mekanik ve çevresel performansın birlikte değerlendirilmesi gerekmektedir (Ye et al., 2025).

3.4. Faz Değiştiren Malzemeler (FDM)

Enerji tasarrufu sağlayan yapı malzemeleri içerisinde geleneksel yalıtım yaklaşımından farklı bir çalışma mekanizmasına sahip olan faz değiştiren malzemeler (FDM), özellikle ısıl enerji depolama uygulamaları açısından önemli bir araştırma konusu hâline gelmiştir. FDM'ler belirli bir sıcaklık aralığında katı-sıvı veya sıvı-katı faz değişimi gerçekleştirirken önemli miktarda gizli ısı depolayabilmektedir. Böylece yapı elemanına ulaşan ısının tamamının doğrudan iç ortama aktarılması yerine bir bölümünün geçici olarak depolanması mümkün olmaktadır. FDM'ler duvar, tavan, döşeme ve bazı özel pencere sistemlerine entegre edilebilmekte; parafinler, yağ asitleri, hidratlı tuzlar ve bazı organik bileşikler başlıca FDM gruplarını oluşturmaktadır (Kurdi et al., 2021).

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Şekil 5. Faz değiştiren malzemenin ısı depolama ve salım mekanizması.

Kurdi ve arkadaşlarının (2021) incelemesinde parafin, yağ asitleri, hidratlı tuzlar ve butil stearat gibi malzemelerin bina duvarı uygulamaları açısından potansiyel taşıdığı belirtilmiştir. FDM'nin yapı içerisindeki çalışma prensibi Şekil 5'te şematik olarak gösterilmektedir. Gündüz saatlerinde güneş ışınımı ve dış ortam sıcaklığındaki artış nedeniyle yapı elemanına ulaşan ısı, FDM'nin faz değişim sıcaklığına ulaştığında malzemenin katı fazdan sıvı faza geçmesine ve bu süreçte ısı enerjisinin gizli ısı olarak depolanmasına neden olmaktadır. Bu mekanizma, iç ortam sıcaklığındaki yükselmeyi geciktirerek sıcaklık dalgalanmalarını sınırlandırmaktadır. Gece saatlerinde dış ortam sıcaklığının düşmesiyle FDM sıvı fazdan tekrar katı faza geçerken depoladığı ısıyı çevreye bırakmaktadır. Böylece tekrarlı olarak ısı depolayıp serbest bırakması sayesinde yapı elemanının ısıl ataletinin artırılması ve iç ortam sıcaklığının daha kararlı tutulması mümkün olmaktadır (Kalnæs & Jelle, 2015).

FDM'lerin bina kabuğuna uygulanmasında faz değişim sıcaklığı, gizli ısı kapasitesi, ısıl iletkenlik, çevrim kararlılığı ve kapsülleme yöntemi temel tasarım parametreleridir. Faz değişim sıcaklığının binanın kullanım amacı ve yerel iklim koşullarına uygun seçilmesi, enerji tasarrufu potansiyelinin etkin biçimde kullanılabilmesi açısından önemlidir. Kalnæs ve Jelle'nin (2015) değerlendirmesine göre FDM'ler iç ortam sıcaklık dalgalanmalarını azaltabilmekte, ısıl konforu iyileştirebilmekte ve özellikle en yüksek ısıtma-soğutma yüklerinin azaltılması veya ötelenmesine katkı sağlayabilmektedir. Bununla birlikte FDM'lerin gerçek bina uygulamalarındaki performansı laboratuvar koşullarından farklılaşabilmekte ve uygulama koşulları elde edilen sonuçlar üzerinde önemli bir etkiye sahip olabilmektedir.

FDM teknolojisinin yaygınlaşmasının önündeki başlıca sorunlar arasında kapsülleme maliyeti, bazı FDM türlerinde düşük ısıl iletkenlik, tekrarlı faz değişimleri sonucunda oluşabilecek performans kayıpları, sızıntı riski ve uzun dönemli çevrim kararlılığı bulunmaktadır. Bu nedenle FDM'lerin yalnızca gizli ısı kapasitesi açısından değil, yapı malzemeleriyle uyumlulukları ve gerçek çalışma koşulları dikkate alınarak değerlendirilmesi gerekmektedir. Özellikle uygun faz değişim sıcaklığına sahip FDM'lerin yalıtım malzemeleriyle birlikte kullanılması, bina kabuğunun hem ısı transferini sınırlandıran hem de ısıl enerji depolayan hibrit bir sistem olarak tasarlanmasına olanak sağlayabilir (Kalnæs & Jelle, 2015; Kurdi et al., 2021).

Genel olarak değerlendirildiğinde, geleneksel yalıtım malzemeleri ısı transferini azaltarak enerji tüketiminin düşürülmesinde temel çözüm olmaya devam ederken, aerogeller daha düşük kalınlıklarla yüksek ısıl direnç sağlama, biyobazlı malzemeler enerji verimliliğini çevresel sürdürülebilirlikle birleştirme ve FDM'ler ise ısı depolama yoluyla iç ortam sıcaklık dalgalanmaları ile en yüksek enerji

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yüklerini azaltma potansiyeline sahiptir. Bu nedenle enerji tasarrufu sağlayan yapı malzemelerinin seçiminde tek bir malzemenin üstünlüğünden ziyade binanın iklimi, yapı elemanlarının özellikleri, kullanım amacı, teknik gereksinimler ve ekonomik koşulların birlikte değerlendirilerek uygun malzeme kombinasyonlarının belirlenmesi daha doğru bir yaklaşım olacaktır.

4. PENCERE VE ŞEFFAF YAPI MALZEMELERİNDE ENERJİ TASARRUFU

Pencereler ve diğer şeffaf yapı elemanları, bina kabuğunun enerji performansında önemli bir role sahiptir. Opak yapı elemanlarına kıyasla daha fazla ısı geçişine izin vermeleri ve güneş ışınımının bina içerisine ulaşmasını sağlamaları nedeniyle pencere sistemlerinin seçimi, özellikle geniş cam yüzeylere sahip binalarda ısıtma ve soğutma için tüketilen enerjiyi önemli ölçüde etkileyebilmektedir. Pencere sistemlerinin enerji performansında camın ısıl geçirgenliği, güneş ısısı kazanç katsayısı, görünür ışık geçirgenliği, yayınım özelliği, cam katmanlarının sayısı ve kaplama özellikleri temel parametreler arasında yer almaktadır. Bu nedenle pencere seçiminde yalnızca ısı kayıplarının azaltılması değil, güneş ısısı kazançları, doğal aydınlatma ve ısıl konforun da birlikte değerlendirilmesi gerekmektedir (Li & Wu, 2025).

4.1. Düşük Yayınımlı Camlar

Düşük yayınımlı (Low-e) camlar, yüzeylerine uygulanan özel metalik veya metal oksit esaslı ince kaplamalar sayesinde uzun dalga boylu ısıl ışınım yoluyla gerçekleşen ısı geçişini azaltan gelişmiş cam sistemleridir. Bu kaplamalar, görünür ışığın önemli bir bölümünün geçirgenliğini korurken kızılötesi ışınım yoluyla gerçekleşen ısı transferini sınırlandırabilmektedir. Böylece kış döneminde bina içerisindeki ısının dış ortama kaybedilmesi azaltılırken, uygun özellikteki Low-e kaplamalar yaz döneminde güneş kaynaklı ısı kazançlarının sınırlandırılmasına da katkı sağlayabilmektedir (Li & Wu, 2025).

Düşük yayınımlı camların enerji performansı yalnızca yayınım değerine bağlı olmayıp camın güneş ısısı kazanç katsayısı, görünür ışık geçirgenliği, cam katmanlarının sayısı, kaplamanın konumu ve binanın bulunduğu iklim koşulları ile birlikte değerlendirilmelidir. Bu nedenle soğuk iklimlerde ısı kayıplarını sınırlandıran düşük yayınımlı camlar ön plana çıkarken, sıcak iklimlerde güneş ısısı kazançlarının kontrol edilmesini sağlayan seçici kaplamaların kullanılması daha önemli hâle gelmektedir. Dolayısıyla uygun cam seçiminin binanın iklim bölgesi, yönlenmesi ve cam yüzey oranı dikkate alınarak yapılması, pencere kaynaklı enerji tüketiminin azaltılması açısından önem taşımaktadır (Li & Wu, 2025).

4.2. Akıllı ve Elektrokromik Camlar

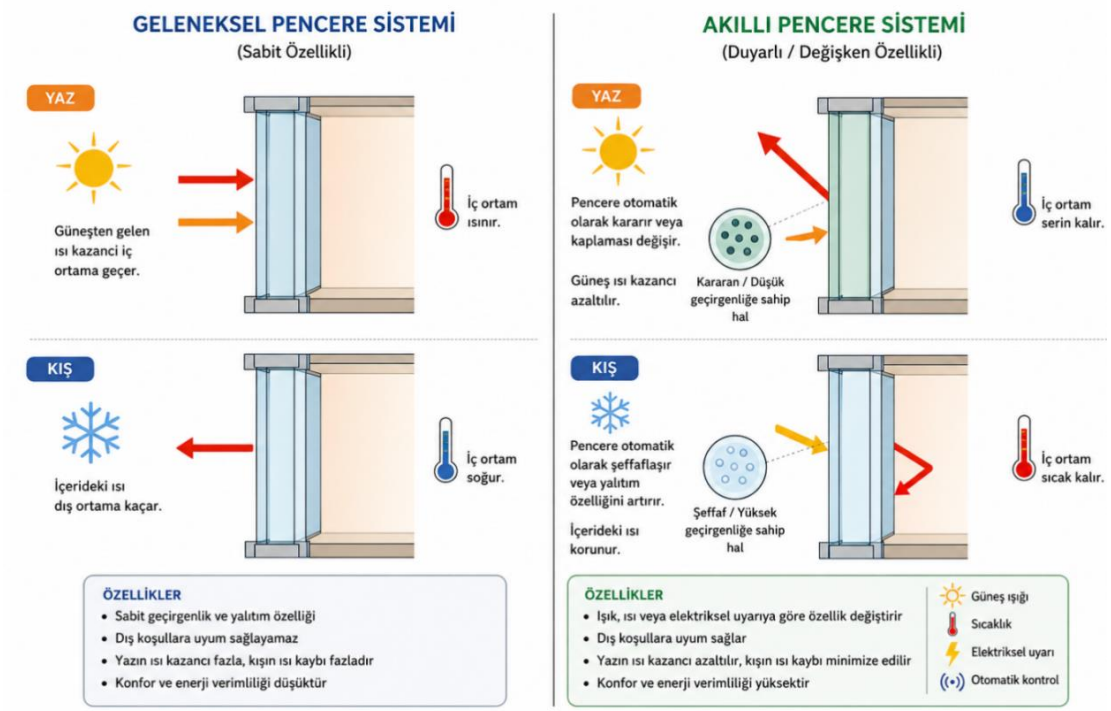
Akıllı cam teknolojileri, pencere sistemlerinin optik ve ısıl özelliklerinin çevresel koşullara veya elektriksel kontrollere bağlı olarak değiştirilebilmesine olanak sağlayan yeni nesil yapı teknolojileridir. Elektrokromik camlarda uygulanan elektriksel gerilim sonucunda camın optik geçirgenliği değiştirilebilmekte ve böylece binaya ulaşan güneş ışınımı ile güneş kaynaklı ısı kazancı dinamik olarak kontrol edilebilmektedir. Zhao ve arkadaşlarının (2025) kapsamlı değerlendirmesine göre elektrokromik akıllı pencereler, ışık ve ısı geçişini gereksinime bağlı olarak düzenleyerek binaların enerji performansının iyileştirilmesine katkı sağlayabilmektedir.

Şekil 3'te geleneksel pencere ile akıllı pencerenin çalışma prensipleri karşılaştırılmaktadır. Geleneksel cam sistemlerinde optik ve ısıl özellikler büyük ölçüde sabit kalırken, akıllı camlarda güneş ışınımı ve bina kullanım koşullarına bağlı olarak ışık ve ısı geçirgenliği değiştirilebilmektedir. Bu özellik, özellikle güneş kazançlarının yüksek olduğu dönemlerde soğutma yüklerinin azaltılmasına ve gün ışığından daha etkin yararlanılmasına olanak sağlayabilmektedir (Zhao et al., 2025).

Bununla birlikte akıllı ve elektrokromik camların yaygın kullanımında ilk yatırım maliyeti, uzun dönemli dayanıklılık, geçiş hızı, optik özelliklerin kararlılığı, kontrol sistemleriyle bütünleşme ve kullanım ömrü sonundaki geri dönüşüm olanakları önemini korumaktadır. Bu nedenle söz konusu teknolojilerin enerji tasarrufu potansiyeli yalnızca camın teknik özellikleri üzerinden değil; binanın iklim koşulları, yönlenmesi, cam yüzey oranı, gölgelenme durumu ve kullanım özellikleriyle birlikte değerlendirilmelidir (Zhao et al., 2025).

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Sonuç olarak, pencere ve şeffaf yapı malzemelerinin seçiminde ısı kayıpları, güneş ısısı kazançları, doğal aydınlatma ve ısıl konfor arasında uygun bir denge kurulması gerekmektedir. Düşük yayınımlı camlar mevcut binalarda ve yeni yapılarda uygulanabilirliği yüksek bir çözüm sunarken, akıllı ve elektrokromik camlar değişen çevresel koşullara uyum sağlayabilmeleri sayesinde geleceğin yüksek enerji performanslı binalarında önemli bir potansiyele sahiptir. Şekil 6'da geleneksel ve akıllı pencere sistemlerinin çalışma prensiplerinin karşılaştırılması verilmiştir. Ancak her iki teknolojinin de etkinliği, binanın tasarım özellikleri ve bulunduğu iklim koşulları dikkate alınarak değerlendirilmelidir.



Şekil 6. Geleneksel ve akıllı pencere sistemlerinin çalışma prensiplerinin karşılaştırılması

5. ENERJİ ÜRETEN AKTİF YAPI MALZEMELERİ VE SİSTEMLERİ

Enerji tasarrufu sağlayan yapı malzemeleri yalnızca bina içerisinde tüketilen enerjinin azaltılmasına yönelik yalıtım ve enerji verimliliği sağlayan malzemelerle sınırlı olmayıp, yapının kendi enerjisini üretebilmesine olanak sağlayan aktif malzeme ve sistemleri de kapsamaktadır. Bu yaklaşımda yapı kabuğu, enerji tüketimini sınırlandıran pasif bir eleman olmanın ötesinde, yenilenebilir enerji üretimine katkıda bulunan aktif bir sistem olarak değerlendirilmektedir. Bu kapsamda bina ile bütünleşik güneş enerjisi sistemleri, yapılarda yerinde enerji üretimi sağlayan önemli uygulamalardan biridir. Bu sistemlerde fotovoltaik modüller, geleneksel güneş panellerinden farklı olarak çatıya sonradan monte edilen bağımsız ekipmanlar şeklinde değil; çatı kaplaması, cephe, güneş kırıcı, korkuluk, gölgeleme elemanı ve yarı saydam cam yüzeyler gibi yapı elemanlarının bir parçası olarak tasarlanabilmektedir. Böylece aynı yapı elemanı hem binanın fiziksel işlevini yerine getirmekte hem de güneş ışınımını elektrik enerjisine dönüştürmektedir (Faes et al., 2025; International Energy Agency Photovoltaic Power Systems Programme [IEA PVPS], 2025). Şekil 7'de yapı kabuğuna bütünleştirilmiş güneş enerjisi sistemine ait örnek bir uygulama verilmiştir.

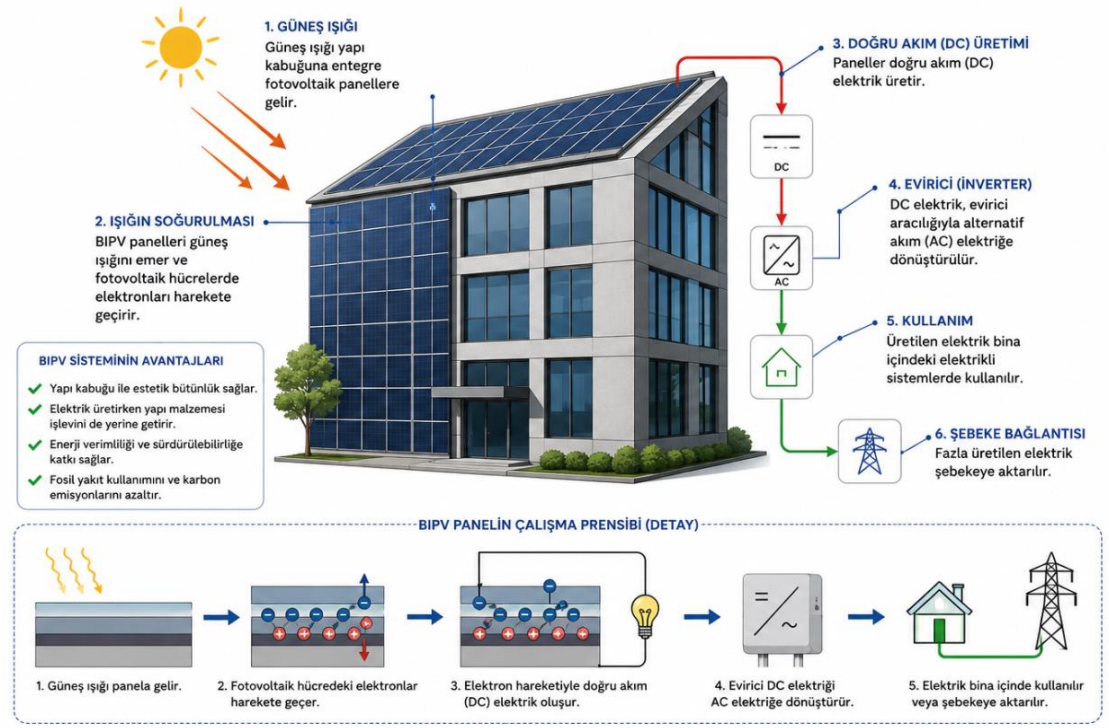
Bina ile bütünleşik güneş enerjisi sistemlerinin enerji üretim performansı; kullanılan fotovoltaik hücre teknolojisi, modülün yönlenmesi ve eğim açısı, güneş ışınımı, gölgelenme, modül çalışma sıcaklığı, cephe geometrisi ve arka yüzey havalandırması gibi birçok parametreye bağlıdır. Bu nedenle sistemlerin performansının yalnızca fotovoltaik elektrik üretimi açısından değil, yapı elemanının elektriksel, optik ve ısıl özellikleri ile binanın toplam enerji performansı birlikte dikkate alınarak değerlendirilmesi gerekmektedir. Özellikle cephe ve çatıya bütünleşik uygulamalarda modülün yapı kabuğuyla olan ilişkisi, güneş kazançları, gölgeleme etkisi ve havalandırma koşulları sistemin gerçek enerji performansını önemli ölçüde etkileyebilmektedir (Faes et al., 2025). Güneş ışınımının fotovoltaik sistem

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aracılığıyla elektrik enerjisine dönüştürülmesiyle elde edilen enerji, öncelikle bina içerisindeki elektriksel yüklerin karşılanmasında kullanılabilmekte; ihtiyaç fazlası üretim ise uygun koşullarda enerji depolama sistemlerine aktarılabilmekte veya elektrik şebekesine verilebilmektedir. Bu yönüyle bina ile bütünleşik güneş enerjisi sistemleri, yapı elemanları ile yenilenebilir enerji üretim teknolojisini bir araya getirerek binanın dışarıdan ihtiyaç duyduğu enerjinin azaltılmasına ve enerji ihtiyacının bir bölümünün yerinde karşılanmasına katkı sağlamaktadır (IEA PVPS, 2025).

Bununla birlikte yapılarda enerji üretimi sağlayan malzeme ve sistemlerin değerlendirilmesinde yalnızca elektrik üretim kapasitesinin dikkate alınması yeterli değildir. Bu sistemlerin yapı elemanı olarak üstlendiği ısı yalıtımı, güneş kontrolü, doğal aydınlatma, yangın güvenliği, dayanıklılık, bakım gereksinimi ve estetik gibi işlevlerin de birlikte değerlendirilmesi gerekmektedir. Ayrıca fotovoltaik sistemlerin yapı elemanlarına bütünleştirilmesi sırasında taşıyıcı sistem, bağlantı detayları, su ve hava sızdırmazlığı, gölgelenme ve yangın güvenliği gibi teknik hususlar dikkate alınmalıdır. Bu nedenle tasarım sürecinde mimari ve elektriksel özelliklerin yanı sıra bina enerji performansı, yerel iklim koşulları, güneşlenme durumu ve yapı elemanlarının teknik özellikleri birlikte değerlendirilmelidir (Faes et al., 2025; IEA PVPS, 2025).

Sonuç olarak, enerji üretimi sağlayan yapı malzeme ve sistemleri yalnızca elektrik üreten teknolojiler olarak değil, yapı kabuğunun fiziksel işlevleri ile yenilenebilir enerji üretimini bütünleştiren aktif yapı çözümleri olarak değerlendirilmelidir. Özellikle yeni binaların tasarımında bu sistemlerin yapının ilk tasarım aşamasından itibaren planlanması, sonradan gerçekleştirilecek uyarlamalara göre daha bütüncül ve verimli çözümler sağlayabilir. Bu yaklaşım, bina enerji tüketiminin azaltılmasının yanında yerinde yenilenebilir enerji üretiminin artırılmasına ve daha düşük karbonlu bina sistemlerinin geliştirilmesine katkı sağlayabilir.



Şekil 7. Yapı kabuğuna bütünleştirilmiş güneş enerjisi sistemi.

6. ENERJİ VERİMLİ YAPI MALZEMELERİNİN DEĞERLENDİRİLMESİ

Enerji tasarrufu sağlayan yapı malzemelerinin seçiminde yalnızca ısıl iletkenlik katsayısı veya ilk yatırım maliyeti gibi tek bir performans parametresine bağlı kalınması, malzemenin bina kullanım ömrü boyunca göstereceği gerçek performansın belirlenmesi açısından yeterli değildir. Bu nedenle iklim koşulları, bina enerji ihtiyacı, yapı elemanlarının özellikleri, malzemenin teknik performansı, ekonomik

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koşulları ve çevresel etkilerinin birlikte değerlendirildiği çok kriterli bir yaklaşımın benimsenmesi gerekmektedir.

Malzeme seçiminde öncelikle binanın bulunduğu iklim bölgesi ve buna bağlı ısıtma-soğutma enerji ihtiyacı belirlenmeli, ardından yapı elemanları opak ve şeffaf yüzeyler açısından değerlendirilmelidir. Opak yüzeylerde uygun ısı yalıtım malzemeleri ve gerektiğinde FDM uygulamaları; şeffaf yüzeylerde ise Low-e ve akıllı cam sistemleri dikkate alınmalıdır. Aday malzemelerin değerlendirilmesinde yalnızca kullanım aşamasındaki enerji tasarrufuna değil, üretim enerjisi, gömülü karbon, taşıma, bakım, kullanım ömrü, geri dönüşüm ve yeniden kullanım potansiyeli gibi yaşam döngüsü etkilerine de bakılmalıdır. Bunun yanında nem davranışı, mekanik dayanım, yangın performansı, boyutsal kararlılık ve uzun dönemli dayanıklılık gibi teknik özellikler de göz önünde bulundurulmalıdır (Asdrubali et al., 2024). Ekonomik açıdan ise ilk yatırım maliyeti ile kullanım süresince sağlanacak enerji tasarrufu birlikte değerlendirilerek yaşam döngüsü maliyeti ve yatırımın geri ödeme süresi belirlenmelidir.

Literatürdeki çalışmalar, enerji tasarrufu sağlayan yapı malzemelerinin bina enerji performansının iyileştirilmesinde önemli bir potansiyele sahip olduğunu göstermektedir. Bununla birlikte herhangi bir malzemenin tüm bina ve iklim koşulları için "en iyi" seçenek olarak değerlendirilmesi bilimsel açıdan uygun değildir. Malzemenin gerçek performansı; iklim bölgesi, bina geometrisi, yönlenme, pencere oranı, yapı elemanlarının tasarımı, uygulama kalitesi, ısıtma-soğutma ve iklimlendirme sistemleri ile kullanıcı davranışları gibi birçok faktörün birlikte değerlendirilmesini gerektirmektedir.

Geleneksel mineral yün, EPS, XPS ve poliüretan esaslı yalıtım malzemeleri; düşük veya orta düzeyde yatırım maliyetleri, yaygın bulunabilirlikleri ve mevcut yapı teknolojileriyle uyumlulukları nedeniyle bina enerji verimliliğinin temel bileşenleri olmaya devam etmektedir (Asdrubali et al., 2024). Buna karşılık aerogel bazlı yüksek performanslı yalıtım malzemeleri, çok düşük ısıl iletkenlikleri sayesinde özellikle tarihi yapıların yenilenmesi ve yapı kalınlığının sınırlı olduğu uygulamalarda avantaj sağlamakta, ancak yüksek maliyetleri yaygın kullanım açısından önemli bir sınırlama oluşturmaktadır (Jelle et al., 2015). Biyobazlı yalıtım malzemeleri ise yenilenebilir hammadde kullanımı ve düşük gömülü karbon potansiyelleriyle öne çıkarken, nem davranışı, yangın güvenliği ve dayanıklılık gibi konuların geliştirilmesi gerekmektedir (Ye et al., 2025).

FDM'ler, geleneksel yalıtım malzemelerinden farklı olarak ısıyı gizli ısı biçiminde depolayarak iç ortam sıcaklık dalgalanmalarını azaltabilmekte ve özellikle günlük sıcaklık değişimlerinin belirgin olduğu koşullarda ısıtma ve soğutma yüklerinin ötelenmesine katkı sağlamaktadır (Kalnæs & Jelle, 2015; Kurdi et al., 2021). Pencere teknolojilerinde Low-e camlar daha olgun ve yaygın bir seçenek olurken, elektrokromik akıllı camlar güneş ışınımı ve ışık geçirgenliğini dinamik olarak kontrol ederek daha gelişmiş bir enerji yönetimi sağlayabilmektedir (Li & Wu, 2025; Zhao et al., 2025). Bununla birlikte akıllı camlarda ilk yatırım maliyeti, dayanıklılık, uzun dönemli optik performans ve kontrol sistemleriyle entegrasyon gibi hususlar dikkate alınmalıdır. BIPV sistemleri ise enerji tüketimini azaltmanın yanı sıra yenilenebilir elektrik üretimine olanak sağlayarak enerji verimliliği ile enerji üretimini aynı yapı elemanında birleştirmektedir (Faes et al., 2025; IEA PVPS, 2025). Bu sistemlerin değerlendirilmesinde modül veriminin yanı sıra yapı elemanına entegrasyon biçimi, gölgeleme koşulları, modül sıcaklığı ve binanın toplam enerji performansı da dikkate alınmalıdır.

Sonuç olarak, enerji tasarrufu sağlayan yapı malzemelerinin seçiminde yalnızca kısa vadeli enerji kazancına odaklanmak yerine teknik performans, ekonomik uygulanabilirlik, yaşam döngüsü etkileri ve çevresel sürdürülebilirliğin birlikte değerlendirilmesi gerekmektedir. Geleceğin enerji verimli binalarında tek bir malzemeye dayalı çözümler yerine geleneksel yalıtım malzemelerinin aerogel, biyobazlı malzemeler, FDM, Low-e veya akıllı cam ve BIPV gibi ileri teknolojilerle uygun biçimde birleştirildiği çok katmanlı, hibrit ve iklim duyarlı yapı elemanı sistemlerinin daha etkin bir yaklaşım oluşturacağı değerlendirilmektedir.

7. SONUÇ

Bu çalışmada enerji tasarrufu sağlayan yapı malzemeleri; ısıl yalıtım, enerji depolama, güneş kazancı kontrolü, akıllı yapı elemanları ve enerji üretimi perspektiflerinden değerlendirilmiştir. Elde edilen sonuçlar aşağıda sıralanmıştır:

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1. Yapı kabuğu, bina enerji performansının temel belirleyicilerinden biri olup duvar, çatı, döşeme ve pencere sistemlerinin ısıl özelliklerinin iyileştirilmesi, ısıtma ve soğutma enerji ihtiyacının azaltılmasında temel bir stratejidir.

2. Geleneksel ısı yalıtım malzemeleri, enerji verimli yapıların en yaygın ve uygulanabilir çözümünü oluşturmaktadır. Ancak yalnızca malzeme seçimi değil, yalıtım sürekliliği ve ısı köprülerinin önlenmesi de kritik öneme sahiptir.

3. Aerogel gibi yüksek performanslı yalıtım malzemeleri, düşük ısıl iletkenlikleri nedeniyle özellikle ince yapı elemanlarında önemli avantaj sağlamaktadır. Bununla birlikte maliyet ve mekanik özellikler yaygın kullanım açısından değerlendirilmelidir.

4. Biyobazlı yapı malzemeleri, enerji verimliliği ile düşük karbonlu yapı yaklaşımını birleştirme potansiyeline sahiptir. Gelecekte tarımsal atıkların ve yenilenebilir liflerin yalıtım malzemelerinde değerlendirilmesi döngüsel ekonomi açısından da önem kazanacaktır.

5. Faz değiştiren malzemeler, klasik yalıtım malzemelerinden farklı olarak ısı depolama işlevi sağlayarak iç ortam sıcaklığındaki dalgalanmaların azaltılmasına ve pik ısıtma/soğutma yüklerinin ötelenmesine katkıda bulunabilmektedir.

6. Low-e camlar ve akıllı camlar, özellikle yüksek cam oranına sahip binalarda enerji performansını önemli ölçüde etkileyebilecek malzeme teknolojileridir. Akıllı camların gelecekte bina otomasyon sistemleriyle daha fazla bütünleşmesi beklenmektedir.

7. BIPV sistemleri, yapı kabuğunun enerji tüketen pasif bir eleman olmaktan çıkarak enerji üreten aktif bir bileşene dönüşmesini sağlamaktadır.

8. Yapı malzemelerinin seçiminde yalnızca kullanım aşamasındaki enerji tasarrufu dikkate alınmamalı; gömülü enerji, gömülü karbon, üretim süreci, taşıma, dayanıklılık, bakım ve geri dönüşüm gibi yaşam döngüsü parametreleri de değerlendirilmelidir.

9. Türkiye açısından 2024 revizyonlu TS 825'in 2025 yılında zorunlu uygulamaya alınması, enerji tasarrufu sağlayan yapı malzemelerinin bina tasarımındaki önemini artırmıştır. Bu nedenle malzeme seçiminde iklim bölgesine bağlı ısıtma ve soğutma ihtiyaçlarının birlikte değerlendirilmesi gerekmektedir.

Sonuç olarak, enerji tasarrufu yapı malzemelerinin geleceği yalnızca daha düşük ısıl iletkenliğe sahip malzemelerin geliştirilmesine değil, yüksek performanslı yalıtım + ısı depolama + dinamik güneş kontrolü + enerji üretimi + düşük gömülü karbon bileşenlerinin aynı yapı sisteminde bütünleştirilmesine bağlıdır. Bu nedenle gelecekteki araştırmaların malzeme bazlı performans çalışmalarından bina ölçeğinde, yaşam döngüsü temelli ve çok kriterli performans değerlendirmelerine yönelmesi önerilmektedir.

TEŞEKKÜR

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COMPARATIVE ANALYSIS OF SUSTAINABILITY STANDARDS IN THE TOURISM SECTOR

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ABSTRACT

In the tourism sector, sustainability has become a critical agenda item due to increasing awareness of environmental issues, stringent legal regulations, competitive market pressure, and changing tourist expectations. Simultaneously, all accommodation facilities, ranging from hotels and motels to large-scale resorts, are experiencing considerable pressure to transform in order to optimise resource consumption, minimise carbon footprint, and contribute positively to local socio-economic ecosystems. In response to these pressures and demands, various certification systems have been developed to encourage and standardise sustainable practices in accommodation enterprises. These certification systems employ a variety of sustainability indicators to evaluate environmental, socio-cultural and economic performance. However, similarities and differences between these indicators have not been sufficiently examined.

The objective of this study is to examine the fundamental sustainability criteria for accommodation facilities, to identify common and differing approaches among certification systems, and to highlight the strengths and weaknesses of Türkiye's national sustainability criteria. To this end, a comparative analysis is conducted between an international benchmark and Türkiye's national regulatory framework. In this context, the Türkiye Sustainable Tourism Industry Criteria (TR-I) and the GSTC Industry Criteria are investigated. The indicators are examined according to four sustainability dimensions: sustainable management, socio-economic impacts, cultural impacts and environmental impacts. Additionally, the comparative analysis evaluates how these two certification systems define, measure and verify their sustainability indicators in practice.

The findings reveal a high degree of structural alignment between the Turkish national standard and the international framework, particularly in environmental management systems. The main differences between the two systems are found in their scope of application and in the way compliance is organised, rather than in the content of the criteria themselves.

Keywords: Sustainable tourism, sustainability indicators, tourism certification, TR-I, GSTC, accommodation sector, environmental criteria.

1. INTRODUCTION

Tourism is an important sector for many national economies, but it also creates pressure on the environment. Accommodation facilities are a central part of this problem. Hotels use large amounts of energy and water, and they produce wastewater, solid waste and greenhouse gas emissions. Because these amounts can be measured directly, hotels are usually the first place where sustainability rules are applied in the tourism sector.

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Certification is the main tool used to apply these rules. Over the last thirty years many eco-labels and certification systems have been developed for accommodation facilities, and each system defines its own criteria and indicators. Certification sets common expectations in a sector with many small businesses. It also gives information to guests who care about the environment, and it allows public authorities to guide the sector without regulating daily operations directly (Dias et al., 2024).

However, the large number of certification systems has also created a new problem. When several standards apply to the same hotel with different wording and different control methods, it becomes difficult to compare them. Rodríguez-García et al. (2023) examined twelve certifications used by large hotel chains and found important differences in how the three pillars of sustainability were included. Elhoushy et al. (2025) reviewed ninety-three studies and concluded that research on certification has focused mainly on why companies join these systems, and much less on the content of the standards. Miller and Torres-Delgado (2023) also found that sustainability indicators often measure procedures rather than results.

Türkiye is an interesting case in this field. In 2022 the Ministry of Culture and Tourism and the Türkiye Tourism Promotion and Development Agency (TGA) published the Türkiye Sustainable Tourism Industry Criteria (TR-I). These criteria are based on the criteria of the Global Sustainable Tourism Council (GSTC), but they are applied as a national requirement (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022). Although TR-I is now an important national instrument, its content has not been compared systematically with the framework on which it is based. Some studies in Türkiye have examined how certified hotels present sustainability on their websites (Türkay, 2024) and how national eco-labels affect environmental strategy in hotels (Yayla et al., 2024). However, these studies do not analyse the criteria documents themselves.

This study therefore compares TR-I with the GSTC Industry Criteria. It first describes what each system contains, and then examines their similarities and differences in terms of purpose, scope, structure, criteria and indicators, and the way compliance is organised. The analysis is based on the two original criteria documents.

2. TURKIYE'S TR-I SUSTAINABLE TOURISM CRITERIA

The Türkiye Sustainable Tourism Industry Criteria (TR-I) are the national sustainable tourism standard of Türkiye. They were developed under the guidance of the Ministry of Culture and Tourism and TGA, in cooperation with the tourism industry and international institutions (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022).

The purpose of TR-I is to ensure the sustainable growth of the Turkish tourism industry. It also aims to develop a common understanding about Turkish tourism with the participation of all tourism stakeholders. The standard is intended to help Türkiye use the natural, cultural and social resources of tourism while keeping a balance between protection and utilisation, so that these resources are not put at risk (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022).

TR-I was developed to be implemented by accommodation facilities and tour operators. It contains both criteria that comply with the social and cultural structure of Türkiye and globally recognised sustainable tourism criteria. The document lists several intended uses of the standard, of which the following are the most relevant for this study (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022):

- It serves as the basis for the certification of Türkiye Sustainable Tourism Criteria across the country.
- It provides basic guidelines for enterprises of all sizes that wish to become more sustainable.
- It aims to increase awareness of sustainable tourism among Turkish society, visitors, the tourism industry and investors.
- It contributes to the obligations of Türkiye arising from the Paris Agreement on Climate Change and the European Green Deal.
- It aims to increase the competitiveness of Türkiye in the growing global tourism market.

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TR-I is organised under four main themes: sustainable management, socio-economic impacts, cultural impacts and environmental impacts. These four themes form Sections A to D of the criteria document. Each section contains a number of criteria, and each criterion is supported by lettered performance indicators that describe the evidence an enterprise is expected to provide. Counting the criteria at the level at which the indicators are attached, the document contains 42 criteria and 167 performance indicators.

The document is clear about the role of the criteria. It states that the criteria indicate what should be done, but not how to do it or whether the goal has been achieved. What is required, and how to comply with the criteria, is defined by the performance indicators, the associated educational materials and the tools for implementation. These are further specified in a Handbook prepared by TGA for the industry (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022).

Compliance with TR-I is not voluntary. The Ministry of Culture and Tourism requires the entire Turkish tourism industry to adhere to all of the criteria. An exception is possible only when there is a valid reason showing that a criterion is irrelevant for a specific condition. Exceptional conditions and other rules are identified by the Ministry and communicated transparently to industrial stakeholders and the public. The document also states that compliance with TR-I will only be achieved on the basis of the criteria specified in the document itself (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022).

A further feature of TR-I is that implementation is organised in stages. The criteria tables include a stage column, and the performance indicators are marked as belonging to Stage 1, Stage 2 or Stage 3. In this way the standard shows which requirements apply at each level of implementation, so that enterprises can move towards full compliance step by step (T.C. Kültür ve Turizm Bakanlığı & TGA, 2022).

3. The Global Sustainable Tourism Council (GSTC) Criteria

The Global Sustainable Tourism Council (GSTC) is the international body that provides guidance for the development of sustainability standards for tourism. The GSTC Criteria were created in order to provide a common understanding of sustainable tourism (GSTC, 2016).

The version used in this study is the GSTC Industry Criteria, Version 3, dated 21 December 2016, published together with suggested performance indicators for hotels and accommodation providers. The criteria are organised around four main topics: sustainable management, socio-economic impacts, cultural impacts and environmental impacts. According to the document, these topics are applicable to the tourism sector as a whole (GSTC, 2016).

The GSTC Criteria were developed and revised in the process of complying with the Standard-Setting Code of the ISEAL Alliance. This body is recognised as providing guidance on international norms for the development of sustainability standards in all sectors. The criteria are reviewed every three to five years, and information about revision plans and public participation is published on the GSTC website (GSTC, 2016).

The document also lists several uses of the criteria. The following are the most relevant for this study (GSTC, 2016):

- They form the basis for sustainability certification.
- They serve as basic guidelines for enterprises of all sizes that wish to become more sustainable.
- They help consumers to identify sustainable tourism programmes and sustainable enterprises.
- They ensure that certification and other voluntary programme standards meet a widely accepted basis.
- They offer a starting point for government, non-governmental and private sector programmes.

As in TR-I, the GSTC document separates criteria from indicators. It states that the criteria tell what should be done, but not how it should be done or whether the goals have been achieved. This role is fulfilled by the performance indicators, the associated educational materials and the implementation tools, which the document describes as an indispensable complement to the criteria. The performance

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indicators are designed to provide guidance in measuring compliance with the GSTC Criteria for hotels, and this set is updated periodically (GSTC, 2016).

Regarding application, the document recommends that all criteria should be applied. An exception is possible where it can be shown with justification that a criterion is not valid for a particular situation. The document notes that local regulations and environmental, social, economic or cultural conditions may make some criteria inapplicable to a specific tourism product. It also accepts that limited resources may prevent the full application of all criteria in micro-scale or publicly owned enterprises with a small footprint (GSTC, 2016).

4. COMPARISON OF THE CERTIFICATION SYSTEMS

This study compared two documents prepared by the GSTC, the Ministry of Culture and Tourism, and the TGA. The documents were compared based on aspects such as the publishing institution/organization, purpose and scope, main headings, structure, relationships, implementation stages, supporting tools, and revisions. The results are summarized in Table 1. The relationship between the two systems is stated directly in the national document. TR-I explains that the process of developing the criteria was designed to adhere to the criteria of the GSTC. In this context, TR-I has adopted all GSTC criteria for Industry as they have been introduced by GSTC. The two documents are therefore not two independent standards that happen to be similar. TR-I is a national standard that is built on the GSTC Industry Criteria.

This explains the first and most important similarity. Both documents are organised under the same four themes: sustainable management, socio-economic impacts, cultural impacts and environmental impacts. Both also use the same two-level structure, in which each criterion is supported by lettered performance indicators. The alignment between the two systems is therefore structural, and not only general.

A second similarity concerns the way both documents describe the function of their criteria. Both state that the criteria indicate what should be done, but not how it should be done or whether the goal has been achieved. Both also explain that this role is fulfilled by performance indicators, educational materials and implementation. TR-I adds one further element, namely the Handbook prepared by TGA. Both documents are revised on a similar cycle of three to five years, and TR-I states that its revision follows the updating period of the GSTC criteria.

The differences are found mainly outside the criteria themselves. The clearest difference concerns application. The GSTC document recommends that all criteria should be applied, unless a justified reason shows that a criterion is not valid for a particular situation. It also accepts that micro-scale enterprises with limited resources may not be able to apply all criteria. TR-I, by contrast, states that the Ministry requires the entire Turkish tourism industry to adhere to all of the criteria, and that exceptional conditions are identified by the Ministry itself. Both systems therefore allow exceptions. However, in GSTC the enterprise justifies them, while in TR-I the responsible authority defines them.

A second difference concerns scope. The GSTC document used in this study presents the Industry Criteria together with performance indicators for hotels and accommodation providers, while stating that the four main topics are applicable to the tourism sector as a whole. TR-I states that it was developed to be implemented by accommodation facilities and tour operators.

A third difference is the staged structure of TR-I. The Turkish criteria tables include a stage column in which the performance indicators are marked as Stage 1, Stage 2 or Stage 3, so that the standard shows which requirements apply at each level of implementation. The GSTC document does not contain a comparable mechanism, and presents the criteria as a single set to be applied. This staged approach can be understood as a way of introducing a national standard gradually across an entire industry.

A fourth difference concerns purpose. Both documents describe similar uses, such as forming a basis for certification, guiding enterprises of all sizes and supporting education. However, the GSTC Criteria are presented as an international reference that supports certification programmes worldwide. TR-I is presented as a national instrument that also serves national policy aims, including the obligations of Türkiye arising from the Paris Agreement and the European Green Deal.

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Finally, both systems rely on similar kinds of evidence. Many indicators are satisfied by documents such as policies, records and plans, while a smaller number require a measured value, such as a consumption figure per guest-night. In the TR-I document, the authors' classification of the 167 indicators shows that only a small proportion require a measurement. Because TR-I adopted the GSTC criteria without modification, this characteristic is shared by both systems rather than being specific to Türkiye.

Table 1. Comparison of TR-I and the GSTC Industry Criteria

Aspect	TR-I (2022)	GSTC Industry Criteria v3 (2016)
Publisher	Ministry of Culture and Tourism and TGA, Türkiye	Global Sustainable Tourism Council
Purpose	National standard for the sustainable growth of Turkish tourism	International reference giving a common understanding of sustainable tourism
Scope	Accommodation facilities and tour operators	Hotels and accommodation; four themes applicable to the whole tourism sector
Main themes	Sustainable management; socio-economic; cultural; environmental impacts	Same four themes
Structure	Criteria with lettered performance indicators	Criteria with lettered performance indicators
Relationship	Adopts all GSTC criteria for Industry as introduced by GSTC	Source standard on which TR-I is based
Application	Required by the Ministry for the entire Turkish tourism industry	Recommended, unless justified as not applicable
Exceptions	Identified by the Ministry and communicated transparently	Justified by the enterprise; limited resources recognised for micro-scale enterprises
Stages	Indicators marked as Stage 1, Stage 2 or Stage 3	No staged structure
Supporting tools	Performance indicators, educational materials, implementation tools and the TGA Handbook	Performance indicators, educational materials and implementation tools
Revision	Every 3–5 years, following the GSTC updating period	Every 3–5 years

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5. RESULTS AND CONCLUSION

This study compared the sustainability criteria applied to accommodation facilities in Türkiye with the international framework on which they are based. The Türkiye Sustainable Tourism Industry Criteria and the GSTC Industry Criteria were examined using the original criteria documents.

Three main results were obtained which are as follows: First, TR-I is organised under four themes and contains 42 criteria and 167 performance indicators. The environmental section is the largest and the cultural section is the smallest. Second, the structural alignment with the GSTC framework is complete rather than partial, because TR-I adopted the GSTC Industry criteria as they were introduced by GSTC. The two documents share the same four themes, the same two-level structure of criteria and indicators, and the same understanding of what criteria and indicators are for. Third, the differences between the two systems are found in the way the standard is applied rather than in its content. TR-I is required by the Ministry for the whole Turkish tourism industry, it covers tour operators as well as accommodation facilities, it organises its indicators in three implementation stages, and it is supported by a national handbook prepared by TGA.

These results have practical implications. As the TR-I criteria are identical to the GSTC criteria, the quality of certification in Turkey depends primarily on how the criteria are applied and controlled, rather than their content. Both systems rely largely on documentary evidence, and only a small number of indicators require a measured value. Improving the framework would therefore not require new criteria, but rather clearer measurable targets inside the criteria that already exist, especially in the management and cultural sections.

Two subjects are suggested for future research. The first is an examination of how the three implementation stages work in practice, and in particular which requirements enterprises meet at each stage. The second is an analysis of the future revision of TR-I, since the document states that it will be revised in line with the updating period of the GSTC criteria.

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SAĞLIK ÇALIŞANLARININ YAPAY ZEKAYA YÖNELİK KAYGI, OKURYAZARLIK, ÖZ YETERLİK VE HAZIRBULUNUŞLUK DÜZEYLERİNİN İNCELENMESİ

ARTIFICIAL INTELLIGENCE ANXIETY, LITERACY, SELF-EFFICACY, AND READINESS AMONG HEALTHCARE WORKERS

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ÖZET

Bu araştırmanın amacı, sağlık çalışanlarının yapay zekaya (YZ) yönelik kaygı, okuryazarlık, öz yeterlik ve tıbbi YZ hazırbulunuşluk düzeylerini incelemek ve bu değişkenler arasındaki ilişkileri değerlendirmektir. Tanımlayıcı, ilişki arayıcı ve kesitsel tasarımdaki araştırma, Türkiye'de farklı meslek gruplarında görev yapan 341 sağlık çalışanıyla yürütülmüştür. Veriler çevrim içi olarak Yapay Zeka Kaygı Ölçeği, Yapay Zeka Okuryazarlık Ölçeği, Yapay Zeka Öz Yeterlik Ölçeği ve Tıbbi Yapay Zeka Hazırbulunuşluk Ölçeği kullanılarak toplanmıştır. Katılımcıların YZ kaygısının düşük-orta aralıkta; YZ okuryazarlığı, öz yeterliği ve tıbbi YZ hazırbulunuşluğunun ise orta düzeyde olduğu belirlenmiştir. Tıbbi YZ hazırbulunuşluğu, YZ okuryazarlığı ve öz yeterlikle pozitif; YZ kaygısıyla negatif yönde ilişkili bulunmuştur. YZ okuryazarlığı ile öz yeterliğin tıbbi YZ hazırbulunuşluğunu destekleyen değişkenler olduğu görülmüştür. Sağlık çalışanlarının YZ teknolojilerine güvenli ve etkili uyumunu artırmak için okuryazarlık, uygulama deneyimi, etik farkındalık ve eleştirel değerlendirme becerilerini birlikte geliştiren eğitim programlarına gereksinim bulunmaktadır.

Anahtar kelimeler: Yapay zekâ, kaygı, yapay zekâ okuryazarlığı, öz yeterlik, hazırbulunuşluk, sağlık çalışanları.

ABSTRACT

This study aimed to examine healthcare workers' artificial intelligence (AI) anxiety, literacy, self-efficacy, and readiness for medical AI and to evaluate the relationships among these variables. The descriptive, correlational, cross-sectional study included 341 healthcare workers from different professional groups in Türkiye. Data were collected online using the Artificial Intelligence Anxiety Scale, Artificial Intelligence Literacy Scale, Artificial Intelligence Self-Efficacy Scale, and Medical Artificial Intelligence Readiness Scale. Participants demonstrated low-to-moderate AI anxiety and moderate AI literacy, self-efficacy, and medical AI readiness. Medical AI readiness was positively associated with AI literacy and self-efficacy and negatively associated with AI anxiety. AI literacy and self-efficacy emerged as variables supporting readiness for medical AI. Educational programs that integrate AI literacy, hands-on experience, ethical awareness, and critical appraisal skills are needed to facilitate healthcare workers' safe and effective adaptation to AI technologies.

Keywords: Artificial intelligence, anxiety, artificial intelligence literacy, self-efficacy, readiness, healthcare workers.

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GİRİŞ

Yapay zekâ (YZ), öğrenme, örüntü tanıma, problem çözme ve karar desteği gibi işlevlerin bilgisayar sistemleri tarafından yürütülmesini sağlayan yöntemleri kapsamaktadır. Makine öğrenmesi ve derin öğrenmedeki gelişmelerle YZ; tıbbi görüntüleme, risk tahmini, klinik karar desteği ve kişiselleştirilmiş bakımda giderek daha fazla kullanılmaktadır (Secinaro et al., 2021). Ancak teknik performansın klinik yarara dönüşmesi; verinin niteliğine, sistemin açıklanabilirliğine, hasta güvenliğine ve sağlık çalışanlarının çıktıları doğru yorumlayabilmesine bağlıdır (Tavares, 2024).

Sağlık çalışanları YZ sistemlerinin temel kullanıcıları ve denetleyicileri olduğundan, bu teknolojilerin benimsenmesi yalnızca altyapıya değil, çalışanların kaygılarına ve yeterliklerine de bağlıdır. YZ kaygısı; yeni sistemleri öğrenme, mesleki rollerin değişmesi, kontrol kaybı, veri mahremiyeti ve etik belirsizliklere ilişkin endişeleri içerebilir. YZ okuryazarlığı, sistem çıktılarının anlamını, sınırlılıklarını ve yanlılık kaynaklarını değerlendirebilme yeterliğini; öz yeterlik ise YZ araçlarıyla etkili biçimde çalışabileceğine ilişkin inancı ifade etmektedir (Wang & Chuang, 2023). Tıbbi YZ hazırbulunuşluğu ise bilgi, beceri, öngörü ve etik boyutlarıyla bu teknolojileri mesleki uygulamaya aktarabilme durumunu göstermektedir (Karaca et al., 2021).

Hemşirelik ve ebelik dâhil sağlık mesleklerinde YZ kullanımının yaygınlaşması, çalışanların hazır oluşunu etkileyen bu değişkenlerin birlikte incelenmesini gerekli kılmaktadır. Sağlık çalışanlarının YZ geliştirme ve uygulama süreçlerine katılımı, sistemlerin bakım gereksinimlerine uygunluğunu ve kullanıcı kabulünü güçlendirebilir (O'Connor et al., 2023). Bu araştırmada sağlık çalışanlarının YZ kaygısı, okuryazarlığı, öz yeterliği ve tıbbi YZ hazırbulunuşluğu birlikte değerlendirilerek değişkenler arasındaki ilişkilerin belirlenmesi amaçlanmıştır.

ARAŞTIRMA VE BULGULAR

Araştırmanın tasarımı ve katılımcılar

Araştırma tanımlayıcı, ilişki arayıcı ve kesitsel tasarımda yürütülmüştür. Araştırmanın evrenini Türkiye'de kamu hastanelerinde görev yapan sağlık çalışanları oluşturmuştur. Veriler Ocak-Haziran 2025 tarihleri arasında çevrim içi anket yoluyla ve kartopu örnekleme yöntemiyle toplanmıştır. Çalışmaya 390 kişi katılmış; uygunluk değerlendirmesi ve veri kontrolü sonrasında analizler 341 sağlık çalışanının verisiyle gerçekleştirilmiştir. Katılım gönüllülük esasına dayanmış ve çevrim içi bilgilendirilmiş onam alınmıştır.

Veri toplama araçları

Veri toplamada araştırmacılar tarafından hazırlanan kişisel bilgi formu ile dört ölçme aracı kullanılmıştır. Yapay Zekâ Kaygı Ölçeği; öğrenme, iş değişimi, sosyo-teknik körlük ve YZ yapılandırılmasıyla ilişkili kaygıları değerlendirmektedir (Wang & Wang, 2019; Akkaya et al., 2021). Yapay Zekâ Okuryazarlık Ölçeği farkındalık, kullanım, değerlendirme ve etik boyutlarından oluşmaktadır (Wang et al., 2023; Polatgil & Güler, 2023). Yapay Zekâ Öz Yeterlik Ölçeği bireylerin YZ ile etkileşim kurma ve teknolojik görevleri yerine getirme konusundaki yeterlik algısını değerlendirmektedir (Wang & Chuang, 2023; Uyan & Gültekin, 2024). Tıbbi Yapay Zekâ Hazırbulunuşluk Ölçeği ise bilişsel yeterlik, beceri, öngörü ve etik hazır oluşu kapsamaktadır (Karaca et al., 2021). Ölçeklerin bu araştırmadaki iç tutarlılık katsayıları kabul edilebilir ve yüksek düzeyde bulunmuştur.

Verilerin değerlendirilmesi ve etik ilkeler

Verilerin değerlendirilmesinde tanımlayıcı istatistikler, bağımsız gruplarda t testi, tek yönlü varyans analizi, Pearson korelasyon analizi ve basit doğrusal regresyon analizleri kullanılmıştır. İstatistiksel anlamlılık düzeyi $p<0.05$ olarak kabul edilmiştir. Araştırma için Atatürk Üniversitesi Girişimsel Olmayan Klinik Araştırmalar Etik Kurulundan onay alınmıştır (Toplantı No: 9, Karar No: 42). Katılımcılardan kimlik bilgisi toplanmamış; gizlilik, anonimlik ve istedikleri zaman araştırmadan çekilme hakları korunmuştur.

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Bulguların genel görünümü

Katılımcıların %72.1'i kadın ve %43.1'i hemşiredir. Genel değerlendirmede sağlık çalışanlarının YZ'ye yönelik kaygılarının düşük-orta aralıkta; YZ okuryazarlığı, YZ öz yeterliği ve tıbbi YZ hazırbulunuşluklarının orta düzeyde olduğu belirlenmiştir. Bu değişkenlerin bazı kişisel, mesleki ve YZ kullanımına ilişkin özelliklere göre farklılaştığı görülmüştür. Değişkenler arasındaki ilişkiler incelendiğinde, tıbbi YZ hazırbulunuşluğunun YZ okuryazarlığı ve öz yeterlikle pozitif, YZ kaygısıyla ise negatif yönde ilişkili olduğu saptanmıştır. Ayrıca YZ okuryazarlığı ve öz yeterliğin tıbbi YZ hazırbulunuşluğunu pozitif yönde desteklediği belirlenmiştir. Bu genel örüntü, hazır oluşun bilişsel, duygusal ve davranışsal bileşenlerle birlikte ele alınması gerektiğine işaret etmektedir.

Bulguların literatür bağlamında değerlendirilmesi

Sağlık çalışanlarında YZ'ye ilişkin kaygının tamamen ortadan kalkmamış olması, klinik kullanımın teknik olduğu kadar duygusal ve etik bir uyum süreci gerektirdiğini göstermektedir. Kaygı, yeni bir sistemi öğrenme yükünün yanı sıra mesleki rollerin değişmesi, hasta güvenliği, algoritmik kararların şeffaflığı ve sorumluluk paylaşımıyla da ilişkili olabilir. Hemşirelerle yürütülen çalışmalar, dijital liderlik ve kurumsal desteğin YZ'ye yönelik kaygı ve tutum üzerinde etkili olabileceğine işaret etmektedir (Tarsuslu et al., 2024). Cinsiyet temelli teknoloji deneyimleri ve YZ kaygısı arasındaki ilişkilerin de eğitim ve destek programları geliştirilirken dikkate alınması önerilmektedir (Russo et al., 2025).

Tıbbi YZ hazırbulunuşluğunun okuryazarlık ve öz yeterlikle birlikte artması, yalnızca bilgi aktarımına dayalı eğitimlerin yeterli olmayacağını düşündürmektedir. Sağlık çalışanları YZ'nin temel çalışma mantığını bilmeli; aynı zamanda gerçek veya simüle klinik örneklerde çıktı yorumlama, hata olasılığını değerlendirme ve gerektiğinde sistem önerisini reddetme deneyimi kazanmalıdır. Sağlık çalışanlarının YZ geliştirme süreçlerine katılması, teknolojiye duyulan güveni ve kullanıma yönelik kabulü güçlendirebilmektedir (Huo et al., 2023). Dolayısıyla hazırbulunuşluk, bilgi, beceri, deneyim ve kurumsal destek bileşenlerinin birlikte ele alınmasını gerektiren çok boyutlu bir yapıdır.

Hazırbulunuşluk ile kaygı arasındaki ters yönlü ilişki, teknolojiye ilişkin aşinalığın ve uygulama kapasitesinin duygusal uyumu destekleyebileceğini göstermektedir. Yenidoğan yoğun bakım hemşirelerinde yapılan bir araştırmada YZ'ye ilişkin kaygı ve hazırbulunuşluğun birlikte değerlendirilmesi gerektiği bildirilmiştir (Ünal & Avcı, 2024). Ebe ve hemşirelerde yürütülen güncel çalışmalar da mesleki kuşak, deneyim ve teknolojiyle etkileşimin kaygı-hazırbulunuşluk ilişkisi bakımından önemli olabileceğine işaret etmektedir (Yilmaz et al., 2025). Bununla birlikte kesitsel tasarım nedeniyle bu araştırmada değişkenler arasında neden-sonuç ilişkisi kurulamaz; daha yüksek hazırbulunuşluğun kaygıyı azalttığı ya da daha düşük kaygının hazırbulunuşluğu artırdığı yönünde kesin bir yorum yapılamaz.

Klinik uygulama ve eğitim açısından çıkarımlar

Sağlık kurumlarında YZ eğitimleri, tek seferlik ve yalnızca teknik kullanım odaklı etkinlikler yerine, kademeli ve uygulama temelli programlar olarak yapılandırılmalıdır. Başlangıç düzeyinde temel kavramlar, veri kalitesi, mahremiyet ve algoritmik yanlılık ele alınmalı; sonraki aşamalarda klinik senaryolar üzerinden çıktıların doğrulanması, belirsizliğin yorumlanması, hasta ve ekip iletişimi ile sorumluluk sınırları çalışılmalıdır. Kullanıcının sistemi sorgulayabilmesi, YZ okuryazarlığının temel göstergelerinden biri olarak kabul edilmelidir. Bu yaklaşım, teknolojiye ilişkin gerçekçi güvenin gelişmesini ve otomasyon yanlılığı riskinin azaltılmasını destekleyebilir.

Hemşirelik ve ebelik eğitimlerinde YZ konularının müfredata dâhil edilmesi, gelecekteki iş gücünün hazır oluşunu artırabilir. Ebelik eğitiminde YZ'nin etkilerini inceleyen çalışmalar, teknik içeriğin bakım ilişkisi, etik karar verme ve mesleki sorumlulukla birlikte ele alınması gerektiğini vurgulamaktadır (Kranz & Abele, 2024). Kurumlar ayrıca çalışanların kaygılarını açıkça ifade edebileceği, hata ve güvenlik bildirimlerinin cezalandırıcı olmayan bir yaklaşımla değerlendirileceği geri bildirim mekanizmaları kurmalıdır. Sağlık çalışanlarının teknoloji geliştirme, pilot uygulama ve değerlendirme süreçlerine erken aşamada katılması, sistemlerin iş akışına uygunluğunu ve hasta güvenliği açısından kullanılabilirliğini güçlendirebilir.

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YZ hazırbulunuşluğunu artırmaya yönelik müdahalelerin etkisi yalnızca bilgi testiyle değerlendirilmemelidir. Çalışanın sistemi doğru kullanabilmesi, hatalı veya belirsiz çıktıyı fark edebilmesi, öneriyi klinik bağlamla karşılaştırabilmesi ve hastaya anlaşılır biçimde açıklayabilmesi de ölçülmelidir. Kurumsal değerlendirmelerde iş yükü, uyarı yorgunluğu, mesleki özerklik, ekip iletişimi ve hasta deneyimi gibi sonuçlara yer verilmesi, teknik başarının gerçek klinik yarara dönüşüp dönüşmediğini göstermeye yardımcı olabilir.

Kurumsal yönetişim ve güvenli uygulama

YZ uygulamalarının güvenli biçimde kullanılabilmesi için kurumların yalnızca bir yazılım satın alması yeterli değildir. Sistemin hangi klinik amaçla kullanılacağı, çıktıyı kimin değerlendireceği, hata veya uyumsuzluk durumunda hangi yolun izleneceği ve nihai karar sorumluluğunun kimde olduğu açık biçimde tanımlanmalıdır. Model çıktısının öneri niteliğinde olduğu ve profesyonel değerlendirmeyi ortadan kaldırmadığı tüm kullanıcılara açıklanmalıdır. Ayrıca algoritmanın eğitim aldığı veri, hedef kullanıcı grubu, bilinen sınırlılıkları ve performansının azalabileceği koşullar erişilebilir biçimde sunulmalıdır. Açıklanabilirlik, sağlık çalışanının sisteme koşulsuz güvenmesi için değil; öneriyi klinik bulgularla karşılaştırabilmesi ve gerekçeli karar verebilmesi için gereklidir (Tavares, 2024).

Uygulama öncesinde küçük ölçekli pilot çalışmalar yürütülmesi ve kullanıcı geri bildirimlerine göre sistemin iş akışına uyarlanması önemlidir. Pilot değerlendirmelerde doğruluk göstergelerinin yanında yanlış uyarıların sıklığı, karar süresine etkisi, ek kayıt yükü, kullanıcı memnuniyeti ve hasta güvenliği göstergeleri izlenmelidir. Sağlık çalışanlarının tasarım ve değerlendirme süreçlerine katılması, gerçek bakım ortamındaki gereksinimlerin geliştiricilere aktarılmasını kolaylaştırabilir ve kullanıma yönelik kabulü artırabilir (Huo et al., 2023). Bu katılım, hemşire ve ebelerin yalnızca son kullanıcı olarak değil, bakımın niteliğini ve hasta deneyimini temsil eden profesyonel paydaşlar olarak sürece dâhil edilmesini gerektirir.

Mahremiyet ve eşitlik, YZ hazırbulunuşluğunun kurumsal boyutları arasında değerlendirilmelidir. Sağlık verilerinin hangi amaçla işlendiği, nerede saklandığı ve kimlerle paylaşılabileceği hem çalışanlara hem de hizmet alan bireylere açık biçimde anlatılmalıdır. Dijital altyapısı sınırlı kurumların veya teknoloji deneyimi daha az olan meslek gruplarının uygulama sürecinde geride kalması, mevcut eşitsizlikleri artırabilir. Bu nedenle eğitim ve teknik destek gereksinimi meslek grubu, görev alanı ve önceki deneyim dikkate alınarak belirlenmelidir. YZ uygulamalarının güvenli entegrasyonu; standart bir eğitim paketinden çok, kullanıcıların başlangıç düzeyine ve klinik sorumluluklarına göre uyarlanmış sürekli öğrenme yaklaşımını gerektirmektedir.

Gelecek araştırmalara yönelik öneriler

Gelecek araştırmalarda YZ okuryazarlığı, öz yeterlik, kaygı ve hazırbulunuşluğun zaman içindeki değişimi boylamsal tasarımlarla değerlendirilmelidir. Eğitim müdahalelerinin etkisini inceleyen deneysel çalışmalarda bilgi düzeyinin yanı sıra klinik senaryoda karar verme, algoritmik yanlılığı fark etme ve güvenli kullanım davranışları ölçülmelidir. Farklı meslek gruplarının ve kurum türlerinin yeterli sayıda temsil edildiği çok merkezli çalışmalar, kurumsal altyapı ile bireysel hazırbulunuşluk arasındaki etkileşimi açıklamaya katkı sağlayabilir. Nicel bulguların nitel görüşmelerle desteklenmesi ise sağlık çalışanlarının kaygı, güven ve sorumluluk algılarının daha ayrıntılı anlaşılmasını sağlayabilir.

Sınırlılıklar

Araştırmanın kesitsel tasarımı değişkenler arasında nedensellik kurulmasını engellemektedir. Kartopu örnekleme ve çevrim içi veri toplama, YZ teknolojilerine ilgi duyan veya dijital araçlara daha kolay erişebilen çalışanların araştırmaya katılımını artırmış olabilir. Verilerin öz bildirime dayanması sosyal beğenirlik ve hatırlama yanlılığına açıktır. Örneklemde kadınların ve belirli meslek gruplarının daha fazla temsil edilmesi sonuçların tüm sağlık çalışanlarına genellenmesini sınırlandırabilir. Ayrıca kurumların dijital altyapısı ve YZ uygulama deneyimi doğrudan değerlendirilmemiştir. Gelecek çalışmaların çok merkezli, boylamsal ve uygulama temelli tasarımlarla yürütülmesi önerilmektedir.

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SONUÇ

Sağlık çalışanlarının tıbbi YZ'ye hazır oluşu, yalnızca teknolojiye erişimle değil; YZ'yi anlama, çıktıları eleştirel biçimde değerlendirme ve bu sistemlerle çalışabileceğine inanma düzeyiyle ilişkilidir. Araştırmanın genel bulguları, YZ okuryazarlığı ve öz yeterliğin hazırbulunuşluğu desteklediğini; kaygının ise hazır oluşla ters yönde ilişkili olduğunu göstermektedir. Sağlık kurumları ve eğitim programları, teknik bilgi ile uygulama deneyimini, etik farkındalığı, veri güvenliğini ve insan denetimini bir araya getiren yapılandırılmış eğitimler geliştirmelidir. YZ, sağlık çalışanının klinik yargısının yerini alan bir sistem olarak değil; güvenli, açıklanabilir ve insan odaklı bakımı destekleyen bir araç olarak konumlandırılmalıdır.

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TALEP DEĞİŞKENLİĞİ VE STOK PERFORMANSI: PERAKENDE MAĞAZA OPERASYONLARINDAN KANITLAR

DEMAND VARIABILITY AND INVENTORY PERFORMANCE: EVIDENCE FROM RETAIL STORE OPERATIONS

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ÖZET

Perakende işletmelerinde talepte meydana gelen dalgalanmalar, stok yönetimi kararlarını zorlaştırarak stok yetersizlikleri, ürün bulunurluğu sorunları ve fire gibi operasyonel sonuçlara yol açabilmektedir. Bu çalışma, perakende mağaza operasyonlarında talep değişkenliği ile stok performansı arasındaki ilişkiyi ürün bazında incelemeyi amaçlamaktadır. Araştırmada stok performansı; fire oranı, stock-out oranı, raf boşluğu oranı ve stok devir hızı göstergeleri üzerinden değerlendirilmiştir. Bir perakende mağazasının dijital satış ve stok takip sistemlerinden elde edilen 44 SKU'ya ait 92 günlük operasyonel veri kullanılmış; taze gıda, gıda/içecek ve gıda dışı kategorileri kapsayan veriler SKU-ay düzeyinde düzenlenerek 132 gözlem oluşturulmuştur. Günlük satış miktarları talebin göstergesi olarak kabul edilmiş ve talep değişkenliği varyasyon katsayısı (CV) ile ölçülmüştür. Değişkenlerin dağılım özellikleri doğrultusunda ilişkilerin incelenmesinde Spearman sıra korelasyonu, ürün kategorilerinin karşılaştırılmasında Kruskal–Wallis testi ve Bonferroni düzeltmeli ikili karşılaştırmalar kullanılmıştır. Talep değişkenliğinin stock-out olasılığı üzerindeki bağımsız ilişkisi ise SKU düzeyindeki tekrarlı gözlemleri dikkate alan binomial-logit Genelleştirilmiş Tahmin Denklemleri (GEE) modeliyle analiz edilmiştir. Sonuçlar, talep değişkenliğinin ürün kategorilerine göre anlamlı biçimde farklılaştığını ve gıda dışı ürünlerde daha yüksek olduğunu göstermiştir. Buna karşılık fire oranı, stok devir hızı, stock-out oranı ve raf boşluğu oranı taze gıda ürünlerinde daha yüksek bulunmuştur. İkili korelasyonlarda talep değişkenliği ile stock-out arasında anlamlı ilişki görülmemesine rağmen, ürün kategorisi, ay, promosyon oranı ve fiyat endeksi kontrol edildiğinde CV'nin stock-out olasılığıyla pozitif ve anlamlı biçimde ilişkili olduğu belirlenmiştir (OR=3,165; p<0,001). CV ile ürün kategorisi arasındaki etkileşimin anlamlı olmaması (p=0,412), bu ilişkinin kategorilere göre anlamlı biçimde farklılaşmadığını göstermektedir. Sonuçlar, perakende stok yönetiminde talep değişkenliğinin tek başına değil, ürün kategorisinin operasyonel özellikleriyle birlikte değerlendirilmesi gerektiğine işaret etmekte ve SKU düzeyinde veri temelli stok kararları için uygulamaya dönük bulgular sunmaktadır.

Anahtar Kelimeler: Talep Değişkenliği, Stok Performansı, Perakende Stok Yönetimi, Stock-Out, SKU Düzeyinde Analiz.

ABSTRACT

Demand fluctuations in retail operations complicate inventory management decisions and may lead to operational problems such as stock shortages, product availability issues, and waste. This study examines the relationship between demand variability and inventory performance at the SKU level in retail store operations. Inventory performance is evaluated using waste rate, stock-out rate, shelf-out rate, and inventory turnover. The study uses 92 days of operational data for 44 SKUs obtained from the digital sales and inventory tracking systems of a retail store. The dataset covers fresh food, food/beverage, and non-food categories and was aggregated at the SKU-month level, yielding 132

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observations. Daily sales quantities were used as a proxy for demand, and demand variability was measured using the coefficient of variation (CV). Given the distributional characteristics of the variables, Spearman's rank correlation was used to examine bivariate relationships, while Kruskal–Wallis tests with Bonferroni-adjusted pairwise comparisons were employed to assess differences across product categories. The independent association between demand variability and stock-out probability was further examined using a binomial-logit Generalized Estimating Equations (GEE) model, accounting for repeated observations at the SKU level. The findings indicate that demand variability differs significantly across product categories and is higher for non-food products. In contrast, waste rate, inventory turnover, stock-out rate, and shelf-out rate are higher for fresh food products. Although the bivariate correlation between demand variability and stock-out was not significant, the GEE results showed that CV was positively and significantly associated with stock-out probability after controlling for product category, month, promotion intensity, and price index (OR=3.165, $p<0.001$). The interaction between CV and product category was not significant ($p=0.412$), indicating that the relationship between demand variability and stock-out did not differ significantly across product categories. The findings suggest that demand variability should be evaluated together with the operational characteristics of product categories and provide practical implications for SKU-level, data-driven inventory management decisions in retail operations.

Key Words: Demand Variability, Inventory Performance, Retail İnventory Management, Stock-Out, SKU-Level Analysis.

1. GİRİŞ

Envanter yönetimi tedarik zincirlerinin etkinliğinde stratejik bir öneme sahiptir (Kumar vd., 2024). Bu stratejik önem, ürün çeşitliliğinin ve talep dinamiklerinin yoğun olduğu perakende sektöründe daha da belirgin hâle gelmektedir. Perakende sektöründe yer alan işletmelerin yüksek çeşitliliğe sahip ürünlerinin envanter yönetimindeki en önemli güçlüklerden biri hiç şüphesiz talepteki değişkenliktir (Wong vd., 2006). Talep değişkenliği, tüketici davranışları, ekonomik koşullar, mevsimsellik, kampanyalar, rakip hareketleri, fiyat değişimleri ve beklenmeyen olaylar gibi birçok faktörden kaynaklanmaktadır. Talepte meydana gelen dalgalanmalar, işletmelerin güvenlik stoğu bulundurma ihtiyacını artırmakta ve stok maliyetleri ile hizmet seviyesi arasında denge kurulmasını zorlaştırmaktadır. Bu nedenle stok kontrol sistemlerinin başarısı için talep değişkenliğinin analizine ihtiyaç duyulmaktadır (Silver vd., 2017; Chopra & Meindl, 2019).

Talepte meydana gelen dalgalanmalar, işletmelerin stok düzeylerini talep ile uyumlu biçimde planlamasını ve kontrol etmesini güçleştirmektedir. Talep değişkenliği stok devir hızını düşürmekte, güvenlik stoğu gereksinimini artırmakta ve stokta bulunurluğu düşürerek stok performansını olumsuz etkilemektedir (Hançerlioğulları vd., 2016; Barros vd., 2021). Bununla birlikte yalnızca hizmet düzeyini değil, aynı zamanda stok kayıpları ve operasyonel maliyetler üzerinde de önemli sonuçlar doğurmaktadır. Bozulabilir ve modası hızla geçen ürün gruplarında talep tahmin hatalarının artması, fire oranlarının yükselmesine ve stokta değer kaybına bağlı maliyetlerin önemli ölçüde artmasına neden olmaktadır (Coniglio vd., 2018). Özellikle perakende sektöründe talep dalgalanmalarının neden olduğu rafta ürün bulunamama (out-of-stock) problemi hem satış kayıplarına hem de tüketicilerin alternatif markalara veya rakip mağazalara yönelmesine yol açarak işletme performansını azaltmaktadır.

Talep değişkenliğinin stok sistemleri üzerindeki etkileri, envanter yönetimi literatüründe farklı analitik ve ampirik yaklaşımlar kapsamında ele alınmaktadır. Özellikle talep belirsizliği ve değişkenliğinin dikkate alınmasının stok seviyelerinin dengelenmesi, stok maliyetlerinin azaltılması ve operasyonel performansın iyileştirilmesi açısından önemli olduğu ortaya konulmaktadır (Yang, 2023; Rumyantsev & Netessine, 2007; Chauhan vd., 2023). Örneğin, Rajagopalan (2013) talep değişkenliği, ürün çeşitliliği, mağaza sayısı ve mevsimsellik gibi faktörlerin perakende stokları üzerindeki etkilerini araştırmış; ürün çeşitliliği ve mağaza sayısının toplam stok üzerinde anlamlı etkileri bulunduğunu göstermiştir. Wan vd. (2020) ise ürün çeşitliliği ve talep değişkenliğinin stok devir hızı üzerindeki etkisini incelemiş ve ürün çeşitliliğinin stok devir hızını olumsuz etkilediğini, ancak bu etkinin talep değişkenliği azaldıkça zayıfladığını ortaya koymuştur. Benzer şekilde Sweeney ve diğerleri (2022), talep değişkenliğinin stok

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performansının önemli belirleyicilerinden biri olduğunu ve artan talep belirsizliğinin stok seviyeleri ile ürün bulunurluğu performansını olumsuz etkileyebildiğini göstermiştir.

Bununla birlikte, perakende literatüründeki çalışmaların önemli bir bölümü talep değişkenliğinin stok performansı ve stok devir hızı gibi firma veya mağaza düzeyindeki göstergeler üzerindeki etkilerine odaklanırken (Gaur vd., 2005; Gaur & Kesavan, 2008; Alan vd., 2014), SKU düzeyinde ve birden fazla stok performansı göstergesini birlikte ele alan ampirik çalışmalar daha sınırlı kalmaktadır (Sweeney vd., 2022). Bu çalışma, gerçek perakende mağaza verilerinden yararlanarak talep değişkenliğini SKU düzeyinde incelemekte ve fire oranı, stock-out oranı, raf boşluğu oranı ve stok devir hızını birlikte değerlendirmektedir. Ayrıca farklı ürün kategorileri arasındaki farklılıklar karşılaştırılmakta ve talep değişkenliğinin stock-out olasılığıyla olan bağımsız ilişkisi ürün kategorisi, ay, promosyon oranı ve fiyat endeksi kontrol edilerek analiz edilmektedir.

2. YÖNTEM

2.1. Veri Setinin Tasarımı

Bu çalışmada, talep değişkenliğinin stok performansı üzerindeki etkisinin belirlenmesi amacıyla bir organize perakende işletmesine ait gerçek mağaza operasyon verileri kullanılmıştır. Araştırma kapsamında mağazanın farklı ürün gruplarını temsil eden toplam 44 stok tutma birimi (Stock Keeping Unit–SKU) incelenmiştir. İncelenen ürünler; taze gıda (15 SKU), gıda/içecek (15 SKU) ve gıda dışı (14 SKU) olmak üzere üç ana kategori altında değerlendirilmiştir. Ürün seçiminde farklı alt ürün gruplarının temsil edilmesine dikkat edilmiş ve ilgili dönemde yüksek satış hacmine sahip SKU'lar esas alınmıştır. Analizlerde kullanılan ham veri seti, 92 günlük mağaza operasyon kayıtlarından oluşmaktadır. Böylece SKU-gün düzeyinde toplam 4.048 gözlemden (44 SKU × 92 gün) oluşan bir veri yapısı elde edilmiştir. Veri setinde günlük bazda satış miktarı, dönem başı ve dönem sonu stok miktarı, gün içi stok girişi (mal kabul), fire/atık miktarı, depo iade miktarı, stock-out durumu, raf boşluğu durumu, promosyon bilgisi ve birim satış fiyatı gibi operasyonel değişkenler yer almaktadır. Stock-out ve raf boşluğu değişkenleri günlük bazda ikili değişkenler (0=hayır, 1=evet) olarak kaydedilmiştir.

Talep değişkenliği ve stok performansı göstergelerinin hesaplanabilmesi amacıyla günlük veriler daha sonra SKU-ay düzeyinde toplanmıştır. Üç aylık dönem sonucunda her SKU için üç gözlem olmak üzere toplam 132 SKU-ay gözlemi elde edilmiştir. Günlük satış miktarları gerçekleşen talebin göstergesi olarak kullanılmış ve talep değişkenliği, her SKU-ay için günlük satışların standart sapmasının ortalama günlük satışa oranlanmasıyla hesaplanan varyasyon katsayısı (CV) ile ölçülmüştür. Stok performansı ise fire oranı, stock-out oranı, raf boşluğu oranı ve miktar bazlı stok devir hızı göstergeleri üzerinden değerlendirilmiştir.

Ticari gizliliğin korunması amacıyla işletme tarafından sağlanan miktarsal ve parasal veriler, işletme tarafından belirlenen bilinmeyen sabit bir katsayı kullanılarak ölçeklendirilmiştir. Aynı doğrusal ölçekleme işleminin ilgili değişkenlere tutarlı biçimde uygulanması; varyasyon katsayısı, oranlar, stok devir hızı ve göreli fiyat endeksi gibi araştırmada kullanılan temel göstergelerin değerlerini veya gözlemler arasındaki göreli ilişkileri değiştirmemektedir. Bu nedenle anonimleştirme işlemi çalışmada gerçekleştirilen istatistiksel analizlerin yorumlanmasını etkilememektedir. İşletmenin ERP sisteminden gelen veriler Microsoft Excel ile işlenmiş veri setine dönüştürülmüştür.

2.2. Değişkenlerin Belirlenmesi

Araştırmanın temel bağımsız değişkeni talep değişkenliğidir ve günlük satış miktarları talebin göstergesi olarak kullanılmıştır. Talep değişkenliği, her bir SKU-ay için günlük satışların standart sapmasının ortalama satışa oranlanmasıyla hesaplanan varyasyon katsayısı (CV) ile ölçülmüştür. Stok performansı ise fire oranı, stock-out oranı, raf boşluğu oranı ve stok devir hızı göstergeleri üzerinden değerlendirilmiştir. Ayrıca ürün kategorisi, ay, promosyon oranı ve fiyat endeksi kontrol değişkenleri olarak analizlere dahil edilmiştir.

2.3. Analiz

Araştırmadaki istatistiksel hesaplamalar IBM SPSS Statistics 32.0 aracı ile yapılmıştır. Öncelikle SKU-ay düzeyinde talep değişkenliği ve stok performansı göstergelerine ilişkin tanımlayıcı istatistikler

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hesaplanmıştır. Değişkenlerin normal dağılım göstermemesi nedeniyle talep değişkenliği ile fire oranı, stock-out oranı, raf boşluğu oranı ve stok devir hızı arasındaki ilişkiler Spearman sıra korelasyonu ile incelenmiştir. Ürün kategorileri arasındaki farklılıkların belirlenmesinde, aynı SKU'ya ait tekrarlı aylık gözlemlerin bağımsızlık varsayımını ihlal etmemesi amacıyla üç aylık değerler SKU düzeyinde toplulaştırılmış ve Kruskal–Wallis testi ile Bonferroni düzeltmeli ikili karşılaştırmalar uygulanmıştır.

Talep değişkenliğinin stock-out üzerindeki bağımsız ilişkisinin belirlenmesinde ise aynı SKU'ya ait tekrarlı gözlemleri dikkate alan binomial dağılımlı ve logit bağlantı fonksiyonlu Genelleştirilmiş Tahmin Denklemleri (Generalized Estimating Equations–GEE) modeli kullanılmıştır. Modelde talep değişkenliği (CV) temel bağımsız değişken olarak ele alınırken, ürün kategorisi, ay, promosyon oranı ve fiyat endeksi kontrol değişkenleri olarak modele dahil edilmiştir. Ayrıca CV ile ürün kategorisi arasındaki etkileşim test edilerek talep değişkenliğinin stock-out üzerindeki ilişkisinin kategorilere göre farklılaşıp farklılaşmadığı incelenmiştir. Tüm analizlerde istatistiksel anlamlılık düzeyi $p<0,05$ olarak kabul edilmiştir.

3. BULGULAR

Araştırmada kullanılan değişkenlere ilişkin tanımlayıcı istatistikler Tablo 1'de sunulmaktadır. Buna göre talep değişkenliğini gösteren CV'nin ortalama değeri 1,639 (s=0,881) olarak hesaplanmıştır. Stok performansı göstergeleri incelendiğinde, fire oranının ortalaması 0,019, stock-out oranının ortalaması 0,087 ve raf boşluğu oranının ortalaması 0,086 olarak bulunmuştur. Stok devir hızının ortalaması ise 3,577'dir

Tablo 1. Değişkenlere ilişkin tanımlayıcı istatistikler (N = 125)

Değişken	Ortalama	Std. Sapma	Medyan	Min.	Maks.	Çarpıklık	Basıklık
CV	1,639	0,881	1,442	0,474	4,094	0,841	0,027
Fire Oranı	0,019	0,064	0,000	0,000	0,412	4,692	24,007
Stok Devir Hızı	3,577	5,403	1,854	0,068	46,500	4,712	32,176
Stock-out Oranı	0,087	0,176	0,000	0,000	0,935	2,432	6,139
Raf Boşluğu Oranı	0,086	0,175	0,000	0,000	0,935	2,511	6,613

Fire oranı, stock-out oranı ve raf boşluğu oranına ilişkin medyan değerlerin sıfır olması, gözlemlerin önemli bir bölümünde bu göstergelerin gerçekleşmediğini göstermektedir. Ayrıca tüm performans göstergelerinde yüksek çarpıklık ve basıklık değerleri elde edilmiş olup, bu durum değişkenlerin normal dağılım göstermediğini göstermektedir. Değişkenlerin normal dağılım göstermemesi nedeniyle talep değişkenliği stok performansıyla nasıl ilişkili olduğunu anlamak amacıyla Spearman korelasyon analizi yapılmış ve sonuçları Tablo 2'de verilmiştir.

Tablo 2. Değişkenler Arasındaki Spearman Korelasyonları

Değişken	1	2	3	4	5
1. Talep değişkenliği (CV)	1				
2. Fire oranı	−0,403***	1			
3. Stok devir hızı	−0,590***	0.452***	1		
4. Stock-out oranı	0,005	0.167	0.504***	1	
5. Raf boşluğu oranı	0.002	0.161	0.508***	0.992***	1

***Anlamlı ilişkiler

Sonuçlara göre talep değişkenliği ile fire oranı arasında negatif ve orta düzeyde anlamlı bir ilişki ($\rho = -0,403; p < 0,001$), talep değişkenliği ile stok devir hızı arasında ise daha güçlü negatif bir ilişki ($\rho = -0,590; p < 0,001$) belirlenmiştir. Buna karşılık talep değişkenliği ile stock-out oranı ($\rho = 0,005; p = 0,959$) ve raf boşluğu oranı ($\rho = 0,002; p = 0,984$) arasında anlamlı ikili ilişki bulunmamıştır. Stock-out ve raf boşluğu oranları arasında ise oldukça yüksek pozitif korelasyon saptanmıştır ($\rho = 0,992; p < 0,001$).

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Spearman korelasyon analizinin ardından, talep değişkenliği ve stok performansı göstergelerinin ürün kategorilerine göre farklılaşıp farklılaşmadığını belirlemek amacıyla Kruskal–Wallis testi uygulanmıştır. Analiz sonuçları Tablo 3'te sunulmuştur. Bulgular, talep değişkenliği ile incelenen tüm stok performansı göstergelerinin ürün kategorilerine göre istatistiksel olarak anlamlı biçimde farklılaştığını göstermektedir.

Tablo 3. Ürün Kategorilerine Göre Talep Değişkenliği ve Stok Performansı Göstergelerinin Karşılaştırılması

Değişken	**Gıda/İçecek Medyan (IQR)**	**Gıda Dışı Medyan (IQR)**	**Taze Gıda Medyan (IQR)**	**p**	**Anlamlı ikili karşılaştırmalar[1]**
Talep değişkenliği (CV)	1,497 (1,38)	2,407 (1,06)	0,960 (0,68)	<0,001	GD > TG (p=0,001); GD > Gİ (p=0,004)
Fire oranı	0,000 (0,00)	0,000 (0,00)	0,007 (0,09)	<0,001	TG > Gİ (p=0,001); TG > GD (p=,001)
Stok devir hızı	1,579 (0,99)	0,749 (0,68)	6,228 (4,77)	<0,001	TG > Gİ (p=0,003); TG > GD (p<0,001)
Stock-out oranı	0,000 (0,11)	0,000 (0,06)	0,118 (0,24)	0,006	TG > Gİ (p=0,023); TG > GD (p=0,012)
Raf boşluğu oranı	0,000 (0,11)	0,000 (0,06)	0,108 (0,25)	0,007	TG > Gİ (p=0,026); TG > GD (p=0,014)

Not: IQR (Interquartile Range)= çeyrekler arası aralık; 25. ve 75. yüzdelikler arasındaki farkı göstermektedir.

Sonuçlara göre, ürün kategorileri, talep değişkenliği ve incelenen stok performansı göstergeleri açısından anlamlı biçimde farklılaşmaktadır. Talep değişkenliği gıda dışı ürünlerde daha yüksek olup, Bonferroni düzeltmeli ikili karşılaştırmalar gıda dışı ürünlerin hem taze gıda hem de gıda/içecek ürünlerinden anlamlı biçimde ayrıştığını göstermiştir. Buna karşılık taze gıda ürünlerinde fire oranı, stok devir hızı, stock-out oranı ve raf boşluğu oranı daha yüksek bulunmuş; ikili karşılaştırmalar taze gıda kategorisinin bu göstergeler bakımından diğer iki kategoriden anlamlı biçimde farklılaştığını ortaya koymuştur. Gıda/içecek ile gıda dışı kategorileri arasında ise bu stok performansı göstergeleri açısından anlamlı bir farklılık belirlenmemiştir.

İkili korelasyon analizinde gözlenmeyen CV–stock-out ilişkisinin, ürün kategorileri arasındaki farklılıklar ve diğer operasyonel faktörler kontrol edildiğinde ortaya çıkıp çıkmadığını belirlemek amacıyla Genelleştirilmiş Tahmin Denklemleri (GEE) analizi gerçekleştirilmiştir. Aynı SKU'ya ait tekrarlı aylık gözlemleri dikkate alan binomial-logit GEE modelinde ürün kategorisi, ay, promosyon oranı ve fiyat endeksi kontrol değişkenleri olarak modele dahil edilmiştir. Analiz sonucunda talep değişkenliğinin stock-out olasılığı üzerinde pozitif ve istatistiksel olarak anlamlı bir etkisi olduğu belirlenmiştir ($B = 1{,}152$; $Wald\ \chi^2 = 27{,}919$; $p < 0{,}001$). Odds oranına göre CV'deki bir birimlik artış, diğer değişkenler sabit tutulduğunda stock-out odds'unu yaklaşık 3,17 katına çıkarmaktadır ($OR = 3{,}165, \%95\ GA = 2{,}065 - 4{,}855$). Talep değişkenliği ve kontrol değişkenlerinin stock-out olasılığı üzerindeki ilişkilerine ilişkin GEE model sonuçları Tablo 4'te gösterilmektedir

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Tablo 4. Stock-out Olasılığına İlişkin Binomial-Logit GEE Modeli

Değişken	B	SH	Wald χ^2	p	OR	%95 GA (OR)
CV	1,152	0,218	27,919	<0,001	3,165	2,065–4,855
Gıda/İçecek[1]	−1,479	0,578	6,553	0,010	0,228	0,073–0,707
Gıda Dışı[1]	−3,593	0,817	19,361	<0,001	0,028	0,006–0,136
Mayıs[2]	1,178	0,365	10,424	0,001	3,248	1,589–6,633
Haziran[2]	1,087	0,369	8,678	0,003	2,965	1,439–6,110
Promosyon oranı	−0,837	0,790	1,124	0,289	0,433	0,092–2,036
Fiyat endeksi	0,358	2,475	0,021	0,885	1,430	0,011–182,911

Not: B = regresyon katsayısı; SH = standart hata; OR = odds oranı; GA = güven aralığı. Model binomial dağılım ve logit bağlantı fonksiyonuyla tahmin edilmiştir. Analiz 44 SKU'ya ait 125 geçerli SKU-ay gözlemini kapsamaktadır. [1] Referans kategori = Taze Gıda. [2] Referans ay = Temmuz.

Ürün kategorisinin stock-out olasılığı üzerindeki genel etkisi anlamlı bulunmuştur (Wald $\chi^2(2)=22,011$; $p<0,001$). Taze gıda referans kategori olarak alındığında, gıda/içecek ürünlerinin stock-out odds'u daha düşük (OR=0,228; p=0,010), gıda dışı ürünlerin odds'u ise belirgin biçimde daha düşük bulunmuştur (OR=0,028; p<0,001). Ay değişkeninin genel etkisi de anlamlıdır (Wald $\chi^2(2)=11,935$; p=0,003); Mayıs ve Haziran aylarında stock-out odds'u Temmuz ayına göre sırasıyla 3,248 ve 2,965 kat daha yüksektir. Buna karşılık promosyon oranı (p=0,289) ve fiyat endeksi (p=0,885) ile stock-out arasında anlamlı bağımsız bir ilişki belirlenmemiştir. Ayrıca CV ile ürün kategorisi arasındaki etkileşim istatistiksel olarak anlamlı bulunmamıştır (Wald $\chi^2(2)=1,773$; p=0,412); dolayısıyla talep değişkenliği ile stock-out arasındaki ilişkinin ürün kategorilerine göre anlamlı biçimde farklılaşmadığı belirlenmiştir.

4. SONUÇ

Perakende işletmelerinde talebin değişken yapısı, stok seviyelerinin etkin biçimde yönetilmesini güçleştirmekte ve ürün bulunabilirliği, fire ve stok devir hızı gibi operasyonel performans göstergelerini etkileyebilmektedir. Özellikle farklı ürün kategorilerinin birbirinden farklı talep ve stok özelliklerine sahip olması, stok yönetimi kararlarının yalnızca toplam satış veya ortalama talep üzerinden değil, SKU düzeyindeki talep değişkenliği dikkate alınarak verilmesini önemli hale getirmektedir. Bu çalışma, gerçek mağaza operasyon verilerinden yararlanarak talep değişkenliği ile stok performansı arasındaki ilişkiyi SKU düzeyinde incelemeyi ve söz konusu ilişkinin farklı ürün kategorilerindeki görünümünü ortaya koymayı amaçlamıştır.

Araştırma bulguları, talep değişkenliği ve stok performansının ürün kategorileri açısından önemli farklılıklar gösterdiğini ortaya koymuştur. Talep değişkenliği gıda dışı ürünlerde daha yüksek bulunurken, taze gıda ürünlerinin fire oranı, stok devir hızı, stock-out oranı ve raf boşluğu oranı açısından diğer kategorilerden anlamlı biçimde ayrıştığı görülmüştür. Bu sonuç, yüksek talep değişkenliğinin tek başına olumsuz stok performansıyla eş anlamlı olmadığını; ürünlerin bozulabilirlik, stoklama ve ikmal özellikleri gibi kategoriye özgü operasyonel koşulların da dikkate alınması gerektiğini göstermektedir.

İkili analizlerde talep değişkenliği ile fire oranı ve stok devir hızı arasında negatif ilişkiler belirlenirken, stock-out ve raf boşluğu oranlarıyla anlamlı bir ilişki gözlenmemiştir. Bununla birlikte, ürün kategorisi, ay, promosyon oranı ve fiyat endeksi kontrol edildiğinde talep değişkenliğinin stock-out olasılığıyla pozitif ve anlamlı biçimde ilişkili olduğu ortaya çıkmıştır. GEE modeli sonuçlarına göre CV'deki bir birimlik artış, diğer değişkenler sabit tutulduğunda stock-out odds'unu yaklaşık 3,17 katına çıkarmaktadır. Bu bulgu, kategori farklılıklarının ve diğer operasyonel faktörlerin kontrol edilmediği ikili analizlerde talep değişkenliği ile stock-out arasındaki ilişkinin görünmeyebileceğini ortaya koymaktadır. Buna karşılık CV ile ürün kategorisi arasındaki etkileşimin anlamlı bulunmaması, talep değişkenliği–stock-out ilişkisinin gücünün incelenen kategoriler arasında anlamlı biçimde farklılaştığına ilişkin bir kanıt bulunmadığını göstermektedir.

Çalışmanın bulguları uygulama açısından, perakende işletmelerinin stok kararlarında yalnızca geçmiş ortalama satışları değil, SKU bazındaki talep değişkenliğini ve ürün kategorisinin operasyonel

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özelliklerini birlikte değerlendirmesi gerektiğini göstermektedir. Talep değişkenliği yüksek SKU'ların düzenli olarak izlenmesi ve özellikle stock-out riski açısından daha dikkatli stok ve ikmal kararlarının alınması ürün bulunabilirliğinin artırılmasına katkı sağlayabilir. Taze gıda ürünlerinde gözlenen daha yüksek fire ve stock-out göstergeleri ise bu kategoride stok bulunabilirliği ile fire riskinin birlikte dengelenmesini gerektiren daha hassas bir yönetim yaklaşımına ihtiyaç olduğunu ortaya koymaktadır.

Araştırma, gerçek mağaza operasyon verilerine ve birden fazla stok performansı göstergesinin birlikte değerlendirilmesine dayanması açısından uygulamaya dönük katkı sunmakla birlikte bazı sınırlılıklara sahiptir. Bulgular tek bir perakende mağazası, 44 SKU ve üç aylık dönemle sınırlıdır. Ayrıca gerçek müşteri talebinin doğrudan gözlemlenememesi nedeniyle günlük satış miktarları talebin göstergesi olarak kullanılmıştır. Gelecek çalışmalarda daha uzun dönemleri, farklı mağazaları ve daha geniş SKU gruplarını kapsayan verilerle bulguların genellenebilirliği araştırılabilir; ayrıca farklı stok politikalarının performans üzerindeki sonuçları simülasyon veya optimizasyon yaklaşımlarıyla değerlendirilebilir.

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THE SARDINIA FILTER: A PATIENT SAFETY MODEL FOR TECHNOLOGY-ASSISTED CLINICAL INTERVENTIONS

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ABSTRACT

The integration of neurotechnology—quantitative EEG (qEEG), transcranial stimulation (tDCS, TMS, tRNS), neurofeedback, and precision pharmacology—into clinical practice offers unprecedented specificity, yet current safety frameworks remain largely device-centred. They regulate stimulation parameters but do not assess whether a patient's biological system retains the reserve capacity to safely process activation. A patient may meet all standard inclusion criteria while presenting autonomic rigidity, neuroendocrine dysregulation, neuroinflammation, and high psychosocial load—states in which intervention accelerates depletion rather than restoring function. This work introduces the Sardinia Filter, a multi-dimensional, reserve-based safety model designed to operate as a protective gate prior to any technology-assisted clinical intervention. Named for the Sardinian Blue Zones, where the AKEA study documented the world's highest male-centenarian ratio, it draws on the epidemiological principle that longevity reflects conservation of biological reserve rather than high-intensity optimization. The model operationalizes reserve across five measurable dimensions—autonomic (HRV/RMSSD), cortical flexibility (EEG Hurst exponent), neuroendocrine (cortisol/DHEA-S, neutrophil-lymphocyte ratio), inflammatory (hs-CRP), and psychosocial load—and activates when two or more criteria co-occur, contraindicating high-intensity protocols (e.g., anodal tDCS, high-frequency rTMS, supraphysiological dosing) and redirecting toward stabilizing alternatives that restore reserve. The framework reframes the pre-intervention question from "what does this patient need?" to "does this patient's system have the reserve to receive it without harm?" Thresholds are theoretically derived and require prospective calibration; the model is presented as a falsifiable hypothesis structure, offering reserve-based safety as a candidate standard for technology-assisted clinical practice.

Keywords: qEEG; neuromodulation; patient safety; biological reserve; allostatic load; Blue Zones; primum non nocere.

1. Introduction

Quantitative EEG, cortical source analysis, transcranial direct current stimulation (tDCS), transcranial magnetic stimulation (TMS), transcranial random noise stimulation (tRNS), neurofeedback and precision pharmacological protocols have substantially increased the specificity with which clinical interventions can be targeted. Comparatively little systematic attention has been given to a corresponding question of safety, namely whether the biological system receiving the intervention retains sufficient capacity to process and regulate it.

Safety frameworks in neuromodulation are predominantly device-centred. They regulate current density, stimulation duration and electrode placement, but they do not require assessment of the patient's physiological state at the time of application (Bikson et al., 2016). A patient may satisfy every standard inclusion criterion for a TMS or tDCS protocol while presenting concurrent autonomic rigidity, neuroendocrine dysregulation, systemic inflammation and high psychosocial load. Under such conditions, activation of the system may plausibly accelerate depletion rather than restore function.

The present paper describes the Sardinia Filter, a multi-dimensional, reserve-based safety model intended to operate as an assessment step preceding technology-assisted clinical intervention. The model takes its name from the Blue Zones of Sardinia, and specifically from the Barbàgia highlands, where an unusually high concentration of male centenarians was documented in the AKEA study (Poulain et al.,

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2004). The principle drawn from that population is that longevity in these communities is associated with the absence of sustained biological overload rather than with high-intensity optimisation (Buettner, 2008). The model was developed by the author within a broader precision-neuromodulation framework and is presented here independently of any particular software implementation.

2. Theoretical Background

2.1 Conservation of biological reserve

The Sardinia Filter takes its name from a logical, rather than an epidemiological, point of departure. The AKEA study identified a geographically circumscribed area of extreme longevity in Sardinia (Poulain et al., 2004), and subsequent comparative analysis of longevity hotspots described a recurring pattern characterised by low chronic biological load (Buettner, 2008): continuous low-intensity physical activity rather than exhaustive exercise, dietary sufficiency rather than aggressive optimisation, and embedded social structures associated with lower cumulative stress exposure. Independently of any debate over the precision of centenarian counts, this lifestyle pattern is well documented and offers the conceptual origin for the model. The present model does not treat longevity statistics as evidence for its validity, since the conservation principle it adopts is supported independently by the allostatic load literature (McEwen & Stellar, 1993; Seeman et al., 1997).

The clinical analogue may be stated as follows. Biological reserve, understood as the autonomic, endocrine, inflammatory and cortical capacity available to absorb a perturbation, is expected to determine how much activation a system can process before adaptation gives way to depletion. Where reserve is available, activating interventions are expected to produce adaptation; where it is not, comparable interventions may produce fatigue, rebound and cumulative wear. The model proposed here is intended to distinguish these two states before an intervention is selected.

2.2 Biological reserve as a clinical variable

The construct of reserve has established precedent in several medical domains. Cognitive reserve predicts differential resilience to neurological insult (Stern, 2002); cardiac reserve defines the safety envelope for exercise stress testing; and allostatic load quantifies the cumulative biological cost of chronic stress, predicting health outcomes independently of current symptom presentation (McEwen & Stellar, 1993; McEwen, 1998). The canonical operationalisation of allostatic load is the multi-system biomarker battery described by Seeman and colleagues (1997).

For the purposes of technology-assisted intervention, reserve is here decomposed into five measurable dimensions. Autonomic reserve is indexed by short-term heart rate variability (RMSSD). Cortical signal flexibility is indexed by the Hurst, or detrended fluctuation analysis, scaling exponent of the EEG amplitude envelope; an exponent of approximately 0.5 denotes an uncorrelated signal, healthy resting alpha-band exponents cluster between 0.65 and 0.85, and values approaching 1.0 indicate reduced variability (Linkenkaer-Hansen et al., 2001; Hardstone et al., 2012). Neuroendocrine reserve is indexed by the cortisol/DHEA-S ratio, which has been reported to predict epigenetic age acceleration more consistently than either hormone measured alone (Takeshita et al., 2025), together with the neutrophil-lymphocyte ratio. Inflammatory state is indexed by high-sensitivity C-reactive protein. Psychosocial load is assessed through a three-domain index (relational, occupational and contextual), each domain scored as a binary indicator; this index is proposed as part of the present framework and has not been independently validated.

2.3 Ethical basis

Four ethical commitments inform the structure of the model and are proposed here as its normative basis. The first is primum non nocere, from which follows the requirement that reserve be assessed before any activating intervention, and that a positive assessment not be set aside on the basis of symptom profile alone. The second is the treatment of automated output as decision support rather than decision: the clinician retains authority to escalate or to override, and the system records the reasoning rather than preventing the action. The third is the rejection of opaque application, which requires that each criterion be published together with its threshold, domain and rationale, including those parameters that remain uncalibrated. The fourth is continuing technical responsibility, which requires that criteria

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be versioned and that clinicians apply the current version. Taken together, these commitments identify a category of iatrogenic risk specific to precision neuromodulation, namely harm arising from intervention in a system not equipped to metabolise it.

3. The Sardinia Filter

3.1 Design principles

• Multi-dimensionality. No single biomarker is treated as sufficient. Reserve failure is understood as a systemic condition expressed simultaneously across autonomic, cortical, endocrine, inflammatory and psychosocial dimensions, and the model therefore requires convergent evidence in at least two dimensions before activation. No single criterion activates the filter.

• Pre-intervention assessment. Reserve is assessed before symptom-based clinical assessment, and independently of diagnosis, as a precondition for any technology-assisted intervention.

• Conservative threshold. Under uncertainty the model defaults to non-activation of the intervention. False positives, which postpone an intervention, are considered preferable to false negatives, which permit one in a depleted system.

• Redirection rather than refusal. Activation of the filter does not terminate care; it indicates that stabilising protocols intended to restore reserve should precede higher-intensity intervention.

3.2 Activation criteria and verdicts

The model sums five criteria of equal weight, one point each, and is considered active at a score of 2 or more. Each criterion describes a state rather than a stable trait: each is in principle reversible, each is expected to respond to the stabilising protocols described in Section 3.4, and each can be re-measured from session to session. This property is what allows the redirection principle to be applied in practice. Structural and irreversible risk factors, including established cardiovascular and cerebrovascular contraindications, fall outside the scope of the model: they are assessed separately, under existing contraindication screening, and are not represented among the criteria, which describe modifiable state.

Three verdicts are returned. The filter is reported as active at a score of 2 or more; as clear at a score below 2 when every criterion has been evaluated; and as insufficient evidence at a score below 2 when one or more criteria remain unevaluated. The third category is included so that an unevaluated criterion is not treated as a negative one. A session containing qEEG data but no laboratory panel and no psychosocial assessment yields insufficient evidence rather than a clear result, since the patient has not been assessed on those dimensions.

Table 1. Sardinia Filter activation criteria. Five criteria of equal weight; the filter is active at a score of 2 or more, corresponding to convergent evidence in at least two biological domains. All thresholds are theoretically derived and require prospective normative calibration.

	Metric	**Threshold**	**Domain**	**Rationale**
C1	RMSSD (HRV)	< 20 ms	Autonomic	Autonomic rigidity, interpreted as parasympathetic reserve insufficient to modulate the activation response. The threshold is set above the more conservative cardiac safety limits applied in transcranial stimulation protocols (RMSSD < 15 ms), so that reduced vagal reserve may be identified before an absolute contraindication is reached.

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C2	1/f spectral slope and NLR	> −0.90 and NLR > 2.7	Cortical and inflammatory	Reduced cortical signal complexity in the presence of an elevated systemic inflammatory index (Gao et al., 2017). Two qualifications apply. The slope should be obtained as the aperiodic exponent of a parameterised spectrum (Donoghue et al., 2020), since band-resolution approximations are not expressed on the same scale. No validated NLR cutpoint is available: the value of 2.7 approximates the upper population quartile boundary of 2.68 reported for NHANES (Song et al., 2021), against a healthy adult reference interval of 0.78–3.53 (Forget et al., 2017). The criterion is conjunctive and is reported as unknown if either term is unavailable.
C3	Cortisol / DHEA-S ratio	> 0.15	Neuroendocrine	Allostatic overload with catabolic predominance and reduced anabolic reserve (McEwen, 1998). The ratio has been reported to track HPA-axis imbalance more sensitively than either hormone alone (Butcher et al., 2005; Takeshita et al., 2025). It is computed on serum cortisol and DHEA-S expressed in matched units (µg/dL) from a morning fasted sample, and does not transfer to salivary or evening sampling, nor to the unsulfated form. The threshold corresponds to the ROC-derived cut-off reported by Yanagita et al. (2020). No consensus reference interval exists, and the ratio is age-, sex- and assay-dependent.
C4	hs-CRP	> 1.0 mg/L	Inflammatory	Systemic inflammation, associated with reduced cortical plasticity. The threshold corresponds to the low-risk boundary of the CDC/AHA stratification (< 1.0 low, 1.0–3.0 average, > 3.0 high; Pearson et al., 2003) rather than to the high-risk boundary, consistent with the conservative-threshold principle. The criterion is intended

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				to identify possible depletion, not to establish cardiovascular risk.
C5	Psychosocial load index	3 of 3 binary domains	Psychosocial	Contextual load across three binary domains: relational, occupational and contextual. Because each domain is scored dichotomously and the threshold is the full set, the criterion identifies global contextual overload rather than isolated adversity. It is the parameter most likely to require revision (from 3 to 2) should it prove insufficiently sensitive in a calibration cohort.

3.3 Interventions contraindicated when the filter is active

The term contraindicated should be read in the context of implementation. In the decision-support systems in which the model has been applied, the filter is advisory: it ranks and documents, but it does not suppress a report or disable an action, and a clinician override is permitted and recorded. The interventions listed below are those for which the activation demand is considered likely to exceed available reserve.

- High-intensity anodal tDCS. Application of exogenous current to a cortex in a state of inflammatory or energetic depletion may accelerate synaptic fatigue and produce rebound effects (Nitsche & Paulus, 2000; Bikson et al., 2016).
- Supraphysiological hormone dosing. In the absence of available energetic reserve, dosing above physiological levels may destabilise rather than optimise hormonal feedback, with a corresponding increase in allostatic load (McEwen, 1998).
- Trauma memory reprocessing. Reprocessing requires autonomic reserve sufficient to modulate the arousal it generates; in a depleted system it may produce dysregulation without integration (van der Kolk, 2014).
- High-frequency repetitive TMS. Facilitatory rTMS applied under conditions of reduced cortical variability and systemic inflammation may produce paradoxical suppression of excitability.
- High-intensity neurofeedback. The sustained cognitive effort required may generate fatigue without measurable neuroplastic benefit in a depleted state.

3.4 Stabilising alternatives

- Protective NAD+ supplementation, administered subcutaneously where oral bioavailability is insufficient, intended to support mitochondrial function and cellular energetic reserve without imposing receptor-level demand (Rajman et al., 2018).
- Low-intensity transcranial random noise stimulation, a sub-threshold stochastic resonance protocol reported to improve cortical signal-to-noise without net excitatory demand (Terney et al., 2008).
- A structured, explicitly non-psychotherapeutic protocol of low-demand neurophysiological engagement, intended to support oscillatory stabilisation.
- Relational co-regulation as the primary intervention, in which relational safety is established before biological stabilisation is attempted (Porges, 2007).

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• Vagal tone protocols, comprising diaphragmatic breathing and slow-paced heart rate variability biofeedback, directed at the parameter assessed in criterion C1 (Thayer & Lane, 2000).

4. Monitoring Reserve Between Sessions

Reserve depletion is not reliably detected by routine clinical observation. A patient may present as motivated, cooperative and symptomatically improved while showing deficits across autonomic, cortical and biochemical dimensions. A composite monitor, referred to here as the mental rate variability (MRV) index (Dasilva & Pino, 2026), was developed to address this, and reads reserve across three parallel dimensions: a physiological dimension, given by cardiac RMSSD; an electrophysiological dimension, given by the scaling exponent of the cortical signal together with the epoch-to-epoch variability of the individual alpha peak frequency; and a psychosocial dimension, given by the three-domain load index. The instrument is intended for longitudinal use, since it is the trend across sessions rather than a single reading that carries interpretive weight. Persistent rigidity of the mental rate despite biochemical normalisation may indicate that environmental load is offsetting the intervention.

A continuous index of the same construct is computed alongside the criterion-based filter, weighting the normalised heart rate variability terms against a plateau function of the scaling exponent, with values below 40 taken to contraindicate activating protocols. The two instruments are maintained separately. The criterion-based filter is categorical and can be audited criterion by criterion, which is appropriate to a safety assessment; the continuous index is suited to trend monitoring. Neither is derived from the other.

5. Clinical Implications

In neuromodulation practice, tDCS and TMS protocols currently assess safety through device parameters and standard medical contraindications, such as implanted metal, seizure history and pregnancy, and do not include an assessment of biological reserve. A patient with hs-CRP above 1.0 mg/L, a cortisol/DHEA-S ratio above 0.15 and reduced heart rate variability may therefore receive a full course of anodal tDCS to the dorsolateral prefrontal cortex without any existing standard identifying this as a potential risk. Under the present model the filter would be active in this case, and stabilising protocols would be indicated first.

In qEEG-guided practice the model functions as an assessment step preceding interpretation. Prefrontal hypoactivation observed in a patient with concurrent reserve depletion does not, on this account, indicate that anodal tDCS to F3 should be prescribed; it raises the possibility that the observed dyscontrol is a consequence of depletion rather than an independent finding, and that restoration of reserve should be attempted first. This interpretation is a hypothesis generated by the model and has not been tested.

The intended clinical contribution of the model is therefore as much in what it indicates as in what it defers. When the filter is active, the clinical question shifts from the selection of an activating protocol to the restoration of the reserve required to tolerate one. Whether this shift improves outcomes is an empirical question that the present work does not answer.

6. Implementation Status and Limitations

The model has been implemented in a clinical decision-support system, in which the criteria, thresholds and rationale presented in Table 1 are computed for a given session. Values are derived at the time of reading and are not persisted, and each index carries a label identifying it as a hypothesis with a priori thresholds rather than a diagnostic output. A criterion that cannot be computed is returned as unavailable together with the inputs it requires. Prospective outcome data are being collected from this observational use; controlled validation has not been conducted.

Several limitations apply. The filter is advisory rather than blocking, since a gate that withholds treatment on the basis of uncalibrated cut-offs would be difficult to justify. Criterion assessment is not fed by continuous instrumentation, as no device interface for continuous heart rate variability, automated laboratory ingestion or arterial tonometry is currently in place, and criteria are therefore evaluated on data entered per session. One specification item in the deployed implementation is superseded by the formulation presented here, in that the 1/f term is obtained as a band-resolution approximation rather than as a parameterised aperiodic exponent. More generally, the thresholds reported in Table 1 are drawn

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from the literature or, where no published anchor exists, adopted for this framework; they have not been calibrated prospectively, and the proposition that activating interventions produce net harm in filter-positive patients remains untested.

Priorities for validation are, accordingly: normative calibration of thresholds across age, sex and diagnostic populations; prospective controlled comparison of outcomes in filter-positive patients who receive activating interventions and those redirected to stabilising protocols; empirical derivation of an NLR cutpoint for this application, the present value being a distributional quartile boundary rather than a risk threshold (Song et al., 2021); age- and sex-stratification of the cortisol/DHEA-S cut-off, given the known decline of DHEA-S across the adult lifespan; and assessment of inter-rater reliability for the psychosocial load index.

7. Discussion

The gap addressed by the present model is architectural rather than evidential. The markers on which it draws, including heart rate variability, EEG scaling exponents, the cortisol/DHEA-S ratio, high-sensitivity C-reactive protein and psychosocial load indices, are widely available and individually well characterised. They are ordinarily used for diagnosis, prognosis and monitoring, but not as pre-intervention safety criteria determining whether a protocol should proceed or be deferred. What is proposed here is that integration. The model introduces no new diagnostic category, treatment or biomarker; it specifies a decision structure in which established markers are evaluated jointly and prior to intervention.

The principal limitation of the framework is that it is theoretical. Its thresholds are informed by published data but have not been calibrated in a prospective cohort, and its central claim is a plausible inference from the allostatic load literature rather than a demonstrated effect. The parameters are stated explicitly, with their published anchors where these exist and with their absence noted where they do not, so that individual criteria may be tested, revised or rejected independently of the structure that contains them. Revision of specific thresholds as empirical data accumulate would be consistent with the intended use of the model rather than contrary to it.

In summary, the Sardinia Filter is offered as a structured, falsifiable proposal for reserve-based pre-intervention assessment in technology-assisted clinical practice. Its value, if any, will be determined by whether patients identified by the criteria and redirected to stabilising protocols show better outcomes than comparable patients who proceed directly to activating intervention. That comparison remains to be performed.

Declaration of Interests

The author declares no competing interests.

Ethical Statement

This paper presents a theoretical framework. No patient data are reported. The observational data collection referred to in Section 6 is conducted under a separate protocol and is not reported here.

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INDUSTRIAL ARTIFICIAL INTELLIGENCE FOR SMART FACTORIES AND IIoT SYSTEMS

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ABSTRACT

The integration of Industrial Artificial Intelligence (Industrial AI) and the Industrial Internet of Things (IIoT) plays an important role in the development of smart factories. IIoT enables real-time data collection and communication among machines, sensors, and industrial equipment, while Industrial AI processes this data to support prediction, fault detection, optimization, and decision-making. This study examines the fundamental structure of Industrial AI and IIoT integration and discusses how sensing, Edge Computing, and artificial intelligence algorithms contribute to intelligent manufacturing processes. The main differences between general-purpose AI and Industrial AI are also evaluated in terms of data sources, operating environments, response time, domain knowledge, and performance requirements. Furthermore, reliability, availability, robustness, fault tolerance, safety, and cybersecurity are discussed as essential requirements for the deployment of AI in industrial environments. Overall, the study highlights the need to consider Industrial AI as an integrated system involving data, communication infrastructure, AI models, and physical production processes.

Keywords: Industrial Artificial Intelligence, Industrial Internet of Things (IIoT), Smart Manufacturing, Edge Computing, Reliability, Cybersecurity

INTRODUCTION

The development of smart factories is shaped by the integration of technologies such as the Industrial Internet of Things (IIoT), cyber-physical systems, artificial intelligence, machine learning, big data analytics, cloud computing, and edge computing. Within this transformation, IIoT is considered one of the fundamental technologies that enables machines, sensors, equipment, and control systems in the production environment to be interconnected and continuously obtain data from production processes. Xu et al. (2018), examining IIoT systems from a cyber-physical systems perspective, stated that the connection between physical production assets and digital systems forms the basis of smart manufacturing. The researchers emphasized that IIoT is not merely about connecting devices to the internet; it represents a more comprehensive system structure integrating sensing, communication, computation, control, and data analytics.

More recent studies in the IIoT field focus on integrating artificial intelligence into connected industrial systems. Hu et al. (2024) comprehensively examined the role of IIoT intelligence in smart manufacturing and revealed that analyzing the large volumes of data generated by IIoT using artificial intelligence and machine learning methods offers significant opportunities for data-driven decision-making, prediction, optimization, and operational improvement in production processes. In this context, while IIoT forms the "data collection and communication" infrastructure of the production system, artificial intelligence plays a crucial role in interpreting this data and transforming it into decision support mechanisms.

Lee et al. (2026) research plays an important role in the development of the concept of Industrial Artificial Intelligence. The researchers have shown that it is not enough to use artificial intelligence only for data analysis purposes in smart production environments; industrial big data, physical systems, engineering knowledge, digital twins and artificial intelligence methods should be considered together. In more recent studies by Lee and Su (2024), Industrial Artificial Intelligence is considered as a structure

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in which information, data and model components are integrated, and it is emphasized that artificial intelligence models should be developed in a way that is compatible with the physical and operational characteristics of production systems.

One of the key differences between industrial AI and general-purpose AI is that AI models interact directly with physical production systems. While prediction accuracy or classification success are key performance metrics in general-purpose AI applications, reliability, explainability, robustness, real-time operation, and compatibility with physical constraints are also critically important in industrial applications. Lee and Su (2025) state that the future of Industrial AI depends not only on the development of data-driven models but also on the integration of industrial information, physical processes, and AI models within a common fundamental framework.

One of the important application areas of artificial intelligence in smart manufacturing systems is predictive maintenance. By analyzing sensor data such as temperature, vibration, pressure, current and energy consumption obtained from production machines, it is possible to determine the current health status of the equipment and predict future failures. Zheng et al. (2020) state that developments in IIoT and artificial intelligence technologies have transformed the traditional predictive maintenance understanding into a more advanced “smart maintenance” approach. In this approach, real-time sensor data, big data analytics and machine learning methods are used together to aim for earlier and more accurate maintenance decisions.

However, one of the major problems of industrial AI applications is the lack of sufficient labeled data. The relatively infrequent occurrence of failures in production facilities and the diverse operating conditions of machines can make it difficult to create the necessary datasets for training AI models. At this point, Li and Zheng (2020) highlighted the importance of transfer learning in smart manufacturing applications. According to the researchers, transfer learning facilitates the development of machine learning models in industrial applications with limited data by enabling the transfer of information obtained from one machine or operating condition to a similar but different production environment.

In the development of Industrial Artificial Intelligence, not only traditional machine learning and deep learning methods but also approaches such as physics-based artificial intelligence, digital twins, and explainable artificial intelligence are gaining importance. In the smart manufacturing roadmap published by Lee et al. (2026), it is predicted that artificial intelligence and machine learning will be integrated with physics-based artificial intelligence, digital twins, explainable artificial intelligence, generative artificial intelligence, big language models, and basic models in the future. This approach makes it possible for Industrial Artificial Intelligence to move beyond being just a system that learns patterns from past data and become a more advanced structure that can understand physical production processes, simulate future situations, and generate decision recommendations.

In recent years, the adaptation of generative artificial intelligence and fundamental models to industrial applications has also become an important research area. Ren et al. (2025), by considering the Industrial Foundation Model approach, proposed the integration of different types of industrial data, engineering knowledge, and artificial intelligence models within a common framework. This approach aims to evaluate different data types together, such as sensor time series, images, maintenance records, technical documents, and production data. Similarly, in a systematic review conducted by Zhao et al. (2025), the potential of Industrial Foundation Models in smart manufacturing was evaluated through data, model, and application levels, and it was revealed that adapting these models to industrial domain knowledge is a fundamental requirement.

In IIoT and Industrial Artificial Intelligence systems, where the data will be processed is also an important research topic. The continuous and high-volume data generation by sensors in production environments does not always make it feasible to send all data to central cloud systems. Shi et al. (2016) stated that the Edge Computing approach can reduce communication latency and support real-time applications by bringing computational and data processing resources closer to the data generation point. Zhou et al. (2019), on the other hand, discussed the Edge Intelligence concept and showed that running artificial intelligence algorithms in edge environments can provide significant advantages in terms of low latency, data privacy and real-time decision-making.

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This approach is particularly important for Industrial Artificial Intelligence. For example, when thousands of vibration measurements are obtained per second from a machine on a production line, instead of continuously transmitting all raw data to the cloud, it may be possible to analyze the data on the edge device. When the AI model running on the edge detects an unusual vibration pattern, only the critical event can be sent to the central system. This reduces latency and network traffic while increasing the production system's real-time response capacity.

The reliability and cybersecurity of IIoT systems are also critical issues in the widespread adoption of Industrial Artificial Intelligence applications. Hu et al. (2024) state that IIoT systems present various challenges in areas such as security, data management, and interoperability. Similarly, Xu et al. (2018) emphasize that IIoT systems have a complex structure in terms of security and system management due to the interconnection of numerous devices and communication infrastructures. Therefore, the reliability of sensors, data integrity, network security, model security, and validation of artificial intelligence outputs should be addressed within an integrated reliability approach.

In terms of the reliability of artificial intelligence systems, the NIST AI Risk Management Framework developed by Tabassi (2023) reveals that artificial intelligence systems should be evaluated not only in terms of accuracy but also in terms of different dimensions such as reliability, security, robustness, explainability, transparency and accountability. This approach becomes even more important in industrial production environments. Because an erroneous decision made by artificial intelligence can not only produce a digital output but also lead to physical consequences in terms of equipment damage, production loss, quality problems or employee safety.

These studies show that Industrial Artificial Intelligence in the future will not consist solely of models that predict machine failures or classify production quality. Future Industrial AI systems are expected to evolve into integrated systems capable of collecting real-time data from IIoT sensors, performing low-latency analysis in edge environments, evaluating alternative production scenarios via digital twins, utilizing physical and engineering knowledge, providing explainable suggestions to humans through generative AI, and making autonomous decisions when necessary.

The aim of this study is to provide a comprehensive overview of Industrial Artificial Intelligence and its integration with IIoT systems in the context of smart manufacturing. First, the fundamental working structure of Industrial AI is explained through IIoT sensors, Edge Computing, and artificial intelligence algorithms. Next, the main differences between general-purpose AI and Industrial AI are examined in terms of their data sources, operating environments, response time requirements, performance expectations, and use of domain knowledge. The study then focuses on the key requirements for deploying Industrial AI and IIoT systems in real-world industrial environments by discussing reliability, availability, robustness, fault tolerance, safety, and cybersecurity. Through this structure, the study aims to highlight that successful Industrial AI applications depend not only on the performance of AI models but also on the reliable and secure integration of data, communication, computing, and physical production systems.

HOW DOES INDUSTRIAL ARTIFICIAL INTELLIGENCE THINK AND WORK?

Artificial intelligence creates a structure where each unit on the production line is self-sufficient, able to communicate, and adapt to circumstances. These systems increase production flexibility, enabling even small-scale and customized production to be carried out with high efficiency. The process is very similar to how the human body works:

Five Senses (IIoT Sensors)

While humans perceive changes in their environment through sensory organs such as eyes, ears, nose, tongue, and skin, in smart factories this function is performed by sensors. IIoT sensors continuously measure the physical state of machines and production equipment, generating data on parameters such as temperature, vibration, pressure, current, rotational speed, energy consumption, and so on. This data forms the basic source of information for determining the current state of the production system and predicting its future behavior (Hu et al. 2024).

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IIoT refers to a connected industrial ecosystem that not only collects data from sensors but also enables the transmission of this data over a network to other devices, data processing systems, and applications. Xu et al. (2018) state that IIoT systems enable the integration of physical and digital systems, allowing devices in the production environment to be monitored, controlled, and communicate with each other. Hu et al. (2024) emphasize that the combined use of IIoT and artificial intelligence makes it possible to use large amounts of data obtained from production processes in intelligent decision-making mechanisms.

Therefore, data obtained from sensors constitutes the basic input of Industrial Artificial Intelligence. However, it is important to remember that raw sensor data alone is not sufficient for decision-making. The data needs to be cleaned, converted into a suitable format, meaningful features extracted, and analyzed.

Nervous System (Edge Computing)

While this function in smart factories does not have a direct biological equivalent, it can be conceptually related to data transmission and preprocessing processes carried out by industrial networks, gateways, and Edge Computing infrastructures.

The continuous generation of high amounts of data from sensors in industrial systems may not always make sending all data to a central cloud system efficient. The Edge Computing approach is important in terms of reducing latency, using bandwidth more effectively, and meeting real-time decision-making requirements by enabling data processing near the point of generation Hu et al. (2024). Especially in applications requiring real-time monitoring of production machines and rapid response, processing data close to the source can provide significant advantages.

Another function of Edge Computing is the ability to preprocess raw data before it is directly transferred to the central system. Operations such as filtering noisy or unnecessary data, feature extraction, and prioritizing specific data can be performed on edge devices. Thus, the amount of data to be transferred to central artificial intelligence systems is reduced while real-time analysis capacity is increased (Hu et al. (2024), Zheng et al. (2020)).

Brain (Artificial Intelligence Algorithms)

One of the fundamental functions of the human brain is to evaluate information from the environment, draw upon past experiences, and generate appropriate responses based on current conditions. In Industrial Artificial Intelligence, this function is performed by computational models such as machine learning, deep learning, and artificial neural networks. Artificial intelligence systems can evaluate the current state of a machine or production process by learning patterns from past and real-time production data, and make predictions about future behavior (Lee et al. 2026).

Artificial neural networks (ANNs) are computational models developed by drawing inspiration from the biological nervous system. These networks, created by connecting multiple artificial neurons, can learn complex relationships between inputs and outputs from data. Important features of ANNs include the ability to model nonlinear relationships, perform parallel processing, generalize, and exhibit a certain degree of error tolerance in the face of noisy or incomplete data. These features make it possible to use artificial neural networks in problems that require the simultaneous evaluation of numerous variables in production systems.

In industrial applications, artificial neural networks can be used in areas such as machine state classification, fault and anomaly detection, quality estimation, process optimization, and predictive maintenance. Machine learning methods play an important role, especially in analyzing the changes in sensor data over time, learning the normal operating behavior of the machine and identifying deviations from normal behavior.

THE DIFFERENCE BETWEEN TRADITIONAL ARTIFICIAL INTELLIGENCE AND INDUSTRIAL ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) generally encompasses methods and techniques that enable computer systems to perform tasks associated with human intelligence, such as learning, pattern recognition, prediction,

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classification, problem solving, and decision making. Methods such as machine learning, deep learning, and artificial neural networks are used in various sectors to solve a wide range of problems, including image recognition, natural language processing, prediction, and decision support. Therefore, in traditional or general-purpose AI applications, the accuracy, generalization ability, and prediction performance of the model are important evaluation criteria in solving a particular problem.

Industrial AI is considered a more specific approach that goes beyond the application of artificial intelligence methods to production and engineering systems, and involves integrating artificial intelligence models with physical systems, industrial data, engineering knowledge, and operational requirements (Li and Zheng (2020), Zheng et al. (2020)). Lee et al. (2026) state that Industrial AI in smart manufacturing does not consist solely of data analytics-based models; it requires the consideration of industrial big data, physical systems, digital twins, engineering knowledge, and artificial intelligence methods together. Lee and Su (2024) evaluate Industrial AI within a basic framework where information, data, and model components are integrated.

While in traditional artificial intelligence applications, one of the main goals is for the model to produce accurate results on a specific dataset, in industrial applications, it is also critically important that the artificial intelligence model works in harmony with the physical production system. This is because an incorrect decision made in the production environment can not only lead to a prediction error but also create risks in terms of machine damage, production loss, quality problems, or occupational safety. Therefore, in Industrial Artificial Intelligence applications, in addition to accuracy, features such as reliability, robustness, explainability, real-time operation, safety, and compatibility with physical constraints are also taken into consideration.

One of the important application areas of Industrial Artificial Intelligence is predictive maintenance. Sensor data such as vibration, temperature, current, etc., obtained from production machines can be analyzed with artificial intelligence algorithms to evaluate the current condition of the equipment and predict future failures. Zheng et al. (2020) state that the combined use of IIoT and artificial intelligence contributes to transforming traditional predictive maintenance applications into a more advanced intelligent maintenance approach. In these applications, it is not enough for the artificial intelligence model to only provide high prediction accuracy; it must also be able to produce reliable results under the actual operating conditions of the production system.

Table 1. Comparison of General-Purpose AI and Industrial AI Across Key Characteristics

Comparison Dimension	**General-Purpose Artificial Intelligence**	**Industrial Artificial Intelligence**
Error Tolerance and Risk	Depending on the application, a certain level of error may be acceptable; the impact of errors is generally limited to information or service quality.	Incorrect predictions or decisions may result in production losses, equipment damage, quality problems, or safety risks; therefore, error tolerance is generally lower.
Data Sources	General-purpose and often heterogeneous data sources such as text, images, audio, web content, and user interactions are used.	Process- and equipment-oriented data such as sensor measurements, machine condition data, temperature, pressure, vibration, flow, and production records are used.
Operating Environment	Typically operates in relatively standard computing environments such as cloud platforms, data centers, or end-user applications.	May operate in environments with physical and operational constraints, such as factory floors, production lines, embedded systems, and edge devices.

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Response Time	Latency requirements depend on the application, and real-time response may not be critical in many applications.	Low-latency or real-time decision-making may be required for applications such as process control, fault detection, and safety.
Key Performance Expectations	Prediction accuracy, generalizability, and user experience are primary considerations.	In addition to accuracy, reliability, robustness, explainability, continuity, and operational safety are critical.
Domain Knowledge	General-purpose models may have relatively limited requirements for domain-specific knowledge.	Incorporating engineering knowledge, physical processes, and operational constraints into the model is an important component.

ROBUSTNESS AND SECURITY IN INDUSTRIAL ARTIFICIAL INTELLIGENCE AND IIoT SYSTEMS

The integration of Industrial Artificial Intelligence (AI) and Industrial Internet of Things (IIoT) technologies into production systems enables production processes to become more connected, data-driven, and autonomous. However, the use of AI and IIoT systems in production environments also brings new requirements regarding reliability and security. In IIoT infrastructures, sensors, machines, communication networks, Edge Computing components, control systems, and AI models are constantly interacting with each other. Therefore, sensor errors, data losses, communication interruptions, hardware failures, model uncertainties, and changing operating conditions can affect the overall performance of the system.

Reliability

Reliability is considered the probability and ability of a system to perform its expected functions under specific conditions and within a given time frame. In the context of industrial AI and IIoT, reliability is not limited solely to the operational status of the physical machine. The accurate production of data by sensors, the accurate and timely transmission of data by the communication infrastructure, the consistent results provided by data processing systems, and the reliable outputs of the artificial intelligence model are also components of system reliability.

For example, in a predictive maintenance system, it is not enough for an AI model to demonstrate high accuracy on a test dataset. Sensor failure over time, data loss, or changes in production conditions can reduce the model's performance in the real operating environment. Therefore, reliability should be considered as a holistic process encompassing all stages: obtaining data from sensors, transmitting it through the communication infrastructure, processing it, analyzing it with the AI model, making decisions, and applying these decisions to the physical system.

Availability

Availability refers to the degree to which a system is operational and able to provide service when needed. Availability is particularly important in industrial production systems because even a short interruption in the production line can lead to production loss, delivery delays, and increased costs.

In IIoT systems, network disconnections, sensor or gateway failures, Edge Computing device malfunctions, or inaccessibility to central AI services can reduce system availability. Therefore, redundant hardware, alternative communication paths, local data processing, and rapid fault recovery mechanisms can be used for high availability. The Edge Computing approach can contribute to the continuation of certain processes locally in situations where central cloud connectivity is temporarily unavailable.

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Robustness

Robustness is the ability of an artificial intelligence or computing system to maintain acceptable performance in the face of changes in inputs, noise, distortion, or unexpected conditions. In industrial environments, data obtained from sensors may not always be under ideal conditions. Temperature variations, mechanical vibration, electromagnetic interference, sensor aging, and calibration errors can cause deviations in measurements. Similarly, changes in production conditions over time can create differences between the data distribution the AI model sees during training and the data distribution in the actual working environment. This is a significant problem, particularly in machine learning models, that can lead to a decrease in performance over time. Therefore, developing reliable and robust AI models is an important research area in current Industrial AI research.

Fault Tolerance

Fault tolerance is the ability of a system to continue operating without completely losing its core functionality even if one or more components fail. Since IIoT systems consist of numerous sensors, network devices, edge devices, and control components, the failure of a single component should not halt the entire system. Redundant sensors, alternative data sources, fault detection mechanisms, and safe operating modes can be used to increase fault tolerance. For example, if data cannot be received from one sensor, the system may be able to use data from another sensor, or a non-critical component may be disabled, allowing production to continue in a safe operating mode. This approach is particularly important in industrial facilities requiring continuous production. A reliable Industrial AI system should not only make correct decisions under normal operating conditions but also define how to behave if one of its data or hardware components fails.

Safety

Safety refers to a system operating in a way that prevents unacceptable harm to people, equipment, the environment, or the production process. Safety is particularly important in industrial AI systems because a decision generated by artificial intelligence can directly affect the behavior of a physical machine or production process. For example, if an AI system fails to detect a sign of failure in critical equipment, equipment damage may occur. Similarly, a production robot's assessment of an unsafe operating condition as normal can pose a risk to worker safety. Therefore, in safety-critical applications, it is important to validate AI outputs, identify ambiguous results, and switch the system to a safe operating mode when necessary.

Security

The interconnected nature of IIoT systems expands the attack surface to which production systems can be exposed to cyber threats. Sensors, gateways, edge computing devices, communication networks, and artificial intelligence systems can be subjected to unauthorized access or malicious interference. Therefore, cybersecurity should be considered an integral component of the reliability of Industrial AI and IIoT systems.

In an industrial environment, the impact of a cyber-attack may not be limited to data privacy breaches. Altering sensor data by an attacker can lead to the artificial intelligence model being fed incorrect data, resulting in erroneous decisions. For example, displaying a machine temperature as lower than it can prevent the predictive maintenance system from detecting a potential overheating situation.

CONCLUSION AND DISCUSSION

The integration of Industrial Artificial Intelligence and IIoT provides an important technological foundation for the development of smart factories. IIoT enables continuous data collection and communication among machines, sensors, and production systems, while Industrial AI transforms this data into information that can support monitoring, prediction, fault detection, optimization, and decision-making. In this architecture, Edge Computing can contribute to low-latency data processing by bringing computational capabilities closer to the production environment. Therefore, the effectiveness of Industrial AI depends not only on the performance of AI algorithms but also on the coordinated operation of sensing, communication, data processing, and physical production components.

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The comparison between general-purpose AI and Industrial AI further demonstrates the specific requirements of industrial environments. While prediction accuracy and generalization are important performance criteria in general-purpose AI, industrial applications must additionally consider physical and operational constraints, real-time response requirements, domain knowledge, robustness, and operational safety. Since AI-generated decisions may directly affect machines and production processes, an incorrect or delayed decision can lead to consequences beyond prediction errors, including production losses, equipment damage, quality problems, and safety risks.

From this perspective, reliability and security should be addressed as system-level requirements rather than solely as characteristics of the AI model. Reliability, availability, robustness, fault tolerance, safety, and cybersecurity represent complementary dimensions that influence the dependable operation of Industrial AI and IIoT systems. Sensor degradation, communication interruptions, hardware failures, changing operating conditions, and cyber threats may propagate through the system and ultimately affect AI-based decisions. Consequently, evaluating the entire process, including data acquisition, communication, data processing, AI-based analysis, decision-making, and interaction with the physical system, is essential for the effective deployment of Industrial AI in real-world industrial environments.

Overall, Industrial AI should be considered not simply as the application of machine learning algorithms to manufacturing data, but as an integrated approach combining industrial data, AI models, communication and computing infrastructures, engineering knowledge, and physical production systems. Future smart factories will therefore require AI solutions that maintain acceptable performance under changing operating conditions while ensuring system continuity, safety, and security. Further studies should focus on the development and real-world validation of such integrated architectures under different industrial conditions, particularly with respect to long-term robustness, fault recovery, real-time operation, and cybersecurity.

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THE FUTURE OF INDUSTRIAL AI: FROM LARGE LANGUAGE MODELS TO AUTONOMOUS AND SUSTAINABLE FACTORIES

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ABSTRACT

Industrial Artificial Intelligence is transforming manufacturing from task-specific automation toward more intelligent, distributed, and autonomous production systems. Recent advances in Large Language Models and foundation models have expanded the ability of AI to use industrial knowledge and support human–machine interaction. At the same time, technologies such as Retrieval-Augmented Generation, Federated Learning, and Edge AI provide new opportunities for knowledge integration, distributed learning, and local decision-making. However, increasing AI capabilities also create important requirements for reliability, explainability, privacy, and human oversight. This study reviews these emerging directions and discusses their role in the future of Industrial AI. Particular attention is given to the transition toward autonomous and sustainable manufacturing within the Industry 5.0 perspective. The study highlights how these technologies can contribute to future factories that are more adaptive, trustworthy, resource-efficient, and human-centered.

Keywords: Industrial Artificial Intelligence, Large Language Models, Industrial Foundation Models, Autonomous Manufacturing, Industry 5.0.

INTRODUCTION

Artificial intelligence has become an important part of modern manufacturing. It supports production planning, quality control, predictive maintenance, process monitoring, and optimization. However, the role of AI in industry is changing. Future manufacturing systems will require more than accurate predictions. They will need AI systems that can use industrial knowledge, interact with humans, operate across distributed environments, and adapt to changing production conditions. At the same time, these systems must remain reliable, secure, and resource-efficient. These requirements are moving Industrial Artificial Intelligence toward a new generation of intelligent manufacturing systems.

Recent developments in AI have accelerated this transformation. (Gao et al. (2024)) examined the state of AI in manufacturing and highlighted its growing role across different stages of manufacturing systems. Large models are also creating new possibilities for industrial applications. Industrial Foundation Models aim to learn from different forms of industrial data and provide reusable capabilities for multiple manufacturing tasks (Zhao et al., 2025). They can combine sensor measurements, images, technical documents, and process information. This direction may reduce the dependence on separate AI models for every industrial task. It also creates a basis for more flexible and knowledge-aware manufacturing systems.

The development of Industrial AI is also closely connected with Industry 5.0. Lu et al. (2022) emphasize human-centric manufacturing and the collaboration between humans and intelligent systems. Zhang et al. (2023) similarly identify human-centered smart manufacturing as an important direction for next-generation production. This transition is not limited to greater automation. Sustainability and resilience are also becoming important industrial objectives. Ivanov (2023) describes Industry 5.0 through the integration of human-centricity, sustainability, and resilience. These developments suggest that the future factory should not simply be more automated. It should also be adaptive, trustworthy, sustainable, and designed to support effective human–AI collaboration.

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This study examines the main technologies and concepts shaping the future of Industrial AI. First, the transition from conventional machine learning to Large Language Models is discussed, together with their emerging industrial applications. Retrieval-Augmented Generation and Industrial Foundation Models are then examined as approaches for integrating industrial knowledge with advanced AI models. The study also addresses distributed and trustworthy Industrial AI through Federated Learning, Edge AI, and explainable AI. Finally, the transition toward autonomous and sustainable manufacturing is discussed within the context of Industry 5.0. The study aims to provide a concise view of how these developments may contribute to the next generation of smart factories.

LARGE LANGUAGE MODELS AND INDUSTRIAL AI

Artificial intelligence has been used in manufacturing for many years, mainly for prediction, classification, monitoring, and optimization. Recent advances in Large Language Models (LLMs) have expanded this role. Industrial AI can now process not only sensor and production data but also technical documents, maintenance records, and other forms of industrial knowledge. This development creates new opportunities for human–machine interaction and decision support in manufacturing. However, general-purpose LLMs alone cannot meet all industrial requirements. They need access to domain-specific knowledge and must operate within the technical constraints of industrial systems. This section discusses this transition from conventional machine learning to LLM-based industrial applications. It also examines Retrieval-Augmented Generation and Industrial Foundation Models as important approaches for building more domain-aware Industrial AI systems.

From Machine Learning to Large Language Models in Industrial AI

Machine learning (ML) has been a core technology in Industrial Artificial Intelligence for many years. Industrial systems generate large amounts of data through sensors, machines, and production processes. ML models use these data to identify patterns and support operational decisions. Common applications include fault detection, predictive maintenance, quality prediction, and process monitoring. In predictive maintenance, for example, a model can analyze vibration or temperature data to detect changes in machine behavior. This allows maintenance teams to identify possible failures before a complete breakdown occurs. Recent studies continue to identify predictive maintenance as an important application of AI in smart manufacturing (Faisal and Diego, 2025).

Deep learning (DL) extended these capabilities by learning complex patterns directly from large and high-dimensional datasets. This is useful when industrial data include images, time series, audio signals, or other complex measurements. However, conventional ML and DL models are usually developed for a specific task. A model trained to detect a particular machine fault generally performs that defined task. It does not naturally interpret maintenance manuals, answer an operator's questions, or combine technical documents with contextual information. This task-specific structure represents an important difference between conventional industrial AI models and emerging foundation models.

Large Language Models (LLMs) introduce a different capability to Industrial AI. They are designed to understand and generate natural language and can also support reasoning, interaction, and knowledge integration. Their role in manufacturing is therefore broader than conventional prediction or classification. Recent reviews show that LLMs are being investigated across product design, process planning, production, quality control, maintenance, supply chains, and decision support (Maghanaki et al. 2026).

This difference can be illustrated through predictive maintenance. A conventional ML model may analyze vibration data and predict that a bearing has a high probability of failure. An LLM can support the next stage of the process. It may interpret the prediction together with maintenance records, technical manuals, and previous fault reports. It can then present this information to an engineer in natural language. Recent research on fault diagnosis suggests that LLMs can provide a complementary layer for contextual reasoning and knowledge integration rather than replacing conventional signal-processing or deep-learning models (Thuan and Anh, 2026).

This complementary relationship is important for the future of Industrial AI. Numerical sensor data remain well suited to specialized ML and DL models. LLMs can add access to unstructured industrial

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knowledge and provide a more natural interface between humans and AI systems. For example, an operator may ask why a machine was classified as abnormal or request relevant maintenance instructions. An LLM-based system can combine available technical information and provide a contextual response. Similar approaches are being explored for manufacturing design, planning, monitoring, maintenance, and worker training (Bajestani et al. 2026).

The emergence of Industrial Foundation Models (IFMs) extends this direction further. These models aim to adapt the capabilities of large foundation models to industrial data, knowledge, and tasks. Current research examines IFMs at the data, model, and application levels. Techniques such as fine-tuning, prompt engineering, and Retrieval-Augmented Generation (RAG) can help connect general models with domain-specific industrial knowledge (Zhao et al. 2025). This is particularly relevant because manufacturing knowledge is distributed across sensor records, maintenance reports, technical documents, process descriptions, and expert experience.

However, LLMs should not be considered a direct replacement for existing industrial AI models. Manufacturing systems have strict requirements for reliability, privacy, latency, and safety. LLMs may also generate incorrect or unsupported information. Their integration with industrial systems therefore requires validation and appropriate human supervision. Current research identifies reliability, interpretability, domain integration, and real-time operation as important challenges for industrial LLM applications [2,4].

The transition from ML to LLMs should therefore be viewed as an expansion of Industrial AI rather than a replacement of previous methods. ML and DL models provide specialized prediction and detection capabilities. LLMs add natural language interaction, knowledge integration, and contextual reasoning. Their combination may support industrial systems that can not only detect a problem but also explain its context and assist humans in deciding what to do next. This transition forms an important step toward more intelligent and autonomous manufacturing systems.

Large Language Models in Industrial Applications

Large Language Models are creating new opportunities for the use of artificial intelligence in manufacturing. Their main advantage is the ability to process and connect different forms of industrial knowledge. Production records, maintenance reports, technical manuals, and operator notes often contain valuable information. However, these sources are usually distributed across different systems. LLMs can help transform such information into accessible knowledge for engineers and operators. Recent studies report applications across production planning, manufacturing operations, quality control, maintenance, engineering, and supply chain management (Maghanaki et al. 2026).

Production planning and scheduling is one important application area. Manufacturing planning requires information about orders, resources, machines, and operational constraints. LLMs can translate natural language instructions into structured planning information. They can also assist planners in evaluating alternative production scenarios. For example, a production manager may need to revise a schedule after a machine becomes unavailable. An LLM-based assistant can interpret the situation and help generate alternative task sequences. However, generated schedules must still be checked against production constraints. LLMs are therefore more suitable as planning assistants than as independent optimization tools.

Another promising area is shop-floor support. Operators frequently interact with complex machines, production instructions, and technical documentation. Finding the correct information during an operational problem can take time. An LLM can provide a natural language interface to this information. For instance, an operator could describe an alarm message and request possible causes or relevant operating instructions. The system could retrieve the related technical information and present it in a simpler form. This approach can reduce the effort required to access industrial knowledge and improve human-machine interaction. LLMs are also being studied as interfaces between workers, robots, and manufacturing systems.

Quality control provides another practical use case. Modern quality systems collect information from inspection reports, production records, sensor measurements, and images. LLMs can help organize this

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information and support the interpretation of quality problems. A model may summarize recurring defect reports or connect a detected problem with previous production records. It may also assist engineers during root-cause analysis. In multimodal systems, language models can be combined with visual information to support the interpretation of product defects. Nevertheless, defect detection itself often requires specialized computer vision or statistical models. LLMs can complement these models by adding contextual information and supporting communication with quality engineers [1].

Maintenance is one of the most suitable industrial applications for LLMs. Maintenance knowledge is often distributed across sensor data, service reports, fault histories, manuals, and expert experience. LLMs can bring these sources together and make them easier to use. Consider a machine whose vibration monitoring system detects an abnormal condition. A specialized predictive model may first identify the anomaly. An LLM can then examine related maintenance records and technical documents. It can summarize possible causes and provide relevant information to the maintenance engineer. In this structure, the LLM does not replace the predictive model. Instead, it connects the prediction with available industrial knowledge and supports the next decision.

LLMs can also support industrial decision-making. Engineers and managers often need to combine information from several sources before making a decision. These may include production reports, machine conditions, quality records, and maintenance histories. An LLM-based system can summarize this information and make it easier to examine. This capability is particularly useful when a large part of the available knowledge is stored as text. It can also provide a conversational interface through which users can ask questions about production processes. Such systems can reduce the time required to search technical information and may improve access to organizational knowledge.

Despite these opportunities, industrial use of LLMs requires careful control. A generated response may contain incorrect or unsupported information. This is particularly important when model outputs influence equipment, production schedules, or safety-related decisions. Industrial applications therefore require reliable data sources, validation mechanisms, and human supervision. Integration with existing Manufacturing Execution Systems and other industrial platforms is another practical challenge. Current research also emphasizes reliability, interpretability, domain integration, and human oversight as key requirements for industrial deployment (Maghanaki et al. 2026).

Overall, LLMs can serve as a new interaction and knowledge layer within Industrial AI. Their value is not limited to generating text. They can connect technical knowledge with production activities and make complex information easier to access. Their combination with specialized AI models, industrial databases, and human expertise is therefore more realistic than using LLMs as standalone systems. This approach may support the transition from task-specific industrial AI toward more interactive and knowledge-aware manufacturing systems.

Retrieval-Augmented Generation for Industrial Knowledge

Large Language Models contain broad knowledge acquired during pre-training. However, industrial applications often require highly specific information. Machine manuals, maintenance records, operating procedures, technical standards, and fault reports may contain knowledge that is not available to a general-purpose LLM. This information can also change over time. Therefore, relying only on the internal knowledge of an LLM is not sufficient for many industrial tasks. Retrieval-Augmented Generation (RAG) provides a practical way to address this limitation. Recent studies identify RAG as one of the main techniques for adapting LLMs to industrial domains (Yu et al. (2026), Chen et al. (2026)).

RAG combines information retrieval with text generation. When a user submits a question, the system first searches an external knowledge source. Relevant information is retrieved and added to the context provided to the LLM. The model then generates its response using both the user query and the retrieved information. In this way, the model does not need to store all industrial knowledge within its parameters. Instead, it can access relevant knowledge when it is needed. This approach is particularly useful in manufacturing, where information is distributed across many documents and systems.

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A simple maintenance example illustrates this process. Suppose an operator receives an unusual alarm from a production machine. The operator asks the system, *"What does this alarm mean, and what should I check first?"* A general-purpose LLM may provide a generic answer. A RAG-based system can first retrieve the relevant sections from the machine manual, previous maintenance reports, and fault documentation. The LLM can then use this information to generate a more specific response. Thus, RAG can connect natural language interaction with the technical knowledge already available within a factory. Research on industrial fault diagnosis also identifies RAG and knowledge integration as useful components for connecting LLMs with domain-specific diagnostic information (Thuan et al. 2026).

The quality of retrieval is an important part of this process. Industrial documents often contain specialized terminology, equipment codes, abbreviations, and technical relationships. A system must retrieve the correct information before the LLM can generate a reliable answer. For this reason, industrial RAG may be combined with structured knowledge sources such as knowledge graphs. Knowledge graphs can represent relationships among machines, components, processes, faults, and maintenance actions. Recent smart manufacturing research identifies knowledge graphs as an important enabler for integrating domain knowledge with LLM-based systems (Chen et al. (2026)).

RAG also offers an important advantage when industrial knowledge changes. Updating an LLM through repeated training can require considerable data and computational resources. With RAG, new manuals, procedures, or maintenance records can instead be added to the external knowledge base. The updated information can then become available during retrieval. This makes RAG suitable for environments where technical knowledge changes throughout the equipment and production lifecycle. Current research also places RAG alongside prompt engineering and parameter-efficient fine-tuning as a major approach for adapting LLMs to industrial tasks (Yu et al. 2016)

Another benefit is traceability. In industrial environments, engineers need to know where technical information comes from. A RAG system can associate an answer with the documents used during generation. This can help users verify recommendations before taking action. Such verification is particularly important when an AI response may affect maintenance, production, or equipment operation. A recent industrial question-answering study developed a RAG approach using a domain-specific knowledge base and reported improved precision in knowledge-intensive industrial queries.

However, RAG does not eliminate the reliability problems of LLMs. Poor retrieval may provide irrelevant or outdated information. The model may also misinterpret retrieved content or generate unsupported conclusions. Industrial knowledge bases therefore require careful document selection, access control, version management, and evaluation. Human verification remains important for safety-critical decisions. Reliability, domain integration, privacy, and validation continue to be major concerns in industrial LLM deployment (Bajestani et al. 2026).

Overall, RAG provides a bridge between general-purpose LLMs and domain-specific industrial knowledge. It allows an LLM to work with information from technical documents, maintenance records, standards, and other industrial sources without requiring all knowledge to be embedded in the model itself. This makes RAG an important component of future industrial AI systems. Its main value lies in providing more relevant, traceable, and context-aware access to industrial knowledge.

Industrial Foundation Models

Foundation Models have changed the way artificial intelligence systems are developed. Instead of training a separate model for every task, a foundation model is trained on large and diverse datasets. It can then be adapted to different downstream tasks. However, general-purpose foundation models are not designed specifically for industrial environments. Manufacturing systems contain specialized data, physical constraints, engineering knowledge, and strict operational requirements. These differences have led to growing interest in Industrial Foundation Models (IFMs) (Zhao et al. (2025), Ren et al. (2025)).

Industrial Foundation Models extend the foundation model concept to manufacturing and other industrial domains. Their objective is to build reusable AI models that understand industrial data, processes, and domain knowledge. Unlike a general Large Language Model, an IFM is not limited to

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textual information. Industrial environments generate time-series signals, sensor measurements, images, maintenance records, process parameters, and engineering documents. An IFM may learn from several of these data types and provide a common intelligence layer for different industrial tasks (Zhao et al. (2025)).

This distinction is important because industrial data have characteristics that differ from common web or language data. A temperature signal from a production line, for example, cannot be interpreted only as a sequence of numbers. Its meaning depends on the machine, operating state, process limits, and production conditions. Similarly, an abnormal vibration pattern may indicate different problems for different equipment. Industrial knowledge is therefore an important part of model development. Recent IFM architectures combine large-scale industrial data with domain knowledge and industrial mechanisms during model training and adaptation.

A major advantage of IFMs is their potential to support multiple industrial tasks with a common model. Conventional industrial AI systems often use separate models for fault diagnosis, quality inspection, process prediction, and maintenance. These models usually require task-specific datasets and training procedures. IFMs aim to provide stronger transfer and generalization capabilities. A base model can be adapted to a particular factory, machine, or production task using domain-specific data. Current research distinguishes between broader industrial domain models and models adapted to specific industrial tasks.

Sensor data may indicate an abnormal operating condition. Maintenance records may describe similar failures from the past. Technical manuals provide information about components and operating limits. An IFM could connect these different sources within a common model architecture. The same foundation model could then be adapted for fault diagnosis, maintenance support, or process analysis. This differs from traditional task-specific AI, where each problem often requires an independent model and training process. Research in the process industry similarly highlights monitoring, diagnosis, optimization, and intelligent decision support as promising areas for foundation-model-based systems (Ren et al. (2025)).

Another important direction is multimodal industrial intelligence. Manufacturing decisions rarely depend on a single data source. A quality engineer may use product images, process parameters, sensor signals, and inspection reports at the same time. Foundation models provide a possible architecture for learning relationships among these different modalities. This capability could support more integrated analysis of production systems. It may also improve the ability of AI systems to transfer knowledge between related industrial tasks (Zhao et al. (2025), Ayyat et al. (2025)).

Foundation models also have potential in human–robot collaboration. Robots operating in flexible production environments must understand tasks and adapt to changing conditions. The approach was designed to improve the ability of robotic systems to generalize beyond fixed manufacturing conditions (Ji et al. (2024)). This direction is important for future factories, where humans, robots, and AI systems are expected to work more closely together.

Industrial datasets are often smaller and less accessible than public datasets used for general foundation models. Data may also be confidential or distributed across different factories. Training large models requires substantial computational resources. More importantly, industrial systems require reliable and trustworthy outputs. An incorrect response may affect product quality, equipment operation, or worker safety. Generalization, data security, computational cost, model validation, and domain adaptation therefore remain important research problems (Ayyat et al. (2025)).

Industrial Foundation Models should therefore be viewed as a step toward more general and reusable industrial intelligence. Their goal is not simply to create larger AI models. The more important objective is to combine industrial data, domain knowledge, and adaptable AI capabilities within a common framework. Such models may reduce dependence on isolated task-specific solutions. They may also provide a foundation for intelligent agents, autonomous production systems, and more flexible smart factories.

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DISTRIBUTED AND TRUSTWORTHY INDUSTRIAL AI

The growing use of AI in manufacturing creates new requirements for data processing, privacy, and trust. Industrial data are often generated across machines, edge devices, production lines, and different factories. Therefore, relying only on centralized AI systems may not be suitable for every industrial application. At the same time, AI-based decisions must be reliable and understandable when they affect physical processes. Distributed and trustworthy Industrial AI addresses these needs by combining decentralized learning, local intelligence, and transparent decision-making. Federated Learning enables collaborative model training while keeping industrial data at their local sources. Edge AI moves computation closer to machines and supports faster responses. Explainable AI helps engineers and operators understand and evaluate model decisions. Together, these approaches provide an important foundation for secure, responsive, and trustworthy AI in future manufacturing systems.

Federated Learning for Industrial AI

Industrial AI depends on large amounts of data collected from machines, sensors, production lines, and industrial systems. In many cases, these data are distributed across different factories or organizations. Bringing all data into a central server is not always possible. Industrial data may contain confidential information about production processes, machine conditions, or company operations. Privacy, security, and data ownership can therefore limit data sharing between manufacturers (Leng et al. (2026), Zhang et al. (2023)).

Federated Learning (FL) offers a different approach to this problem. It allows several participants to train a shared model without directly exchanging their raw data. Each participant trains the model locally using its own dataset. Only model updates are sent to an aggregation server. These updates are combined to improve a global model. The new global model can then be distributed back to the participants. In this way, the data remain at their original locations while knowledge is shared through model updates (Leng et al. (2026), Liu et al. (2024)).

This approach is useful in manufacturing because valuable data are often separated into data silos. For example, several factories may operate similar machines. Each factory may have only a limited number of failure examples. Sharing the complete datasets may not be acceptable because of confidentiality concerns. With FL, each factory can train a local model using its own machine data. The locally learned information can then contribute to a common model. The factories can therefore benefit from collective knowledge without transferring their raw production data to each other.

Predictive maintenance is a good example. Machine failures are relatively rare, and a single factory may not have enough failure data to train a robust model. Several factories using similar equipment could participate in federated training. Local models could learn from vibration, temperature, or other condition-monitoring data. Their model updates could then contribute to a shared predictive maintenance model. Recent studies identify predictive maintenance as an important application area for FL because it combines distributed industrial data with strong privacy requirements (Purkayastha et al. (2024)).

FL can also support distributed quality monitoring. Production sites may manufacture similar products under different operating conditions. A model trained at only one site may not capture this variation. Federated training allows knowledge from several production environments to contribute to the learning process. A 2025 study, for example, examined federated learning for hierarchical and distributed quality monitoring in smart manufacturing (Chen et al. (2025)).

The connection between FL and Edge Computing is also important. Modern factories contain many edge devices that collect and process data close to machines. These devices can perform local model training without continuously transferring raw sensor data to the cloud. Edge-based FL can therefore reduce unnecessary data transmission and support privacy-preserving distributed learning. This combination is becoming increasingly relevant for Industrial Internet of Things (IIoT) environments.

However, keeping raw data local does not make FL completely secure. Information may still be exposed through model updates. Malicious participants can also send manipulated updates and affect the global

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model. Additional protection mechanisms may therefore be required. Recent industrial FL research considers privacy leakage and model poisoning as important security problems (Liu et al. (2023)).

Another challenge comes from differences between factories. Machines may operate under different loads, environmental conditions, maintenance histories, and production settings. As a result, local datasets may have different statistical distributions. This is commonly described as the non-IID data problem. Such differences can reduce the performance of the global model. Communication overhead and differences in computing resources also create practical difficulties for large industrial FL systems (Chen et al. (2025), Sah et al. (2025)).

Overall, Federated Learning provides a promising approach for collaborative Industrial AI. Its main value is not simply keeping data in different locations. It enables organizations and industrial devices to learn from distributed data while maintaining greater control over their own information. This capability can support predictive maintenance, quality monitoring, and other data-driven manufacturing applications. However, privacy protection, security, communication efficiency, and differences between local datasets must still be addressed before FL can be widely deployed in industrial environments (Leng et al. (2025), Sah et al. (2025)).

Edge AI and Distributed Intelligence

Industrial systems continuously generate data through sensors, machines, cameras, and control devices. Sending all these data to a remote cloud platform is not always efficient. Network delays may affect real-time decisions. Communication failures can also interrupt access to cloud services. In addition, continuous data transmission requires network bandwidth and may create privacy concerns. These limitations have increased the importance of Edge AI in industrial environments (Savaglio et al. (2024), Singh et al. (2023)).

Edge AI brings artificial intelligence closer to the source of industrial data. AI models can operate on edge devices, industrial computers, gateways, or other computing units located near production equipment. Data can therefore be analyzed locally instead of being continuously transferred to a central cloud server. This changes the traditional flow of industrial data. The system can process important information where it is generated and send only selected results to other layers of the network.

One of the main advantages is low latency. Some industrial decisions must be made within a short time. Consider a camera that monitors workers near a hazardous machine. A cloud-based system first sends video data to a remote server and waits for the analysis result. Edge AI can analyze the video close to the production area. If a dangerous situation is detected, the system can react without depending on a distant data center. A 2024 study comparing cloud and edge intelligence for safety-critical IIoT video analytics highlighted responsiveness, reliability, bandwidth use, and energy consumption as important differences between these approaches.

Predictive maintenance is another relevant example. Machines can generate continuous streams of vibration, temperature, acoustic, and electrical data. Transmitting every measurement to the cloud may be unnecessary. An AI model deployed at the edge can continuously monitor these signals. It can detect abnormal patterns locally and transmit an alert when necessary. Recent research on AI and edge computing for machine maintenance identifies faster inference, reduced dependence on centralized computing, and improved availability as important benefits of this architecture.

Edge AI is also useful for quality inspection. Production lines may generate large numbers of high-resolution images. These images can be analyzed directly by AI models deployed near industrial cameras. Defective products can then be identified before they move to the next production stage. A recent smart manufacturing study demonstrated the deployment of a lightweight convolutional neural network for industrial component recognition in an edge environment. Such applications show how local intelligence can support rapid monitoring and control on the factory floor.

However, Edge AI should not be understood as a complete replacement for cloud computing. Edge devices usually have less processing power, memory, and storage than cloud servers. Large AI models may therefore be difficult to deploy directly on these devices. Techniques such as model compression, quantization, and lightweight neural networks can help reduce computational requirements. The cloud

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can still perform computationally intensive tasks, long-term data analysis, and centralized model management. Edge devices can focus on tasks that require fast local decisions.

This relationship leads to the broader concept of distributed intelligence. Intelligence does not need to exist at a single point in an industrial system. Different computational tasks can be distributed among sensors, edge devices, factory servers, and cloud platforms. A machine may perform local anomaly detection, while a factory-level server combines information from several production lines. The cloud may then provide long-term analysis or coordinate models across multiple sites. Edge AI therefore becomes one layer of a larger distributed Industrial AI architecture. Recent Edge AI research describes distributed and hierarchical architectures as important approaches for deploying intelligence across connected systems (Shankar (2024)).

Despite these advantages, distributed intelligence introduces new challenges. Edge devices have different hardware capabilities and may operate under changing network conditions. Managing many distributed AI models can also be difficult. Security becomes important because intelligence is deployed across a larger number of devices and network points. Research on secured edge intelligence notes that Edge AI can improve smart manufacturing while also introducing new security vulnerabilities that must be considered during deployment.

Overall, Edge AI moves Industrial AI from centralized processing toward more distributed intelligence. Its main value is the ability to make decisions close to machines and production processes. This can reduce latency, limit unnecessary data transmission, and improve responsiveness. Cloud and edge systems can also work together rather than compete with each other. Such a distributed structure is particularly important for future factories that require real-time monitoring, flexible automation, and increasingly autonomous operation.

Explainable and Trustworthy Industrial AI

The increasing use of complex AI models in manufacturing creates an important trust problem. Many models can provide accurate predictions without clearly showing how the result was obtained. This “black-box” behavior can limit their acceptance by engineers and operators. In industrial environments, understanding a prediction can be as important as the prediction itself. This is particularly relevant when AI outputs affect maintenance, quality control, or production decisions (Goldman et al. (2023))

Explainable Artificial Intelligence (XAI) aims to make AI decisions more understandable to humans. XAI methods can show which features or observations contributed most to a prediction. Consider a predictive maintenance system that reports a high risk of machine failure. An explanation may show that increasing vibration and temperature values were the main factors behind this prediction. The maintenance engineer can then compare the explanation with physical knowledge of the machine. Similar approaches can be used in quality inspection. For image-based defect detection, XAI methods can indicate which region of a product image influenced the model's decision (Nikiforidis et al. (2025)).

Explainability is also closely related to trustworthy Industrial AI. However, trustworthiness is broader than explainability alone. It also involves factors such as reliability, robustness, fairness, transparency, and accountability. An understandable model is not automatically a reliable model. Similarly, an accurate model may not be suitable for industrial use if its decisions cannot be verified. For this reason, trustworthy Industrial AI requires both technical performance and mechanisms that allow humans to understand and evaluate AI-supported decisions.

This need becomes more important with the transition toward Industry 5.0. Future manufacturing systems are expected to increase collaboration between humans and intelligent machines. Engineers and operators must therefore be able to evaluate AI recommendations rather than simply accept them. Explainability can support this interaction by making model behavior more transparent. It can also help identify incorrect predictions before they influence physical processes. XAI is therefore an important step toward Industrial AI systems that are not only intelligent, but also understandable and trustworthy (Agostinho et al. (2023)).

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AUTONOMOUS AND SUSTAINABLE INDUSTRIAL AI

The future of Industrial AI is moving toward production systems that can operate with greater autonomy. AI is already used in manufacturing for process planning, optimization, quality assurance, maintenance, and automated assembly (Gao et al. (2024)). Future systems are expected to go beyond individual AI-supported tasks. They will increasingly monitor production conditions, evaluate alternatives, and adapt their operations with less direct intervention. This transition represents an important step from automated manufacturing toward more autonomous manufacturing.

Autonomous manufacturing does not mean removing humans from production. Instead, AI can take responsibility for repetitive analysis and support complex operational decisions. Humans can remain responsible for supervision, strategic decisions, and unexpected situations. This approach is closely related to Industry 5.0, which places human needs alongside technological development. Human-centric manufacturing combines the flexibility and experience of humans with the precision and computational capabilities of machines (Lu et al. (2022)).

Consider an unexpected machine failure on a production line. An intelligent system may first detect the abnormal condition using sensor data. It can then evaluate the effect of the failure on the current production plan. The system may recommend an alternative machine or adjust the production sequence. An operator can review the recommendation before a major change is applied. In this way, autonomy can be introduced at different levels rather than as an all-or-nothing concept. AI can support decisions while human control is maintained when necessary. This balance between automation and human involvement is an important part of human-centric manufacturing (Lu et al. (2022), Zhang et al. (2023))

Sustainability is another important objective of future Industrial AI. Manufacturing systems consume energy, raw materials, and other resources. AI can support more efficient use of these resources by analyzing production data and identifying inefficient operating conditions. Research has identified applications in energy management, resource optimization, sustainable scheduling, remanufacturing, and waste reduction [4,5]. For example, an AI system can analyze energy consumption across machines and production schedules. Production activities can then be adjusted to reduce unnecessary energy use without compromising production requirements.

The combination of autonomy and sustainability creates an important opportunity. Future production systems may consider environmental objectives during operational decision-making rather than evaluating them only after production. A production plan could consider energy consumption together with delivery time and machine availability. Maintenance decisions could also consider equipment life and resource use. Such approaches connect Industrial AI with broader concepts such as sustainable manufacturing and the circular economy (Waltersmann et al. (2021), Agrawal et al. (2023)).

These developments also reflect the transition from Industry 4.0 toward Industry 5.0. Industry 5.0 extends the focus beyond automation and productivity. Sustainability, resilience, and human-centricity become important objectives of industrial development (Ivanov, (2023)). Therefore, a highly automated factory should not be considered successful only because it produces more with less human intervention. Future factories must also use resources responsibly, adapt to disruptions, and support human well-being.

Industrial AI can play an important role in this transition. However, higher autonomy also increases the importance of reliable decisions and human oversight. AI systems that directly influence machines and production processes must operate within clearly defined limits. The future of Industrial AI should therefore not be understood as a move toward completely human-free factories. A more realistic direction is the development of adaptive, resource-efficient, and human-centered production systems. In such factories, AI, machines, and humans work together to achieve both operational and sustainability goals.

CONCLUSION AND DISCUSSION

Industrial AI is evolving beyond task-specific prediction and automation. Large Language Models, Retrieval-Augmented Generation, and Industrial Foundation Models are extending AI toward knowledge-aware and interactive industrial systems. At the same time, Federated Learning and Edge AI

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enable intelligence to operate across distributed industrial environments. These developments show that the future of Industrial AI will depend not on a single technology, but on the integration of specialized AI models, industrial knowledge, distributed computing, and human expertise.

Despite this progress, several challenges remain. Industrial environments require high levels of reliability, privacy, security, and responsiveness. LLMs may generate incorrect information, distributed learning can introduce privacy and security risks, and edge devices have limited computational resources. Increasing model complexity also makes explainability and human oversight more important. Therefore, greater autonomy should not mean removing humans from industrial decision-making. Trustworthy deployment requires AI decisions to be validated and their role to be clearly defined, particularly when they influence equipment, production processes, or worker safety.

Future Industrial AI is expected to move toward more autonomous, sustainable, and human-centered manufacturing. AI systems may increasingly monitor production, use industrial knowledge, adapt to changing conditions, and optimize the use of energy and resources. However, technological capability alone will not define the future smart factory. The integration of autonomy with sustainability, trustworthiness, and human collaboration will be equally important. From this perspective, Industrial AI can become a key enabler of Industry 5.0 and support factories that are not only more intelligent, but also more adaptive, resource-efficient, and responsible.

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SGMMNS KONTEYNER TAŞIYICI VAGONUN FARKLI KONTEYNER YÜKLEME DURUMLARINDA AERODİNAMİK PERFORMANSININ SAYISAL İNCELENMESİ

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ÖZET

Demiryolu yük taşımacılığında artan işletme hızları ve enerji verimliliği gereksinimleri, yük vagonlarının aerodinamik performansının iyileştirilmesini önemli bir araştırma konusu hâline getirmiştir. Bu çalışmada, Sgmmns tipi konteyner taşıyıcı vagonun farklı yükleme konfigürasyonlarının aerodinamik performansa etkisi hesaplamalı akışkanlar dinamiği (HAD) yöntemi kullanılarak incelenmiştir. Vagonun üç boyutlu modeli SolidWorks ortamında oluşturulmuş, aerodinamik analizler ise ANSYS Fluent yazılımında gerçekleştirilmiştir. Sayısal analizlerde yaklaşık 5 milyon elemandan oluşan polyhedral ağ yapısı kullanılmış ve türbülans modeli olarak SST k-ω modeli tercih edilmiştir. CFD modeli, EN 14067-4 standardı esas alınarak oluşturulmuş olup analizler 80, 100 ve 120 km/h işletme hızlarında boş vagon, 20 ft, 2×20 ft, 30 ft ve 40 ft konteyner yükleme durumları için gerçekleştirilmiştir.

Analizler sonucunda hız, statik basınç ve türbülans kinetik enerjisi dağılımları ile sürükleme katsayısı (Cd), sürükleme kuvveti ve kaldırma kuvveti değerleri karşılaştırmalı olarak değerlendirilmiştir. Sonuçlar, konteyner boyutunun artmasıyla birlikte akış ayrılmasının belirginleştiğini, wake bölgesinin genişlediğini ve buna bağlı olarak aerodinamik sürüklemenin arttığını göstermiştir. En düşük aerodinamik direnç boş vagon konfigürasyonunda elde edilirken, en yüksek sürükleme katsayısı ve sürükleme kuvveti 40 ft konteyner yükleme durumunda hesaplanmıştır. Ayrıca, işletme hızının artmasıyla birlikte sürükleme ve kaldırma kuvvetlerinde belirgin artışlar gözlenmiş, buna karşın sürükleme katsayısının hızdan sınırlı düzeyde etkilendiği belirlenmiştir.

Elde edilen bulgular, konteyner yerleşim geometrisinin yük vagonlarının aerodinamik performansı üzerinde önemli bir tasarım parametresi olduğunu ortaya koymaktadır. Çalışmanın, yüksek hızlı yük vagonlarının aerodinamik tasarımına yönelik optimizasyon çalışmalarına ve enerji tüketiminin azaltılmasına katkı sağlayacağı değerlendirilmektedir.

Anahtar Kelimeler: Sgmmns konteyner taşıyıcı vagon, Hesaplamalı Akışkanlar Dinamiği (HAD), ANSYS Fluent, Aerodinamik, Sürükleme Katsayısı, EN 14067-4.

ABSTRACT

Increasing operating speeds and the growing demand for energy efficiency in railway freight transportation have highlighted the importance of improving the aerodynamic performance of freight wagons. In this study, the aerodynamic characteristics of an Sgmmns container wagon carrying different container configurations were investigated using Computational Fluid Dynamics (CFD). A three-dimensional model of the wagon was developed in SolidWorks, and the numerical simulations were performed using ANSYS Fluent. The computational domain was generated in accordance with the principles of EN 14067-4, employing a polyhedral mesh consisting of approximately five million cells. The SST k-ω turbulence model was adopted to accurately predict the external flow characteristics around the wagon. Aerodynamic analyses were conducted at operating speeds of 80, 100, and 120 km/h

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for five loading configurations: empty wagon, 20 ft container, two 20 ft containers, 30 ft container, and 40 ft container.

The velocity, static pressure, and turbulence kinetic energy distributions were analyzed to evaluate the influence of container geometry on the aerodynamic behavior of the wagon. In addition, the drag coefficient (Cd), drag force, and lift force were determined for each loading condition. The results indicated that increasing the container size intensified flow separation and enlarged the wake region behind the wagon, leading to higher aerodynamic resistance. The lowest drag coefficient and drag force were obtained for the empty wagon configuration, whereas the highest values were observed for the 40 ft container configuration. Furthermore, drag and lift forces increased with operating speed due to the increase in dynamic pressure, while the drag coefficient exhibited only minor variations over the investigated speed range.

The findings demonstrate that container loading geometry is a critical parameter affecting the aerodynamic performance of container wagons. The results provide useful guidance for the aerodynamic optimization of freight wagons and contribute to the development of more energy-efficient railway transportation systems.

Keywords: Sgmmns container wagon, Computational Fluid Dynamics (CFD), ANSYS Fluent, Aerodynamics, Drag Coefficient, Railway Freight Wagon, EN 14067-4.

GİRİŞ

Demiryolu taşımacılığı, yüksek taşıma kapasitesi, düşük enerji tüketimi ve çevresel sürdürülebilirlik avantajları nedeniyle dünya genelinde yük taşımacılığında stratejik bir ulaşım modu olarak öne çıkmaktadır. Özellikle uzun mesafeli konteyner taşımacılığında demiryolu sistemleri, karayolu taşımacılığına kıyasla daha düşük karbon emisyonu ve daha yüksek enerji verimliliği sunmaktadır. Avrupa Birliği'nin Yeşil Mutabakat (European Green Deal) hedefleri doğrultusunda yük taşımacılığının önemli bir bölümünün demiryoluna kaydırılması planlanmakta olup, bu durum yük vagonlarının performansının artırılmasına yönelik araştırmaları daha da önemli hale getirmektedir (European Commission, 2019).

Yük trenlerinin enerji tüketimini belirleyen temel parametrelerden biri aerodinamik dirençtir. Düşük hızlarda yuvarlanma direnci baskın olmakla birlikte, tren hızının artmasıyla birlikte aerodinamik sürükleme kuvveti toplam direnç içerisinde önemli bir paya ulaşmaktadır. Aerodinamik sürükleme kuvveti, trenin geometrisi, yükleme şekli, araçlar arasındaki boşluklar, konteyner yüksekliği ve akış ayrılması gibi birçok parametreden etkilenmektedir. Özellikle konteyner taşıyıcı yük trenlerinde yükleme konfigürasyonu, akış yapısını doğrudan değiştirmekte ve bunun sonucunda sürükleme kuvveti ile enerji tüketiminde önemli değişiklikler meydana gelebilmektedir (Schetz, 2001).

Günümüzde yük trenlerinin işletme maliyetlerinin azaltılması, enerji verimliliğinin artırılması ve karbon emisyonlarının düşürülmesi amacıyla aerodinamik optimizasyon çalışmaları giderek önem kazanmaktadır. Özellikle farklı konteyner tiplerinin aynı platform vagon üzerinde taşınabilmesi, hava akışının değişmesine neden olmakta ve bu durum aerodinamik performansın değerlendirilmesini gerekli kılmaktadır. Bununla birlikte, yüksek hızlı yolcu trenlerine yönelik aerodinamik çalışmalar literatürde oldukça geniş yer bulmasına rağmen, konteyner taşıyıcı yük vagonlarının farklı yükleme senaryolarına bağlı aerodinamik davranışlarını inceleyen çalışmaların sayısı oldukça sınırlıdır.

Son yıllarda Hesaplamalı Akışkanlar Dinamiği yöntemleri, demiryolu araçlarının aerodinamik performanslarının analizinde yaygın olarak kullanılmaktadır. HAD yöntemleri, deneysel rüzgâr tüneli çalışmalarına göre daha düşük maliyetli olmaları, farklı çalışma koşullarının hızlı bir şekilde analiz edilebilmesi ve akış alanının ayrıntılı olarak incelenmesine olanak sağlamaları nedeniyle önemli avantajlar sunmaktadır. Özellikle sonlu hacimler yöntemini kullanan ticari yazılımlar, karmaşık geometrilere sahip demiryolu araçlarının üç boyutlu akış analizlerinin güvenilir biçimde gerçekleştirilmesine imkân vermektedir (Ferziger & Perić, 2002).

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Demiryolu araçlarının aerodinamik analizlerinde en yaygın kullanılan yazılımlardan biri ANSYS Fluent'tir. Bu yazılım, farklı türbülans modelleri yardımıyla sürükleme katsayısı, basınç dağılımı, hız alanı, akış ayrılması, girdap oluşumu ve türbülans kinetik enerjisi gibi birçok aerodinamik parametrenin yüksek doğrulukla hesaplanmasına olanak sağlamaktadır. Özellikle k-ω SST türbülans modeli, yüzey yakınındaki sınır tabaka davranışını başarılı şekilde tahmin edebilmesi nedeniyle tren aerodinamiği çalışmalarında sıklıkla tercih edilmektedir (Menter, 1994).

Konteyner taşıyıcı Sgmmns tipi platform vagonlar, intermodal taşımacılıkta en yaygın kullanılan yük vagonlarından biridir. Bu vagonlar üzerinde 20 ft, 30 ft, 40 ft ve 45 ft ISO konteynerler farklı kombinasyonlarda taşınabilmektedir. Ancak konteyner boyutları, yükseklikleri ve yerleşim düzenleri değiştikçe akış alanı da önemli ölçüde değişmektedir. Konteynerler arasındaki boşluklar, keskin kenarlar ve ani geometrik değişimler akış ayrılmasına neden olarak sürükleme kuvvetinin artmasına yol açabilmektedir. Bu nedenle farklı yükleme senaryolarının aerodinamik açıdan değerlendirilmesi hem enerji tüketiminin azaltılması hem de işletme performansının artırılması açısından önem taşımaktadır.

Literatürde yük trenlerinin aerodinamiği üzerine gerçekleştirilen çalışmaların önemli bir kısmı tren dizisinin tamamını veya yalnızca lokomotif aerodinamiğini incelemektedir. Baker (2010), demiryolu araçlarının aerodinamik karakteristiklerini kapsamlı biçimde incelemiş ve özellikle yük trenlerinde araç geometrisinin akış yapısı üzerindeki etkilerini ortaya koymuştur. Benzer şekilde Baker (2014), tren aerodinamiğinde çapraz rüzgâr etkileri, sürükleme kuvveti ve akış ayrılması gibi temel aerodinamik olayları ayrıntılı olarak açıklamıştır. Bununla birlikte farklı konteyner yükleme konfigürasyonlarının aynı platform vagon üzerindeki etkilerini karşılaştıran sayısal çalışmaların sınırlı olduğu görülmektedir. Demiryolu araçlarının aerodinamik performansının iyileştirilmesine yönelik çalışmalar son yıllarda enerji tüketiminin azaltılması ve işletme verimliliğinin artırılması amacıyla önemli ölçüde artmıştır. Özellikle yük trenlerinde konteyner yükleme düzeninin akış yapısını değiştirmesi nedeniyle Hesaplamalı Akışkanlar Dinamiği (HAD) tabanlı çalışmalar ön plana çıkmaktadır.

Hemida ve Baker (2010), konteyner taşıyan yük vagonunun yan rüzgâr altında aerodinamik davranışını Large Eddy Simulation-LES yöntemi ile incelemiştir. Çalışmada tek bir konteyner vagonu modellenmiş ve komşu vagonların etkisi periyodik sınır şartları kullanılarak temsil edilmiştir. Sonuçlar, konteyner ön üst köşesinde akış ayrılması meydana geldiğini ve bunun çatı bölgesinde geniş bir türbülans alanı oluşturduğunu göstermiştir. Ayrıca hareketli zemin kullanımının kaldırma ve yan kuvvet katsayılarını önemli ölçüde değiştirdiği belirlenmiştir. Bu çalışma, yük vagonlarının HAD analizlerinde LES yönteminin güvenilirliğini göstermesi açısından temel referans niteliğindedir.

Beagles ve Fletcher (2013), farklı konteyner yükleme senaryolarının tren aerodinamiği ve enerji tüketimine etkilerini deneysel veriler ve CFD analizleri yardımıyla değerlendirmiştir. Araştırmada konteyner dizilişinin sürükleme kuvvetini önemli ölçüde değiştirdiği, özellikle boşluklu yüklemelerin aerodinamik direnci artırdığı belirlenmiştir. Bunun yanında yan rüzgâr etkileri de dikkate alınarak farklı yükleme stratejilerinin enerji tüketimine katkısı hesaplanmıştır. Araştırmacılar, uygun yükleme planlaması ile enerji tüketiminde anlamlı iyileşmeler elde edilebileceğini göstermiştir. Bu çalışma, konteyner yerleşiminin aerodinamik performans üzerindeki etkisini ortaya koyan önemli çalışmalardan biridir.

Östh ve Krajnović (2014), jenerik bir konteyner yük vagonunun aerodinamik davranışını LES yöntemi kullanarak incelemiştir. Çalışmada tek vagon ve sonsuz uzunluktaki tren dizisi olmak üzere iki farklı durum analiz edilmiştir. Tek vagon modelinde çatı üzerindeki ayrılma kabarcığının zamana bağlı salınım yaptığı belirlenirken, tren dizisi içerisinde bulunan vagonda sürükleme kuvvetinin tek vagona göre yaklaşık %90 oranında azaldığı rapor edilmiştir. Ayrıca vagonlar arasındaki boşluklarda oluşan akış yapısının yan kuvvetlerde periyodik değişimlere neden olduğu gösterilmiştir. Bu çalışma, yük trenlerinde vagonlar arası etkileşimin aerodinamik direnç üzerindeki önemini ortaya koymaktadır.

Maleki, Burton ve Thompson (2017), konteyner taşıyan yük vagonlarında farklı türbülans modellerinin doğruluğunu karşılaştırmıştır. ELES, SAS, URANS ve RANS modelleri deneysel rüzgâr tüneli verileri ile karşılaştırılmıştır. Çalışmada sürükleme katsayısı, yüzey basıncı, hız alanı ve akış çizgileri değerlendirilmiş; hibrit türbülans modellerinin karmaşık ayrılma bölgelerinde daha başarılı sonuçlar verdiği belirlenmiştir. Araştırmacılar, mühendislik uygulamalarında doğruluk ve hesaplama maliyeti

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açısından SST tabanlı modellerin uygun bir seçenek olduğunu belirtmiştir. Bu çalışma, Fluent analizlerinde kullanılacak türbülans modelinin seçimi açısından önemli bir referans oluşturmaktadır.

Liu, Hemida ve Liu (2014), yüksek hızlı bir yolcu treninin sabit durumdaki konteyner yük vagonunu geçmesi sırasında oluşan akış yapısını LES yöntemiyle incelemiştir. Çalışmada ray açıklığının basınç dalgaları ve aerodinamik yükler üzerindeki etkisi araştırılmıştır. Sonuçlar, geçiş sırasında oluşan ani basınç değişimlerinin konteyner yüzeylerinde önemli aerodinamik yükler oluşturduğunu göstermiştir. Araştırma özellikle geçiş aerodinamiği açısından yük vagonlarının davranışını ortaya koyması bakımından literatüre önemli katkı sağlamaktadır

Bu çalışmada, Sgmmns tipi konteyner taşıyıcı bir yük vagonunun farklı konteyner yükleme senaryoları altındaki aerodinamik davranışı Hesaplamalı Akışkanlar Dinamiği yöntemi kullanılarak incelenecektir. Öncelikle vagon ve farklı konteyner konfigürasyonları SolidWorks ortamında üç boyutlu olarak modellenmiş, daha sonra ANSYS Fluent yazılımında sayısal akış analizleri gerçekleştirilmiştir. Analizler sonucunda farklı yükleme senaryoları için sürükleme katsayısı, hız dağılımları, basınç konturları, akış ayrılması, girdap oluşumu ve türbülans yapıları karşılaştırılarak yükleme düzeninin aerodinamik performans üzerindeki etkileri ortaya konulacaktır. Çalışmanın, konteyner taşıyıcı yük vagonlarının aerodinamik tasarımına katkı sağlaması ve enerji verimliliğini artırmaya yönelik gelecekteki optimizasyon çalışmalarına temel oluşturması amaçlanmaktadır.

METARYEL VE YÖNTEM

Sgmmns Konteyner Taşıyıcı Vagon

Bu çalışmada analiz modeli olarak, Avrupa demiryolu ağlarında intermodal yük taşımacılığında yaygın olarak kullanılan Sgmmns tipi konteyner taşıyıcı platform vagon esas alınmıştır. Sgmmns vagonları; ISO standartlarına uygun 20 ft, 30 ft, 40 ft ve 45 ft konteynerlerin tekli veya farklı kombinasyonlar hâlinde taşınmasına imkân sağlayan dört dingilli platform tipi yük vagonlarıdır. Sahip oldukları yüksek taşıma kapasitesi, modüler yükleme yapısı ve farklı yük konfigürasyonlarına uygun tasarımı sayesinde uluslararası kombine taşımacılıkta yaygın olarak kullanılmaktadır.



Şekil-1 Sgmmns Konteyner Taşıyıcı Vagon (Epsilon Solentek)

Şekil-1'de gösterilen Vagon, kaynaklı yüksek dayanımlı çelik şasi yapısına sahip olup iki adet iki dingilli bojiden oluşmaktadır. Ana taşıyıcı yapı; orta boyuna kirişler, yan kirişler, enine traversler ve konteyner kilitleme noktalarını (twist-lock) taşıyan platform elemanlarından meydana gelmektedir. Açık platform yapısı sayesinde farklı boyutlardaki konteynerlerin taşınmasına olanak sağlamakta, yükleme senaryosuna bağlı olarak üst yapı geometrisi önemli ölçüde değişebilmektedir. Bu durum, hava akışının gelişimini doğrudan etkileyerek vagonun aerodinamik karakteristiğinde değişikliklere neden olmaktadır.

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Tablo 1. Analizde kullanılan Sgmmns tipi konteyner vagonunun temel teknik özellikleri

Teknik Özellik	**Değer**
Bogie	Y25Ls(s)1-K
Dara	28 ton
Yükleme Kapasitesi	107 ton
Toplam ağırlık	135 ton
Tamponlar arası mesafe	26.700 mm
Ray aralığı	1.435 mm
Yükleme uzunluğu	2*40ft
Yükleme genişliği	2.600 mm
Minimum dönüş çapı	150 m
Kinematik zarf	TSI-G1
Maksimum dingil yükü	22,5 ton
Maksimum hız	120 km/h

Sgmmns vagonunun temel teknik özellikleri Tablo 1'de verilmiştir. Bu özellikler, sayısal modelin oluşturulmasında esas alınan geometrik parametreleri temsil etmektedir.

Korunum Denklemleri

Dış akış problemlerinin çözümünde akışkan hareketi, kütlenin ve momentumun korunumu esasına dayanan Reynolds Ortalamalı Navier–Stokes (RANS) denklemleri ile tanımlanmaktadır. Bu çalışmada hava akışı sürekli, Newtonyen ve sıkıştırılamaz akış olarak kabul edilmiş olup sayısal çözüm ANSYS Fluent 2024 R1 yazılımı kullanılarak gerçekleştirilmiştir. Türbülanslı akışın modellenmesinde Reynolds ortalamalı denklemler çözülmüş ve türbülans etkileri SST k-ω modeli ile hesaplanmıştır.

Süreklilik Denklemi

Sıkıştırılamaz akış için süreklilik denklemi aşağıdaki şekilde ifade edilmektedir.

$$\frac{\partial u_i}{\partial x_i} = 0$$

Burada;

- u_i: hız bileşeni (m/s)
- x_i: koordinat bileşeni (m)

ifade etmektedir.

Momentum Denklemi

Reynolds ortalamalı momentum denklemi aşağıdaki şekilde yazılmaktadır.

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$$\rho\left(u_j\frac{\partial u_i}{\partial x_j}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)\right]-\frac{\partial}{\partial x_j}\left(\rho\overline{u_i'u_j'}\right)$$

Burada, ρ hava yoğunluğunu, p basıncı, μ dinamik viskoziteyi, $\overline{u_i'u_j'}$ise Reynolds gerilmelerini göstermektedir.

Momentum denklemlerinde yer alan Reynolds gerilmeleri doğrudan çözülemediğinden türbülans modeli kullanılarak kapatılmaktadır.

Türbülans Modeli

Bu çalışmada türbülans modeli olarak Shear Stress Transport (SST) k-ω modeli tercih edilmiştir. SST k-ω modeli ilk olarak Menter (1994) tarafından geliştirilmiş olup, standart k-ω modelinin duvar yakınındaki yüksek doğruluğu ile k-ε modelinin serbest akış bölgelerindeki kararlılığını birleştirmektedir. Böylece özellikle ters basınç gradyanlarının bulunduğu dış akış problemlerinde daha başarılı sonuçlar vermektedir.

Demiryolu araçlarının aerodinamik analizlerinde konteyner ön yüzeyleri, boji bölgeleri, şasi altı ve vagon arkasında yoğun akış ayrılması meydana gelmektedir. Bu bölgelerde oluşan karmaşık girdap yapılarının doğru tahmin edilmesi için SST k-ω modeli literatürde yaygın olarak kullanılmaktadır (Hemida & Baker, 2010; Maleki et al., 2017).

Model, türbülans kinetik enerjisi (k) ve özgül türbülans yayılım oranı (ω) için iki ayrı transport denklemi çözmektedir.

Türbülans kinetik enerjisi denklemi

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho u_j k)}{\partial x_j}=P_k-\beta^*\rho k\omega+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_k\mu_t)\frac{\partial k}{\partial x_j}\right]$$

Türbülans frekansı denklemi

$$\frac{\partial(\rho\omega)}{\partial t}+\frac{\partial(\rho u_j\omega)}{\partial x_j}=\alpha\frac{\omega}{k}P_k-\beta\rho\omega^2+\frac{\partial}{\partial x_j}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial\omega}{\partial x_j}\right]+2(1-F_1)\rho\sigma_{\omega2}\frac{1}{\omega}\frac{\partial k}{\partial x_j}\frac{\partial\omega}{\partial x_j}$$

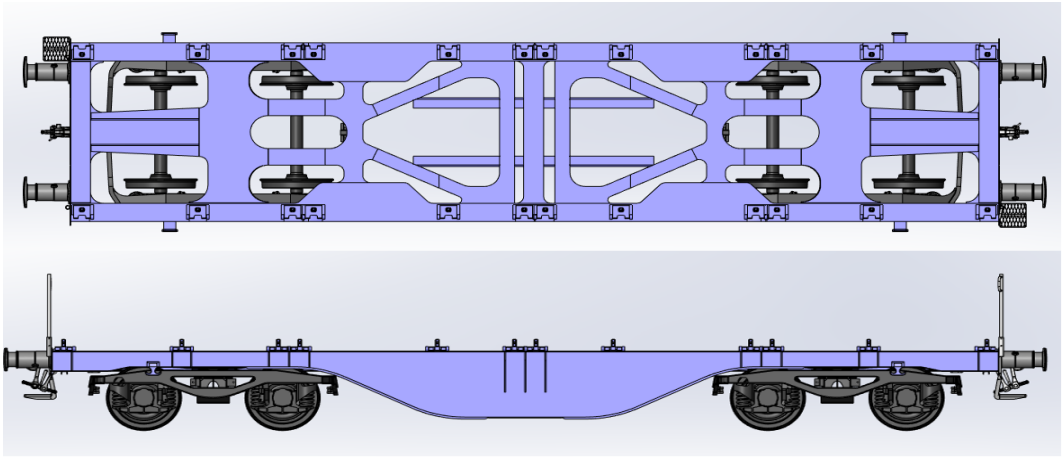
Burada; k: Türbülans kinetik enerjisi (m²/s²) ω: Türbülans frekansı (1/s) Pk: Türbülans üretim terimi μt: Türbülans viskozitesi F1: Geçiş (blending) fonksiyonu olarak tanımlanmaktadır.

SST k-ω modeli, duvar yakınında otomatik olarak k-ω, serbest akış bölgesinde ise k-ε formülasyonuna geçiş yaparak her iki modelin avantajlarını birlikte kullanmaktadır. Bu nedenle özellikle dış aerodinamik uygulamalarında sürükleme katsayısı, basınç dağılımı ve akış ayrılmasının tahmininde yüksek doğruluk sağlamaktadır. Maleki ve arkadaşları (2017), yük vagonlarının aerodinamik analizlerinde SST tabanlı modellerin deneysel sonuçlarla yüksek uyum gösterdiğini bildirmiştir. Benzer şekilde Hemida ve Baker (2010), tren aerodinamiğinde oluşan ayrılmalı akışların güvenilir şekilde tahmin edilmesi için SST ve LES tabanlı gelişmiş türbülans modellerinin kullanılmasını önermiştir.

Sayısal Model

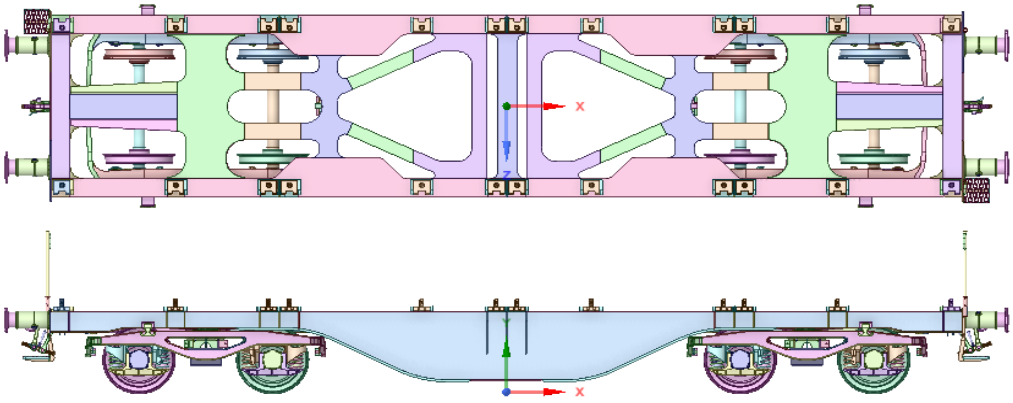
Şekil-2'de gösterilen Sgmmns tipi konteyner taşıyıcı vagonun üç boyutlu geometrik modeli, Solidworks bilgisayar destekli tasarım (CAD) yazılımı kullanılarak oluşturulmuştur. Modelleme sürecinde, vagonun gerçek üretim resimleri ve teknik boyutları esas alınmış, geometrik doğruluğun korunmasına özen gösterilmiştir. Oluşturulan model, konteyner taşımacılığında kullanılan Sgmmns platform vagonunun ana taşıyıcı şasisini, bojilerini, tamponlarını, kuplaj sistemini ve konteyner bağlantı elemanlarını içermektedir.

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Şekil-2 CAD Model

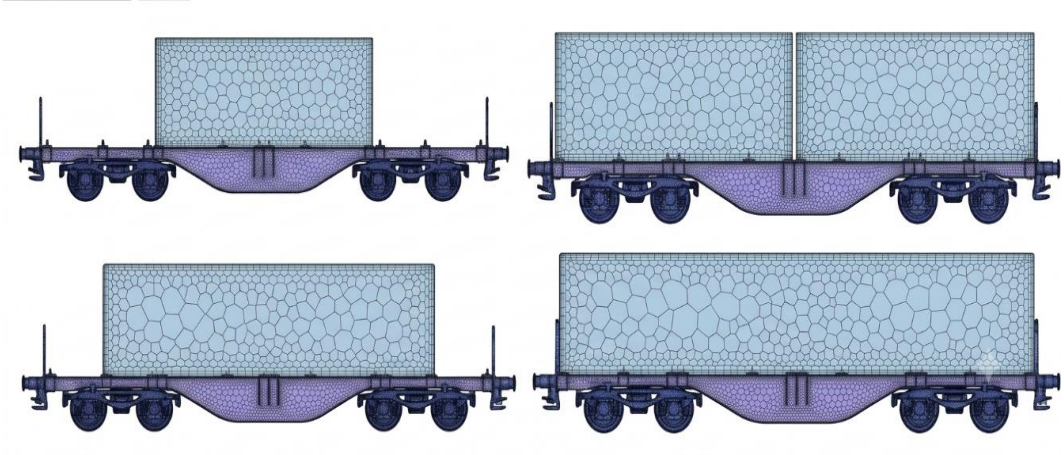
Sayısal akış analizlerinde hesaplama maliyetini azaltmak ve çözüm süresini optimize etmek amacıyla geometri üzerinde çeşitli sadeleştirmeler uygulanmıştır. Aerodinamik davranış üzerinde ihmal edilebilir etkiye sahip olan cıvatalar, somunlar, kaynak dikişleri, küçük montaj elemanları, fren boruları, kablo bağlantıları ve benzeri ikincil detaylar modelden çıkarılmıştır. Buna karşın hava akışını doğrudan etkileyen ana taşıyıcı şasi, orta kirişler, yan kirişler, traversler, tamponlar, bojiler ve konteyner bağlantı noktaları korunmuştur. Böylece hem gerçek geometriye yakın bir model elde edilmiş hem de hesaplama ağı yönetilebilir seviyeye indirilmiş olup şekil-3'te gösterilen sayısal model elde edilmiştir.



Şekil-2 Sayısal Model

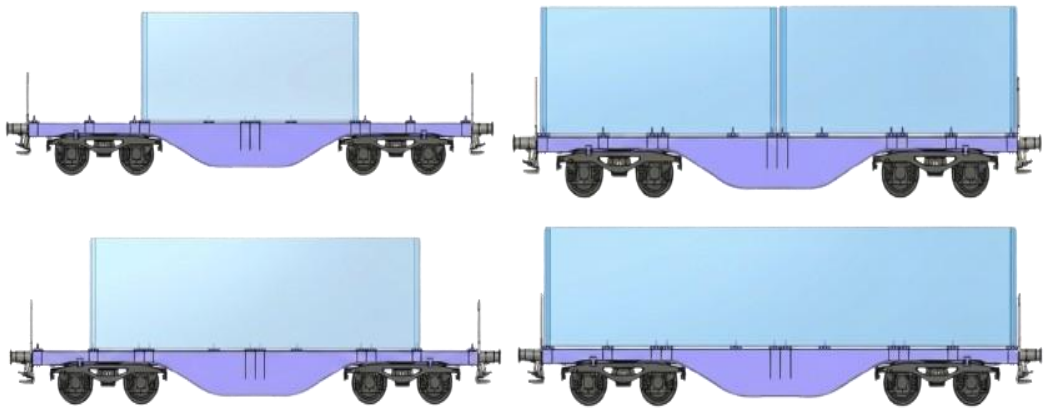
Model oluşturulurken vagonun aerodinamik karakteristiğini etkileyebilecek keskin köşeler, boşluklar ve şasi altındaki açıklıklar gerçek geometrisine uygun şekilde modellenmiştir. Özellikle bojilerin ve alt şasi yapısının korunması, bu bölgelerde oluşabilecek akış ayrılması ve girdap yapılarının doğru şekilde tahmin edilebilmesi açısından önem taşımaktadır.

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Şekil-3 Mesh Yapısı

Karmaşık geometriye sahip Sgmmns tipi konteyner taşıyıcı vagonun doğru temsil edilebilmesi amacıyla, hesaplama hacminde ağırlıklı olarak Poly-Hexcore hücre yapısı tercih edilmiştir. Bu ağ yapısı, yüksek çözüm doğruluğu sağlarken hesaplama maliyetini de önemli ölçüde azaltmaktadır. Akış ayrılmasının yoğun olarak gerçekleştiği konteyner ön yüzeyleri, boji bölgeleri, şasi altı, tamponlar ve vagon arka kısmında yerel ağ iyileştirmeleri (local sizing) uygulanmıştır. Katı yüzeylerde sınır tabakasının doğru modellenebilmesi amacıyla yüzey boyunca inflation katmanları oluşturulmuş ve hız gradyanlarının yüksek olduğu bölgelerde daha ince hücre yapısı kullanılmıştır. Oluşturulan hesaplama ağı yaklaşık 5 milyon hücreden oluşmaktadır. Hazırlanan ağ yapısı hem çözüm doğruluğu hem de hesaplama süresi açısından uygun bir denge sağlayacak şekilde oluşturulmuş olup, tüm analizlerde aynı ağ stratejisi kullanılmıştır.



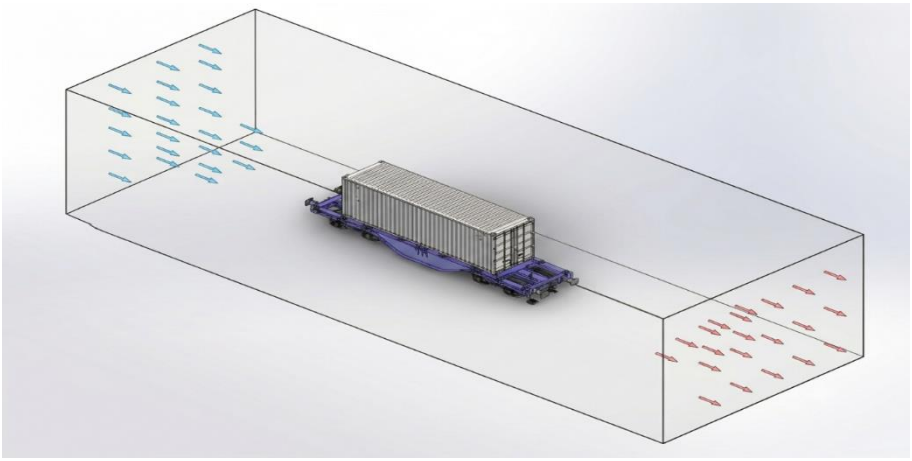
Şekil-4 Konteyner Dizilimleri

Şekil-4'te konteyner dizilimleri gösterilen Sgmmns tipi konteyner taşıyıcı vagonun aerodinamik davranışını belirlemek amacıyla üç boyutlu dış akış (external flow) analizi gerçekleştirilmiştir. Sayısal analizler ANSYS Fluent 2024 R1 yazılımı kullanılarak gerçekleştirilmiş olup, çözümler basınç tabanlı (Pressure-Based) sürekli rejim (Steady-State) çözücü ile elde edilmiştir. Hava akışı sıkıştırılamaz (Incompressible) ve izotermal kabul edilmiştir.

CFD modeli oluşturulurken EN 14067-4 standardında tanımlanan açık hat aerodinamiği prensipleri ve değerlendirme yaklaşımı esas alınmış, hesaplama alanı ve sınır koşulları ise literatürde kabul gören CFD uygulamaları dikkate alınarak oluşturulmuştur. Şekil-5'te gösterildiği gibi hesaplama alanı (computational domain), giriş ve çıkış bölgelerinde geri akış etkilerinin önlenmesi ve sınır koşullarının çözüm üzerindeki etkisinin en aza indirilmesi amacıyla yeterli büyüklükte oluşturulmuştur. Akış hacmi oluşturulurken vagonun karakteristik uzunluğu (L) esas alınmış ve hesaplama alanı; model önünde

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yaklaşık 5L, model arkasında 10L, yan yüzeylerde 5L ve üst bölgede 5L mesafe bırakılarak oluşturulmuştur. Bu yaklaşım literatürde tren aerodinamiği çalışmalarında yaygın olarak kullanılmaktadır.



Şekil-5 Sınır koşulları

Analizlerde tablo-2'de verilen parametreler ve sınır şartları tanımlanmıştır. Giriş hızının, yük trenlerinin tipik işletme koşullarını temsil edecek şekilde 33,33 m/s (120 km/h) olarak seçilmesi planlanmıştır. Giriş akışının türbülans yoğunluğu %5, hidrolik çap ise hesaplama alanı boyutlarına göre Fluent içerisinde tanımlanmıştır.

Tablo 2. Fluent analizlerinde kullanılan çözüm parametreleri

Parametre	**Değer**
Yazılım	ANSYS Fluent 2024 R1
Analiz tipi	3 Boyutlu, Steady-State
Çözücü	Pressure-Based
Akışkan	Hava
Yoğunluk	1.225 kg/m³
Dinamik viskozite	1.7894×10^{-5} kg/(m·s)
Giriş hızı	120 km/h
Türbülans yoğunluğu	%5
Çıkış şartı	Pressure Outlet (0 Pa)
Basınç-Hız Bağlaştırması	Couple
Türbülans Modeli	SST k-omega
Yakınsama Kriteri	Residual $<10^{-5}$

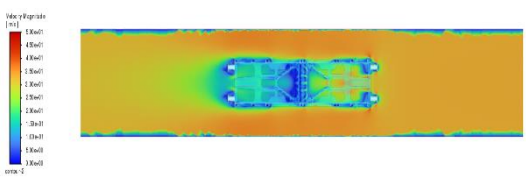
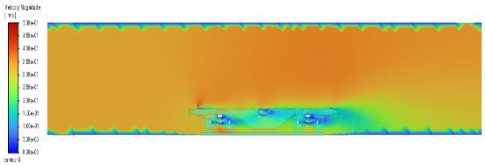
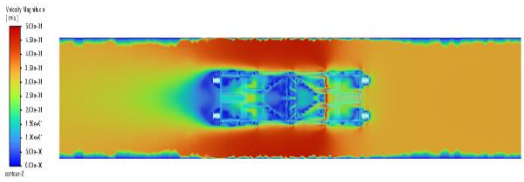
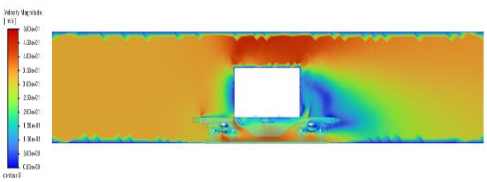
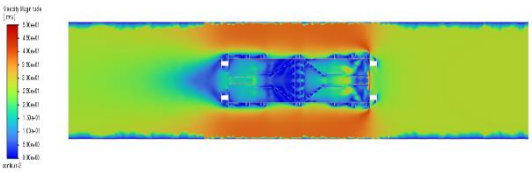
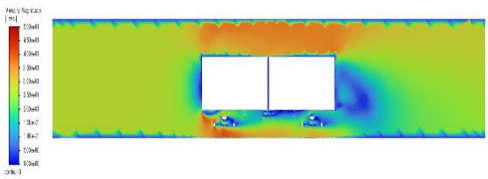
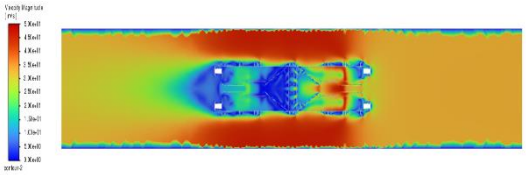
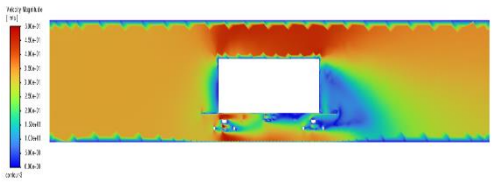
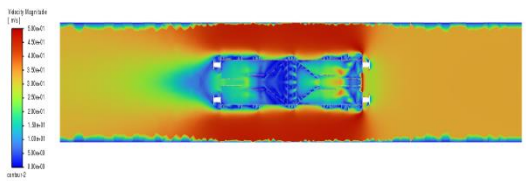
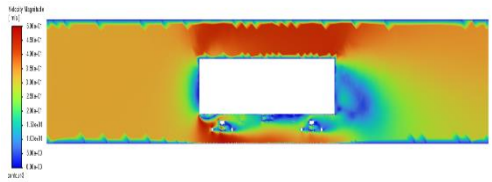
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Çıkış yüzeyinde Pressure Outlet sınır şartı uygulanmış ve çıkış basıncı atmosfer basıncını temsil edecek şekilde 0 Pa gösterge basıncı (Gauge Pressure) olarak tanımlanmıştır. Böylece akışın doğal şekilde hesaplama alanını terk etmesi sağlanmıştır.

BULGULAR VE TARTIŞMA

Bu bölümde, farklı konteyner yükleme senaryolarına sahip Sgmmns tipi konteyner taşıyıcı vagonun aerodinamik davranışı karşılaştırmalı olarak incelenmiştir. İlk olarak hız ve basınç alanları üzerinden akış karakteristiği değerlendirilmiş, ardından akış ayrılması ve türbülans yapıları analiz edilmiştir. Son olarak, aerodinamik kuvvetler ve katsayılar nicel olarak karşılaştırılarak konteyner geometrisinin sürükleme karakteristiği üzerindeki etkisi tartışılmıştır. Bu yaklaşım, farklı yükleme konfigürasyonlarının aerodinamik performansa etkisinin hem nitel hem de nicel olarak değerlendirilmesine olanak sağlamaktadır.

Tablo 3. 120 km/h hızda Yükleme durumuna göre Hız Dağılım Grafiği

Yükleme Durumu	Yatay Referans Düzlemi	Boyuna Referans Düzlemi
Boş vagon		
20 ft konteyner		
20-20 ft konteyner		
30 ft konteyner		
40 ft konteyner		

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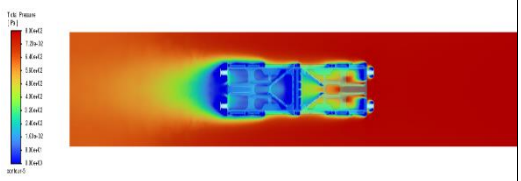
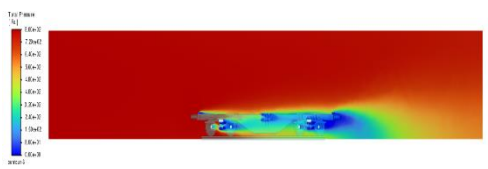
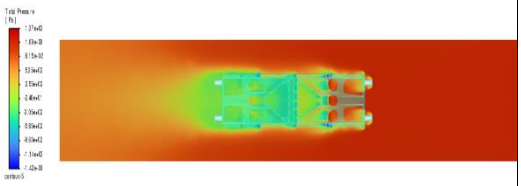
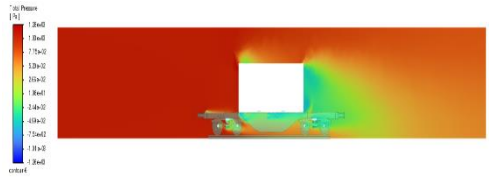
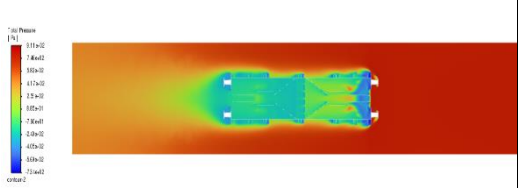
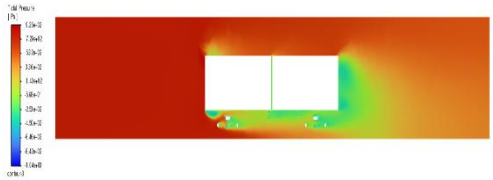
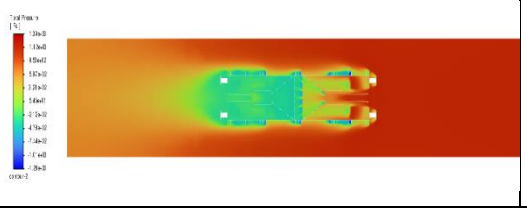
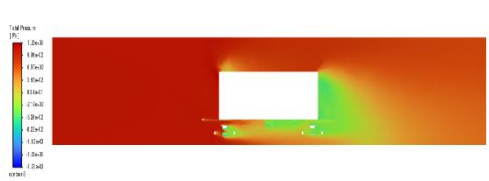
Tablo 3'te, Sgmmns tipi konteyner taşıyıcı vagonun 120 km/h işletme hızında farklı yükleme konfigürasyonları için elde edilen hız dağılımı konturları boyuna ve yatay referans düzlemlerinde sunulmaktadır. Boş vagon durumunda akışın şasi boyunca daha düzenli ilerlediği ve vagon arkasında oluşan wake bölgesinin sınırlı olduğu görülmektedir. Bu durum, boş vagon için elde edilen düşük sürükleme katsayısı ve sürükleme kuvveti ile uyumludur.

20 ft konteyner yükleme durumunda konteyner ön yüzeyinde durma (stagnation) bölgesi oluşurken, arka bölgede wake alanının belirgin şekilde genişlediği gözlenmektedir. İki adet 20 ft konteyner taşınan konfigürasyonda ise konteynerler arasındaki boşluk akış yapısını değiştirerek ilave türbülans bölgeleri oluşturmakta ve wake yapısını büyütmektedir.

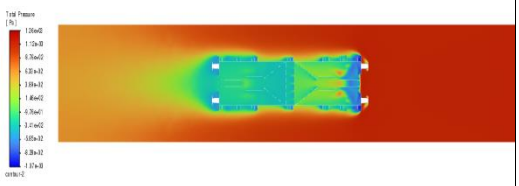
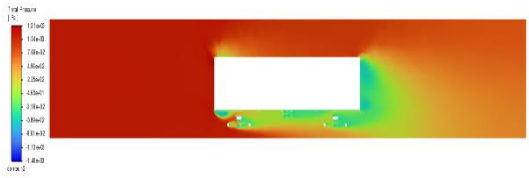
30 ft ve 40 ft konteyner yükleme durumlarında konteyner yüksekliğinin artmasına bağlı olarak wake bölgesi hem boyuna hem de yatay referans düzleminde daha geniş bir alana yayılmaktadır. Özellikle 40 ft konteyner konfigürasyonunda akış ayrılmasının daha belirgin olduğu ve düşük hızlı akış bölgesinin en büyük boyutlara ulaştığı görülmektedir.

Genel olarak, konteyner boyutunun artması akış ayrılmasını hızlandırmakta, wake bölgesini büyütmekte ve aerodinamik sürüklemeyi artırmaktadır. Hız konturlarından elde edilen bulgular, sürükleme katsayısı ve sürükleme kuvveti sonuçları ile uyumlu olup, yükleme geometrisinin vagonun aerodinamik performansı üzerinde belirleyici bir etkiye sahip olduğunu göstermektedir.

Tablo 4. 120 km/h hızda Yükleme durumuna göre Basınç Dağılım Grafiği

Yükleme Durumu	**Yatay Referans Düzlemi**	**Boyuna Referans Düzlemi**
Boş vagon		
20 ft konteyner		
20-20 ft konteyner		
30 ft konteyner		

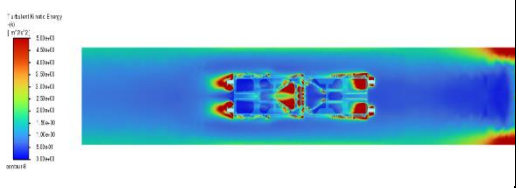
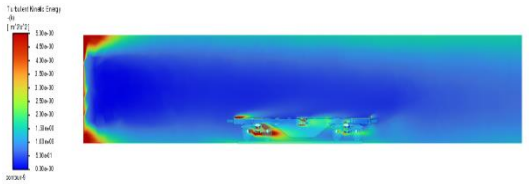
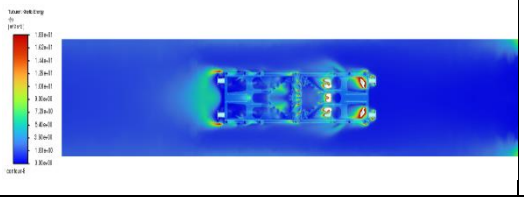
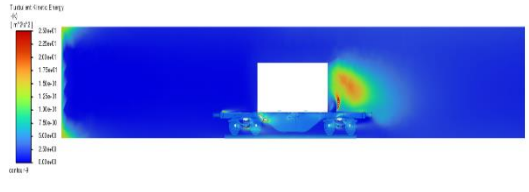
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40 ft konteyner		

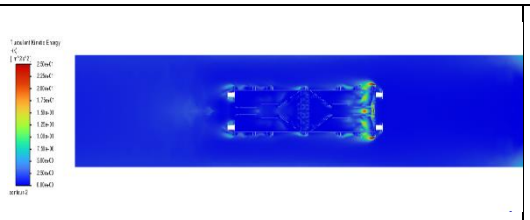
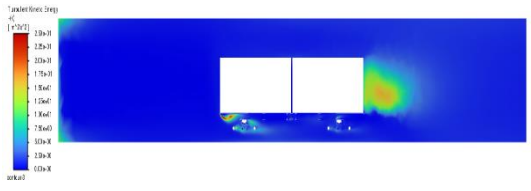
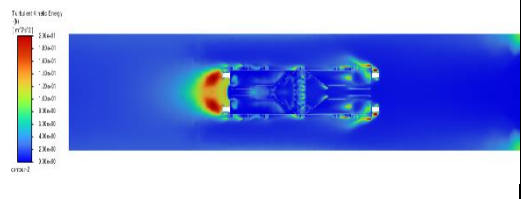
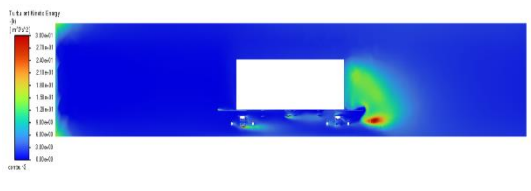
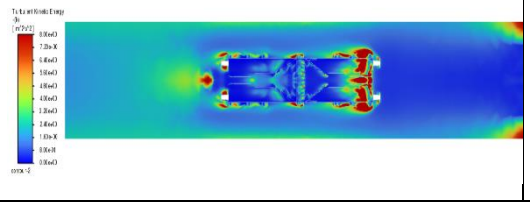
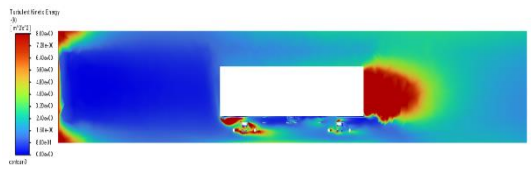
Tablo 4'te, Sgmmns tipi konteyner taşıyıcı vagonun 120 km/h işletme hızında farklı yükleme konfigürasyonları için elde edilen statik basınç dağılımları yatay ve boyuna referans düzlemlerinde sunulmaktadır. Basınç konturları, yükleme geometrisinin akış alanındaki basınç dağılımını önemli ölçüde etkilediğini göstermektedir.

Boş vagon durumunda yüksek basınç bölgeleri yalnızca boji ve şasi elemanlarının ön yüzeylerinde oluşurken, arka bölgede sınırlı bir düşük basınç alanı meydana gelmektedir. Bu durum, boş vagon için elde edilen düşük sürükleme katsayısı ve sürükleme kuvveti ile uyumludur. 20 ft konteyner yükleme durumunda konteyner ön yüzeyinde belirgin bir durma (stagnation) bölgesi oluşurken, arka bölgede düşük basınçlı wake yapısı gelişmektedir. İki adet 20 ft konteyner taşınan konfigürasyonda ise konteynerler arasındaki boşluk, yerel basınç değişimlerine neden olarak akış yapısını daha karmaşık hâle getirmektedir.30 ft ve 40 ft konteyner yükleme durumlarında ön yüzeydeki yüksek basınç bölgesi genişlerken, konteyner arkasında oluşan düşük basınç bölgesinin hem büyüklüğü hem de etkisi artmaktadır. Özellikle boyuna referans düzleminde wake bölgesinin uzadığı ve basınç toparlanmasının geciktiği görülmektedir. Bu durum, basınç sürüklemesinin artmasına ve sürükleme kuvvetinin yükselmesine neden olmaktadır. Genel olarak, konteyner boyutunun artması ön ve arka yüzey arasındaki basınç farkını büyüterek wake bölgesini genişletmekte ve vagonun aerodinamik direncini artırmaktadır. Elde edilen basınç konturları, sürükleme katsayısı ve sürükleme kuvveti sonuçlarıyla uyumlu bir eğilim göstermektedir.

Tablo 5. 120 km/h hızda Yükleme durumuna göre Türbülans Kinetik Enerji Dağılım Grafiği

Yükleme Durumu	**Yatay Referans Düzlemi**	**Boyuna Referans Düzlemi**
Boş vagon		
20 ft konteyner		

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20-20 ft konteyner		
30 ft konteyner		
40 ft konteyner		

Tablo 5'te, Sgmmns tipi konteyner taşıyıcı vagonun 120 km/h işletme hızında farklı yükleme konfigürasyonları için elde edilen türbülans kinetik enerjisi (TKE) dağılımları yatay ve boyuna referans düzlemlerinde sunulmaktadır. Türbülans kinetik enerjisi dağılımları, akış ayrılması ve wake bölgesinin gelişimini değerlendirmek açısından önemli bilgiler sağlamaktadır.

Boş vagon konfigürasyonunda türbülans kinetik enerjisi ağırlıklı olarak boji ve şasi elemanları çevresinde yoğunlaşırken, arka bölgede oluşan wake yapısının dar ve düşük türbülans seviyesine sahip olduğu görülmektedir. 20 ft konteyner yükleme durumunda ise konteyner ön kenarlarında akış ayrılması belirginleşmiş, arka bölgede türbülans kinetik enerjisi ve wake yapısı boş vagona göre artmıştır. İki adet 20 ft konteyner taşınan konfigürasyonda, konteynerler arasındaki boşluk akışın yeniden yönlenmesine neden olarak daha karmaşık türbülans yapıları oluşturmuştur. 30 ft ve 40 ft konteyner yükleme durumlarında türbülans kinetik enerjisinin hem büyüklüğü hem de yayılım alanı belirgin şekilde artmaktadır. Özellikle 40 ft konteyner konfigürasyonunda wake bölgesinin en geniş alana ulaştığı ve maksimum türbülans seviyelerinin oluştuğu görülmektedir. Bu durum, konteyner yüksekliğinin artmasıyla akış ayrılmasının kuvvetlendiğini ve wake yapısının daha kararsız hâle geldiğini göstermektedir. Genel olarak, konteyner boyutunun artması türbülans seviyesini ve wake bölgesini büyüterek aerodinamik kayıpları artırmaktadır. Türbülans kinetik enerjisi konturları, hız ve basınç dağılımlarından elde edilen bulguları desteklemekte olup, sürükleme katsayısı ve sürükleme kuvvetindeki artışın temel nedenlerinden birinin büyüyen wake yapısı olduğunu ortaya koymaktadır. Bu sonuçlar, konteyner yerleşim geometrisinin yüksek hızlı yük vagonlarının aerodinamik performansını belirleyen önemli tasarım parametrelerinden biri olduğunu göstermektedir.

Tablo 6. Farklı hız ve Yükleme durumuna göre Sürüklenme Katsayısı (Cd)

Yükleme Durumu	80 km/h	100 Km/h	120 hm/h
Boş	0.438	0.429	0.422
20 ft konteyner	0.521	0.512	0.503
20-20 ft konteyner	0.656	0.645	0.635
30 ft konteyner	0.769	0.756	0.744
40 ft konteyner	0.855	0.843	0.842

Tablo 6'da farklı konteyner yükleme konfigürasyonları için 80, 100 ve 120 km/h işletme hızlarında elde edilen sürükleme katsayısı (Cd) değerleri sunulmaktadır. Tüm analizlerde sürükleme katsayısının hesaplanmasında aynı referans alanı kullanılmıştır. Böylece farklı yükleme konfigürasyonlarının

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aerodinamik performansı doğrudan karşılaştırılabilir hâle getirilmiştir. Sonuçlar incelendiğinde, aynı yükleme konfigürasyonu için hızın artmasına bağlı olarak Cd değerlerinde yalnızca sınırlı bir değişim meydana geldiği görülmektedir. Bu durum, dış aerodinamik uygulamalarda sürükleme katsayısının belirli Reynolds sayısı aralığında büyük ölçüde hızdan bağımsız davrandığını göstermektedir.

Buna karşılık, konteyner yüksekliği ve taşınan konteyner sayısının artmasıyla birlikte sürükleme katsayısının düzenli olarak yükseldiği belirlenmiştir. En düşük Cd değeri boş vagon konfigürasyonunda elde edilirken, en yüksek değer 40 ft konteyner taşınan durumda hesaplanmıştır. Bunun temel nedeni, konteyner yüksekliğinin artmasıyla birlikte akışın karşılaştığı frontal alanın büyümesi, akış ayrılmasının daha belirgin hâle gelmesi ve vagon arkasında oluşan iz (wake) bölgesinin genişlemesidir. Özellikle 30 ft ve 40 ft konteyner konfigürasyonlarında akış ayrılmasının daha erken gerçekleşmesi, basınç sürüklemesini artırarak toplam sürükleme katsayısının yükselmesine neden olmaktadır.

Tablo 7. Farklı hız ve Yükleme durumuna göre Sürüklenme Kuvveti (Drag Force)

Yükleme Durumu	80 km/h	100 Km/h	120 hm/h
Boş	691	1079	1554
20 ft konteyner	832	1299	1871
20-20 ft konteyner	889	1386	2250
30 ft konteyner	1330	2078	2992
40 ft konteyner	1490	2120	3059

Tablo 7'de farklı hızlar ve yükleme konfigürasyonları için hesaplanan sürükleme kuvvetleri (Drag Force) verilmiştir. Sonuçlar, tüm yükleme durumlarında hız arttıkça sürükleme kuvvetinin belirgin şekilde yükseldiğini göstermektedir. Bu eğilim, aerodinamik sürükleme kuvvetinin dinamik basınca bağlı olarak hızın karesi ile değiştiğini ifade eden temel akışkanlar mekaniği prensibi ile uyumludur.

Yükleme konfigürasyonları karşılaştırıldığında, boş vagonda en düşük sürükleme kuvveti elde edilirken, en yüksek değer 40 ft konteyner taşınan durumda hesaplanmıştır. Bunun nedeni, konteyner boyutunun artmasıyla birlikte hava akışına maruz kalan ön alanın büyümesi ve buna bağlı olarak basınç farklarının artmasıdır. Ayrıca yüksek konteynerlerde akış ayrılması sonucunda oluşan geniş iz bölgesi, toplam aerodinamik direncin önemli ölçüde artmasına neden olmaktadır. Elde edilen sonuçlar, yükleme geometrisinin sürükleme kuvveti üzerinde hız kadar belirleyici bir parametre olduğunu ortaya koymaktadır.

Tablo 8'de farklı yükleme durumları için elde edilen kaldırma kuvveti (Lift Force) değerleri sunulmaktadır. Sonuçlar incelendiğinde, işletme hızının artmasına bağlı olarak kaldırma kuvvetinin tüm yükleme konfigürasyonlarında arttığı görülmektedir. Bu artış, hız yükseldikçe dinamik basıncın büyümesi ve vagonun üst ile alt yüzeyleri arasındaki basınç farkının artmasından kaynaklanmaktadır.

Tablo 8. Farklı hız ve Yükleme durumuna göre Kaldırma Kuvveti (Lift Force)

Yükleme Durumu	80 km/h	100 Km/h	120 hm/h
Boş	84	132	190
20 ft konteyner	89	140	201
20-20 ft konteyner	104	163	235
30 ft konteyner	143	224	322
40 ft konteyner	155	242	349

Yükleme konfigürasyonları karşılaştırıldığında, boş vagonda en düşük kaldırma kuvveti elde edilirken, 40 ft konteyner taşınan durumda en yüksek kaldırma kuvveti hesaplanmıştır. Konteyner yüksekliğinin artması, üst yüzey boyunca akan hava hızının değişmesine ve basınç dağılımının farklılaşmasına neden olarak kaldırma kuvvetinin büyümesine katkı sağlamaktadır. Bununla birlikte kaldırma kuvvetindeki artış, sürükleme kuvvetindeki artış kadar belirgin değildir. Bu durum, konteyner geometrisinin aerodinamik davranış üzerinde öncelikle sürükleme karakteristiğini etkilediğini göstermektedir.

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Demiryolu araçlarında yüksek kaldırma kuvvetleri özellikle yüksek hızlarda tekerlek-ray temas kuvvetlerini etkileyebileceğinden, aerodinamik tasarım açısından dikkate alınması gereken önemli bir parametredir.

SONUÇLAR

Bu çalışmada, Sgmmns tipi konteyner taşıyıcı vagonun farklı yükleme konfigürasyonlarının aerodinamik performansa etkisi, ANSYS Fluent yazılımı kullanılarak hesaplamalı akışkanlar dinamiği yöntemi ile incelenmiştir. Analizler sonucunda aşağıdaki bulgular elde edilmiştir.

- Farklı konteyner yükleme konfigürasyonlarının vagonun dış akış karakteristiğini önemli ölçüde değiştirdiği belirlenmiştir. Konteyner boyutunun ve yükleme hacminin artmasıyla birlikte akış ayrılması daha erken gerçekleşmiş ve wake bölgesi belirgin şekilde büyümüştür.
- Hız konturları incelendiğinde, boş vagon konfigürasyonunda akışın daha düzenli ilerlediği, konteyner yüksekliğinin artmasıyla birlikte özellikle konteyner arka bölgesinde düşük hızlı akış alanlarının genişlediği görülmüştür.
- Basınç dağılımlarında, konteyner ön yüzeyinde oluşan yüksek basınç bölgesi ile arka yüzeyde meydana gelen düşük basınç bölgesi arasındaki farkın konteyner boyutuna bağlı olarak arttığı belirlenmiştir. Bu durum basınç sürüklemesinin artmasına neden olmuştur.
- Türbülans kinetik enerjisi dağılımları, konteyner geometrisinin wake yapısını doğrudan etkilediğini göstermiştir. Özellikle 30 ft ve 40 ft konteyner yükleme durumlarında daha büyük türbülans bölgeleri oluşmuş ve akışın yeniden düzenli hale gelme mesafesi uzamıştır.
- Sürükleme katsayısı (Cd) değerleri incelendiğinde, aynı yükleme konfigürasyonu için hız değişiminin Cd üzerinde sınırlı bir etkiye sahip olduğu, buna karşılık konteyner boyutunun artmasının Cd değerini önemli ölçüde yükselttiği belirlenmiştir.
- En düşük sürükleme katsayısı boş vagon konfigürasyonunda elde edilirken, en yüksek sürükleme katsayısı 40 ft konteyner taşınan durumda hesaplanmıştır. Bu sonuç, artan frontal alan ve genişleyen wake bölgesi ile uyumludur.
- Sürükleme kuvveti (Drag Force), tüm yükleme konfigürasyonlarında hızın artmasına bağlı olarak düzenli şekilde yükselmiştir. Ayrıca konteyner yüksekliğinin artmasıyla birlikte sürükleme kuvvetinde önemli artışlar meydana gelmiş olup, en yüksek değer 40 ft konteyner yükleme durumunda elde edilmiştir.
- Kaldırma kuvveti (Lift Force) da hız ve konteyner boyutunun artmasına bağlı olarak yükselmiştir. Bununla birlikte kaldırma kuvvetindeki artışın, sürükleme kuvvetindeki artış kadar belirgin olmadığı görülmüştür.
- Yatay ve boyuna referans düzlemlerinden elde edilen konturlar birlikte değerlendirildiğinde, konteyner geometrisinin yalnızca ön alanı artırmadığı, aynı zamanda akış ayrılması, wake oluşumu ve türbülans yapısını da önemli ölçüde değiştirdiği belirlenmiştir.
- Analiz sonuçları, konteyner yerleşim geometrisinin yüksek hızlı yük vagonlarının aerodinamik performansı üzerinde belirleyici bir tasarım parametresi olduğunu göstermektedir. Aerodinamik sürüklemenin azaltılması amacıyla konteyner yerleşiminin optimize edilmesi, enerji tüketiminin ve işletme maliyetlerinin düşürülmesine katkı sağlayacaktır.
- Bu çalışma, farklı konteyner yükleme konfigürasyonlarının aerodinamik davranış üzerindeki etkisini karşılaştırmalı olarak ortaya koyması bakımından literatüre katkı sağlamaktadır. Elde edilen sonuçların, yeni nesil konteyner taşıyıcı yük vagonlarının tasarımında ve aerodinamik iyileştirme çalışmalarında yol gösterici olacağı değerlendirilmektedir.

Bu çalışma yalnızca sabit hız koşullarındaki aerodinamik davranışın incelenmesi ile sınırlandırılmıştır. Gelecek çalışmalarda, yan rüzgâr etkisi (crosswind), farklı tren dizilimleri, birden fazla vagonun oluşturduğu aerodinamik etkileşim, hareketli zemin (moving ground) ve dönen tekerlek (rotating wheel)

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modellerinin analize dahil edilmesiyle daha gerçekçi işletme koşullarının değerlendirilmesi önerilmektedir. Ayrıca, HAD sonuçlarının rüzgâr tüneli deneyleri ile doğrulanması, elde edilen bulguların güvenilirliğini artıracak ve demiryolu araçlarının aerodinamik tasarımına yönelik daha kapsamlı mühendislik değerlendirmelerine katkı sağlayacaktır.

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EXPERIENCE AND OUTCOMES REPORTED BY PATIENTS TREATED IN THE AMBULATORY SURGERY UNIT

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ABSTRACT

Ambulatory surgery is characterised by scheduled procedures that allow admission and discharge on the same day, requiring coordinated nursing care throughout the perioperative pathway. This study aimed to describe the experience and outcomes reported by patients treated in the Ambulatory Surgery Unit of Hospital Dr. Nélio Mendonça. A quantitative, descriptive, and exploratory design was used. A 25-item questionnaire was administered by telephone to 205 randomly selected patients who underwent surgery during the second half of 2023 and the first half of 2024: 100 vascular surgery patients, 100 ophthalmology patients, and 5 urology patients. The two main groups were predominantly female; vascular surgery patients were concentrated between 58 and 67 years of age, whereas most ophthalmology patients were aged 68 years or older. Reception on the day of surgery was rated Good or Very Good by 97% of both vascular surgery and ophthalmology patients. The way professionals introduced themselves during the intraoperative period was rated Good or Very Good by 99% of vascular surgery patients and 64% of ophthalmology patients. Information provided at discharge was rated Good or Very Good by 94% and 91%, respectively, and the overall experience in the post-anaesthesia care pathway by 92% and 93%. Regarding nursing consultations, in vascular surgery 0% reported not having a preoperative nursing consultation and 0% reported not having a postoperative nursing consultation; in ophthalmology, 34% reported not having a preoperative consultation and 56% reported not having a postoperative consultation. Pre- and postoperative care, intraoperative communication, and reinforcement of nursing consultations were identified as priority areas for improvement.

Keywords: Ambulatory surgery; Patient experience; Perioperative nursing; Nursing care; Satisfaction.

INTRODUCTION

The Health Regulatory Authority defines ambulatory surgery as scheduled surgery performed under general, locoregional, or local anaesthesia, in appropriate facilities and in accordance with current leges artis, allowing the patient to be admitted and discharged on the same day. This organisational model of surgical care has become increasingly important in healthcare systems, alongside advances in surgical and anaesthetic techniques and the demand for more efficient, safe, and person-centred care. The possibility of performing progressively less invasive procedures, with shorter recovery times and less need for hospital admission, reinforces the importance of rigorous organisation throughout the perioperative pathway.

The expansion of ambulatory surgery is closely associated with technological developments in surgical devices and instruments, advances in anaesthetic and analgesic drugs, and improvements in infection prevention and control measures. These advances have increased both the number and complexity of procedures that can be performed on an ambulatory basis, while simultaneously requiring close coordination among patient selection, preoperative assessment, preparation for the procedure, intraoperative monitoring, post-anaesthesia recovery, and preparation for discharge.

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Within this care context, approaches are required that ensure efficient, individualised, and safe preoperative assessment, allowing risk factors and specific needs to be identified at an early stage. The integration of technological resources into nursing care may help optimise assessment, improve the flow of clinical information, and support more personalised preparation. Nurse-led screening tools and structured questionnaires can facilitate the identification of situations requiring early intervention and may help prevent less favourable perioperative experiences.

Patient-reported experience is an essential dimension of care quality assessment. De Rosis et al. (2020) emphasise that patient-reported measures provide objective information on how care is experienced and can support changes in care delivery and organisational development. Assessing experience makes it possible to consider, in addition to clinical outcomes, dimensions such as reception, communication, information received, comfort, privacy, perceived safety, preparation for discharge, and continuity of care after returning home.

The literature considered in the background of this study reinforces that favourable outcomes in ambulatory surgery depend on evidence-based interventions and coordinated practice among the different professionals involved. It is therefore important to define indicators that allow patient-reported experience and outcomes to be assessed, promote team involvement in continuous improvement processes, and respond systematically to identified needs. Clinical communication is particularly important, as the clarity of information and the relationship established with professionals may influence anxiety, confidence, and self-care capacity throughout the perioperative pathway (Gonçalves et al., 2017; Morris et al., 2023).

At the Ambulatory Surgery Unit of Hospital Dr. Nélio Mendonça (HNM), the increase in surgical activity and the introduction of new procedures in vascular surgery, ophthalmology, and urology represented both a challenge and an opportunity to analyse patients' experiences. The diversity of procedures and needs associated with the different specialties requires differentiated nursing care during the preoperative, intraoperative, and postoperative phases, as well as preparation for continuity of care after discharge.

The surgical pathway may generate questions, insecurity, and anxiety in patients and significant others, particularly when there is uncertainty regarding the procedure, anaesthesia, recovery, or care to be maintained at home. In this context, nurses play a key role in safety and continuity of care, in communicating and validating information, and in preparing patients to participate actively in their recovery. Multiprofessional practice should be coordinated, ensuring consistency of information and recognition of individual needs throughout the perioperative pathway.

This study was developed from this perspective, in a professional practice setting, with the aim of systematising information reported by patients themselves and integrating it into the assessment of care quality. The limited amount of local research on this topic reinforced the relevance of the following research question: “What are the experience and outcomes reported by patients treated in the Ambulatory Surgery Unit of Hospital Dr. Nélio Mendonça, EPERAM?” The study therefore sought to describe patient-reported experience and outcomes and to identify aspects of the pathway that could be consolidated or improved.

Obtaining data on patients' experiences can provide a basis for defining continuous improvement measures and refining nursing care protocols. Understanding how patients evaluate the different stages of ambulatory surgery can guide clinical and organisational decisions, consolidate practices recognised as positive, and support intervention in areas that may compromise safety, satisfaction, or continuity of care, thereby contributing to high-quality nursing care aligned with the institution's mission.

1. BACKGROUND: PATIENT EXPERIENCE AND OUTCOMES IN AMBULATORY SURGERY

Patient experience is part of the concept of person-centred care and enables assessment of dimensions such as respect, clarity of information, participation in care, and response to expectations. Patients are in a privileged position to report how they experience interactions with professionals and the organisation of the service. Systematic collection of these perceptions can guide continuous

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improvement processes, particularly when combined with clinical outcomes and quality indicators (De Rosis et al., 2020).

During the preoperative period, satisfaction may be influenced by waiting time, the quality of information, and preparation for surgery. Gonzalez et al. (2023) relate waiting times to patient satisfaction. The nursing consultation provides an important opportunity to clarify questions, support self-care education, and reduce anxiety, while adapting information to the patient's level of health literacy is a relevant component of preparation for discharge (Breda & Cerejo, 2021; Dyer et al., 2022).

During the intraoperative period, contact with professionals takes place in a context of particular vulnerability, in which team introductions, identification of roles, and clinical communication may influence perceived safety. The operating theatre environment, affected by factors such as temperature, lighting, noise, and the presence of equipment, may also influence comfort and the experience reported. Appropriate communication and ongoing team training are therefore relevant dimensions of care quality and safety (Andrade, 2023; Morris et al., 2023).

During the postoperative period, care in the Post-Anaesthesia Care Unit (PACU) focuses on physiological stability, comfort, monitoring, and symptom control, followed by preparation for returning home. The literature highlights the need to reinforce health education, provide written instructions, and assess the understanding of both the patient and the significant other (Bennett et al., 2023; Crisp et al., 2023; Kearney et al., 2022). Postoperative nursing consultations and follow-up contact may provide opportunities to identify complications at an early stage, clarify questions, and support recovery (Camarinha, 2020; McCarthy et al., 2023).

2. METHODOLOGY

A quantitative, descriptive, and exploratory study was conducted. The quantitative approach enabled the responses obtained to be organised and analysed numerically (Álvares, 2021). The population included people who underwent ambulatory surgery in vascular surgery, ophthalmology, and urology during the second half of 2023 and the first half of 2024.

Following random selection, patients were contacted by telephone and a questionnaire developed for the study was administered. The sample comprised 205 participants: 100 vascular surgery patients, 100 ophthalmology patients, and 5 urology patients. Given the small number of urology participants, this group did not allow robust statistical comparisons; therefore, the main comparative tables focus on vascular surgery and ophthalmology.

The questionnaire comprised 25 items organised according to the perioperative phases: 10 related to the preoperative period, 2 to the intraoperative period, and 13 to the postoperative period. Dimensions assessed included nursing consultations, reception, communication, comfort, information at discharge, symptoms, questions or concerns, contact with professionals, and overall assessment of the experience. Characterisation variables included age, gender, marital status, education, employment status, presence of a companion, previous surgical experience, and previous contact with someone in the same clinical situation.

Institutional authorisations and a favourable opinion from the Ethics Committee were obtained, ensuring anonymity, confidentiality, voluntary participation, and the right to withdraw. Data were collected by telephone contact, and the analysis was structured according to the preoperative, intraoperative, and postoperative phases.

3. RESULTS

3.1. Participant characteristics

Characterisation of the sample provides context for the outcomes reported by participants. Overall, 205 patients participated, distributed across the three specialties shown in Table 1.

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Table 1. *Sample distribution by specialty*

Specialty	n
Vascular surgery	100
Ophthalmology	100
Urology	5
Total	205

In the two main groups, most participants were female: 69% in vascular surgery and 63% in ophthalmology. In vascular surgery, the highest age concentration was between 58 and 67 years; in ophthalmology, the group aged 68 years or older predominated. A high proportion of participants also had lower levels of education, particularly in the older age groups, which is relevant when adapting communication and health education.

Table 2. *Sample characteristics (%)*

	Vascular surgery (%)			Ophthalmology (%)		
Characteristic / category	**M**	**F**	**Total**	**M**	**F**	**Total**
Age						
38 to 47 years	3	11	14	0	0	0
48 to 57 years	12	25	37	3	4	7
58 to 67 years	16	33	49	11	19	30
68 years or older	0	0	0	23	40	63
Education						
No formal education	—	—	0	—	—	4
4th grade	—	—	42	—	—	54
6th grade	—	—	26	—	—	18
Bachelor's degree	—	—	0	—	—	4
Surgical history						
Previous surgery	—	—	50	—	—	92
No previous surgery	—	—	50	—	—	8
Companion present during the first 24 h	—	—	100	—	—	100
Contact with someone in the same clinical situation	—	—	100	—	—	100

Regarding area of residence, Funchal had the highest proportion in both groups: 35% in vascular surgery and 51% in ophthalmology. In vascular surgery, this was followed by Santa Cruz (20%), Machico

(16%), and Câmara de Lobos (16%); in ophthalmology, by Câmara de Lobos (17%), Machico (8%), Ponta do Sol (7%), and Porto Santo (6%).

Table 3. *Distribution by area of residence (%)*

Municipality	Vascular surgery	Ophthalmology
Calheta	3	1
Porto Moniz	0	0
Ponta do Sol	2	7
Ribeira Brava	2	4
Câmara de Lobos	16	17
Funchal	35	51
Santa Cruz	20	5
Machico	16	8
Santana	3	1
São Vicente	2	0
Porto Santo	1	6

3.2. Preoperative phase

During the preoperative phase, the dimensions analysed included whether a nursing consultation had taken place and the assessment of reception on the day of surgery.

Regarding reception on the day of surgery, 85% of vascular surgery patients rated it as “Good” and 12% as “Very Good”. In ophthalmology, 77% rated it as “Good” and 20% as “Very Good”. In both groups, “Good/Very Good” ratings totalled 97%.

Table 4. *Preoperative phase results (%)*

Indicator	Response	Vascular	Ophthalmology
Preoperative nursing consultation	Yes	0	66
Preoperative nursing consultation	No	0	34
Reception on the day of surgery	Poor	0	0
Reception on the day of surgery	Unsatisfactory	0	1
Reception on the day of surgery	Fair	3	2
Reception on the day of surgery	Good	85	77
Reception on the day of surgery	Very Good	12	20

In vascular surgery, 0% of patients reported not having a preoperative nursing consultation. In ophthalmology, 34% reported not having a consultation and 66% reported having a preoperative nursing consultation.

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3.3. Intraoperative and postoperative phases

During the intraoperative period, the way professionals introduced themselves was rated as "Good" or "Very Good" by 99% of vascular surgery patients and 64% of ophthalmology patients. In ophthalmology, ratings of "Fair", "Unsatisfactory", and "Poor" were also recorded, as shown in Table 5.

During the postoperative period, the information provided at discharge about continuity of care was rated as "Good" or "Very Good" by 94% of vascular surgery patients and 91% of ophthalmology patients.

The overall experience through the PACU was rated as "Good" or "Very Good" by 92% of vascular surgery patients and 93% of ophthalmology patients.

Table 5. *Intraoperative and postoperative phase results (%)*

Indicator	Response	Vascular	Ophthalmology
Professional introduction	Poor	0	5
Professional introduction	Unsatisfactory	0	10
Professional introduction	Fair	1	21
Professional introduction	Good	90	57
Professional introduction	Very Good	9	7
Discharge information on continuity of care	Poor	0	0
Discharge information on continuity of care	Unsatisfactory	2	2
Discharge information on continuity of care	Fair	4	7
Discharge information on continuity of care	Good	72	79
Discharge information on continuity of care	Very Good	22	12
Overall experience in the PACU	Poor	0	1
Overall experience in the PACU	Unsatisfactory	2	3
Overall experience in the PACU	Fair	6	3
Overall experience in the PACU	Good	67	78
Overall experience in the PACU	Very Good	25	15
Postoperative nursing consultation	Yes	0	44
Postoperative nursing consultation	No	0	56

During the first hours after surgery, participants were asked about the occurrence of postoperative symptoms, namely nausea, vomiting, pain, and fever. Among the manifestations assessed, pain showed the highest values. In the "Sometimes" category, pain was reported by 52% of vascular surgery patients, 5% of ophthalmology patients, and 20% of urology patients. In the "Often" category, the highest proportion occurred in urology (40%), followed by vascular surgery (12%) and ophthalmology (3%). These findings reinforce the importance of systematic pain assessment and of adapting nursing interventions during the postoperative period. Table 6 provides a combined summary of the symptoms reported in the "Sometimes" and "Often" categories across the three specialties.

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Table 6. *Postoperative symptoms during the first hours after surgery (%)*

Indicator	Response	Vascular	Ophthalmology	Urology
Nausea	Sometimes	2	4	0
Nausea	Often	0	1	0
Vomiting	Sometimes	1	0	0
Vomiting	Often	0	2	0
Pain	Sometimes	52	5	20
Pain	Often	12	3	40
Fever	Sometimes	1	0	0
Fever	Often	1	1	20

Overall, the findings indicate a predominantly favourable experience throughout the pathway in the Ambulatory Surgery Unit. Positive ratings of reception, information at discharge, and the overall PACU experience stand out, while the way professionals introduced themselves received less favourable ratings in the ophthalmology group.

Regarding nursing consultations, 0% of vascular surgery patients reported not having a preoperative consultation and 0% reported not having a postoperative consultation. In ophthalmology, 34% reported not having a preoperative consultation and 56% reported not having a postoperative consultation.

Less favourable aspects included the waiting time for surgery and the occurrence of some discomfort or complications during the postoperative period. Despite these aspects, the overall assessment of the care pathway was predominantly positive, with good accessibility to professionals and a high intention to recommend the unit.

DISCUSSION

The results should be interpreted as an expression of the patient's overall experience across a care pathway composed of several interdependent stages. The predominance of vascular surgery and ophthalmology allows a more consistent analysis of these two groups, whereas the small number of urology participants requires caution when interpreting results for that specialty. Rather than comparing individual responses or percentages in isolation, it is important to understand how the organisation of the pathway, clinical communication, and continuity of care influence perceived safety and satisfaction.

During the preoperative period, the data highlight the importance of balancing organisational efficiency with individualised preparation. Waiting time and the extent to which preparation meets patient expectations may shape the experience before entering the operating theatre. Gonzalez et al. (2023) emphasise the relationship between waiting times and satisfaction in surgical settings. At the same time, Gonçalves et al. (2017) and Breda and Cerejo (2021) reinforce that information provided by nurses can help reduce anxiety, clarify questions, and support more informed participation in the surgical process. Given the age profile and education levels observed, communication should be clear, accessible, and adapted to each person's health literacy.

During the intraoperative period, how professionals introduce themselves and communicate is particularly relevant at a time when the patient is more vulnerable and dependent on the team. The difference observed between specialties supports the relevance of standardising practices for introductions, identification of roles, and explanation of the immediate pathway, although the data do not allow causal relationships to be established. Andrade (2023) and Morris et al. (2023) identify clinical communication as an essential component of perioperative care quality and safety, supporting the importance of a consistent approach across the whole team.

Comfort in the operating theatre should also be understood from a multidimensional perspective. Temperature, lighting, and noise influence the patient's sensory experience and may be particularly relevant in older people or in patients undergoing procedures with different forms of anaesthesia. Protection of privacy must also be considered and depends on both the physical conditions of the

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environment and professional practices. Systematic attention to these dimensions helps reduce discomfort, preserve dignity, and strengthen perceived safety during the procedure.

During the postoperative period, the favourable assessment of information provided at discharge and of the PACU pathway should be valued, but it does not remove the need for rigorous preparation for returning home. Crisp et al. (2023) and Dyer et al. (2022) emphasise the importance of ensuring that patients and significant others understand the care to be maintained, warning signs, and the resources available after discharge. Harrison et al. (2023) reinforce the nurse's role in educating patients to recognise potentially relevant signs and symptoms at an early stage, including bleeding, severe pain, fever, nausea, and vomiting, noting that clear and comprehensive communication can improve understanding of the recovery process and reduce anxiety associated with possible complications. The presence of pain, discomfort, and other events reported in this study shows that perceived quality and clinical safety are complementary dimensions; a favourable experience should coexist with monitoring, health education, and the capacity to respond to potential complications.

Continuity of care is a central element of the ambulatory surgery pathway. Postoperative nursing consultations and follow-up contact make it possible to assess clinical progress, clarify questions, reinforce guidance, and identify at an early stage situations that may require intervention. McCarthy et al. (2023) highlight the contribution of this follow-up to patient recovery and satisfaction. The findings relating to nursing consultations should therefore be understood as indicators of the need to ensure continuity between preoperative preparation, discharge, and follow-up at home.

Overall, the findings reinforce the value of integrating the patient perspective into care quality assessment. De Rosis et al. (2020) argue that measures reported by patients themselves can support organisational change and guide improvement processes. In this study, that perspective makes it possible to identify not only positively rated dimensions, but also stages of the pathway in which organisation, clinical communication, or follow-up can be improved. This interpretation should take into account the resources and specific characteristics of the Ambulatory Surgery Unit.

CONCLUSION

This study analysed and discussed the findings considered most relevant to understanding the experience and outcomes reported by patients undergoing ambulatory surgery. The descriptive, quantitative design enabled the study population to be characterised and the way participants assessed different stages of the care pathway to be systematised.

The sample comprised 205 patients: 100 from vascular surgery, 100 from ophthalmology, and 5 from urology. The small size of the urology group does not allow robust conclusions to be drawn for that specialty; therefore, the final synthesis focuses mainly on vascular surgery and ophthalmology. Females predominated in both groups, with a higher concentration between 58 and 67 years in vascular surgery and among those aged 68 years or older in ophthalmology.

Analysis by phase showed that the ambulatory surgery experience results from a set of factors that extend beyond the surgical procedure itself. The preoperative, intraoperative, and postoperative periods, together with nursing consultations, are interdependent stages in which clinical communication, reception, safety, comfort, and continuity of care influence the patient's experience.

During the preoperative period, waiting time stood out as a less favourable dimension, with greater dissatisfaction in vascular surgery than in ophthalmology. The extent to which preparation met patient expectations was also rated unfavourably by part of the sample. By contrast, reception on the day of surgery and perceived safety during the pathway to the operating theatre were generally rated positively.

The preoperative nursing consultation plays an essential role in preparing the person for surgery, providing information, and reducing uncertainty. In vascular surgery, 0% of patients reported not having a preoperative nursing consultation. In ophthalmology, 34% reported not having had this consultation and 66% reported having had it. These findings reinforce the importance of ensuring access to the consultation and adapting its content to each person's information needs and health literacy.

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During the intraoperative period, most patients rated the way professionals introduced themselves favourably, although the findings were more positive in vascular surgery than in ophthalmology. Identification of team members and explanation of their respective roles should continue to be valued, as a clear introduction may strengthen trust and reduce the sense of vulnerability associated with the surgical environment.

Environmental conditions in the operating theatre were also part of the experience assessment. Temperature and lighting were generally rated well, despite some reports of dissatisfaction, particularly among ophthalmology participants. Perceived noise was also a relevant dimension. Controlling these factors, together with protecting privacy, contributes to a more comfortable, safe, and person-centred surgical environment.

During the postoperative period, information provided at discharge, the overall PACU experience, and food were mostly rated positively. Information concerning continuity of care was rated as “Good” or “Very Good” by 94% of vascular surgery patients and 91% of ophthalmology patients. The overall PACU experience received “Good” or “Very Good” ratings from 92% and 93%, respectively.

Despite this favourable assessment, symptoms and complications were identified that justify continued monitoring. Pain was reported “Often” by 12% of vascular surgery patients and 3% of ophthalmology patients. Complications were more frequently reported in ophthalmology, particularly burning sensations and reduced visual acuity, whereas episodes of bleeding were described in vascular surgery. These findings highlight the importance of health education about warning signs and of providing contact pathways after discharge.

Continuity of care through a postoperative nursing consultation should be regarded as an integral part of the perioperative pathway. In vascular surgery, 0% of patients reported not having a postoperative nursing consultation. In ophthalmology, 56% reported not having had this consultation and 44% reported having had it. The favourable reports from participants who received follow-up contact demonstrate the usefulness of this stage for clarifying questions, reinforcing guidance, and assessing recovery.

Perceived general health improved after surgery and was rated as “Very Good” by 63% of vascular surgery patients and 39% of ophthalmology patients. Ease of contact with professionals was also rated positively by most participants, although 2% of vascular surgery patients and 10% of ophthalmology patients reported difficulties. Intention to recommend the unit was high: 100% of vascular surgery patients stated that they would recommend it, whereas 4% of ophthalmology patients stated that they would not.

The findings make it possible to identify areas for consolidation and areas for improvement. Priorities include optimising pre- and postoperative care, strengthening clinical communication during the intraoperative period, consolidating nursing consultations and follow-up after discharge, continuing health literacy interventions, training teams in communication skills, and systematically monitoring satisfaction and quality indicators.

Conducting this study also contributed to the development of research skills and to structured reflection on the different stages of ambulatory surgery. The information produced can support the review of protocols and practices in the Ambulatory Surgery Unit, while recognising that available human and material resources may affect implementation of some measures.

Future research should consider replicating the study in other units and regions, using samples that are more balanced across specialties, and developing longitudinal and qualitative studies to gain a deeper understanding of changes in satisfaction, patients' needs after discharge, and the impact of nursing interventions over time.

In summary, patients' experience in the Ambulatory Surgery Unit was generally positive. Nevertheless, opportunities remain for improvement in pre- and postoperative care, communication with patients during the intraoperative period, and continuity of nursing consultations. Monitoring these indicators may contribute to safer, more consistent care that is better aligned with the needs and expectations of people undergoing ambulatory surgery.

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RECOMMENDATIONS

• Systematically implement preoperative and postoperative nursing consultations for all ambulatory surgery procedures.

• Implement a nursing follow-up consultation on day 30, including administration of a patient satisfaction scale.

• Strengthen health education for patients, family members, and/or significant others by providing relevant information about the surgery and the perioperative pathway.

• Continue the information and health education initiatives already developed in Ambulatory Surgery, promoting the health literacy of patients and significant others.

• Implement ongoing team training, with emphasis on technical, interpersonal, and clinical communication skills.

• Standardise the way professionals introduce themselves and strengthen team training in clinical communication, particularly regarding identification and explanation of their respective roles to the patient. This approach should contribute to greater comfort and better information for the person undergoing surgery, while respecting the principles of confidentiality and professional secrecy.

• Optimise workflow by promoting efficient use of equipment and human resources and preventing situations of excessive workload.

• Ensure systematic monitoring of quality indicators, including complication rates and times associated with the surgical pathway.

• Periodically assess patient satisfaction in order to identify areas of dissatisfaction that may not be fully captured by exclusively quantitative methods.

• Assess team workload and identify needs for additional human or material resources, promoting equity and quality in care delivery.

• Create a structured mechanism for collecting patients' opinions, concerns, and suggestions, providing the team with useful information for reviewing practices and protocols.

Regarding limitations in the development of the study, the research team consisted of only two members, which made it difficult to reconcile the time required for the research with professional and personal responsibilities. Administration of the questionnaires, data processing, and analysis were time-consuming processes and required careful management of the available resources.

The time made available by the Nursing Directorate was important for completion of the study, although it was limited in relation to the demands of data collection, processing, and analysis. This limitation should be considered when planning future research, particularly if the aim is to increase sample size, include other specialties, or deepen patient follow-up over tim

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YÜKSEK KAPASİTELİ LİTYUM-İYON BATARYA PAKETLERİNDE 1C DEŞARJ KOŞULLARI İÇİN TERMAL-HİDROLİK HAD OPTİMİZASYONU

THERMAL-HYDRAULIC CFD OPTIMIZATION OF HIGH-CAPACITY LITHIUM-ION BATTERY PACKS FOR 1C DISCHARGE CONDITIONS

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ÖZET

Enerji depolama sistemlerinde artan kapasite talepleri ve hızlı şarj/deşarj gereksinimleri yüksek enerjili batarya paketlerinin ısıl yönetiminde yüksek termal verimlilik ile soğutma grubu ve pompalama maliyetlerinin oluşturduğu düşük toplam sistem enerji tüketiminin eşzamanlı olarak sağlanmasını kritik hale getirmiştir. Bu çalışmada 52 kWh kapasiteye sahip büyük ölçekli bir lityum-iyon batarya paketinin termal ve hidrolik performansı Hesaplamalı Akışkanlar Dinamiği yöntemiyle incelenmiştir. Batarya paketinin 1C sürekli deşarj koşulunda çalışması ve paket genelinde toplam 1872 W ısı üretmesi senaryosu temel alınmıştır. Bu yüksek ısıl yüke karşı; sadece alttan soğutma plakası, alttan ve üstten soğutma plakaları ile alttan soğutma plakasına ek olarak yandan ara soğutucu plakaların kullanıldığı üç farklı sıvı soğutma konfigürasyonunun performansı karşılaştırmalı olarak analiz edilmiştir. Gerçekleştirilen tüm analiz senaryolarında sonuçların doğrudan karşılaştırılabilmesi amacıyla akışkan debisi ve diğer tüm sınır şartları sabit tutulmuştur. Soğutucu akışkan olarak sıcaklığa bağlı değişken termofiziksel özelliklere sahip %50 etilen glikol-su karışımı kullanılmıştır. Soğutma konfigürasyonlarının yanı sıra, 10°C ve 20°C akışkan giriş sıcaklıklarının sistem üzerindeki termal ve hidrolik etkileri parametrik olarak değerlendirilmiştir. Analiz bulguları, üç konfigürasyonun da maksimum hücre sıcaklığını güvenli aralıkta tuttuğunu, aralarındaki belirleyici farkın ise paket içi sıcaklık homojenliği ve pompalama gücü gereksiniminde ortaya çıktığını göstermiştir. Sadece alttan soğutma plakasının kullanıldığı konfigürasyonda, 20°C akışkan giriş sıcaklığında maksimum hücre sıcaklığı 30.13°C ve basınç kaybı yaklaşık 13.5 kPa olarak elde edilmiştir. Akışkan giriş sıcaklığının 10°C'ye düşürülmesi maksimum hücre sıcaklığını 20.84°C'ye düşürerek termal performansı belirgin şekilde iyileştirmiştir ancak azalan sıvı sıcaklığına bağlı olarak artan dinamik viskozite sistemdeki cidar sürtünmesini artırmış ve basınç kaybını 15.2 kPa seviyesine yükseltmiştir. Isı transfer yüzey alanının artırıldığı alttan ve üstten soğutma plakalarının kullanıldığı konfigürasyonda ise plaka başına düşen ısı yükünün azalması sonucu akışkanın ortalama sıcaklığı daha düşük kalmıştır ve bu durum hidrolik direnci belirgin bir şekilde artırarak basınç kaybını 17.6 kPa mertebelerine yükseltmiştir. Termal homojenlik ve düşük pompalama gücü gereksinimi bir arada değerlendirildiğinde paket içi sıcaklık farkını 2.05°C ile en aza indiren ve ekstra hidrolik yük yaratmayan alttan soğutma plakasına ek olarak yandan ara soğutucu plakaların kullanıldığı konfigürasyonun optimum çözüm olduğu tespit edilmiştir. Çalışma, soğutma kapasitesini artırmak amacıyla yüzey alanını veya akışkan giriş sıcaklığını değiştirmenin hem aktif soğutma yükünü hem de artan viskozite kaynaklı pompalama gücü ihtiyacını nasıl etkilediğini sayısal verilerle ortaya koyarak sistem düzeyinde enerji verimli batarya termal yönetim tasarımlarına kapsamlı bir perspektif sunmaktadır.

Anahtar Kelimeler: Lityum-İyon Batarya, Termal Yönetim, Sıvı Soğutma, Hesaplamalı Akışkanlar Dinamiği, Pompalama Gücü

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ABSTRACT

In energy storage systems, achieving high thermal efficiency and low total system energy consumption, which includes cooling and pumping costs, at the same time is made critical by increasing capacity demands and fast charge/discharge requirements. In this study, the thermal and hydraulic performance of a large-scale lithium-ion battery pack with a 52 kWh capacity was analyzed using the Computational Fluid Dynamics method. A scenario was considered where the battery pack operates at a 1C continuous discharge condition and produces a total of 1872 W heat. Against this high heat load, the performance of three different liquid cooling configurations was analyzed comparatively: only a bottom cooling plate, bottom and top cooling plates, and a bottom cooling plate with side intermediate cooling plates. In all analysis scenarios, the fluid flow rate and all other boundary conditions were kept constant to compare the results directly. A 50% ethylene glycol-water mixture with temperature-dependent thermophysical properties was used as the cooling fluid. In addition to the cooling configurations, the thermal and hydraulic effects of 10°C and 20°C fluid inlet temperatures on the system were evaluated parametrically. The analysis results showed that all three configurations kept the maximum cell temperature within the safe range, and that the decisive difference between them emerged in the in-pack temperature homogeneity and the pumping power requirement. In the configuration where only a bottom cooling plate was used, at a 20°C fluid inlet temperature, the maximum cell temperature was obtained as 30.13°C and the pressure drop as approximately 13.5 kPa. Decreasing the fluid inlet temperature to 10°C significantly improved the thermal performance by reducing the maximum cell temperature to 20.84°C, but the increased dynamic viscosity due to the decreasing fluid temperature increased the wall friction in the system and raised the pressure drop to 15.2 kPa. However, in the configuration where bottom and top cooling plates were used and the heat transfer surface area was increased, the average temperature of the fluid remained lower as a result of the decrease in the heat load per plate, and this situation significantly increased the hydraulic resistance and raised the pressure drop to 17.6 kPa levels. When thermal homogeneity and low pumping power requirement were evaluated together, it was determined that the configuration where side intermediate cooling plates are used in addition to the bottom cooling plate, which minimizes the temperature difference inside the pack to 2.05°C and does not create extra hydraulic load, is the optimum solution. The study provides a comprehensive perspective for system-level energy-efficient battery thermal management designs by showing with numerical data how changing the surface area or fluid inlet temperature to increase the cooling capacity affects both the active cooling load and the pumping power requirement due to increased viscosity.

Keywords: Lithium-Ion Battery, Thermal Management, Liquid Cooling, Computational Fluid Dynamics, Pumping Power

GİRİŞ

Yenilenebilir enerji kaynaklarının şebekeye entegrasyonu, talep yönetimi ve kesintisiz güç sağlama uygulamalarının yaygınlaşmasıyla birlikte lityum-iyon esaslı Batarya Enerji Depolama Sistemleri (BESS) enerji altyapısının belirleyici bileşenlerinden biri hâline gelmiştir. Bu sistemlerde birim hacme düşen enerji miktarının sürekli artması ve şebeke hizmetlerinin gerektirdiği yüksek C-oranlı şarj/deşarj rejimleri ve paket içerisinde birim zamanda açığa çıkan ısıl gücü de aynı oranda büyütmektedir. Dolayısıyla ısıl yönetim günümüzde yalnızca bir güvenlik önlemi değil sistemin kullanılabilir kapasitesini, çevrim ömrünü ve net enerji verimini doğrudan belirleyen bir tasarım disiplinidir (Wang, Jiang, Li ve Yan, 2016; Kim, Oh ve Lee, 2019).

Lityum-iyon hücrelerin elektrokimyasal davranışı sıcaklığa güçlü biçimde bağımlıdır. Literatürde hücrelerin verim ve ömür açısından en uygun çalışma aralığının yaklaşık 15-35 °C olduğu ve paket içindeki hücreler arası sıcaklık farkının ise 5 °C'nin altında tutulması gerektiği yaygın olarak kabul edilmektedir (Liu, Chen, Huang, Jiao ve Chen, 2023). Bu aralığın üzerindeki sıcaklıklar katı elektrolit ara yüzey (SEI) filminin büyümesini ve elektrolit ayrışmasını hızlandırarak kapasite kaybına yol açarken paket içindeki sıcaklık dağılımının homojen olmaması hücrelerin farklı hızlarda yaşlanmasına ve modül genelinde dengesizliğe neden olmaktadır (Bandhauer, Garimella ve Fuller, 2011; Ma vd., 2018). Sıcaklık kontrolünün tamamen kaybedilmesi durumunda ise ekzotermik ayrışma reaksiyonlarının kendi

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kendini besleyerek ısıl sürüklenmeye (thermal runaway) dönüşmesi söz konusudur (Feng, Ouyang, Liu, Lu, Xia ve He, 2018). Lityum demir fosfat (LFP) katotlu prizmatik hücreler için yapılan deneysel çalışmalar, ısıl sürüklenmenin tetiklendiği yüzey sıcaklığı eşiğinin 170 °C mertebesinde olduğunu ortaya koymuştur (Zhou, Zhou, Cao, Yang ve Liew, 2022).

Yüksek ısıl yüklerde hava soğutmalı çözümler yetersiz kaldığından büyük ölçekli paketlerde soğutma plakası esaslı dolaylı sıvı soğutma standart yaklaşım hâline gelmiştir (Chen, Jiang, Kim, Yang ve Pesaran, 2016). Ancak sıvı soğutma tasarımı tek amaçlı bir problem değildir. Soğutma kapasitesini artırmak için başvurulan iki temel yol – ısı transfer yüzey alanını büyütmek ve akışkan giriş sıcaklığını düşürmek – hidrolik tarafta bir karşılık doğurur. Kanal veya plaka sayısının artırılması sürtünme kayıplarını, giriş sıcaklığının düşürülmesi ise dinamik viskoziteyi ve dolayısıyla cidar sürtünmesini yükseltir. Her iki durumda da devrede gereken basınç farkı ve buna bağlı pompalama gücü artar; bu güç depolama sisteminin kendi ürettiği enerjiden karşılandığından doğrudan net verim kaybına dönüşür. Nitekim Madani, Schaltz ve Kær (2020), soğutma kanalı sayısının 4'ten 10'a çıkarılmasının sıcaklık homojenliğini belirgin biçimde iyileştirdiğini ve buna karşılık aynı giriş hızında basınç kaybını yaklaşık %97 oranında artırdığını göstermiştir. Benzer biçimde Jarrett ve Kim (2011) tek bir amaca göre optimize edilen plaka geometrilerinin diğer amaçlar bakımından kötüleştiğini, Huo, Rao, Liu ve Zhao (2015) kanal sayısı ve debi artışıyla sağlanan termal iyileşmenin belirli bir noktadan sonra doyuma ulaşırken hidrolik direncin artmaya devam ettiğini, Deng, Zhang ve Ran (2018) ise akış yolu uzunluğunun homojenlik-basınç kaybı dengesini belirleyen ana parametre olduğunu ortaya koymuştur.

Mevcut literatürde soğutma plakası içi kanal geometrisinin optimizasyonu kapsamlı biçimde ele alınmış olmakla birlikte plakaların paket üzerindeki konumlandırma stratejisinin (alt, üst, yan) termal ve hidrolik performansa etkisini sabit debi ve sabit sınır koşulları altında karşılaştıran üstelik akışkan giriş sıcaklığının etkisini de aynı çerçevede değerlendiren çalışmalar sınırlıdır. Bu çalışmanın amacı, 52 kWh kapasiteli bir lityum-iyon batarya paketinde 1C sürekli deşarj koşulu için üç farklı soğutma plakası yerleşimini ve iki farklı akışkan giriş sıcaklığını HAD yöntemiyle karşılaştırarak yalnızca maksimum hücre sıcaklığını değil paket içi sıcaklık homojenliğini ve pompalama gücü gereksinimini birlikte gözeten bir tasarım kriteri ortaya koymaktır.

MATERYAL VE YÖNTEM

İncelenen Sistem ve Isıl Yük

Çalışmaya konu olan sistem 52 kWh kapasiteli bir lityum-iyon batarya paketidir. Paket, modüllerin yanı sıra soğutma donanımını, batarya yönetim sistemini ve kasa yapısını da kapsamaktadır. Analizlerde paketin 1C sürekli deşarj koşulunda çalıştığı yani nominal kapasitesini yaklaşık bir saat içinde boşalttığı senaryo esas alınmıştır. Bu koşulda paket genelinde açığa çıkan toplam ısıl güç 1872 W olarak belirlenmiştir ve bu değer deşarj sırasında çekilen elektriksel güce oranla yaklaşık %3,6 mertebesinde bir ısı üretimine karşılık gelmektedir.

Isı üretimi, hücrelerin iç direncinden kaynaklanan tersinmez Joule kaybı ile entropi değişimine bağlı tersinir bileşenin toplamı olarak ele alınmıştır. Bernardi, Pawlikowski ve Newman (1985) tarafından önerilen genel enerji dengesi uyarınca bu ısı, hücre hacimleri içinde düzgün dağılımlı hacimsel kaynak olarak tanımlanmıştır. Paket ölçeğindeki analizlerde yaygın biçimde tercih edilen bir yaklaşımdır (Pesaran, 2002). Sürekli deşarj boyunca kararlı hâl çözümü aranmış ve böylece en olumsuz ısıl yük durumu temsil edilmiştir.

Soğutucu Akışkan ve Sınır Koşulları

Soğutucu akışkan olarak %50 hacimsel etilen glikol-su karışımı seçilmiştir. Bu karışım düşük ortam sıcaklıklarında donma koruması sağladığı için sahada yaygın olarak kullanılmaktadır. Karışımın yoğunluk, özgül ısı, ısıl iletkenlik ve dinamik viskozite değerleri sabit kabul edilmemiş olup sıcaklığa bağlı değişken özellikler olarak modele tanımlanmıştır (Melinder, 2007). Bu tercih çalışmanın temel sorusu açısından belirleyicidir çünkü etilen glikol-su karışımlarının viskozitesi sıcaklık düştükçe belirgin biçimde artar ve özgül ısısı azalır. Sabit özellik kabulü yapılsaydı giriş sıcaklığının hidrolik taraftaki etkisi hiç görünmeyecekti.

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Konfigürasyonlar arasındaki farkın yalnızca plaka yerleşiminden kaynaklanması için akışkan kütlesel debisi, hücre ısı üretimi, geometri temeli ve dış ortam koşulları tüm senaryolarda sabit tutulmuştur. Giriş sınırında sabit kütlesel debi ve sabit sıcaklık, çıkış sınırında ise sabit basınç tanımlanmıştır. Katı-akışkan ara yüzeylerinde kaymama koşulu geçerlidir.

Sayısal Model

Analizler, sonlu hacimler yöntemini esas alan EFD çözücüsü kullanılarak gerçekleştirilmiştir. Kütlenin, momentumun ve enerjinin korunumu denklemleri, katı bölgelerdeki iletim ile akışkan bölgelerindeki taşınım eş zamanlı olacak biçimde konjuge ısı transferi yaklaşımıyla çözülmüştür. Türbülans için düşük Reynolds sayılı bölgelerde de geçerliliğini koruyan değiştirilmiş k-ε modeli ve iki katmanlı duvar fonksiyonları kullanılmıştır. Böylece soğutma kanallarındaki geçiş rejimine yakın akış koşulları tek bir çözüm çerçevesinde ele alınabilmiştir.

Hesaplama ağı olarak ana eksenlere hizalı Kartezyen ağ yapısı tercih edilmiş olup katı-akışkan ara yüzeyleri ise geometriyi kesen hücrelerin kısmi hacim ve yüzey alanı bilgisiyle temsil edildiği kesme hücre yaklaşımıyla çözülmüştür. Bu sayede modülleri, plakaları ve kasayı içeren karmaşık paket geometrisi her konfigürasyon için ağ yeniden kurulmadan aynı temel üzerinde çözülebilmiştir.

Konfigürasyonların her biri için ayrı ağ bağımsızlık çalışması yürütmek geometrik farklılıklar nedeniyle karşılaştırılabilir bir temel sunmayacağından bunun yerine çözüme bağlı otomatik ağ iyileştirme kullanılmıştır. Çözüm belirli iterasyon aralıklarında duraklatılmakta ve sıcaklık, hız ve basınç alanlarındaki yerel gradyanlar değerlendirilmektedir. Gradyanın yüksek olduğu bölgelerde hücreler bölünür ve ihmal edilebilir olduğu bölgelerde ise birleştirilir. İyileştirme ağırlıklı olarak soğutma kanallarında ve sınır tabakası bölgelerinde yoğunlaşmıştır ve ardışık adımlar arasında izlenen çıktı büyüklüklerindeki değişim ihmal edilebilir düzeye indiğinde ise ağ nihai hâlini almıştır. Nihai ağ konfigürasyona bağlı olarak 500.000 ile 1.000.000 hücre arasında değişmiştir.

Yakınsama için üç ölçüt birlikte aranmıştır. Birincisi, normalize edilmiş kütle ve momentum rezidüellerinin 10^{-4}, enerji rezidüelinin ise 10^{-6} değerinin altına inmesidir. İkinci olarak maksimum hücre sıcaklığı, paket içi sıcaklık farkı, akışkan çıkış sıcaklığı ve devre basınç farkı birer hedef büyüklük olarak tanımlanmış ve bu büyüklüklerin son iterasyon penceresindeki salınım genliğinin ortalama değerin %1'inin altında kalması beklenmiştir. Üçüncü ölçüt global enerji dengesidir. Hücrelerde tanımlanan 1872 W'lık ısıl gücün, akışkan tarafından uzaklaştırılan ısı ile kasa yüzeylerinden ortama atılan ısının toplamına %1'den küçük bir sapmayla eşit olduğu her senaryo için doğrulanmıştır.

Analiz çıktısı olarak üç büyüklük izlenmiştir. Maksimum hücre sıcaklığı ısıl güvenlik sınırlarına olan mesafeyi, paket içi sıcaklık farkı hücreler arası homojenliği, devredeki toplam basınç kaybı ise pompalama gücü gereksinimini temsil etmektedir. Debi tüm senaryolarda sabit olduğundan pompalama gücü basınç kaybıyla doğru orantılıdır ve basınç kaybındaki yüzdesel değişim pompalama gücündeki değişime eşdeğer kabul edilebilir.

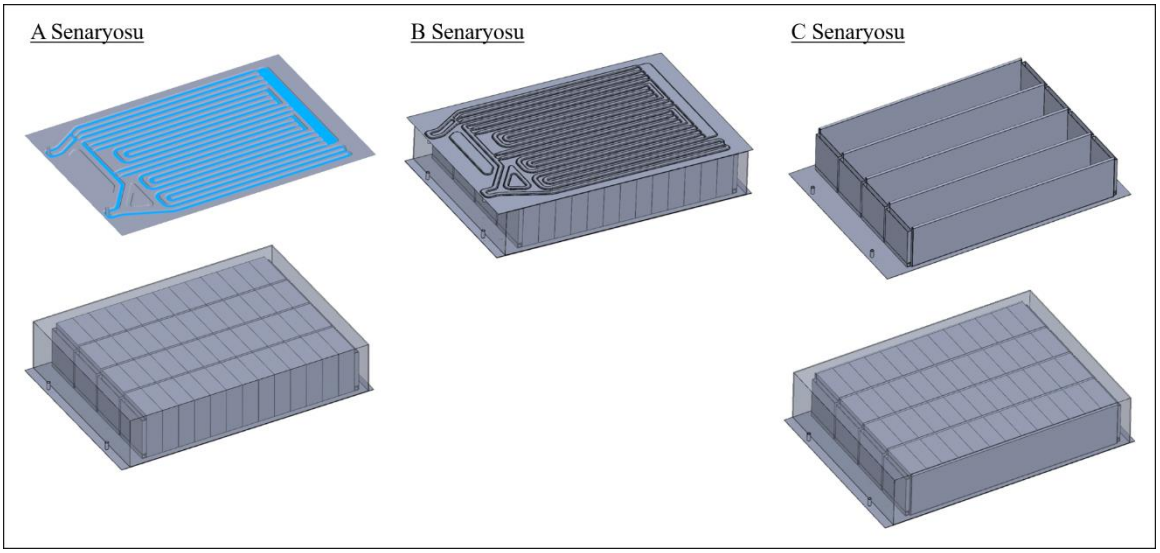
İncelenen Soğutma Konfigürasyonları

Üç farklı soğutma plakası yerleşimi ve iki farklı akışkan giriş sıcaklığı incelenmiştir. Senaryolar Tablo 1'de özetlenmiş, konfigürasyonların şematik gösterimi ise Şekil 1'de verilmiştir.

Tablo 1. İncelenen analiz senaryoları

Senaryo	Soğutma plakası yerleşimi	Giriş sıcaklığı
A	Sadece alttan soğutma plakası	20 °C
A-10	Sadece alttan soğutma plakası	10 °C
B	Alttan ve üstten soğutma plakası	20 °C
C	Alttan soğutma plakası ve yandan ara soğutucu plakalar	20 °C

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Şekil 1. Batarya paketi geometrisi ve incelenen soğutma plakası yerleşimleri

BULGULAR VE TARTIŞMA

Dört analiz senaryosundan elde edilen termal ve hidrolik sonuçlar Tablo 2'de topluca verilmiştir.

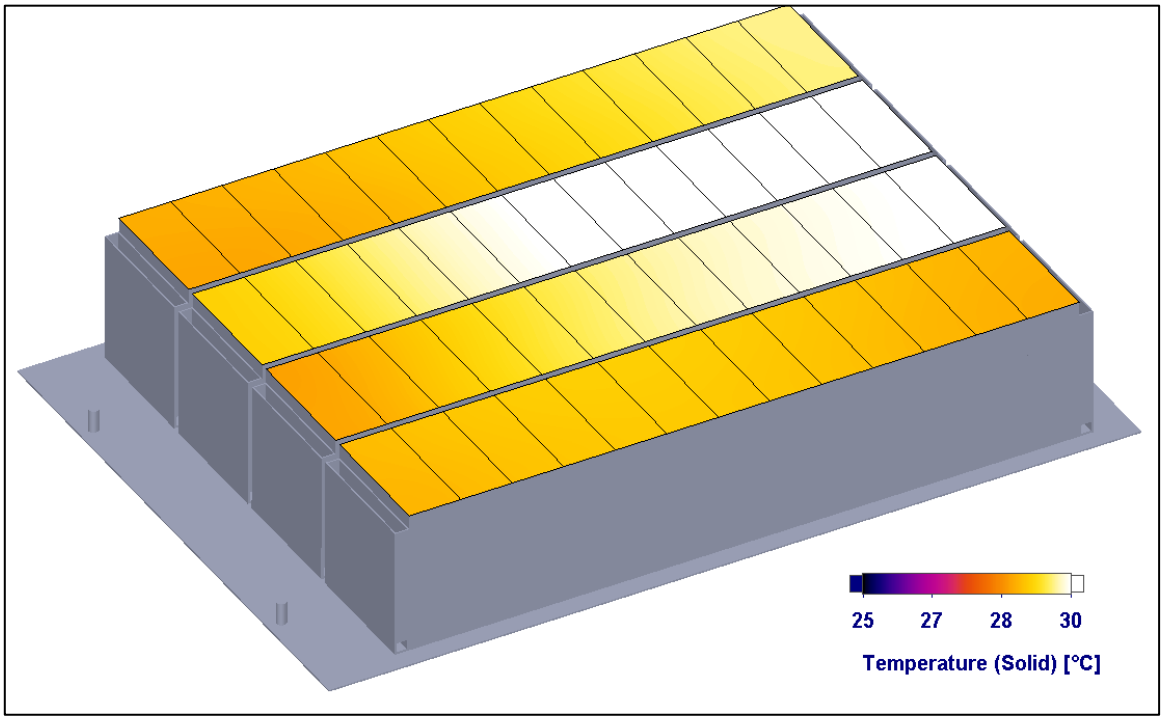
Tablo 2. Analiz senaryolarına ait termal ve hidrolik sonuçlar

Senaryo	Maks. hücre sıcaklığı [°C]	Paket içi ΔT [°C]	Akışkanın ısınması [°C]	Basınç kaybı (ana devre) [kPa]	Basınç kaybı (ikincil devre) [kPa]
A	30,13	2,64	6,55	13,51	-
A-10	20,84	2,89	7,53	15,25	-
B	25,09	2,35	3,50	17,48	17,67 (üst devre)
C	25,03	2,05	3,85	13,52	1,63 (yan devre)

Sadece Alttan Soğutma Plakası

Yalnızca alttan plakanın kullanıldığı ve 20 °C giriş sıcaklığının uygulandığı A senaryosunda maksimum hücre sıcaklığı 30,13 °C, paket içi sıcaklık farkı 2,64 °C ve basınç kaybı 13,51 kPa olarak hesaplanmıştır. Tek bir plaka bile ısıl güvenlik sınırlarını geniş bir marjla sağlamaktadır. Ancak ısı yalnızca alt yüzeyden çekildiği için akışkan plaka boyunca 6,55 °C ısınmakta ve plakanın giriş ile çıkış tarafı arasında belirgin bir sıcaklık gradyanı oluşmaktadır. Paket içindeki 2,64 °C'lik farkın önemli bir bölümü hücrelerin farklı ısı üretim davranışından değil, doğrudan bu akışkan ısınmasından kaynaklanmaktadır. Plaka boyunca oluşan bu gradyan Şekil 2'de açıkça görülmektedir.

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Şekil 2. Konfigürasyon A için paket içi sıcaklık dağılımı (20 °C giriş sıcaklığı, 1C deşarj)

Akışkan Giriş Sıcaklığının Etkisi

Giriş sıcaklığı 20 °C'den 10 °C'ye düşürüldüğünde maksimum hücre sıcaklığı 30,13 °C'den 20,84 °C'ye gerilemiştir. Buradaki 9,29 °C'lik düşüşün, uygulanan 10 °C'lik giriş sıcaklığı azalmasına neredeyse birebir karşılık gelmesi dikkat çekicidir. Bu durum giriş sıcaklığını düşürmenin sistemin toplam ısıl direncini iyileştirmediğini gösterir. Sıcaklık alanı yalnızca daha düşük bir seviyeye ötelenmektedir.

Nitekim paket içi sıcaklık farkı iyileşmemiş, aksine 2,64 °C'den 2,89 °C'ye çıkmıştır. Nedeni karışımın sıcaklığa bağlı özelliklerinde aranmalıdır. Sıcaklık düştükçe özgül ısı azalır ve sabit debide aynı ısıyı taşıyabilmek için akışkanın daha fazla ısınması gerekir. Akışkanın plaka boyunca ısınması 6,55 °C'den 7,53 °C'ye çıkmış ve paket genelindeki gradyan büyümüştür. Aynı anda dinamik viskozitedeki artış cidar sürtünmesini yükselterek basınç kaybını 13,51 kPa'dan 15,25 kPa'ya taşımıştır. Bu %12,8'lik bir artıştır ve sabit debide pompalama gücüne birebir yansır.

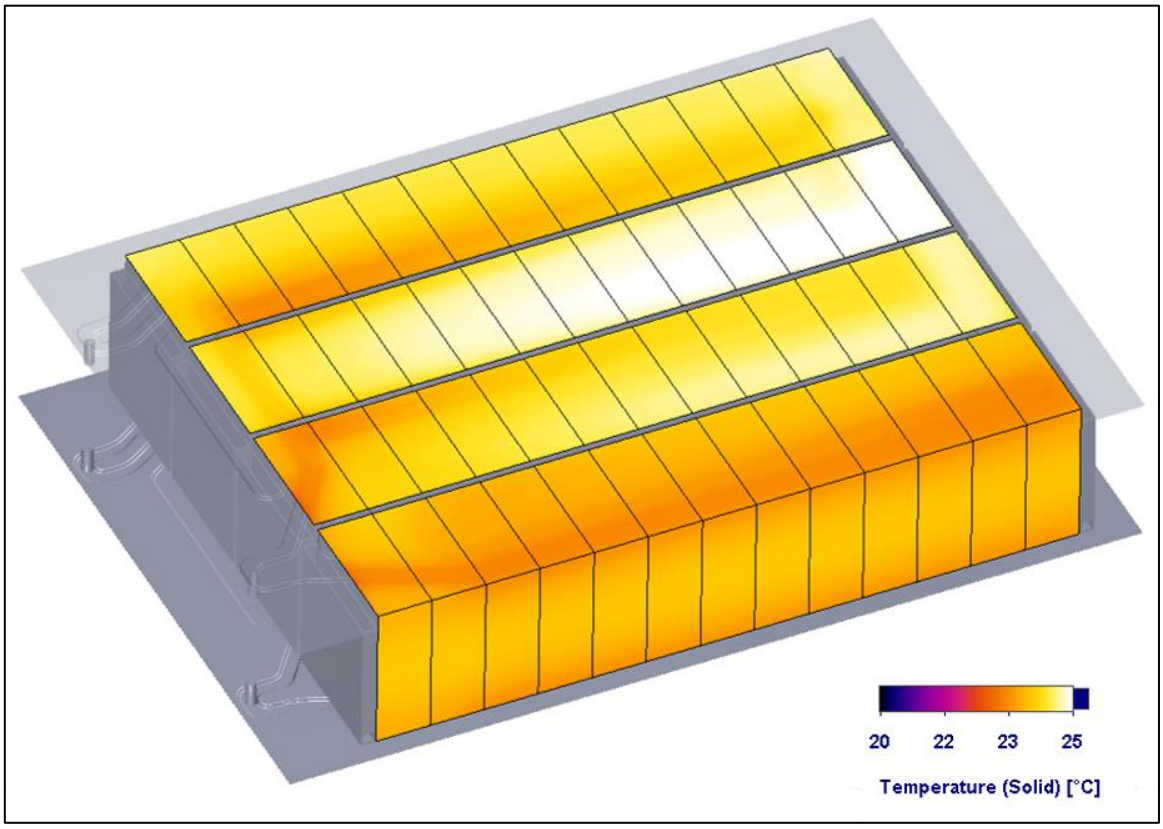
Bulgu tasarım açısından iki sonuç doğurmaktadır. Giriş sıcaklığını düşürmek homojenlik problemine çözüm sunmaz, hatta onu bir miktar kötüleştirir. Ayrıca daha düşük akışkan sıcaklığı için soğutma grubunun daha düşük buharlaşma sıcaklığında çalıştırılması gerekeceğinden çillerin performans katsayısı da düşer ve sistem düzeyindeki bedel pompalama gücündeki artışın ötesine geçer. Maksimum sıcaklığın zaten güvenli aralıkta olduğu bir tasarımda giriş sıcaklığını düşürmek verimli bir strateji değildir.

Alttan ve Üstten Soğutma Plakaları

Isı transfer yüzeyinin iki katına çıkarıldığı B senaryosunda maksimum hücre sıcaklığı 25,09 °C'ye, paket içi sıcaklık farkı ise 2,35 °C'ye gerilemiştir. Plaka başına düşen ısıl yük azaldığı için akışkanın ısınması 6,55 °C'den 3,50 °C'ye inmiş ve akışkan devre boyunca daha soğuk kalmıştır. Termal açıdan bu açık bir iyileşmedir. Sıcaklık dağılımındaki iyileşme Şekil 3'te izlenebilir.

Ancak akışkanın daha düşük ortalama sıcaklıkta kalması, viskozitenin devre boyunca yüksek seyretmesi anlamına gelir. Buna ikinci plakanın getirdiği ıslak yüzey alanı ve akış yolu uzunluğu artışı eklenince hidrolik direnç belirgin biçimde yükselmiş, alt devrede 17,48 kPa ve üst devrede 17,67 kPa basınç kaybı hesaplanmıştır. Pompa boyutlandırmasında devrelerin en yükseği belirleyici olduğundan B konfigürasyonu A'ya göre yaklaşık %31 daha fazla pompalama gücü ister. Elde edilen homojenlik kazancı ise yalnızca 0,29 °C'dir ve bu kazanç söz konusu bedeli karşılamamaktadır.

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Şekil 3. Konfigürasyon B için paket içi sıcaklık dağılımı (20 °C giriş sıcaklığı, 1C deşarj)

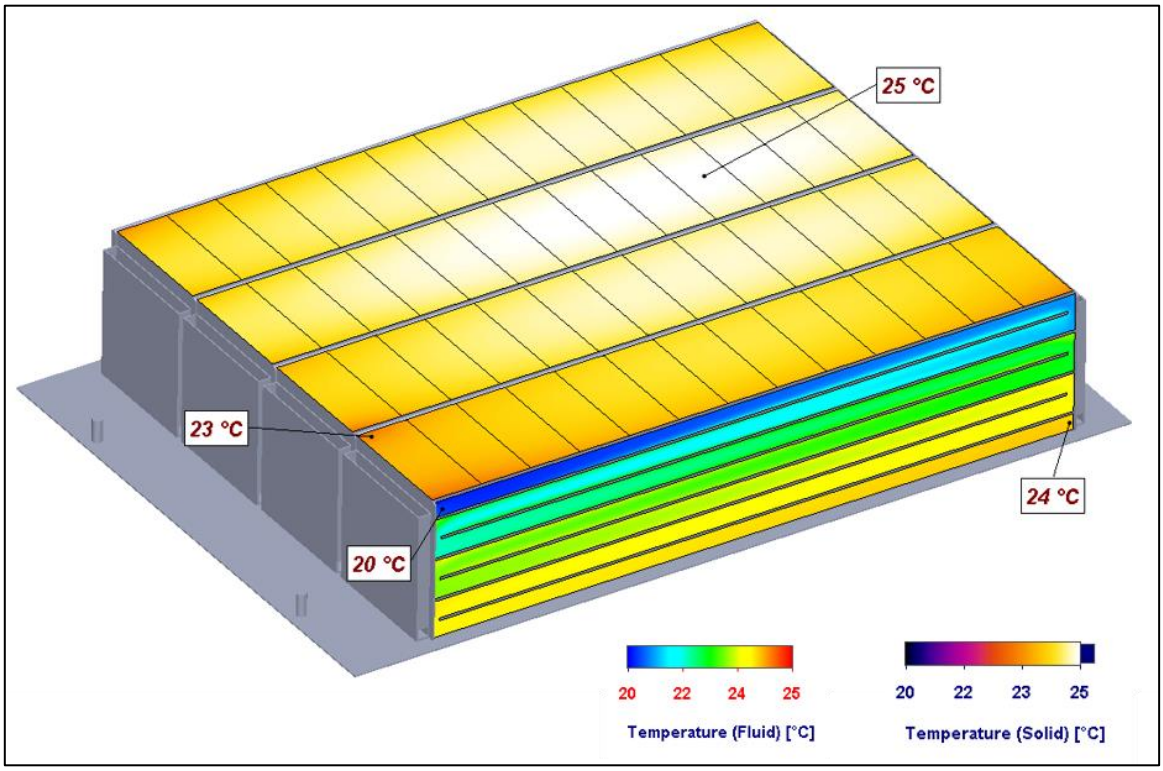
Alttan Soğutma Plakası ve Yandan Ara Soğutucu Plakalar

Modüller arasına yerleştirilen yandan ara plakaların devreye alındığı C senaryosunda maksimum hücre sıcaklığı 25,03 °C ile B senaryosuyla pratik olarak aynı seviyede kalmıştır. Paket içi sıcaklık farkı ise 2,05 °C ile üç konfigürasyonun en düşüğüdür. Bu değer A senaryosuna göre %22,3, B senaryosuna göre %12,8 iyileşme demektir.

Hidrolik taraftaki sonuç daha çarpıcıdır. Ana devredeki basınç kaybı 13,52 kPa ile A senaryosunun 13,51 kPa seviyesinde kalmış, yandan plakaları besleyen ikincil devrede ise yalnızca 1,63 kPa kayıp oluşmuştur. Bu, ana devre kaybının yaklaşık %12'si kadardır ve toplam hidrolik yüke sınırlı bir katkı yapar. Yani C konfigürasyonu, B konfigürasyonunun sağladığı sıcaklık seviyesini onun getirdiği bedel olmadan elde etmektedir. Konfigürasyon C için elde edilen sıcaklık dağılımı Şekil 4'te verilmiştir.

Bu davranışın nedeni ısı transfer yüzeyinin nereye yerleştirildiğiyle ilgilidir. Üstten soğutma ısıyı hücrelerin zaten görece serin olan bölgelerinden çekerken, yandan ara plakalar ısıyı paketin merkezinde biriken ve komşularıyla çevrili olduğu için en zor soğuyan hücrelerden alır. Aynı ilave yüzey alanı böylece sıcaklık dağılımının en olumsuz olduğu bölgeye yönlendirilmiş olur. Literatürde plaka geometrisi için vurgulanan homojenlik ve basınç kaybı dengesinin (Jarrett ve Kim, 2011; Huo vd., 2015) yerleşim düzeyinde de geçerli olduğu görülmektedir.

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Şekil 4. Konfigürasyon C için paket içi sıcaklık dağılımı (20 °C giriş sıcaklığı, 1C deşarj)

Termal ve Hidrolik Performansın Birlikte Değerlendirilmesi

Konfigürasyonlar yalnızca maksimum hücre sıcaklığı üzerinden karşılaştırıldığında B ve C senaryoları birbirine denk görünür. Paket içi sıcaklık farkı ve pompalama gücü birlikte ele alındığında ise sıralama netleşmektedir. Tablo 3'te sonuçlar A senaryosu referans alınarak normalize edilmiştir.

Tablo 3. Konfigürasyon A'ya göre normalize edilmiş performans karşılaştırması

Senaryo	Maks. sıcaklık değişimi [°C]	Paket içi ΔT değişimi	Pompalama gücü değişimi
A (referans)	-	-	-
A-10	−9,29	+%9,5	+%12,8
B	−5,04	−%11,0	+%30,8
C	−5,10	−%22,3	+%0,0 (ana devre)

A-10 senaryosu maksimum sıcaklıkta en büyük düşüşü sağlar ama homojenliği kötüleştirir ve pompalama gücünü artırır. B senaryosu homojenliği iyileştirir, bunu ise en yüksek hidrolik bedelle yapar. C senaryosu ise homojenlikteki en büyük kazancı pratikte hiçbir ek pompalama gücü olmadan verir ve incelenen koşullar altında optimum çözüm olarak öne çıkar. Bu tablo, ısıl yönetim tasarımında yaygın olan daha fazla soğutmanın her zaman daha iyi olduğu yaklaşımına karşı niceliksel bir uyarıdır. Asıl kazanç ısıyı daha çok çekmekten değil, ısı transfer yüzeyini sıcaklık dağılımının en olumsuz olduğu bölgeye yönlendirerek ısıyı daha iyi dağıtmaktan gelmektedir.

SONUÇ

Bu çalışmada 52 kWh kapasiteli bir lityum-iyon batarya paketinin 1C sürekli deşarj koşulundaki termal ve hidrolik performansı, üç farklı soğutma plakası yerleşimi ve iki farklı akışkan giriş sıcaklığı için HAD yöntemiyle karşılaştırmalı olarak incelenmiştir. Başlıca sonuçlar şunlardır:

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- Sadece alttan soğutma plakası bile maksimum hücre sıcaklığını 30,13 °C'de tutarak güvenlik sınırlarını geniş bir marjla sağlamaktadır. Bu konfigürasyondaki asıl kısıt sıcaklık seviyesi değil, 2,64 °C'lik paket içi sıcaklık farkıdır.

- Akışkan giriş sıcaklığının 20 °C'den 10 °C'ye düşürülmesi maksimum sıcaklığı 9,29 °C azaltır ama paket içi sıcaklık farkını %9,5, basınç kaybını ise %12,8 artırır. Giriş sıcaklığını düşürmek homojenlik problemine çözüm değildir.

- Alttan ve üstten plakaların birlikte kullanılması sıcaklık farkını %11 iyileştirirken pompalama gücü gereksinimini yaklaşık %31 artırmaktadır.

- Alttan plakaya ek olarak yandan ara soğutucu plakaların kullanıldığı konfigürasyon paket içi sıcaklık farkını 2,05 °C ile en düşük seviyeye indirir, ana devre basınç kaybını değiştirmez ve yalnızca 1,63 kPa'lık ikincil bir hidrolik yük getirir. İncelenen koşullar altında optimum çözüm budur.

Bundan sonraki aşamada bulguların prototip paket üzerinde deneysel olarak doğrulanması, değişken C-oranlı gerçek şebeke yük profilleri altında geçici rejim analizlerinin yapılması ve yandan ara plaka sayısı ile yerleşiminin çok amaçlı optimizasyonla iyileştirilmesi planlanmaktadır.

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EPIVARIANTS AND EPIGENETIC SIGNATURES: THE ROLE OF DNA METHYLATION IN THE MOLECULAR DIAGNOSIS OF RARE DISEASES

EPİVARYANTLAR VE EPİGENETİK İMZALAR: NADİR HASTALIKLARIN MOLEKÜLER TANISINDA DNA METİLASYONUNUN ROLÜ

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ABSTRACT

It is increasingly recognized that epigenetic mechanisms, in addition to genetic alterations, play an important role in elucidating the molecular basis of hereditary and rare diseases. In this context, epivariants arising in specific genomic regions and epigenetic signatures (episignatures), which represent disease-specific genome-wide DNA methylation patterns, are gaining importance in molecular diagnosis.

Epivariants refer to rare and marked epigenetic deviations observed in a specific gene or genomic region. These alterations may arise in the absence of a known DNA sequence change or may develop secondary to regulatory-region variants, structural alterations, or repeat expansions, potentially leading to disrupted gene expression. In Fragile X syndrome, DNA methylation and gene silencing accompanying an expansion of more than 200 CGG repeats in the *FMR1* gene represent one of the best-known examples of an epigenetic abnormality secondary to a genetic alteration. Similarly, constitutional promoter methylation of *MLH1* may represent a rare mechanism of Lynch syndrome-associated cancer predisposition in some individuals without a germline pathogenic *MLH1* variant.

Epigenetic signatures (episignatures), in contrast to alterations restricted to a single locus, are reproducible genome-wide DNA methylation patterns associated with a specific disease, gene, or molecular mechanism. Distinct DNA methylation profiles have been identified in neurodevelopmental disorders with partially overlapping clinical features, including Kabuki, Sotos, CHARGE, and Coffin–Siris syndromes, in which chromatin and epigenetic regulatory genes are affected. Moreover, in disorders involving impaired DNA demethylation, such as *TET3*-related Beck–Fahrner syndrome, in which *TET3* plays an important role in epigenetic programming, genome-wide methylation patterns are considered functional biomarkers reflecting the molecular consequences of the disease.

Genome-wide DNA methylation analysis may provide complementary information for distinguishing clinically similar syndromes, evaluating variants of uncertain significance, and investigating patients who remain undiagnosed after exome or genome sequencing. However, not every local methylation alteration constitutes an episignature, and a negative episignature result does not definitively exclude the suspected disorder. Tissue specificity, blood cell-type proportions, age, mosaicism, technical differences, and the limited availability of sufficiently validated reference samples for some rare diseases should be considered when interpreting the results. This review aims to evaluate the biological basis of epivariants and episignatures, their relationship, representative disease examples, and their current applications in the molecular diagnosis of rare diseases in light of the recent literature.

Keywords: DNA methylation, epivariant, epigenetic signature, episignature, rare diseases, molecular diagnosis

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ÖZET

Kalıtsal ve nadir hastalıkların moleküler temelinin aydınlatılmasında genetik değişikliklerin yanı sıra epigenetik mekanizmaların da önemli rol oynadığı giderek daha iyi anlaşılmaktadır. Bu kapsamda, belirli genomik bölgelerde ortaya çıkan epivaryantların ve hastalıklara özgü genom çaplı DNA metilasyon örüntülerini ifade eden epigenetik imzaların (episignature'lar) moleküler tanıdaki önemi artmaktadır.

Epivaryantlar, belirli bir gen veya genomik bölgede gözlenen nadir ve belirgin epigenetik sapmaları ifade etmektedir. Bu değişiklikler, bilinen bir DNA dizi değişikliği olmaksızın ortaya çıkabileceği gibi düzenleyici bölge varyantları, yapısal değişiklikler veya tekrar genişlemelerine ikincil olarak da gelişebilir ve gen ekspresyonunun bozulmasına yol açabilir. Frajil X sendromunda, FMR1 genindeki 200'den fazla CGG tekrar genişlemesine eşlik eden DNA metilasyonu ve gen susturulması, genetik bir değişikliğe ikincil gelişen epigenetik bozuklukların en iyi bilinen örneklerinden biridir. Benzer şekilde, konstitüsyonel MLH1 promotör metilasyonu, germ hattı patojenik MLH1 varyantı saptanmayan bazı bireylerde Lynch sendromu ilişkili kanser yatkınlığının nadir bir mekanizmasını oluşturabilir.

Epigenetik imzalar (episignature'lar) ise tek bir lokustaki değişiklikten farklı olarak, belirli bir hastalık, gen veya moleküler mekanizma ile ilişkili, genom çapında tekrarlanabilir DNA metilasyon örüntüleridir. Özellikle kromatin ve epigenetik düzenleyici genlerin etkilendiği Kabuki, Sotos, CHARGE ve Coffin–Siris sendromları gibi klinik özellikleri kısmen örtüşebilen nörogelişimsel bozukluklarda özgün DNA metilasyon profilleri tanımlanmıştır. Ayrıca epigenetik programlamada önemli bir gen olan *TET3* ilişkili Beck–Fahrner sendromu gibi DNA demetilasyon mekanizmasının bozulduğu hastalıklarda, genom çapındaki metilasyon örüntüleri hastalığın moleküler etkilerini yansıtan fonksiyonel biyobelirteçler olarak değerlendirilmektedir.

Genom çapında DNA metilasyon analizi; klinik olarak benzer sendromların ayırt edilmesi, önemi belirsiz varyantların değerlendirilmesi ve ekzom/genom dizilemeleriyle tanı konulamayan hastaların araştırılmasında tamamlayıcı bilgi sağlayabilir. Bununla birlikte, her lokal metilasyon değişikliği bir episignature oluşturmadığı gibi negatif bir episignature sonucu da şüphelenilen hastalığı kesin olarak dışlamaz. Doku özgüllüğü, kan örneklerindeki hücre tipi oranları, yaş, mozaisizm, teknik farklılıklar ve bazı nadir hastalıklar için yeterli sayıda doğrulanmış referans örneğinin bulunmaması sonuçların yorumlanmasında dikkate alınmalıdır. Bu derlemede epivaryant ve episignature kavramlarının biyolojik temellerinin, aralarındaki ilişkinin, temsil edici hastalık örneklerinin ve nadir hastalıkların moleküler tanısındaki mevcut kullanım alanlarının güncel literatür doğrultusunda değerlendirilmesi amaçlanmaktadır.

Anahtar kelimeler: DNA metilasyonu, epivaryant, epigenetik imza (episignature), nadir hastalıklar, moleküler tanı

GİRİŞ

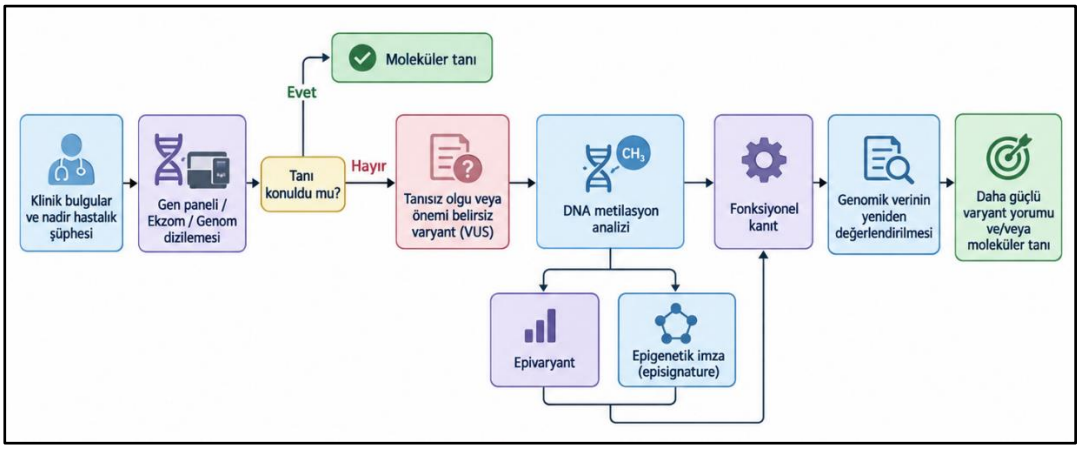
Nadir hastalıkların önemli bir bölümü genetik kökenli olmakla birlikte, moleküler neden her zaman ortaya konamamaktadır. Yeni nesil dizileme teknolojilerindeki gelişmeler; hedefe yönelik gen panelleri, ekzom dizileme ve genom dizilemesinin tanısal kullanımını önemli ölçüde güçlendirmiştir. Bununla birlikte, kapsamlı genomik incelemelere rağmen hastaların önemli bir kısmında kesin moleküler tanıya ulaşılamamaktadır (Kernohan & Boycott, 2024). Klinik bulguların farklı sendromlar arasında örtüşmesi, kodlamayan bölgelerdeki değişikliklerin yorumlanmasındaki güçlükler, yapısal varyantların veya tekrar genişlemelerinin bazı yöntemlerle gözden kaçabilmesi ve önemi belirsiz varyantların (variant of uncertain significance, VUS) saptanması tanısal sürecin başlıca güçlükleri arasındadır (Horsthemke, 2024; Kernohan & Boycott, 2024).

Gen ekspresyonu yalnızca DNA dizisi tarafından değil, kromatin yapısını ve genlerin transkripsiyonel aktivitesini düzenleyen epigenetik mekanizmalar tarafından da kontrol edilmektedir. DNA metilasyonu, histon modifikasyonları, kromatin yeniden düzenlenmesi ve kodlamayan RNA aracılı düzenleme bu mekanizmaların başlıcalarıdır (Horsthemke, 2024). Bunlar arasında DNA metilasyonu, insan hastalıklarında en iyi karakterize edilmiş epigenetik düzenleme mekanizmalarından biridir. Özellikle

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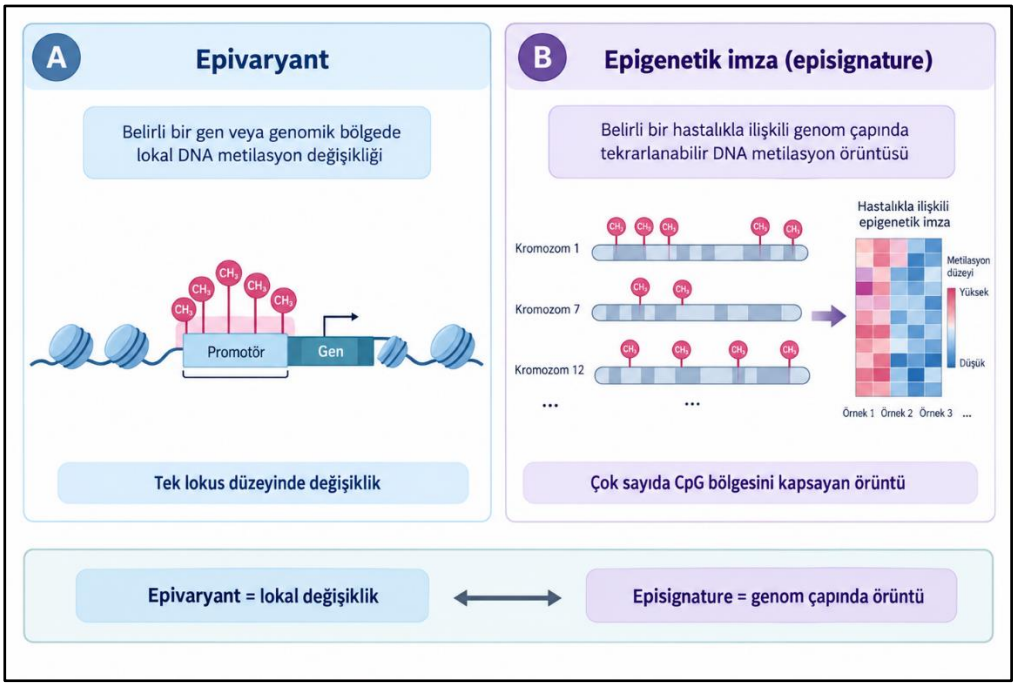
CpG dinükleotidlerinde sitozinin metillenmesi gen ekspresyonunun düzenlenmesine katkıda bulunurken, promotör ve diğer düzenleyici bölgelerdeki anormal metilasyon değişiklikleri gen ekspresyonunun bozulmasıyla sonuçlanabilir (Horsthemke, 2024; Tan et al., 2025).

Nadir hastalıkların moleküler tanısında genomik ve epigenomik yaklaşımların tamamlayıcı kullanımı Şekil 1'de gösterilmiştir.



Şekil 1. Nadir hastalıkların moleküler tanısında genomik ve epigenomik yaklaşım (BioRender.com kullanılarak oluşturulmuştur.)

Nadir hastalıkların moleküler tanısında DNA metilasyon analizlerinin önemi son yıllarda artmıştır. Genom çaplı çalışmalar, bazı bireylerde belirli gen veya genomik bölgeleri etkileyen nadir lokal metilasyon değişikliklerinin yanı sıra belirli hastalıklarla ilişkili tekrarlanabilir genom çaplı metilasyon örüntülerinin de bulunduğunu göstermiştir (Barbosa et al., 2018; Garg et al., 2020; Tan et al., 2025). Bu bulgular iki ilişkili ancak farklı kavramı ön plana çıkarmıştır: belirli bir lokustaki değişikliği ifade eden epivaryantlar ve çok sayıda CpG bölgesini kapsayan epigenetik imzalar (episignaturelar). Epivaryant ve epigenetik imza arasındaki temel farklar Şekil 2'de özetlenmiştir.



Şekil 2. Epivaryant ve epigenetik imzanın (episignature) karşılaştırılması (BioRender.com kullanılarak oluşturulmuştur.)

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Bu derlemede epivaryant ve epigenetik imza kavramlarının biyolojik temelleri, birbirleriyle ilişkileri ve farklılıkları ele alınacak; bu değişikliklerin ortaya çıkış mekanizmaları temsil edici hastalık örnekleri üzerinden değerlendirilecek ve genom çaplı DNA metilasyon analizlerinin nadir hastalıkların moleküler tanısındaki güncel kullanım alanları ve sınırlılıkları tartışılacaktır.

EPİVARYANTLAR: LOKAL DNA METİLASYON DEĞİŞİKLİKLERİ

Epivaryant kavramı

İnsan genomundaki DNA metilasyon düzeyi bireyler arasında belirli ölçüde değişkenlik gösterebilmekle birlikte, bazı bireylerde belirli genomik bölgelerde toplumdaki genel dağılımdan belirgin biçimde ayrılan metilasyon örüntüleri ortaya çıkabilmektedir. Bu nadir ve belirgin epigenetik sapmalar genel olarak epivaryant veya epivaryasyon olarak tanımlanmaktadır (Barbosa et al., 2018; Garg et al., 2020). Hastalık mekanizmasıyla doğrudan ilişkili ve gen ekspresyonunu bozduğu gösterilmiş epivaryantlar için literatürde "epimutasyon" terimi de kullanılmaktadır (Horsthemke, 2024; Lønning et al., 2025).

Epivaryantların en sık tanımlanan biçimlerinden biri, bir genin promotör veya düzenleyici bölgesinde ortaya çıkan anormal hipermetilasyondur. Promotör hipermetilasyonu transkripsiyonun azalmasına veya baskılanmasına yol açarak fonksiyonel gen kaybına benzer bir etki oluşturabilir. Bununla birlikte epivaryasyonlar yalnızca hipermetilasyonla sınırlı değildir; normalde metillenmiş bir bölgede ortaya çıkan hipometilasyon da gen düzenlenmesini bozabilir (Barbosa et al., 2018; Horsthemke, 2024).

Garg et al. (2020), 23.116 bireyin genom çaplı DNA metilasyon profillerini inceleyerek 4.452 farklı otozomal epivaryasyon tanımlamıştır. Hastalıklarla ilişkili çok sayıda genin promotörünü etkileyen değişikliklerin saptanması, nadir epigenetik değişikliklerin bazı hastalık mekanizmalarına katkıda bulunabileceğini düşündürmektedir. Aynı çalışmada epivaryasyonların önemli bir bölümünün altta yatan genetik varyasyonlarla ilişkili bulunması, genom ile epigenom arasındaki yakın ilişkiyi desteklemektedir.

Benzer şekilde Barbosa et al. (2018), genomik olarak açıklanamayan nörogelişimsel bozukluk ve konjenital anomalisi bulunan bireylerde nadir epivaryasyonların kontrol örneklerine göre arttığını ve bazı epivaryasyonların gen ekspresyonundaki değişikliklerle ilişkili olduğunu göstermiştir. Bu bulgular, epivaryasyonların bazı olgularda hastalığın doğrudan moleküler mekanizmasına katkıda bulunabileceğini, bazı olgularda ise gözden kaçmış düzenleyici veya yapısal bir genetik değişikliğin fonksiyonel işareti olabileceğini düşündürmektedir.

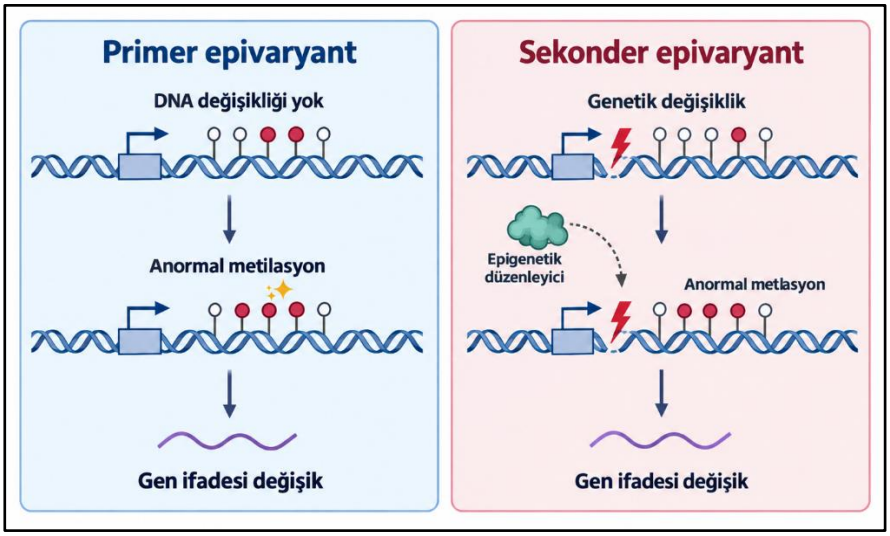
Primer ve sekonder epivaryantlar

Epivaryantlar oluşum mekanizmalarına göre genel olarak primer ve sekonder epivaryantlar şeklinde sınıflandırılabilir (Garg et al., 2020; Horsthemke, 2024; Lønning et al., 2025). Bu ayrım moleküler tanı açısından önemlidir; çünkü anormal DNA metilasyonu her zaman başlangıçtaki moleküler olay değildir.

Primer epivaryantlar, epigenetik durumun kurulması veya sürdürülmesi sırasında ortaya çıkan ve altında açıklayıcı bir DNA dizi değişikliğinin gösterilemediği metilasyon anomalileridir. Değişikliklerin erken gelişim döneminde ortaya çıkması konstitüsyonel bir epigenetik değişikliğe, postzigotik dönemde gelişmesi ise farklı dokularda değişken oranlarda izlenebilen epigenetik mozaisizme yol açabilir (Horsthemke, 2024; Lønning et al., 2025).

Sekonder epivaryantlarda anormal DNA metilasyonu, altta yatan bir genetik değişikliğin sonucudur. Cis-etkili düzenleyici varyantlar, kopya sayısı veya diğer yapısal varyantlar ve tekrar genişlemeleri bu mekanizmaya yol açabilir; ayrıca epigenetik düzenleyici bir trans-etkili faktördeki bozukluk da genomun başka bölgelerinde metilasyon değişiklikleri oluşturabilir (Garg et al., 2020; Horsthemke, 2024; Lønning et al., 2025). Primer ve sekonder epivaryantların temel oluşum mekanizmaları Şekil 3'te şematik olarak gösterilmiştir.

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Şekil 3. Primer ve sekonder epivaryantların oluşum mekanizmalarının şematik gösterimi (BioRender.com kullanılarak oluşturulmuştur.)

Bu nedenle bir epivaryantın saptanması yalnızca epigenetik bir bozukluğun gösterilmesi anlamına gelmez. Özellikle sekonder epivaryantlarda anormal metilasyon profili, standart ekzom dizilemesi veya kısa-okuma genom analizleri sırasında gözden kaçabilen düzenleyici varyantların, yapısal değişikliklerin ya da tekrar genişlemelerinin fonksiyonel izi olabilir (Garg et al., 2020; Kernohan & Boycott, 2024; Tan et al., 2025).

Konstitüsyonel MLH1 epimutasyonu

Epivaryantların klinik önemini gösteren iyi bilinen örneklerden biri MLH1 geninin konstitüsyonel promotör metilasyonudur. MLH1, DNA yanlış eşleşme onarım (mismatch repair) sisteminin temel bileşenlerinden biridir. Promotör bölgesindeki anormal hipermetilasyon, etkilenen allelde transkripsiyonun baskılanmasına ve fonksiyonel MLH1 kaybına yol açarak bazı bireylerde Lynch sendromu ile ilişkili özellikle kolorektal ve endometrium kanserlerine yatkınlık oluşturabilir (Bishop et al., 2026; Joo et al., 2023).

Konstitüsyonel MLH1 epimutasyonlarının tümü aynı mekanizma ile ortaya çıkmaz. Metilasyonu açıklayan cis-etkili bir genetik değişikliğin gösterilemediği olgular primer, MLH1 promotörü veya komşu düzenleyici bölgelerdeki germ hattı varyantlarının metilasyonu tetiklediği olgular ise sekonder epimutasyon olarak değerlendirilebilir (Lønning et al., 2025). Joo et al. (2023) düşük düzeyli mozaik konstitüsyonel MLH1 metilasyonunun saptanabileceğini, Bishop et al. (2026) ise 422 bireylik klinik seride bazı olgularda epimutasyonla ilişkili germ hattı promotör varyantlarının bulunduğunu göstermiştir.

Sekonder epivaryantın klasik örneği: Frajil X sendromu

Sekonder epivaryantların klasik örneklerinden biri Frajil X sendromudur. Hastalığın temel moleküler değişikliği, FMR1 geninin 5′ çevrilmeyen bölgesindeki (5′ UTR) CGG tekrar dizisinin genişlemesidir. CGG tekrar sayısının 200'ün üzerine çıkması tam mutasyon olarak tanımlanır ve genişlemiş allelde FMR1 promotörü ile çevresindeki CpG bölgelerinin hipermetilasyonu ile ilişkilidir (Ciobanu et al., 2023; Garg et al., 2020).

Bu durumda başlangıçtaki olay CGG tekrar genişlemesi, DNA metilasyonundaki değişiklik ise buna ikincil gelişen epigenetik sonuçtur. Hipermetilasyon FMR1 transkripsiyonunun baskılanmasına, FMRP düzeyinin azalmasına veya kaybına ve hastalık fenotipinin gelişmesine katkıda bulunur. Bu nedenle tekrar sayısının yanı sıra metilasyon durumu ve mozaisizm düzeyi de moleküler değerlendirmede önem taşır (Ciobanu et al., 2023).

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EPİGENETİK İMZALAR (EPISIGNATURE'LAR)

Epigenetik imza kavramı

Epigenetik imzalar (episignaturelar), belirli bir hastalık, genetik değişiklik veya moleküler mekanizma ile ilişkili, genom boyunca çok sayıda CpG bölgesini kapsayan tekrarlanabilir DNA metilasyon örüntüleridir (Aref-Eshghi et al., 2020; Sadikovic et al., 2020). Epivaryantlardan farklı olarak tek bir lokustaki değişikliği değil, çok sayıda genomik bölgenin birlikte oluşturduğu karakteristik metilasyon profilini yansıtırlar.

Hastalığa özgü metilasyon imzaları özellikle kromatin organizasyonu, histon modifikasyonları ve diğer epigenetik düzenleyici süreçlerde görev alan genlerin etkilendiği Mendel tipi nörogelişimsel bozukluklarda belirgindir. Bir epigenetik düzenleyicinin fonksiyon kaybı genom boyunca çok sayıda bölgenin düzenlenmesini etkileyebildiğinden, periferik kan gibi klinik olarak erişilebilir örneklerde dahi tekrarlanabilir metilasyon profilleri saptanabilmektedir (Aref-Eshghi et al., 2020; Sadikovic et al., 2020).

Aref-Eshghi et al. (2020), 42 Mendel tipi nörogelişimsel bozukluğu değerlendirdikleri çalışmada 34 güçlü hastalıkla ilişkili DNA metilasyon imzası tanımlamıştır. Bazı moleküler olarak ilişkili hastalıklarda imzalar arasında benzerlik ve hiyerarşik ilişkiler bulunması, bu profillerin yalnızca hastalık sınıflandırmasını değil, ortak biyolojik mekanizmaları da yansıtabildiğini göstermektedir.

Epigenetik imzaların moleküler tanıdaki yeri

Genetik hastalıkların tanısında DNA dizi analizi temel yaklaşım olmakla birlikte, saptanan varyantın klinik öneminin belirsiz kaldığı veya klinik şüpheye rağmen nedensel varyantın bulunamadığı olgular önemli bir tanısal sorun oluşturmaktadır. Epigenetik imza analizi bu noktada genomik testlerin yerine geçen bağımsız bir yöntemden çok, klinik ve genetik bulguları tamamlayan fonksiyonel bir değerlendirme yaklaşımıdır. Başlıca kullanım alanları klinik olarak benzer sendromların ayrılması, VUS'ların fonksiyonel değerlendirilmesi ve genomik testlerle tanı konulamayan olguların yeniden araştırılmasıdır (Kerkhof et al., 2024; Sadikovic et al., 2020, 2021).

Sadikovic et al. (2021), nadir Mendel tipi hastalık şüphesi bulunan 207 olgunun 57'sinde (%27,6) tanısal bir epigenetik imza saptamış ve pozitifliğin önceden belirsiz veya sonuçlandırılamamış genetik bulguları bulunan hedefli olgularda daha yüksek olduğunu göstermiştir.

Daha geniş bir klinik seride Kerkhof et al. (2024), EpiSign Clinical Testing Network kapsamında 2.399 olguyu değerlendirmiştir. Kapsamlı tarama yapılan 1.667 olgunun %18,7'sinde, belirli bir varyantın veya klinik tanının hedefli olarak değerlendirildiği 732 olgunun ise %32,4'ünde pozitif sonuç bildirilmiştir. Bu bulgular, yöntemin özellikle önceden tanımlanmış bir klinik veya genomik hipotezin bulunduğu olgularda yararlı olabileceğini göstermektedir.

VUS değerlendirmesinde, klinik fenotiple uyumlu bir gende saptanan varyantın aynı genin patojenik varyantlarıyla ilişkili bilinen bir epigenetik imzayı oluşturması, varyantın fonksiyonel etkisini destekleyen ek kanıt sağlayabilir. Buna karşılık negatif bir sonuç tek başına varyantın benign olduğunu göstermez; yorum hastalığa özgü imzanın doğrulanma düzeyi ve diğer klinik-genetik kanıtlarla birlikte yapılmalıdır (Kerkhof et al., 2024; Sadikovic et al., 2020).

Bu sınırlama bağımsız doğrulama çalışmalarında da görülmektedir. Husson et al. (2024), on nörogelişimsel bozukluğa ait yayımlanmış epigenetik imzaları bağımsız olarak değerlendirirken özgüllüğün yüksek olmasına karşın duyarlılığın hastalıklar arasında değişebildiğini göstermiştir. Bu nedenle özellikle negatif sonuçların dikkatle yorumlanması gerekmektedir.

Epigenetik imza analizi, kapsamlı genomik incelemelere rağmen moleküler tanı alamayan hastaların yeniden değerlendirilmesinde de kullanılabilir. Bilinen bir hastalık imzasıyla eşleşme, başlangıçta düşünülmeyen bir tanıya yönlendirebilir ve önceki genomik verilerin bu tanı doğrultusunda yeniden incelenmesini sağlayabilir; bu yaklaşım ters fenotipleme (reverse phenotyping) açısından da yararlıdır (Kerkhof et al., 2024; Sadikovic et al., 2021).

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Smits et al. (2025), önceki tanısal incelemelerle çözülememiş 223 olgunun %9'unda hastalıkla ilişkili bir DNA metilasyon imzası saptamıştır. Fenotip ile uyumlu pozitif olguların bir bölümünde geriye dönük genomik değerlendirme nedensel varyantın ortaya çıkarılmasını veya daha önce tanınmamış bir imprinting bozukluğunun doğrulanmasını sağlamıştır. Bu sonuçlar, epigenetik imzanın bazı hastalarda genomik verilerin hangi yönde yeniden incelenmesi gerektiğini gösteren işlevsel bir biyobelirteç olarak kullanılabileceğini desteklemektedir.

NADİR HASTALIKLARDA EPİGENETİK İMZA ÖRNEKLERİ

Hastalığa özgü DNA metilasyon imzalarının tanımlanması özellikle epigenetik ve kromatin düzenleyici genlerin etkilendiği nörogelişimsel hastalıklarda moleküler tanıya katkı sağlamıştır (Aref-Eshghi et al., 2020; Sadikovic et al., 2020). Aşağıdaki örnekler, epigenetik imzaların farklı tanısal kullanım biçimlerini göstermektedir.

Sotos sendromu çoğunlukla histon metilasyonunda görev alan NSD1 genindeki fonksiyon kaybı varyantlarıyla ilişkilidir. Choufani et al. (2015), patojenik NSD1 varyantı taşıyan bireylerde Sotos sendromuna özgü bir genom çaplı DNA metilasyon imzası tanımlamış ve bu imzanın olguları sağlıklı kontrollerden, benign NSD1 varyantı taşıyanlardan ve klinik olarak benzer Weaver sendromundan ayırabildiğini göstermiştir.

Kabuki ve CHARGE sendromları klinik olarak kısmen örtüşebilmekle birlikte farklı epigenetik düzenleyici genlerle ilişkilidir. Kabuki sendromunda KMT2D, CHARGE sendromunda ise CHD7 bozukluğu karakteristik ve birbirinden ayrılabilen DNA metilasyon imzaları oluşturabilmektedir (Butcher et al., 2017). Kabuki sendromuna ilişkin daha yeni bir çalışmada Wang et al. (2026), 110 KMT2D varyantlı birey üzerinden geliştirilen imzanın varyant tipi, gen içindeki konum ve mozaisizm düzeyi hakkında da ek bilgi sağlayabileceğini göstermiştir.

Coffin–Siris sendromu ve ilişkili BAFopatilerde, kromatin yeniden düzenleme kompleksinin bileşenlerini kodlayan ARID1B, SMARCB1 ve SMARCA4 gibi genlerle ilişkili karakteristik DNA metilasyon profilleri tanımlanmıştır. Bu profillerin Nicolaides–Baraitser sendromuyla kısmen örtüşmesi, epigenetik imzaların ortak moleküler mekanizmaları da yansıtabildiğini göstermektedir (Aref-Eshghi et al., 2018).

TET3 ilişkili Beck–Fahrner sendromu ise mekanistik açıdan dikkat çekici bir örnektir. DNA demetilasyonunda görev alan TET3 fonksiyonunun bozulması, periferik kanda ağırlıklı olarak hipermetilasyonla karakterize genom çaplı bir imza oluşturur; bu profil patojenik varyantların ve VUS'ların değerlendirilmesine katkı sağlayabilir (Levy et al., 2021).

EPİGENETİK İMZA ANALİZİ VE KLİNİK YORUMLAMA

Epigenetik imza analizleri çoğunlukla periferik kandan izole edilen genomik DNA ile gerçekleştirilir. Genom çaplı DNA metilasyon profili yaygın olarak Illumina Infinium metilasyon mikrodizin platformlarıyla elde edilir; kalite kontrol ve normalizasyonun ardından hastanın metilasyon örüntüsü sağlıklı kontroller ve moleküler olarak doğrulanmış hastalık kohortlarından oluşturulan referans profillerle karşılaştırılır. Hastalığa özgü CpG bölgelerinin birlikte değerlendirilmesinde kümeleme yöntemleri ve destek vektör makinesi gibi sınıflandırma algoritmalarından yararlanılabilir (Kerkhof et al., 2024; Sadikovic et al., 2021).

Analiz sonucunda hastanın metilasyon profilinin bilinen bir hastalık imzasıyla uyumlu olup olmadığı değerlendirilir. Sonuçlar pozitif, negatif veya bazı durumlarda belirsiz olarak raporlanabilir ve klinik fenotip ile mevcut genetik bulgularla birlikte yorumlanmalıdır (Kerkhof et al., 2024).

SINIRLILIKLAR, GELECEK PERSPEKTİFİ VE SONUÇ

Epigenetik imza analizleri nadir hastalıkların moleküler tanısında önemli bir tamamlayıcı yaklaşım olmakla birlikte bazı sınırlılıklara sahiptir. Mevcut imzaların büyük bölümü periferik kan DNA'sı kullanılarak geliştirilmiştir; DNA metilasyonunun doku ve hücre tipine özgü olması, bazı hastalıklardaki moleküler değişikliklerin kanda yeterince yansımamasına neden olabilir. Yaş, kan hücre kompozisyonu, teknik farklılıklar ve düşük düzeyli mozaisizm de metilasyon sinyalini etkileyebilir. Ayrıca her nadir hastalık için yeterli sayıda doğrulanmış olgu ve güvenilir referans imzası bulunmamaktadır. Bu nedenle

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negatif bir sonuç şüphelenilen hastalığı kesin olarak dışlamaz (Husson et al., 2024; Kerkhof et al., 2024; Tan et al., 2025).

Daha geniş ve bağımsız hasta kohortlarının oluşturulması, referans veri setlerinin genişletilmesi ve analiz yöntemlerinin standardizasyonu epigenetik imza testlerinin klinik kullanımını güçlendirebilir. Genomik ve epigenomik verilerin diğer fonksiyonel omik yaklaşımlarla birlikte değerlendirilmesi, özellikle klasik dizileme yöntemleriyle tanı konulamayan olgularda moleküler mekanizmaların daha bütüncül biçimde ortaya konmasına olanak sağlayabilir. Uzun-okuma dizileme teknolojileri de yapısal varyantlar, tekrar genişlemeleri ve DNA metilasyon bilgisinin aynı tanısal çerçevede değerlendirilmesi açısından önemli bir gelişme alanıdır (Kernohan & Boycott, 2024; Tan et al., 2025).

Sonuç olarak epivaryantlar ve hastalığa özgü epigenetik imzalar, DNA dizisinin ötesinde hastalığın fonksiyonel moleküler sonuçları hakkında bilgi sağlayan biyobelirteçlerdir. DNA metilasyon analizi; klinik olarak benzer sendromların ayrılması, VUS'ların değerlendirilmesi ve genomik incelemeler sonrasında tanısız kalan olguların yeniden araştırılmasında tamamlayıcı bir yaklaşım sunmaktadır. Genomik ve epigenomik verilerin birlikte değerlendirilmesi, nadir hastalıkların moleküler tanısında giderek daha önemli bir yer kazanacaktır.

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EVALUATION OF THE ASSOCIATION OF THE hTERT rs10069690 VARIANT WITH DISEASE RISK AND CLINICAL PARAMETERS IN METABOLIC SYNDROME

METABOLİK SENDROMDA hTERT rs10069690 VARYANTININ HASTALIK RİSKİ VE KLİNİK PARAMETRELERLE İLİŞKİSİNİN DEĞERLENDİRİLMESİ

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ABSTRACT

Metabolic syndrome (MetS) is characterized by obesity, insulin resistance, dyslipidemia, hypertension, and impaired glucose metabolism. The human telomerase reverse transcriptase (*hTERT*) gene plays a role in maintaining telomere integrity and may contribute to metabolic aging and susceptibility to MetS. This study aimed to evaluate the association of the *hTERT* rs10069690 variant with MetS by comparing patients and healthy controls and to investigate its possible relationship with clinical parameters in patients with MetS. A total of 223 patients diagnosed with MetS and 160 healthy controls were included in the study. Genomic DNA was isolated from peripheral blood, and the *hTERT* rs10069690 variant was analyzed using the TaqMan SNP genotyping method. Genotype and allele distributions were compared between the patient and control groups. Disease risk was evaluated under codominant, dominant, recessive, overdominant, and allelic models using odds ratios and 95% confidence intervals. In the patient group, clinical and laboratory parameters were compared between the CC and CT+TT genotype groups according to the dominant model. The CT genotype was more frequent in the MetS group than the CC genotype and was associated with an increased disease risk (OR=2.90; 95% CI: 1.39–6.01; p=0.0039). In the dominant model, the CT+TT genotypes were associated with an increased risk of MetS compared with the CC genotype (OR=2.95; 95% CI: 1.42–6.13; p=0.0036). A significant association was also observed under the overdominant model (OR=2.17; 95% CI: 1.11–4.26; p=0.0259). In contrast, no significant associations were found under the recessive or allelic models. In the dominant model analysis within the patient group, individuals with the CC genotype had a higher body mass index than those with the CT+TT genotypes [39.06 (34.40–44.00) vs. 31.14 (28.29–34.92) kg/m²; p=0.023]. Similarly, fasting insulin levels were higher in the CC group [22.05 (16.52–26.48) vs. 11.80 (9.08–20.30); p=0.024]. No significant differences were observed between the groups in terms of age, sex, fasting plasma glucose, HbA1c, liver enzymes, lipid parameters, or the frequency of hypertension. Our findings suggest that the *hTERT* rs10069690 variant may be associated with susceptibility to MetS, particularly under codominant, dominant, and overdominant models. In addition, the association of the CC genotype with higher body mass index and fasting insulin levels suggests that this variant may also influence metabolic characteristics.

Keywords: Metabolic syndrome, *hTERT*, rs10069690, telomerase, genetic variant, DNA

ÖZET

Metabolik sendrom (MetS), obezite, insülin direnci, dislipidemi, hipertansiyon ve bozulmuş glukoz metabolizması ile karakterizedir. İnsan telomeraz ters transkriptaz (*hTERT*) geni telomer bütünlüğünün

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korunmasında rol oynar ve metabolik yaşlanma ile MetS yatkınlığına katkıda bulunabilir. Bu çalışmada, *hTERT* rs10069690 varyantının MetS ile ilişkisinin hasta ve sağlıklı kontrol grupları arasında değerlendirilmesi ve MetS hastalarındaki klinik parametrelerle olası ilişkisinin araştırılması amaçlandı. Araştırmaya MetS tanısı almış 223 hasta ile 160 sağlıklı kontrol dahil edildi. Genomik DNA periferik kandan izole edildi ve *hTERT* rs10069690 varyantı TaqMan SNP genotipleme yöntemiyle analiz edildi. Genotip ve allel dağılımları hasta ve kontrol grupları arasında karşılaştırıldı. Hastalık riski kodominant, dominant, resesif, over-dominant ve allelik modeller altında odds oranı ve %95 güven aralığı kullanılarak değerlendirildi. Hasta grubunda klinik ve laboratuvar parametreleri dominant modele göre CC ve CT+TT genotip grupları arasında karşılaştırıldı. CT genotipi, CC genotipine kıyasla metabolik sendrom grubunda daha sık görüldü ve hastalık riskiyle ilişkili bulundu (OR=2,90; %95 GA: 1,39–6,01; p=0,0039). Dominant modelde CT+TT genotipleri, CC genotipine göre metabolik sendrom riskinde artışla ilişkiliydi (OR=2,95; %95 GA: 1,42–6,13; p=0,0036). Over-dominant modelde de anlamlı ilişki saptandı (OR=2,17; %95 GA: 1,11–4,26; p=0,0259). Buna karşılık resesif ve allelik modellerde anlamlı ilişki bulunmadı. Hasta grubundaki dominant model analizinde, CC genotipine sahip bireylerde beden kitle indeksi CT+TT genotip grubuna göre daha yüksek bulundu [39,06 (34,40–44,00) ve 31,14 (28,29–34,92) kg/m²; p=0,023]. Benzer şekilde açlık insülin düzeyi de CC grubunda daha yüksekti [22,05 (16,52–26,48) ve 11,80 (9,08–20,30); p=0,024]. Yaş, cinsiyet, açlık plazma glukozu, HbA1c, karaciğer enzimleri, lipid parametreleri ve hipertansiyon sıklığı açısından gruplar arasında anlamlı fark saptanmadı.Bulgularımız, *hTERT* rs10069690 varyantının özellikle kodominant, dominant ve over-dominant modeller altında MetS yatkınlığıyla ilişkili olabileceğini göstermektedir. Ayrıca CC genotipinin daha yüksek beden kitle indeksi ve açlık insülin düzeyleriyle ilişkili olması, bu varyantın metabolik özellikler üzerinde de etkili olabileceğini düşündürmektedir.

Anahtar Kelimeler: Metabolik sendrom, *hTERT*, rs10069690, telomeraz, genetik varyant, DNA.

GİRİŞ

Metabolik sendrom (MetS), abdominal obezite, dislipidemi, yüksek kan basıncı ve glukoz metabolizmasındaki bozuklukların aynı bireyde kümelenmesiyle karakterize kompleks bir klinik tablodur. Güncel ortak tanımlamada abdominal obezite, yüksek trigliserid, düşük HDL-kolesterol, yüksek kan basıncı ve yüksek açlık glukozundan oluşan beş bileşenden en az üçünün bulunması MetS tanısı için yeterli kabul edilmekte; abdominal obezite zorunlu bir kriter olarak değerlendirilmemektedir (Alberti et al., 2009). MetS, tip 2 diyabet ve kardiyovasküler hastalık gelişimi açısından önemli bir risk göstergesidir.

MetS patofizyolojisinde visseral adipoz doku disfonksiyonu ve insülin direnci temel mekanizmalar arasında yer almaktadır. Adipoz doku genişlemesine eşlik eden serbest yağ asidi akışındaki artış, karaciğer ve iskelet kasında insülin sinyalinin bozulmasına ve ektopik lipid birikimine katkıda bulunabilir. Bunun yanı sıra adipokin dengesizliği, kronik düşük dereceli inflamasyon, oksidatif stres ve endotel disfonksiyonu MetS'nin metabolik ve kardiyovasküler bileşenlerinin gelişiminde rol oynamaktadır (Fahed et al., 2022; Rochlani et al., 2017). Bu nedenle MetS, tek tek risk faktörlerinin birlikteliğinden çok, birbirleriyle etkileşen metabolik ve inflamatuvar süreçlerin oluşturduğu kompleks bir bozukluk olarak değerlendirilmektedir (Fahed et al., 2022).

Telomerler, kromozom uçlarında bulunan ve genomik bütünlüğün korunmasına katkı sağlayan tekrarlayan DNA-protein yapılarıdır. Somatik hücrelerde hücre bölünmeleriyle birlikte telomerlerin giderek kısalması ve kritik telomer kaybının hücresel senesens veya apoptozu tetiklemesi, telomer biyolojisini yaşlanma ve yaşlanmayla ilişkili hastalıklarla bağlantılı hale getirmiştir. Oksidatif stres ve kronik inflamasyon telomer kaybını hızlandırabilen önemli biyolojik faktörlerdir. MetS ile telomer uzunluğu arasındaki ilişkiyi değerlendiren 2024 tarihli bir meta-analizde dokuz çalışma ve 8606 katılımcı incelenmiş; ortalama telomer uzunluğu açısından gruplar arasında belirgin fark gösterilememesine karşın, düzeltilmiş analizlerin birleştirilmesinde MetS ile telomer uzunluğu arasında zayıf ancak negatif bir ilişki bildirilmiştir. Bu bulgular ilişkinin var olabileceğini, ancak literatürün halen heterojen olduğunu göstermektedir (Al-Hawary et al., 2024).

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Telomeraz enziminin katalitik alt birimini kodlayan telomeraz ters transkriptaz (telomerase reverse transcriptase, *TERT*) geni kromozom 5p15.33 bölgesinde yer almaktadır. TERT, telomeraz RNA bileşeni TERC ile kromozom uçlarına yeni telomerik tekrarların eklenmesini sağlar. Bununla birlikte TERT'nin işlevleri telomer uzamasıyla sınırlı değildir. Mitokondriyal fonksiyonun korunması, oksidatif stres yanıtı, redoks dengesi, hücre sağkalımı ve çeşitli metabolik sinyal yolları ile ilişkili telomerden bağımsız işlevleri de tanımlanmıştır (Marinaccio et al., 2023).

Bu çalışmada incelenen rs10069690 (C>T), *TERT* geninin intron 4 bölgesinde bulunan fonksiyonel bir varyanttır. Killedar et al. (2015), rs10069690'ın minör allelinin intron 4 içinde yeni bir alternatif splice donor bölgesi oluşturarak INS1b adı verilen alternatif bir *TERT* transkriptinin ortaya çıkmasına yol açabildiğini göstermiştir. INS1b tam fonksiyonlu ters transkriptaz domenini içermez ve telomeraz aktivitesini azaltabilecek dominant-negatif özellik gösterebilir. Daha yakın tarihli fonksiyonel veriler de rs10069690-T allelinin intron 4 retansiyonu, alternatif splicing ve nonsense-mediated decay üzerinden toplam TERT ekspresyonunu ve fonksiyonel tam uzunluktaki TERT transkriptlerinin oranını etkileyebileceğini desteklemektedir (Florez-Vargas et al., 2025).

TERT genetik varyasyonları tip 2 diyabet ve diğer metabolik fenotiplerle ilişkilendirilmiş olmakla birlikte, rs10069690'ın MetS yatkınlığı ile doğrudan ilişkisine yönelik veriler oldukça sınırlıdır. Bu nedenle bu çalışmada *hTERT* rs10069690 varyantının MetS gelişme riski ile ilişkisinin değerlendirilmesi ve MetS hastalarında bu varyantın klinik ve metabolik parametrelerle olası bağlantısının araştırılması amaçlandı. Bu kapsamda genotip ve allel dağılımları MetS ve sağlıklı kontrol grupları arasında karşılaştırıldı; ayrıca MetS grubunda rs10069690 genotipleri ile klinik ve laboratuvar parametreleri arasındaki ilişkiler değerlendirildi.

GEREÇ VE YÖNTEM

Çalışma grubu

Çalışmaya, 1 Ağustos 2022–20 Mayıs 2023 tarihleri arasında İstanbul Üniversitesi İstanbul Tıp Fakültesi İç Hastalıkları Polikliniği'ne başvuran metabolik sendrom (MetS) tanılı 223 hasta ve 160 sağlıklı kontrol dahil edildi.

Metabolik sendrom tanısı, National Cholesterol Education Program Adult Treatment Panel III (NCEP ATP III) kriterlerine göre konuldu. Buna göre aşağıdaki beş bileşenden en az üçünün bulunması MetS olarak kabul edildi: artmış bel çevresi (erkeklerde ≥102 cm, kadınlarda ≥88 cm), yüksek trigliserid düzeyi (≥150 mg/dL veya hipertrigliseridemi nedeniyle tedavi kullanımı), düşük yüksek yoğunluklu lipoprotein kolesterol (HDL-C) düzeyi (erkeklerde <40 mg/dL, kadınlarda <50 mg/dL veya lipid düşürücü tedavi kullanımı), yüksek kan basıncı (sistolik kan basıncı ≥130 mmHg ve/veya diyastolik kan basıncı ≥85 mmHg veya antihipertansif tedavi kullanımı) ve yüksek açlık plazma glukozu (≥100 mg/dL veya glukoz düşürücü tedavi kullanımı).

Kardiyovasküler hastalık, endokrin hastalık, kronik karaciğer veya böbrek hastalığı, malignite, gebelik ya da başka bir kronik sistemik hastalık öyküsü bulunan bireyler çalışma dışı bırakıldı. Kontrol grubu; MetS veya bilinen herhangi bir kronik hastalığı bulunmayan, bel çevresi, trigliserid, açlık plazma glukozu, kan basıncı ve lipid profili değerleri normal sınırlarda olan bireylerden oluşturuldu.

Örneklerin alınması ve DNA izolasyonu

Tüm katılımcılardan gece boyu açlığın ardından periferik venöz kan örnekleri alındı. Kan örnekleri EDTA içeren tüplere alındı ve DNA izolasyonuna kadar uygun koşullarda saklandı. Genomik DNA, üreticinin talimatları doğrultusunda Blood/Cell/Tissue Genomic DNA Extraction Kit (ELK Biotechnology, Cat. No: EP007) kullanılarak izole edildi. Elde edilen DNA örneklerinin konsantrasyon ve saflıkları spektrofotometrik olarak değerlendirildi ve gerekli kalite kriterlerini karşılayan örnekler genotipleme analizine dahil edildi.

hTERT rs10069690 genotiplemesi

hTERT rs10069690 varyantının genotiplemesi TaqMan SNP genotipleme yöntemi kullanılarak gerçekleştirildi. Genomik DNA örneklerinde rs10069690 varyantına ait genotipler allel-spesifik

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floresan problara dayalı TaqMan yöntemiyle belirlendi. Elde edilen genotip sonuçlarına göre bireyler CC, CT ve TT genotipleri şeklinde sınıflandırıldı.

MetS ve kontrol grupları arasında genotip ve allel dağılımları karşılaştırıldı. rs10069690 varyantının MetS riskiyle ilişkisi kodominant, dominant, resesif, over-dominant ve allelik genetik modeller altında değerlendirildi. Hastalık riski odds oranı (OR) ve %95 güven aralığı (GA) ile ifade edildi. Ayrıca MetS grubunda klinik ve laboratuvar parametreleri dominant genetik modele göre CC ve CT+TT grupları arasında karşılaştırıldı.

BULGULAR

Hasta grubunda rs10069690 genotip dağılımı CC=12, CT=207 ve TT=4, kontrol grubunda ise CC=23, CT=137 ve TT=0 olarak saptandı. Kodominant modelde CT genotipi, CC genotipine kıyasla MetS grubunda daha sık bulundu ve yaklaşık 2,9 kat artmış hastalık riski ile ilişkiliydi (OR=2,90; %95 GA: 1,39–6,01; p=0,0039). Dominant modelde CT+TT genotipleri de CC genotipine göre artmış MetS riski gösterdi (OR=2,95; %95 GA: 1,42–6,13; p=0,0036). Over-dominant modelde CT genotipi ile MetS arasında anlamlı ilişki saptandı (OR=2,17; %95 GA: 1,11–4,26; p=0,0259). Buna karşılık resesif ve allelik modellerde anlamlı ilişki bulunmadı. *hTERT* rs10069690 varyantının farklı genetik modeller altında MetS ile ilişkisine ait bulgular Tablo 1'de gösterilmiştir.

Tablo 1. *hTERT* rs10069690 varyantının farklı genetik modeller altında metabolik sendrom ile ilişkisi

Genetik model	MetS, n	Kontrol, n	OR	95% GA	p
Kodominant model (CT vs CC)	207/12	137/23	2.90	1.39–6.01	**0.0039**
Kodominant model (TT vs CC)	4/12	0/23	16.92	0.84–340.28	**0.0221**
Dominant model (CT+TT vs CC)	211/12	137/23	2.95	1.42–6.13	**0.0036**
Resesif model (TT vs CC+CT)	4/219	0/160	6.58	0.35–123.11	0.1434
Overdominant model (CT vs CC+TT)	207/16	137/23	2.17	1.11–4.26	**0.0259**
Allelik model (T vs C)	215/231	137/183	1.24	0.93–1.66	0.1424

MetS grubunda dominant modele göre yapılan değerlendirmede, CC genotipine sahip bireylerin beden kitle indeksi CT+TT grubuna göre daha yüksekti [39,06 (34,40–44,00) ve 31,14 (28,29–34,92) kg/m²; p=0,023]. Benzer şekilde açlık insülin düzeyi CC grubunda daha yüksek bulundu [22,05 (16,52–26,48) ve 11,80 (9,08–20,30); p=0,024]. Yaş, cinsiyet, açlık plazma glukozu, HbA1c, AST, ALT, total kolesterol, LDL-C, HDL-C, trigliserid düzeyleri ve hipertansiyon sıklığı açısından gruplar arasında anlamlı fark saptanmadı. MetS hasta grubunda dominant genetik modele göre CC ve CT+TT genotip gruplarının klinik ve laboratuvar özellikleri Tablo 2'de karşılaştırılmıştır

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Tablo 2. MetS hasta grubunda *hTERT* rs10069690 dominant modeline göre klinik ve laboratuvar parametrelerinin karşılaştırılması

Değişken	CC (n=12)	CT+TT (n=211)	p değeri
Yaş (yıl)	55,50 (52,50–57,25)	59,00 (50,00–66,00)	0,241
Erkek cinsiyet, n (%)	4 (33,3)	77 (36,5)	1,000
Beden kitle indeksi (kg/m²)	39,06 (34,40–44,00)	31,14 (28,29–34,92)	**0,023**
Açlık plazma glukozu (mg/dL)	122,00 (109,50–142,00)	128,00 (109,00–167,00)	0,734
HbA1c (%)	6,50 (5,43–8,15)	6,90 (6,20–8,17)	0,307
Açlık insülini	22,05 (16,52–26,48)	11,80 (9,08–20,30)	**0,024**
AST (U/L)	21,00 (17,80–27,50)	16,30 (14,00–21,85)	0,068
ALT (U/L)	19,00 (13,50–40,50)	18,10 (14,00–24,75)	0,660
Total kolesterol (mg/dL)	208,00 (164,50–227,00)	199,50 (169,25–231,75)	0,905
LDL-C (mg/dL)	127,00 (106,00–158,25)	124,50 (96,00–156,00)	0,841
HDL-C (mg/dL)	42,00 (40,00–50,50)	43,00 (37,00–51,00)	0,488
Trigliserid (mg/dL)	155,50 (113,50–231,00)	172,00 (126,00–222,20)	0,800
Hipertansiyon, n (%)	8 (72,7)	159 (82,4)	0,423

TARTIŞMA

Bu çalışmanın temel bulgusu, *hTERT* rs10069690 varyantının MetS yatkınlığı ile ilişkili olabileceğinin gösterilmesidir. CT genotipi CC genotipine kıyasla MetS grubunda daha sık bulunmuş ve artmış hastalık riski ile ilişkili saptanmıştır. Benzer ilişki dominant ve over-dominant modellerde de gözlenirken, resesif ve allelik modellerde anlamlı sonuç elde edilmemiştir. Bununla birlikte özellikle TT genotipinin çok düşük sayıda olması, model-spesifik sonuçların dikkatli yorumlanmasını gerektirmektedir.

TERT genetik varyasyonlarının metabolik hastalıklarla ilişkisini değerlendiren çalışmalar sınırlıdır. Montesanto et al. (2018), 503 tip 2 diyabet hastası ve 580 sağlıklı kontrolü değerlendirdikleri çalışmalarında *TERT* rs2735940 ve rs2736098 varyantlarının tip 2 diyabet riskiyle ilişkili olduğunu bildirmiştir. rs2735940-C alleli artmış tip 2 diyabet riskiyle ilişkiliyken, rs2736098-A alleli koruyucu yönde ilişki göstermiştir. Bu çalışmada söz konusu *TERT* varyantları ile telomer uzunluğu arasında ilişki gösterilememiş olması, TERT'nin metabolik hastalıklar üzerindeki etkilerinin yalnızca telomer uzunluğu üzerinden açıklanamayabileceğini düşündürmüştür (Montesanto et al., 2018).

Buna karşılık Gutmajster et al. (2018), obez yaşlı bireylerde *TERT* promoter bölgesindeki rs2735940, rs7712562 ve rs2853669 varyantlarını değerlendirmiş ve bu varyantlarla tip 2 diyabet riski arasında güçlü ve tutarlı bir ilişki gösterememiştir. Bununla birlikte rs2853669 genotipi ile telomer uzunluğu arasında genotipe bağlı farklılıklar gözlenmiştir. Bu sonuçlar, *TERT* varyasyonlarının farklı popülasyonlarda hastalık riski ve metabolik fenotip üzerinde farklı etkiler gösterebileceğini düşündürmektedir.

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rs10069690 açısından çalışmamızın biyolojik olarak dikkat çekici yönü, bu varyantın yalnızca genomik bir belirteç olmayıp *TERT* transkript oluşumunu etkileyebilen fonksiyonel özellik taşımasıdır. Killedar et al. (2015), rs10069690 minör allelinin intron 4'te alternatif splice donor bölgesi oluşturarak INS1b transkriptinin üretimine yol açtığını ve bu izoformun telomeraz aktivitesini azaltabileceğini göstermiştir. Florez-Vargas et al. (2025) ise rs10069690-T allelinin intron 4 retansiyonu ile güçlü biçimde ilişkili olduğunu ve alternatif splicing/nonsense-mediated decay mekanizmaları üzerinden toplam *TERT* ekspresyonunu ve fonksiyonel TERT-FL izoformunun oranını değiştirebildiğini göstermiştir.

MetS'de artmış oksidatif stres, kronik inflamasyon ve hücresel senesens göz önünde bulundurulduğunda, TERT ekspresyonundaki genetik olarak belirlenen farklılıkların metabolik stres karşısındaki hücresel yanıtı etkileyebileceği düşünülebilir. TERT'nin antioksidan yanıt ve mitokondriyal fonksiyonla ilişkili telomer-dışı işlevlerinin gösterilmiş olması bu görüş için biyolojik bir temel sağlamaktadır (Marinaccio et al., 2023). Bununla birlikte rs10069690'ın bu mekanizmalar üzerinden doğrudan metabolik sendroma yol açtığı gösterilmiş değildir; dolayısıyla bu açıklama mevcut sonuçlarımız için olası bir mekanizma olarak değerlendirilmelidir.

MetS grubundaki genotip–fenotip analizinde CC genotipine sahip bireylerde BMI ve açlık insülin düzeylerinin CT+TT grubuna kıyasla daha yüksek bulunması dikkat çekicidir. Bu bulgu, T alleli taşıyan genotiplerin hastalık riskiyle ilişkili olmasıyla ilk bakışta farklı yönde görünmektedir. Bununla birlikte hastalık yatkınlığının değerlendirilmesi ile hastalık geliştikten sonraki metabolik özelliklerin incelenmesi farklı biyolojik soruları temsil etmektedir. Bir varyantın hastalık gelişme olasılığı üzerindeki etkisi ile hastalar arasındaki fenotipik şiddet üzerindeki etkisinin aynı yönde olması zorunlu değildir. Bununla birlikte CC grubunda yalnızca 12 birey bulunması, BMI ve insülin sonuçlarının keşifsel olarak değerlendirilmesini gerektiren önemli bir sınırlılıktır.

TERT'nin metabolik süreçlerdeki olası rolünü destekleyen deneysel veriler de bulunmaktadır. Braud ve ark. (2025), yüksek yağlı diyetle obezite oluşturulan farelerde koşullu TERT ekspresyonunun insülin direnci ve glukoz intoleransını azalttığını; adipoz dokuda hücresel senesens, kritik telomer kısalması ve oksidatif DNA hasarını hafiflettiğini göstermiştir. Aynı çalışmada adipoz kök/progenitör hücrelerde mitokondriyal fonksiyonun ve farklılaşma kapasitesinin iyileştiği bildirilmiştir. Bu bulgular TERT'nin obeziteyle ilişkili metabolik bozukluklarla bağlantısının telomer bakımının yanı sıra hücresel senesens, oksidatif stres ve mitokondriyal fonksiyon üzerinden de şekillenebileceğini desteklemektedir.

SONUÇ

Bulgularımız, *hTERT* rs10069690 varyantının MetS yatkınlığı ile ilişkili olabileceğini ve bu ilişkinin özellikle kodominant, dominant ve over-dominant genetik modellerde belirginleştiğini göstermektedir. MetS grubunda CC genotipinin daha yüksek BMI ve açlık insülin düzeyleriyle ilişkili bulunması, rs10069690'ın hastalık yatkınlığının yanı sıra metabolik fenotipin bazı özellikleriyle de bağlantılı olabileceğini düşündürmektedir. Bununla birlikte sınırlı genotip alt grup büyüklükleri nedeniyle sonuçların temkinli yorumlanması ve daha geniş bağımsız kohortlarda telomer uzunluğu, telomeraz aktivitesi ve TERT ekspresyonu gibi fonksiyonel göstergelerle doğrulanması gerekmektedir.

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THE ANXIETY OF THE ANTHROPOCENE AND THE END OF THE NOVEL

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ABSTRACT

The traditional realist novel, predicated on the deep excavation of individual bourgeois interiority and the orderly unfolding of linear plot, has long been indicted by ecocritics as constitutively inadequate to the representational demands of the Anthropocene. Positioning itself on Timothy Morton's concept of the 'hyperobject' alongside Jane Bennett's theory of 'vibrant materialism', this paper interrogates the growing critical consensus that the novel must radically decentre the human subject or risk obsolescence in an era of ecological catastrophe. The paper argues that this demand, while politically urgent, rests upon a reductive account of the formal capacities of the novel. To cede the novel entirely to the nonhuman turn and to treat it as incapable of registering anything beyond anthropocentric enclosure is to overlook how novelistic interiority has always been entangled with nonhuman forces. Reading Virginia Woolf's *The Waves* against contemporary Anthropocene fiction, such as Richard Powers's *The Overstory*, this paper traces formal experimentation, in which the delineation of human consciousness becomes, paradoxically, a portal rather than a barrier to the nonhuman. When Percival's death sends undulations through the intertwined soliloquies of Woolf's novel, or when Powers's human characters recede into the arboreal timescale of old-growth forests, the novel does not abandon interiority. On the contrary, it stretches it beyond recognition, transforming the self into a sensorium for planetary distress. This paper refuses the defective choice between bourgeois realism and posthuman abstraction, arguing instead that the most ecologically potent gesture of the novel lies in the radical reimagining of what dispersed and porous human attention might register. The way forward is not the end of the novel. It is the replenishment of its formal vocabularies, which enables a narrative art that holds the human and the nonhuman in productive and perturbing tension.

Keywords: Anthropocene Fiction, Ecocriticism, Nonhuman Turn, Object-Oriented Ontology, Scalar Aesthetics.

INTRODUCTION

The declaration of the Anthropocene as a geological epoch defined by the planetary-scale impact of humanity has triggered an intellectual crisis across the humanities that has found particularly acute expression in literary studies. The novel, as the preeminent literary form of modernity, has become the locus of anxiety, with critics increasingly questioning, whether this quintessentially anthropocentric genre can survive, or indeed deserves to survive, the ecological unravelling of the twenty-first century. The charge against the novel is many-sided, since it is accused of perpetuating the very modes of thought that have enabled environmental devastation, comprising the elevation of individual human consciousness above all other forms of existence, the reduction of the nonhuman world to mere setting or metaphor, as well as the imposition of linear narratives, which obscure the complex temporalities of ecological systems. As Ursula K. Heise observes in *Sense of Place and Sense of Planet* (2008), "the novel as a form has been so intimately tied to the articulation of individual identity and bourgeois subjectivity that it seems almost impossible to imagine it as a vehicle for the collective, multiscalar, and nonhuman perspectives that ecocriticism has called for" (p. 56) - this assessment, while widely shared, may be premature in its dismissal of the capacity of the novel for formal reinvention.

The anxiety surrounding the fate of the novel in the Anthropocene is symptomatic of a broader crisis in representational aesthetics, for if, as Timothy Morton argues in *Hyperobjects: Philosophy and Ecology after the End of the World* (2013), the defining phenomena of our era, be it climate change, nuclear

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radiation, or plastic pollution, are hyperobjects that are "massively distributed in time and space relative to humans" (p. 1), then the conventional apparatus of narrative representation appears woefully inadequate. How can a form, which is predicated on the boundedness of individual experience and the sequential unfolding of events, capture phenomena that exceed human perceptual capacities and temporal frames? This question has spawned a critical discourse that alternates between apocalyptic pronouncements of the obsolescence of the novel and utopian celebrations of posthuman narrative forms. However, what both positions share is a tendency to misrecognize the formal resources of the novel, conflating the specific conventions of nineteenth-century bourgeois realism with the novel as such. This paper intervenes in this debate by arguing that the most ecologically potent resource of the novel supersedes the abandonment of human interiority and stretches that interiority beyond recognition by transforming individual consciousness into a sensorium for planetary distress.

The critical standoff that this paper addresses is, perhaps, best exemplified by the work of scholars, who have called for a break with novelistic traditions. As Timothy Clark contends in *Ecocriticism on the Edge: The Anthropocene as a Threshold Concept* (2015), "character, person, and narrative consciousness, all of which [critics] cite as the said basic foci of fictional writing, may not be adequate means of dealing with the larger-than-individual process of evolution, or the vastness of the biotic community" (p. 138). This position, while grounded in a legitimate concern for the adequacy of representational forms, risks reducing the novel to its most conservative manifestations, overlooking the rich tradition of formal experimentation, in which the representation of consciousness serves to dissolve the boundaries between the self and the world. The fiction of Virginia Woolf, particularly *The Waves*, offers an important counterexample to the claim that novelistic interiority is inherently inimical to ecological awareness, as in Woolf's hands, the stream of consciousness becomes a technique for registering the nonhuman forces that impinge upon and constitute human subjectivity, thus anticipating the very modes of attention that contemporary ecocritics have called for.

This paper proceeds through a comparative analysis of two novels that, though separated by nearly a century, share a commitment to stretching the formal resources of fiction ahead of the conventions of bourgeois realism. Virginia Woolf's *The Waves* (1931) serves as an unlikely precursor to the concerns of Anthropocene fiction, demonstrating how the depiction of interiority can function as a portal rather than a barrier to the nonhuman. Richard Powers's *The Overstory* (2018), as a defining work of contemporary Anthropocene fiction, expands this tradition, while developing new formal strategies for registering ecological scales and temporalities. By reading these novels together, this paper tracks a genealogy of formal experimentation that challenges the critical consensus that the novel must abandon interiority to engage meaningfully with ecological crisis. As a consequence, the argument proceeds in three movements: first, an examination of the critical discourse that has constructed the novel as inadequate to the representational demands of the Anthropocene; second, a reading of Woolf's *The Waves* that reveals the ecological dimensions of high modernist interiority; and third, an analysis of Powers's *The Overstory* that explores how contemporary fiction extends and transforms this tradition. The conclusion considers the implications of this analysis for the future of the novel, arguing that the survival of the genre in the Anthropocene depends not on its continued capacity for formal invention.

THE CRITICAL CONSTRUCTION OF THE INADEQUACY OF THE NOVEL

The claim that the novel is constitutively inadequate to the representational demands of the Anthropocene has been advanced with increasing resolution across the environmental humanities, drawing on a constellation of arguments that converge on the supposed anthropocentrism of the novel, its commitment to linear temporality, as well as its focus on individual experience at the expense of systemic and ecological scales. While varying in their theoretical commitments, these criticisms share a common assumption that the formal properties of the novel are inextricably linked to the ideological structures that have produced the Anthropocene. As Lawrence Buell argues in "The Future of Environmental Criticism" (2005), the novel "has been so thoroughly implicated in the project of bourgeois self-fashioning that it is difficult to imagine how it might serve as a vehicle for the kind of ecological thinking that the current crisis demands" (p. 45), echoing broader critiques of narrative form in poststructuralist and posthumanist thought, which have questioned the political and epistemological implications of narrative itself.

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The theoretical foundations of this critical position can be traced to the work of object-oriented ontologists and speculative realists, who have sought to decentre the human subject as the locus of meaning and value. Thus, Morton's concept of the 'hyperobjects' has been markedly influential in shaping the critique of novelistic form, defined as phenomena, such as climate change and radioactive fallout, which "are so massively distributed in time and space that they defeat traditional ideas about what a thing is" (p. 1). For Morton, the resistance of the hyperobject to human-scale representation demands a fundamental rethinking of aesthetic forms; hence, the novel, with its conventional commitment to human-scale experience and linear narrative, appears particularly ill-suited to this task. Similarly, Jane Bennett's theory of 'vibrant materialism', elaborated in *Vibrant Matter: A Political Ecology of Things* (2010), which posits the agency of nonhuman matter, challenges the tendency of the novel to treat the nonhuman world as passive background or symbolic resource, arguing that "the image of dead or thoroughly instrumentalized matter feeds human hubris and our earth-destroying fantasies of conquest and consumption" (p. ix). The novel, by prioritizing human consciousness and agency, is, thus, complicit in a broader cultural project of denying nonhuman agency.

This critique has been developed in various directions within ecocritical scholarship. Accordingly, Clark contends that ecological crisis involves "capitalist economics, growing population pressure, tropical deforestation, impoverishment, neo-colonialism, alongside such material factors such as levels of methane from thawing tundra in Siberia, rates of soil degradation in Africa, the varying reflectivity of clouds, as well as environmentally dubious cultural norms, such as those of patriarchy, and anthropocentric fantasies of control and sovereignty" (2015, p. 94), emphasising that "known and unknown non-human agencies interact in badly understood ways with increasingly obtrusive human actions" (p. 94). This position highlights the formal limitations of conventional narrative techniques in addressing the systemic and scalar dimensions of ecological crisis. This formal critique has been extended by other scholars working on the Anthropocene and narrative, who have argued that the conventional novel perpetuates "the mystification of the human as a collective and geological agent" (Chakrabarty, 2009, p. 213). In this connection, Dipesh Chakrabarty's essay "The Climate of History: Four Theses" (2013) argues that the Anthropocene demands a structural rethinking of the categories, through which we understand human history and agency, since the novel, as a form that has historically been concerned with individual human destiny, appears to offer little in the way of resources for this rethinking.

However, this critical construction of the inadequacy of the novel rests upon a series of questionable assumptions. First, it tends to conflate the novel with its nineteenth-century realist iterations, oft overlooking the formal innovations of modernism and its aftermath. Second, it assumes that the representation of interiority is inherently anthropocentric, failing to recognize how literary techniques for representing consciousness can dissolve, rather than reinforce, the boundaries between the self and the world. Third, it underestimates the capacity of the novel for formal reinvention, by treating the genre as a fixed set of conventions rather than a dynamic and adaptive form. As this paper will demonstrate through its readings of Woolf and Powers, the engagement of the novel with the nonhuman has been more extensive and more nuanced than critics of its supposed inadequacy have recognized.

VIRGINIA WOOLF'S *THE WAVES* AND THE ECOLOGICAL DIMENSIONS OF MODERNIST INTERIORITY

Virginia Woolf's *The Waves* (1931) presents a challenge to the claim that novelistic interiority is inherently incompatible with ecological consciousness, as the novel, which consists of the interwoven soliloquies of six characters from childhood to old age, represents the culmination of Woolf's experiments with the representation of consciousness. Yet, *The Waves* is more than a study of individual subjectivity. It is a work that uses interiority as a means of registering the nonhuman forces that constitute and disrupt human experience. Thus, the famous interlude passages of the novel, which describe the movement of the sun across a seaside landscape, provide a nonhuman setting for the human soliloquies, establishing a temporal and spatial scale, which exceeds individual human experience. As Derek Ryan argues in *Virginia Woolf and the Materiality of Theory* (2013), the interludes transform human characters into "natural objects" (p. 181), with life perceived "in terms of quantum materiality"

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(p. 181). This subordination is crucial, since rather than treating the nonhuman as setting for human drama, Woolf makes the nonhuman the governing formal principle of the novel.

The ecological dimensions of Woolf's formal experimentation are most evident in the treatment of time and temporality. The structure of the novel, moving from dawn to night across the course of a single day, while simultaneously following its characters across a lifetime, enacts a compression of temporal scales that anticipates the concerns of Anthropocene fiction. Indeed, the interludes, with their descriptions of the arc of the sun and the changing light, establish a geological and astronomical temporality, against which the human soliloquies appear as brief and flickering moments. This scalar play, or what scholars have termed 'scalar aesthetics', is central to the ecological significance of the novel. Ursula K. Heise argues in *Sense of Place and Sense of Planet: The Environmental Imagination of the Global* (2008) that "the ability to think across scales, from the intimate to the planetary, is one of the most important cognitive resources that literature can offer in the Anthropocene" (p. 78), and Woolf's novel, in its juxtaposition of the daily course of the sun with human lifetimes, performs this scalar imagination, training readers to hold multiple temporal frames in simultaneous awareness.

The death of Percival, the absent centre, around which the characters of the novel orbit, exemplifies how Woolf uses interiority to register nonhuman forces. In fact, Percival's death in India, reported rather than depicted, sends shockwaves through the soliloquies of the surviving characters, each of whom struggles to incorporate this loss into their consciousness. At the same time, the death is also a colonial event, and an incursion of imperial violence that disrupts the European order of the novel. As the characters process their grief, their interiority becomes a site for registering forces, be they imperial, ecological, or historical, that exceed individual experience. This is particularly evident in Bernard's attempt to narrate Percival's death, which he repeatedly fails to adequately represent. Bernard's failure is significant, as it marks the limits of narrative, the point, at which the techniques of the novel for representing consciousness encounter phenomena that resist representation. This moment, in which interiority confronts its own inadequacy, is where Woolf's novel opens onto the nonhuman plane. As Sylwia Wojciechowska observes in "Polyphonic Elegiac Lament over Percival in *The Waves* by Virginia Woolf" (2024), "the thematic scope involving the death of the major character, Percival, is argued to be a major reason for prioritising the fifth section of *The Waves* as the midpoint, and indeed the central point, of the narration" (p. 74). This staging of failure is the most ecologically potent gesture of the novel, revealing the limits of human-centred representation, while simultaneously demonstrating the capacity of the novel to register what lies beyond those limits.

The engagement of the novel with matter and materiality further challenges the assumption that interiority is inherently anthropocentric. Indeed, the interludes, with their detailed descriptions of light, water, and vegetable life, participate in, what Bennett would call 'vibrant materialism', treating the nonhuman world as a field of active forces, rather than a passive setting. Yet, this vibrant materiality is not separate from the human soliloquies, it interpenetrates them, since the consciousness of the characters is constituted by their sensory engagement with the nonhuman world, with the texture of light, the rhythm of waves, the smell of gardens. As a consequence, Woolf's prose dissolves the boundaries between inner and outer, suggesting that consciousness is itself a product of the material forces that surround it. This dissolution of boundaries anticipates the comprehensions of posthumanist thought, which has challenged the Cartesian dualism, which separates the mind from the world. As Cary Wolfe argues in *What Is Posthumanism?* (2010), "the posthuman is not about abandoning the human, but about recognizing the imbrication of the human with other forms of life and matter" (p. 31), hence, Woolf's representation of consciousness, in which the self is porous and constituted by nonhuman forces, exemplifies this posthuman perception, even as it remains grounded in the techniques of high modernist interiority.

RICHARD POWERS'S *THE OVERSTORY* AND THE REPLENISHMENT OF NOVELISTIC FORM

Richard Powers's *The Overstory* (2018), distinguished as a defining work of Anthropocene fiction, represents an extension and transformation of the tradition that Woolf's novel exemplifies, weaving together the stories of nine characters, whose lives become entangled with trees. Yet, the achievement of the novel lies not in stretching the conventions of novelistic interiority to encompass nonhuman

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temporalities and perspectives, as "the human apprehension alone is too partial for the novel's narrative. Neither the temporal nor spatial scales, nor the realist approach, fit into the traditional scale of the novel. Powers goes beyond all these scales, extending and partially breaking them to situate non-human entities together with the Anthropos into an authentic narrative of the natural world" (Dahlmann, 2024, p. 4). Hence, this approach of extending rather than abandoning interiority distinguishes *The Overstory* from more radical experiments in nonhuman narration and accounts for its ability to reach a broad readership, while simultaneously challenging anthropocentric assumptions.

The most significant formal innovation of the novel is its treatment of time, as it unfolds across multiple temporal scales, from the evolutionary history of trees to the lifetimes of its human characters and the deep time of geological processes, making this scalar range central to the ecological vision of the novel. As Patricia Westerford, one of the characters of the novel and a botanist, who discovers the communicative networks of trees, reflects: "The forest was a standing wave, a great slow pulse that contained within it the future and the past, all the generations of trees that had ever been and all that would ever be" (Powers, 2018, p. 217). Westerford's perception, which emerges from her professional training and personal experience, exemplifies how Powers uses interiority to register nonhuman temporalities, with her consciousness becoming a place for the apprehension of temporal scale, which exceeds individual human experience, a sort of sensorium for the deep time of the forest, with this scalar stretching of interiority becoming the radical expansion of the human.

The structure of the novel enacts this scalar imagination at the formal level. *The Overstory* is divided into sections named after tree species, Roots, Trunk, Crown, Seeds, each of which corresponds to different temporal and narrative registers. The 'Roots' section establishes the deep history of trees and the intergenerational experiences of human characters, the 'Trunk' section follows the characters through their adult lives, while the 'Crown' explores their entanglements with each other and with the trees they seek to protect, thus emphasizing the nonhuman patterns that organize the narrative with this arboreal structure. As Timothy Clark argues in *The Value of Ecocriticism* (2019), prose narrative faces "the challenge [of representing] events and processes that exceed or escape the usual geographical and temporal limits of how we think, or feel involved" (p. 49). Powers meets this challenge through, what Clark terms, "scalar translation" (2019, p. 49), or the capacity of literary form to transpose complex ecological realities into a humanly perceptible narrative register, enacting what might be called 'scalar aesthetics', or the ability to make visible relations across different scales of experience

The character treatment in the novel also demonstrates Powers's extension of interiority into nonhuman domains, as the human characters in *The Overstory* are simultaneously psychological subjects and participants in ecological networks. Their interiority becomes a locus for the registration of nonhuman forces, including the mycorrhizal networks of fungi, the chemical signals of trees under stress, the slow growth of root systems. This is most evident in the character of Nicholas Hoel, whose family photographs of a chestnut tree encompass generations, establishing an intergenerational and interspecies continuity that exceeds individual consciousness. Hence, Hoel's interiority, as it develops through his engagement with the tree, becomes constituted by nonhuman connections. This does not diminish his humanity but rather expands it, suggesting that human subjectivity is inseparable from the ecological networks, in which it is embedded. As Powers writes, "There are no individuals. There aren't even separate species. Everything in the forest is the forest" (2018, p. 414). This stance, articulated through the interiorities of his characters, challenges the individualist assumptions of bourgeois realism, while, at the same time, remaining grounded in the techniques of psychological representation.

The preoccupation of *The Overstory* with the nonhuman is also evident in its treatment of death and extinction. Indeed, the novel repeatedly stages the encounter between human mortality and the longer rhythms of ecological and geological time, where the death of the chestnut tree, the loss of old-growth forests, the extinction of species, for instance, are registered through the consciousness of human characters, who struggle to comprehend losses that exceed personal experience. This staging of the intersection between human interiority and nonhuman loss lies at the centre of the ecological work in the novel, never abandoning the human perspective, but rather subjecting it to the pressure of nonhuman scales and forces. As Adam Trexler argues in *Anthropocene Fictions: The Novel in a Time of Climate Change* (2015), "climate change is not just a 'theme' in fiction. It remakes basic narrative operations. It

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undermines the passivity of place, elevating it to an actor that is itself shaped by world systems. It alters the interactions between characters and introduces entirely new things to fiction" (p. 233). This approach preserves the affective power of the novel, and, concurrently, expands its representational range.

CONCLUSION

The comparative analysis of Virginia Woolf's *The Waves* and Richard Powers's *The Overstory* reveals formal experimentation, which challenges the critical consensus that the novel must abandon interiority to engage meaningfully with the Anthropocene, since both novels demonstrate that the representation of consciousness can function as a portal to the nonhuman, which stretches human attention to encompass planetary scales and ecological entanglements. This understanding requires a revaluation of novelistic interiority, one that recognizes its capacity for transformation under the pressure of ecological crisis, since the most ecologically potent gesture of the novel is the radical reimagining of what dispersed and porous human attention might register. This revaluation has significant implications for critical practice, as it suggests that the critique of the inadequacy of the novel to the representational demands of the Anthropocene is based on a reduction of the genre to its most conservative manifestations. The novel is not a fixed set of conventions; it is a dynamic form that has repeatedly reinvented itself in response to historical and cultural pressures. The formal innovations of modernism, of which Woolf is a focal figure, already anticipate many of the concerns of Anthropocene fiction, since "the modernist novel's preoccupation with the representation of consciousness was not a retreat from the world but a means of registering the pressures of a world that had become increasingly difficult to represent through conventional narrative techniques" (2005, p. 195), suggesting that the capacity of the novel for ecological engagement is a continuation of its long history of formal experimentation.

At the same time, this revaluation challenges the dichotomy between bourgeois realism and posthuman abstraction that structures much of the present-day critical discourse on the Anthropocene and the novel. The choice between these terms is a false one, for the ecological work of the novel never lies in choosing between human and nonhuman perspectives; on the contrary, it lies in staging their entanglement. Both Woolf and Powers demonstrate that the most effective way to make visible the nonhuman is to subject it to the pressure of nonhuman scales and forces. This approach preserves the affective power of the novel and expands its representational range, allowing readers to experience ecological crisis with intellectual and emotional force. As Trexler argues, the distinctive contribution of the novel lies in its capacity to turn "abstract predictions into subjectively tangible experiences of place, identity, and culture" (2015, p. 2), thereby integrating the intellectual apprehension of climate science with the emotional and experiential dimensions of human life. The capability of the novel to make us feel our connections to the nonhuman world is not antithetical to its capacity to make us think about those connections. The integration of thought and feeling, together with abstraction and affect, is the distinguishing contribution of the novel to the cultural work of the Anthropocene. The novel that emerges from this process, in its turn, will not be the novel of bourgeois realism, with its deep excavation of individual interiority, and it will also not be the novel of posthuman abstraction that abandons the human altogether. In its place, it will be a form that holds the human and the nonhuman in productive tension, and a form, stretching interiority to encompass the planetary scales and ecological entanglements of the Anthropocene. The task of criticism, therefore, is to avoid pronouncing the obsolescence of the novel, and to trace, instead, its ongoing transformation, recognizing the formal innovations, which enable fiction to respond to the insistent demands of our ecological moment.

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THE DEATH OF THE AUTHOR AND THE RESURRECTION OF THE READER IN THE AGE OF PARTICIPATORY CULTURE

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ABSTRACT

In 2019, a fan-authored reinterpretation of Jane Austen's *Pride and Prejudice*, relocating the Bennet sisters to contemporary Lagos and depicting Mr. Darcy as a Nigerian tech entrepreneur, accumulated millions of reads on an online platform, far surpassing the circulation of most scholarly monographs on Austen published that same year. Such phenomena have moved fan studies from the disciplinary periphery to the centre of debates concerning textual interpretive legitimacy and the ontology of the literary work itself. This paper questions whether the proliferation of participatory culture and transmedia storytelling constitutes the long-prophesied fulfilment of Roland Barthes's 'death of the author', or whether it endorses a fundamentally different relationship between reader and text than Barthes envisioned. Based on Michel de Certeau's concept of 'textual poaching' alongside Henry Jenkins's work on 'convergence culture', the paper tracks a genealogy of readerly appropriation that complicates the celebratory narrative of liberation. Barthes's reader, born at the expense of the author, was a site of textual unity, where meaning gathered, however provisionally. The participatory reader of fanfiction, by contrast, builds worlds and timelines and sustains interpretive communities, operating according to their own evolving conventions. When S.E. Hinton's *The Outsiders* produces decades of fan-authored continuations, or when the collective 'fanon' of the Harry Potter universe coagulates around interpretations nowhere present in J.K. Rowling's original volumes, the text is absorbed into a collaborative process of meaning-making, which replaces the singular author with a networked and often contentious interpretive polity. This paper refuses to adjudicate between the competing claims of traditional literary criticism and fan studies, arguing instead that the opposition itself is symptomatic of a deeper unease about the democratization of interpretive authority. The more imperative critical task, then, is to recognize that the text has never been a site of struggle, and fanfiction makes that struggle visible, rather than inaugurating it anew.

Keywords: Fan Studies, Death of the Author, Participatory Culture, Textual Poaching, Transmedia Storytelling.

INTRODUCTION

In 1967, Roland Barthes published a short, polemical essay "The Death of the Author" that would become one of the most cited texts in twentieth-century literary theory, arguing that the meaning of a work is assembled, always provisionally, at the site of reading. The closing sentence of the essay, proclaiming that the birth of the reader must be bought at the cost of the death of the Author, has been treated for more than half a century as an establishing gesture of poststructuralist criticism, and it continues to generate scholarly disagreement about what, exactly, was being killed. As Ansgar Allen observes in "Roland Barthes and the Death of the Teacher" (2023), a recent reassessment of the afterlife of the essay in educational theory, Barthes' argument has repeatedly been read as though it authorises "the parallel question of 'The Death of the Teacher'" (p. 36), a formulation that signals how readily the central figure of the essay, the Author, has been generalised into other authority-bearing roles, those of the teacher, the critic, the editor, the platform. This generalising tendency is what makes Barthes' essay useful, and, at the same time, what makes it dangerous to resort to uncritically when describing contemporary participatory culture.

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Fan studies, a field that emerged largely outside the institutional structures of literary criticism, has been claiming Barthes as an ancestor. Thus, Katy Dillon, writing in "The Author is Dead, Long Live the Fan?" (2010), a discussion of the relationship between Barthes' announcement and reader-response theory, notes that in contemporary literary culture, "to be an author is to be another form of celebrity" (para. 1) - a reminder that the sociological conditions of authorship in the twenty-first century radically differ from those Barthes was describing in 1967. Dillon's observation is important because it identifies a tension that runs through the whole of this paper, namely that the same decades that produced participatory culture, transmedia storytelling, as well as fan fiction on an industrial scale also produced an intensified and celebrity-driven cult of the individual author, when the reader and the author have been re-negotiated in relation to one another and, often, within the same cultural text.

It is worth pausing on why this question has become newly pressing, rather than merely academic. Barthes wrote at a moment when the technologies of textual circulation, print runs, broadcast schedules, editorial gatekeeping made it comparatively easy to identify the point where a text ended and its commentary began. Yet, present-day participatory digital platforms have collapsed that distinction, so a fan-authored continuation of a novel can now accumulate a readership larger than the scholarly commentary on the same novel, it can be revised in response to reader feedback within hours, and it can itself generate further continuations, art, and commentary in a recursive structure that has no clear analogue in the print culture Barthes was describing. The question, then, is whether the sociotechnical conditions that make participatory authorship possible have outpaced the interpretive vocabulary, such as 'author', 'reader', 'text', that Barthes bequeathed to literary theory.

This paper asks whether the proliferation of fan-authored continuations, transformative works, and transmedia storytelling constitutes the long-prophesied fulfilment of Barthes' thesis, or whether it endorses a substantially different relationship between reader and text than Barthes envisioned. To answer this question, the paper builds upon Michel de Certeau's concept of 'textual poaching', as elaborated and popularised within media studies by Henry Jenkins, and situates this line of reasoning against more recent scholarship on the 'postinternet' author function, conducted within fan studies proper. The argument proceeds in three stages: first, it examines how Barthes' theory has itself been received and complicated within recent scholarship; second, it investigates how de Certeau's and Jenkins' theorisation of the 'reader-as-poacher' departs from Barthes' more abstract, textualist notion of the 'reader as a site of unity'; third, it considers what contemporary fan practice, exemplified by long-running fan continuations of established literary texts, tells us about the durability of authorial authority in a networked and participatory mediascape. The paper argues that the opposition between traditional literary criticism and fan studies is itself symptomatic of an older and more persistent restlessness about who holds legitimate interpretive authority over a text.

BARTHES' DEATH OF THE AUTHOR AND ITS SCHOLARLY AFTERLIFE

Contemporary scholarship on 'the death of the author' tends to converge on the observation that Barthes was never assaulting the empirical existence of writers; in fact, the attack was aimed at a particular, historically situated image of the Author-God, the figure whose intention functions as a single, theological meaning of the text. Jing Du, revisiting the structuralist roots of the essay in "The Death of the Author: A Difficult Demise - Rethinking Roland Barthes' "The Death of the Author" (2026), describes Barthes' intervention as amounting to "a pivotal revolution in 20th-century literary criticism" (p. 37), one that depends on a prior distinction between the 'author', who precedes and produces the work, and the 'scriptor', who exists only in and through the performative act of writing itself. This distinction matters for participatory culture, because fan authors, unlike the classical Author-God, rarely claim originary ownership over the fictional worlds they extend; the fan author enters the text after its initial 'death', making Barthes' scriptor an apt description of transformative practice, even though Barthes himself was not writing with fan fiction in mind.

At the same time, scholars working outside literary theory proper have shown that the 'death' Barthes proclaimed has produced astonishing afterlives alongside an obvious succession. Allen's analysis of the uptake of the essay in education is illustrative here, because it demonstrates a recurring pattern in the reception of the essay, when each new domain that adopts Barthes' vocabulary discovers that the abolished authority never disappears, but is displaced onto some other organising figure. Allen argues

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that this displacement has consequences "not all happy as regards the integrity and value" (2023, p. 36) of the domain being reorganised, which is worth extending to the enthusiastic adoption of the 'death of the author' by fan studies as a legitimating slogan. If the classical Author dies only to be replaced by the platform, the algorithm, or the most-followed fan-creator within a given fandom, then Barthes' thesis has not so much been fulfilled as it has been reassigned.

Hannah Dahlberg-Dodd's study of authorship in 'postinternet' fan communities in "The Author in the Postinternet Age: Fan Works, Authorial Function, and the Archive" (2019) offers an empirical investigation of this question. Working from a Foucauldian account of the author function, rather than a strictly Barthesian one, Dahlberg-Dodd argues that fifty years after Barthes, "it remains difficult to frame the nature of the interaction between commercial […] and fan […] authors" (para. 1.1), and that in both Euro-American and Japanese fan traditions, the author persists as a heuristic device, a search term, as well as an organising label that allows fans to manage an otherwise unbounded archive of derivative material. This finding complicates any simple narrative of liberation, for the author has not been killed so much as functionally repurposed, surviving as metadata even in instances where authorial intention has ceased to govern interpretation.

TEXTUAL POACHING, PARTICIPATORY CULTURE AND THE READER AS PRODUCER

If Barthes' reader was, in his own words, the location, in which multiple writings of the text are gathered without being unified by an origin, the reader, theorised by Michel de Certeau in *The Practice of Everyday Life* (1984) and, subsequently, by Henry Jenkins in "Star Trek Rerun, Reread, Rewritten: Fan Writing as Textual Poaching" (1988), is a considerably more active and proprietary figure. Jenkins' article explicitly borrows de Certeau's vocabulary, describing fans as "poachers of textual meanings who appropriate popular texts" (Jenkins, 1988, p. 85), as against the passive dupes of mass culture that earlier audience research had assumed them to be. This reformulation relocates the site of meaning-making from the abstract philosophical space Barthes described to the concrete and sociologically observable space of fan communities, conventions, letterzines, and, later, online archives.

Lucy Bennett's retrospective "Tracing Textual Poachers: Reflections on the Development of Fan Studies and Digital Fandom" (2014) on the influence of Jenkins' 'textual poachers' argues that the central metaphor of the book has matured unevenly. Reflecting on more than two decades of fan studies scholarship built on Jenkins' thesis, Bennett warns that the premise of fans operating from a position of "cultural marginality and social weakness" (Jenkins, 1992, as cited in Bennett, 2014, p. 6) is positioned uneasily with a digital fandom, in which some fan creators command audiences, platforms, societies and even commercial contracts of their own. If Jenkins' original study depicted poaching as a tactic available to the relatively powerless, Bennett's reassessment suggests that textual poaching has, in some corners of contemporary fandom, become an institutionally recognised and even monetised mode of cultural production, further destabilising any opposition between author and reader.

Legal scholarship on fandom offers a complementary perspective. Accordingly, Rebecca Tushnet, writing on the relationship between 'textual poachers' and 'fair use' doctrine in "I'm a Lawyer, not an Ethnographer, Jim: Textual Poachers and Fair Use" (2014), credits Jenkins' study with helping to establish "the positive aspects of fandom cultures and creativity" (p. 21) as a matter of public record, a contribution she treats as consequential well beyond media studies, because it has shaped the legal arguments used to defend transformative fan works against claims of copyright infringement. This is a reminder that no matter whether fan-authored continuations are understood as poaching, as transformation or as infringement, they have material consequences for the individuals who produce them.

A more recent empirical study develops Jenkins' theory within new geographic and generational contexts. In this connection, Amor Jude Thadeus Soriano's study "Textual Poachers and Fandom Dynamics: A Study of Filipino College Students" (2024) places Jenkins' concept of textual poaching within a qualitative analysis of youth fandom, finding that "students' decisions to affiliate with particular fandoms depend [as much] on their immediate needs, interests, and social standing" (p. 51) as on any single official meaning of text. Zhiheng Shi's review of *Textual Poachers*, published on the occasion of the continued circulation of the book in translation, similarly emphasises that Jenkins' theory

"provide[s] a new way of thinking for fan studies" (Shi, 2022, p. 175) because it treats consumers as poachers "escaping institutional control" (Shi, 2022, p. 175) rather than as an audience awaiting a sanctioned meaning by the author. Taken together, this body of scholarship suggests that textual poaching has proved to be a sturdy and geographically portable framework, even as its original claims about fan marginality have required revision.

TRANSMEDIA CONTINUATIONS AND THE LIMITS OF AUTHORIAL DEATH

The conceptual history traced above helps explain why long-running fan continuations of canonical texts do not straightforwardly confirm Barthes' thesis. When S. E. Hinton's *The Outsiders* generates decades of fan-authored sequels, or when the collective "fanon" of the *Harry Potter* universe solidifies around characterisations and pairings absent from J. K. Rowling's published volumes, what arises is a text with two kinds of authors, operating in an uneasy, sometimes adversarial, division of labour: the commercially sanctioned originator, whose name continues to organise the archive as Dahlberg-Dodd's heuristic device, and the networked community of transformative authors, whose collective interpretive decisions increasingly shape how the 'original' text is read even by readers who have never encountered a single work of fan fiction. Hence, one might admit that Barthes' "The Death of the Author" anticipated the second kind of authority, with the reader serving as the destination where the multiplicity of the text gathers, but it did not anticipate the persistence of the first commercially defended and legally consequential author-function that Dahlberg-Dodd and Tushnet both describe as remaining stubbornly operative even within highly participatory fan ecosystems.

A further complication arises when transmedia storytelling is considered alongside textual poaching rather than as a separate phenomenon. Where poaching describes readers appropriating an existing text, transmedia storytelling, as elaborated in Jenkins' later work and taken up across subsequent media studies scholarship, describes producers deliberately distributing a single fictional world across multiple platforms, film, television, games, tie-in fiction, so that no single medium contains the whole story. This matters for the Barthesian question because transmedia storytelling is often commercially planned to invite the kind of active, world-building reading that de Certeau and Jenkins associate with poaching. A media franchise that releases deliberately incomplete instalments across several platforms is, in effect, outsourcing part of the interpretive labour that Barthes assigned to the reader back to an industrially organised production process. The resulting reader is neither the abstract textualist figure of 1967, nor the purely oppositional poacher of 1988 and 1992, but something closer to an invited collaborator, whose participation has, in many contemporary franchises, been anticipated and structurally built into the design of the text. The *Harry Potter* franchise exemplifies this dynamic, being built upon seven novels, eight films, a stage play (*Harry Potter and the Cursed Child*), the interactive digital platform *Pottermore* (now known as *Wizarding World*), the *Fantastic Beasts* film series, and the upcoming HBO television series *Harry Potter and the Philosopher's Stone*, thus inviting fans to explore and expand its narrative across media. Yet, J.K. Rowling's continued authorial interventions through social media and paratextual pronouncements have simultaneously asserted control over the rapidly expanding trend, thereby exposing the tension between invitation and authorial authority. As a consequence, this blurring of invitation and appropriation is what makes it difficult to say, in any given instance of fan continuation, whether the author has been killed, has delegated authority, or has simply relocated authority to a marketing department.

This is the deeper unease that this paper takes as its main claim, for the recurring critical anxiety about fan fiction, transmedia storytelling, and participatory culture more broadly is not really a debate about whether authors have died; both traditional criticism and fan studies scholarship, as reviewed above, agree that some form of authorial function survives. The real disagreement concerns who is authorised to exercise interpretive power over a text once it circulates beyond its point of origin, and that disagreement, as Allen's account of the afterlife of the essay in education suggests, recurs in every institutional domain that borrows Barthes' vocabulary. Hence, fan fiction renders visible a struggle that has arguably always structured the relationship between texts, their producers, their readers and their publics.

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CONCLUSION

This paper has argued that participatory culture reconceptualises Roland Barthes' 1967 prophecy of the 'death of the author' in ways Barthes could not have anticipated, since Barthes' reader was a textualist abstraction and a locus, at which the multiple non-original writings of a text achieve a provisional unity. The reader produced by contemporary fan culture, by contrast, is an empirically observable, often highly organised social actor, who writes, argues, builds continuities, and, sometimes, earns income from the texts they poach. The scholarship reviewed here, from Allen's account of the migration of the essay into educational theory, through Du's and Dillon's reassessments of Barthes' original claims, to Dahlberg-Dodd's, Jenkins', Bennett's, Tushnet's, Soriano's, and Shi's empirical and legal accounts of fan practice, congregates on a single finding that authorial authority has been distributed, contested, and, in some cases, re-institutionalised in new forms. The more insistent critical task, then, is not to determine whether Barthes was correct, nor to praise fan fiction as the fulfilment of poststructuralist theory, it is to recognise that the text has never been a stable place of settled meaning, and that the proliferation of transformative fan practice has made an old ongoing struggle over interpretive legitimacy newly visible and newly consequential for the individuals and institutions involved. Future research might usefully extend this analysis by examining how platform governance and algorithmic curation, rather than the 'commercial' author alone, are beginning to function as a third contender for the interpretive authority that Barthes once located exclusively in the reader.

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FRANSA'DAKİ TÜRK GENÇLERİNİN HZ. MUHAMMED'İN AHLAKÎ VE İNSANÎ VASIFLARINA YÖNELİK ALGILARI ÜZERİNE BİR ALAN ARAŞTIRMASI

A FIELD STUDY ON THE PERCEPTIONS OF TURKISH YOUTH IN FRANCE REGARDING THE MORAL AND HUMAN QUALITIES OF PROPHET MUHAMMAD

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ÖZET

Bu tebliğ,[1] Fransa'nın Paris bölgesinde (Île-de-France) yaşayan Türk kökenli, üniversite okuyan 18-25 yaş arası gençlerin Hz. Muhammed'in ahlakî ve insanî vasıflarına yönelik algılarını ortaya koymayı amaçlamaktadır. Araştırma nitel yöntemle tasarlanmış; veriler, açık uçlu sorulardan oluşan bir form aracılığıyla toplanmıştır. Görüşmeler, Fransa DİTİB Merkezi (Bagnolet), üniversite kampüsleri, Türk derneklerine bağlı cami ve dernek lokalleri ile bazı katılımcıların evlerinde gerçekleştirilmiştir. Çalışmanın bu bölümünde, Hz. Muhammed'in "insani yönü" bağlamında üç temel soruya odaklanılmıştır: 1. Hz. Muhammed'in çocuklarla ve gençlerle iletişimi ve bu iletişime dair somut örnekler, 2. Hz. Muhammed'in hayatında gençlerin en çok dikkatini çeken ahlaki özellikler, 3. Kadın hakları, çocuk hakları, engelli bireyler, çevre temizliği ve hayvan hakları gibi toplumsal konularda Hz. Muhammed'in tavsiye ve davranışlarına dair farkındalık düzeyi. Bulgular, katılımcıların büyük çoğunluğunun Hz. Muhammed'in çocuklar ve gençlerle iletişimini sevgi, şefkat, sabır ve anlayışla tanımladığını; yarısının bu iletişimi somut örneklerle desteklediğini göstermektedir. Hz. Muhammed'in hayatında en çok dikkat çeken özellikler arasında merhamet, sabır ve adalet ilk üç sırada yer almaktadır. Kadın hakları, hayvan hakları, çocuk hakları ve çevre temizliği konularında katılımcıların büyük çoğunluğu en az bir tavsiye veya davranış örneğini bildiğini belirtmiştir. En çok bilinen örnekler arasında Veda Hutbesi'nde (10/632) kadınların emanet olarak nitelendirilmesi, "Cennet annelerin ayakları altındadır" hadisi, kedilere gösterilen şefkat ve kıyamet kopsa bile fidan dikilmesi tavsiyesi yer almaktadır. Bu bulgular, yurt dışında yaşayan Türk gençliğinin Hz. Muhammed algısında ahlakî ve insanî erdemlerin merkezi bir rol oynadığını; merhamet, adalet ve sabrın en çok vurgulanan değerler olduğunu göstermektedir. Katılımcıların Hz. Muhammed'i öncelikle bir "ahlak örneği" ve "rol model örnek şahsiyet denebilir" olarak konumlandırması, onun biçimsel ve kural odaklı yönlerinden ziyade insanî yönünün öne çıktığını ortaya koymaktadır. Ayrıca, kadın ve hayvan hakları gibi konulardaki farkındalığın yüksek olması, katılımcıların Hz. Muhammed'i evrensel ve toplumsal değerlerle ilişkilendirdiğini, engelli bireyler konusundaki farkındalık eksikliği ise bu alanda daha fazla eğitim ve bilinçlendirme ihtiyacını işaret etmektedir.

Anahtar Kelimeler: Hz. Muhammed, Ahlak, Karakter, Merhamet, Adalet, Fransa, Gençlik.

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[1] Bu çalışma, "Çok Kültürlü Toplumda Dini Kimlik İnşası Bağlamında Hz. Muhammed Tasavvuru: Fransa'da Yaşayan Türk Öğrenciler Üzerine Bir Alan Araştırması (Paris Örneği)" başlıklı devam eden ve tarafımızca yürütülen Paris CNRS (Centre national de la recherche scientifique/Ulusal Bilimsel Araştırma Merkezi) ile Eskişehir Osmangazi Üniversitesi arasında gerçekleştirilen Etik Kurul Onayı alınmış Uluslararası İş birliği Projesi'nin (BAP Proje Kodu: SUİ-2026-3920) bir parçası olarak hazırlanmıştır.

ABSTRACT

This paper[2] aims to examine the perceptions of Turkish-origin university students aged 18–25 living in the Paris region (Île-de-France) regarding the moral and human attributes of Prophet Muhammad. Designed using a qualitative methodology, the study gathered data through a questionnaire consisting of open-ended questions. Interviews were conducted at the DITIB France headquarters in Bagnolet, university campuses, mosques and cultural centers affiliated with Turkish associations, and in the homes of several participants. This section of the study focuses on three fundamental questions within the context of the "human dimension" of Prophet Muhammad: 1. His communication with children and youth, along with concrete examples of this interaction; 2. The moral characteristics in his life that draw the most attention from youth; and 3. The level of awareness regarding his advice and behaviors on social issues such as women's rights, children's rights, individuals with disabilities, environmental cleanliness, and animal rights. The findings indicate that the vast majority of participants describe Prophet Muhammad's communication with children and youth through love, compassion, patience, and understanding, with half of them supporting this communication with concrete examples. Mercy, patience, and justice rank as the top three most prominent characteristics in his life. Regarding women's rights, animal rights, children's rights, and environmental cleanliness, the great majority of participants stated that they were aware of at least one piece of advice or behavior. The most widely known examples include the characterization of women as a trust in the Farewell Sermon (10/632), the hadith stating that "Paradise lies beneath the feet of mothers," the compassion shown toward cats, and the recommendation to plant a sapling even if the Day of Judgment were to occur. These findings demonstrate that moral and human virtues play a central role in the perception of Prophet Muhammad among Turkish youth living abroad, with mercy, justice, and compassion being the most heavily emphasized values. The participants' positioning of Prophet Muhammad primarily as a "moral exemplar" and "role model" reveals that his human dimension stands out over formalistic aspects and rigid rules. Furthermore, while the high level of awareness regarding issues such as women's and animal rights indicates that participants associate Prophet Muhammad with universal and social values, the relative lack of awareness regarding individuals with disabilities highlights a need for greater education and consciousness-raising in this specific area.

Keywords: Prophet Muhammad, Morality, Character, Mercy, Justice, France, Youth.

GİRİŞ

Fransa, Avrupa'nın en büyük Müslüman nüfusuna ev sahipliği yapmakta olup, İslam ülkenin ikinci en yaygın dinidir (INSEE, 2023). Göç, İslam, laiklik ve ulusal kimlik gibi konuların iç içe geçtiği bu bağlamda, özellikle ikinci ve üçüncü kuşak Türk kökenli gençlerin dini kimliklerini nasıl inşa ettikleri ve Hz. Muhammed algısının bu inşa sürecinde nasıl şekillendiği önemli bir araştırma alanıdır.

Bu çalışma, Paris bölgesinde yaşayan 18–25 yaş arasındaki Türk kökenli üniversite öğrencilerinin Hz. Muhammed'in ahlakî ve insanî vasıflarına yönelik algılarını üç temel boyutta ortaya koymayı hedeflemektedir: a) Hz. Muhammed'in çocuklar ve gençlerle iletişimi ve bu iletişime dair somut örnekler, b) Hz. Muhammed'in hayatında en çok dikkat çeken ahlaki özellikler, kadın hakları, çocuk hakları, hayvan hakları, çevre temizliği, c) engelli bireyler gibi evrensel konularda Hz. Muhammed'in tavsiyelerine dair farkındalık düzeyi. Bu araştırma, konuya ilişkin sınırlı sayıdaki nitel çalışmaya katkı sunmayı ve Hz. Muhammed'in ahlaki ve insani özelliklerinin araştırmaya katılan gençlerin dinî kimlik oluşumundaki rolünü incelemeyi amaçlamaktadır.

[2] This study has been prepared as a part of an ongoing international cooperation project titled 'The Perception of Prophet Muhammad in the Context of Religious Identity Construction in a Multicultural Society: A Field Research on Turkish Students Living in France (The Case of Paris)', conducted by us and carried out jointly between Paris CNRS (Centre national de la recherche scientifique) and Eskişehir Osmangazi University, which has received Ethics Committee Approval (BAP Project Code: SUİ-2026-3920).

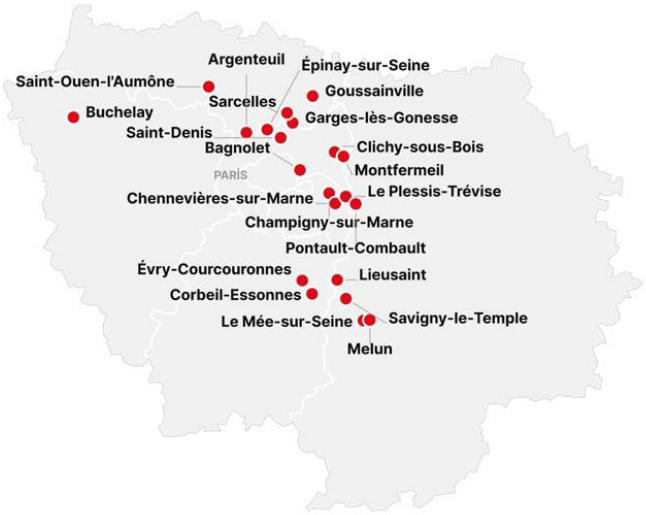
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ARAŞTIRMA VE BULGULAR

Yöntem

Araştırmanın verileri, proje yürütücüsü Doç. Dr. İsmail Metin ve proje araştırmacısı Dr. Bayram Demirtaş tarafından 36 katılımcıyla gerçekleştirilen saha araştırmasından elde edilmiştir. Görüşmeler, yarı yapılandırılmış mülakat tekniği kullanılarak, her katılımcıyla yüz yüze gerçekleştirilen ve yaklaşık 60–90 dakika süren görüşmeler hâlinde gerçekleştirilmiştir. Katılımcıların kendilerini daha rahat ifade edebilmelerini sağlamak amacıyla görüşme dilinin seçimi katılımcılara bırakılmış; bu doğrultuda görüşmeler çoğunlukla Türkçe, kimi zaman ise Fransızca yürütülmüştür.

Araştırmanın örneklem tasarımında, istatistiksel temsil kabiliyetinden ziyade katılımcıların sosyo-demografik ve dini çeşitliliğin örnekleme yansıtılması hedeflenmiştir. Katılımcılara ulaşmak için öncelikle Fransa DİTİB'e bağlı dernekler ve araştırmacıların kişisel bağlantılarından yararlanılmış; ardından katılımcı ağı, kartopu örnekleme yoluyla katılımcıların yakın çevrelerine ulaşılarak genişletilmiştir. Görüşmeler yazılı olarak kaydedilmiş, elde edilen ham veriler düzenlenerek analiz edilebilir metinlere dönüştürülmüştür. Katılımcı yanıtları içerik analizi yöntemiyle incelenmiş; iletişim biçimleri, özellikler ve örnek olaylar belirli kategoriler altında sınıflandırılarak sistematik bir şekilde değerlendirilmiştir. Etik Kurul Kararı ve Onayı alınmış bu araştırmaya katılmayı kabul eden tüm katılımcıların kimlik bilgileri, etik ilkeler gereği anonim tutulmuştur.



HARİTA. Alan araştırmasına katılan gençlerin Paris bölgesinde (Île-de-France)[3] ikamet ettikleri şehirleri gösteren harita (Görsel, araştırmacılar tarafından oluşturulmuştur)

1. Hz. Muhammed'in Çocuklar ve Gençlerle İletişimi (1. Soru)

Araştırmaya katılan bireylerin büyük çoğunluğu (%94,4), Hz. Muhammed'in çocuklar ve gençlerle olan iletişimini "sevgi, şefkat, sabır ve anlayış" gibi olumlu niteliklerle tanımlamıştır. Katılımcıların yarısı (%50) ise bu genel kanıyı somut bir örnekle desteklemiştir.

[3] Günlük dilde "Paris bölgesi" olarak adlandırılan coğrafi alanla çoğunlukla Île-de-France idarî bölgesi kastedilmektedir. Île-de-France, Paris'in de aralarında bulunduğu toplam sekiz departmandan oluşmaktadır. Bunlar Paris, Seine-et-Marne, Yvelines, Essonne, Hauts-de-Seine, Seine-Saint-Denis, Val-de-Marne ve Val-d'Oise'dır. Yaklaşık 12.000 km² yüzölçümüne ve 12 milyonu aşan nüfusa sahip olan Île-de-France, Fransa'nın en kalabalık bölgesi ve Avrupa'nın başlıca ekonomik ve kültürel merkezlerinden biridir.

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Tablo 1. Katılımcıların Hz. Muhammed'in Çocuklar ve Gençlerle İletişimine İlişkin Değerlendirmeleri

Özellik	Sayı	Yüzde
Olumlu/Sevgi Dolu İletişim Vurgusu	34	%94,4
Somut Örnek Verenler	18	%50,0
Örnek Vermeyen / Bilmiyorum	3	%8,3

Sevgi ve Şefkat: Katılımcılar tarafından en yüksek frekansa sahip tema "sevgi ve şefkat" olarak tespit edilmiştir (27 tekrar, %75). Bu durum, katılımcıların zihninde Hz. Muhammed'in çocuklarla iletişiminin merkezinde sevgi unsurunun yer aldığını açıkça ortaya koymaktadır. Bir katılımcı bu durumu şöyle ifade etmiştir: "Hz. Muhammed çocuklara ve gençlere karşı sevgi, şefkat ve anlayışla yaklaşırdı."

Sabır ve Hoşgörü: En sık vurgulanan temalar arasında sevgi ve şefkatin ardından sabır gelmektedir (12 tekrar, %33,3). Özellikle Enes bin Malik örneği ile torunların namaz esnasında Hz. Peygamber'in sırtına çıkmasına dair anlatılar, Hz. Muhammed'in çocuklara karşı sergilediği hoşgörü ve sabrın somut göstergeleri olarak öne çıkmaktadır: "Çok iyiydi; hatta camide çocukların koşup oynamasına kızmazdı, namaz kılarken torunlarının sırtına çıkmasına da kızmazdı."

Oyun ve Şakalaşma: Katılımcıların oyun ve şakalaşma temalarını sıklıkla vurgulaması, Hz. Muhammed'in çocuklarla iletişiminde neşe ve samimiyetin merkezi bir rol oynadığını göstermektedir: "Hz. Muhammed çocuklara ve gençlere sevgi ve şefkatle davranırdı. Onlarla ilgilenir, oyun oynar ve güzel sözler söylerdi."

Değer Verme ve Sorumluluk Yükleme: Katılımcılar, Hz. Muhammed'in gençlere değer verdiğini ve onlara sorumluluk yüklediğini sıklıkla ifade etmiştir. Savaşta gençlere sorumluluk vermesi (Mus'ab bin Umeyr örneği) ve bir gencin fikirlerine değer vermesi (zina isteyen genç kıssası) bu algıyı destekleyen örnekler olarak öne çıkmaktadır: "Peygamberimiz çocuklarla ve gençlerle yaşlarına ve anlayış seviyelerine göre öğüt verirdi; onların düşünce, duygu ve fikirlerine önem verirdi."

Somut Örnekler: Katılımcıların yarısı (%50), Hz. Muhammed'in çocuklarla iletişimine dair somut bir örnek verebilmiştir. En çok zikredilen örnekler torunları (Hasan ve Hüseyin) ile Enes bin Malik'e ilişkin anlatılardır. Bu durum, söz konusu örneklerin araştırmaya katılan gençler arasında görece yaygın olarak bilindiğini göstermektedir.

2. Hz. Muhammed'in En Çok Dikkat Çeken Ahlaki Özellikleri (2. Soru)

Katılımcıların büyük çoğunluğu Hz. Muhammed'in merhamet (%66,7), sabır (%57,6) ve adalet (%45,5) erdemlerini en dikkat çekici özellikler olarak vurgulamıştır. Bu üç özellik, diğer erdemlere göre açık ara öncelikli olarak öne çıkmıştır.

Tablo 2. Katılımcılar Tarafından En Sık Vurgulanan Ahlaki Özellikler

Özellik	Sıklık	Yüzde
Merhamet	22	%61,1
Sabır	19	%52,8
Adalet	15	%41,7

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Merhamet: Katılımcılar tarafından en baskın özellik olarak öne çıkmaktadır (22 tekrar, %66,7). Özellikle düşmanlara ve gayrimüslimlere karşı sergilenen merhamet, katılımcılar nezdinde örnek alınması gereken bir davranış biçimi olarak değerlendirilmektedir: "Merhametidir; gayrimüslimlere karşı bile merhametliydi."

Sabır: İkinci en sık vurgulanan özellik olarak öne çıkmaktadır (19 tekrar, %57,6). Katılımcılar, özellikle Hüzün Yılı (Senetü'l-Hüzn, 620 yılı) ve diğer zorlu dönemlerde Hz. Muhammed'in gösterdiği sabrı ön plana çıkarmıştır. Ayrıca, katılımcıların önemli bir kısmı bu erdemi kendi yaşam pratiklerine aktarma çabasında olduklarını ifade etmiştir: "En çok dikkatimi çeken özelliği sabrıydı. Zor durumlarda bile sakin kalması ve pes etmeden insanlara iyilikle yaklaşması."

Adalet: Üçüncü sırada yer almakta ve katılımcıların %45,5'i tarafından vurgulanmaktadır. Özellikle Mekke'nin fethi sırasında düşmanlarını affetmesi, katılımcılar için adaletin en güçlü örneği olarak öne çıkmaktadır. Bir katılımcının *"Kendimde bir hukukçu olduğum için"* diyerek adaleti vurgulaması, mesleki kimliğin dinî algıyı şekillendirmedeki etkisini gösteren dikkat çekici bir örnektir: "Kendimde bir hukukçu olduğum için Hz. Muhammed'in en çok adaletine hayranım."

Tevazu ve Güvenilirlik: Tevazu (%15,2) ve "el-Emîn" (Güvenilir) sıfatı (%9,1) daha az vurgulanmış olsa da, Hz. Muhammed'in kişisel erdemleri arasında önemli bir yer tutmaktadır. Özellikle tevazu, onun sahip olduğu yüce konuma rağmen sergilediği alçakgönüllü tutumun katılımcılar üzerinde derin bir etki bıraktığını göstermektedir: "Haya sahibi ve alçakgönüllü olması. Âlemlere rahmet bir peygamber olarak gönderilmesine rağmen böyle olabilmesi beni etkileyen bir şey."

3. Kadın Hakları, Hayvan Hakları, Çocuk Hakları ve Çevre Duyarlılığı (3. Soru)

Katılımcıların büyük çoğunluğu (%91,4) Hz. Muhammed'in bu konulardaki tavsiyelerinden en az birini bildiğini ifade etmiştir. Bu oran, katılımcıların Hz. Peygamber'i yalnızca ibadet ve ritüel boyutuyla değil, aynı zamanda sosyal sorumluluk ve evrensel değerler bağlamında da tanıdıklarına işaret etmektedir. Bununla birlikte, katılımcıların yalnızca %34,3'ü bu konuda somut bir örnek verebilmiştir.

Tablo 3. Katılımcıların Toplumsal Konulara İlişkin Bilgi ve Somut Örnek Verme Durumları

Özellik	Sayı	Yüzde
En Az Bir Konuda Bilgi Sahibi Olanlar	32	%91,4
Hiçbir Konuda Bilgi Sahibi Olmayanlar	3	%8,6
Somut Örnek Verenler	12	%34,3

Kadın Hakları: Katılımcılar tarafından en yüksek oranda bilinen tema olarak öne çıkmaktadır (%42,9). Bu bağlamda en sık zikredilen örnekler Veda Hutbesi ve "Cennet annelerin ayakları altındadır" (Nesâî, *Cihâd*, 6; İbn Mâce, *Cihâd*, 12) hadisidir: "Veda hutbesinde kadınların emanet olduğunu söylemesi ve kıyamet kopsa bile fidan dikilmesini emretmesi beni çok etkiledi ve duygulandırdı."

Hayvan Hakları: İkinci sırada yer almakta olup, katılımcıların %40,0'ı bu konuda en az bir tavsiyeyi hatırlamaktadır. Özellikle kedilere gösterilen şefkat (hırka kesme örneği) ve kurbanlık hayvanlara duyarlılık, en çok bilinen örnekler arasındadır: "Bir kedi, Peygamberimiz'in hırkası üzerinde uyurken, Peygamberimiz kediyi rahatsız etmemek için hırkayı kesip almıştı."

Çocuk Hakları ve Çevre Temizliği: Eşit oranda (%28,6) vurgulanmıştır. Çocuk hakları bağlamında sevgi ve şefkat boyutu öne çıkarken, çevre konusunda fidan dikme tavsiyesi ve çevrenin bir emanet olarak nitelendirilmesi ön plana çıkmaktadır: "Kıyamet kopsa bile fidan dikilmesini emretmesi."

Engelli Bireyler: Dikkat çekici bir bulgu olarak, engelli bireyler konusunda hiçbir katılımcı Hz. Muhammed'e ait bir tavsiye veya davranış örneği zikretmemiştir. Bu durum, söz konusu konunun yurt dışındaki toplulukta yeterince bilinmediğine veya öne çıkarılmadığına işaret etmektedir.

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SONUÇ VE ÖNERİLER

Bu araştırma, Paris bölgesinde yaşayan Türk kökenli genç Müslümanların Hz. Muhammed'in ahlakî ve insanî vasıflarına yönelik algılarının üç temel boyutta şekillendiğini ortaya koymaktadır. Hz. Muhammed'in "Şefkat Peygamberi" olarak algılanması araştırmanın en dikkat çekici bulgularından biridir. Katılımcıların tamamına yakını, Hz. Muhammed'in çocuklar ve gençlerle iletişimini sevgi, şefkat, sabır ve anlayışla özdeşleştirmektedir (%94,4). Bu bulgu, Hz. Muhammed'in "Rahmet Peygamberi" vasfının araştırmaya katılan gençler tarafından güçlü biçimde benimsendiğini göstermektedir.

Ahlaki erdemlerin baskınlığı bir diğer önemli bulgudur. Katılımcılar, Hz. Muhammed'in hayatında en çok merhamet (%66,7), sabır (%57,6) ve adalet (%45,5) gibi ahlaki erdemleri öne çıkarmaktadır. Bu bulgu, katılımcıların Hz. Peygamber'i öncelikle bir "ahlak örneği" ve "manevi rehber" olarak konumlandırdığını göstermektedir. Evrensel değerlere ilişkin yüksek farkındalık da araştırmanın önemli sonuçları arasındadır. Katılımcıların %91,4'ü, Hz. Muhammed'in kadın hakları, hayvan hakları, çocuk hakları ve çevre duyarlılığı gibi konulardaki tavsiyelerinden en az birini bilmektedir. Bu durum, onun evrensel ve toplumsal mesajının yurt dışında yaşayan Türk gençliği tarafından da tanındığını göstermektedir.

Ancak engelli bireyler konusunda hiçbir katılımcının Hz. Muhammed'e ait bir tavsiye veya davranış örneği zikretmemiş olması, bu konunun yeterince bilinmediğine veya öne çıkarılmadığına işaret etmektedir. Ayrıca, katılımcıların genel farkındalık düzeyi yüksek olmakla birlikte, somut örnek verebilme oranının sınırlı olması (%34,3), bilginin genel kültür düzeyinde kaldığını ve derinleşmediğini düşündürmektedir.

Araştırma bulguları ışığında şu öneriler geliştirilebilir:

1. Hz. Muhammed'in sosyal ve evrensel mesajlarının (kadın hakları, hayvan hakları, çevre bilinci, engelli bireylere yaklaşım vb.) daha somut örneklerle cami, aile ve okul müfredatında işlenmesi gerekmektedir.

2. Özellikle engelli bireyler konusundaki farkındalık eksikliği, bu alanda özel çalışmalar yapılmasını zorunlu kılmaktadır.

3. Gençlerin bilgi ediniminde önemli bir yer tutan dijital platformlarda (YouTube, Instagram, podcastler), Hz. Muhammed'in ahlaki ve evrensel mesajlarını içeren içeriklerin güvenilir kaynaklarla üretilmesi ve yaygınlaştırılması teşvik edilmelidir.

4. Katılımcıların genel farkındalık düzeyi yüksek olsa da somut örnek verebilme oranının sınırlı olması, bilgi derinliğinin artırılması ihtiyacını göstermektedir. Bu doğrultuda, Hz. Peygamber'in hayatından pratik ve günlük hayata uyarlanabilir örneklerin ön plana çıkarılması faydalı olacaktır.

5. Aile ve cami/dernek, dinî bilgi aktarımında hâlâ en temel kaynaklar olarak işlev görmektedir. Bu iki kurum arasındaki işbirliğinin güçlendirilmesi, gençlerin dini kimlik inşasında daha tutarlı ve derinlikli bir bilgi aktarımına imkân tanıyacaktır. Hz. Muhammed'in engelli bireylere yönelik örnek davranışlarının ve tavsiyelerinin cami, okul ve aile ortamında daha fazla gündeme getirilmesi, bu alandaki farkındalık eksikliğinin giderilmesine katkı sağlayacaktır.

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FRANSA'DA YAŞAYAN TÜRK GENÇLERİNİN HZ. MUHAMMED ALGISI VE SİYER BİLGİSİ ÜZERİNE BİR ALAN ARAŞTIRMASI

A FIELD STUDY ON THE PERCEPTION OF PROPHET MUHAMMAD AND SÎRA KNOWLEDGE AMONG TURKISH YOUTH LIVING IN FRANCE

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ÖZET

Bu bildiri,[4] Fransa'nın Paris bölgesinde (Île-de-France) yaşayan Türk kökenli üniversite öğrencilerinin (18-25 yaş arası) Hz. Muhammed algısını ve siyer bilgi düzeylerini ortaya koymayı amaçlamaktadır. Araştırma nitel yöntemle tasarlanmış, veriler açık uçlu sorulardan oluşan bir anket formu aracılığıyla toplanmıştır. Görüşmeler, Fransa DİTİB'in merkezi Bagnolet'de, üniversite kampüslerinde, Türk derneklerine bağlı cami ve lokaller ile katılımcıların evlerinde gerçekleştirilmiştir. Çalışmanın bu bölümünde, üç temel soruya odaklanılmıştır: a) Hz. Muhammed'i nasıl tanımladıkları ve onun kendileri için ne ifade ettiği, b) Hz. Muhammed'in hayatı hakkında kitap okuma alışkanlıkları ve okunan eserlerin dilsel dağılımı, c) Hz. Muhammed hakkındaki bilgilere hangi kaynaklar (aile, cami, kitaplar, internet/sosyal medya vb.) aracılığıyla ulaştıkları. Bulgular, katılımcıların büyük çoğunluğunun Hz. Muhammed'i bir "örnek" ve "rehber" olarak tanımladığını; en çok vurgulanan erdemlerin ise merhamet, dürüstlük, adalet ve sabır olduğunu göstermektedir. Hz. Muhammed'in teolojik kimliği (son peygamber, Allah'ın elçisi) de önemli bir yer tutmakla birlikte ahlaki vurgu daha baskındır. Okuma alışkanlıkları açısından, katılımcıların çoğunluğu Hz. Muhammed'in hayatı hakkında en az bir kitap okuduğunu belirtmiştir. Okunan kitapların büyük çoğunluğu Türkçe olup Fransızca ve Arapça eserlerin oranı oldukça düşüktür. Bilgi kaynakları açısından ise, katılımcıların en çok cami ve aile gibi geleneksel kaynakları kullandığı; internet ve sosyal medyanın da önemli bir tamamlayıcı kaynak olduğu; arkadaş çevresinin ise daha az etkili olduğu görülmüştür. Bu bulgular, Fransa'da yaşayan Türk gençliğinin Hz. Muhammed algısında ahlaki erdemlerin teolojik kimliğin önüne geçtiğini, siyer okuryazarlığında Türkçe kaynakların baskın olduğunu ve bilgi ediniminde geleneksel kurumların (cami ve aile) hâlâ merkezi bir rol oynadığını ortaya koymaktadır. Ancak, okunan eserlerin çok az bir kısmının adları ve yazarlarıyla hatırlanabilmesi, okuma pratiğinin derinlikten yoksun olduğunu düşündürmektedir. Dijital kaynakların artan kullanımı, gelecekte bilgi edinme alışkanlıklarının dönüşümüne işaret etmektedir. Çalışma, yurt dışı bağlamında dini bilgi aktarımının güncel dinamiklerini anlamak için önemli veriler sunmakta ve siyer eğitimi, kaynak güvenilirliği ve dijital medya kullanımı konularında bazı öneriler geliştirmektedir.

Anahtar Kelimeler: Hz. Muhammed, Siyer, Algı, Fransa, Gençlik.

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[4] Bu çalışma, "Çok Kültürlü Toplumda Dini Kimlik İnşası Bağlamında Hz. Muhammed Tasavvuru: Fransa'da Yaşayan Türk Öğrenciler Üzerine Bir Alan Araştırması (Paris Örneği)" başlıklı devam eden ve tarafımızca yürütülen Paris CNRS (Centre national de la recherche scientifique/Ulusal Bilimsel Araştırma Merkezi) ile Eskişehir Osmangazi Üniversitesi arasında gerçekleştirilen Etik Kurul Onayı alınmış Uluslararası İşbirliği Projesi'nin (BAP Proje Kodu: SUİ-2026-3920) bir parçası olarak hazırlanmıştır.

ABSTRACT

This paper[5] aims to reveal the perception of Prophet Muhammad and the level of knowledge regarding his biography (*siyar*) among Turkish-origin university students aged 18-25 living in the Paris region (Île-de-France). Designed using a qualitative methodology, the study gathered data through a questionnaire consisting of open-ended questions. Interviews were conducted at the DITIB France headquarters in Bagnolet, university campuses, mosques and cultural centers affiliated with Turkish associations, and in the participants' homes. This section of the study focuses on three fundamental questions: a) how they define Prophet Muhammad and what he represents for them, b) their reading habits regarding the life of Prophet Muhammad and the linguistic distribution of the works read, and c) the sources (family, mosque, books, internet/social media, etc.) through which they access information about Prophet Muhammad. The findings indicate that the vast majority of participants define Prophet Muhammad as an "exemplar" and a "guide," with mercy, honesty, justice, and patience being the most heavily emphasized virtues. Although theological identity (the final prophet, the messenger of Allah) also holds a significant place, moral emphasis is more dominant. Regarding reading habits, the majority of participants stated that they had read at least one book on the life of Prophet Muhammad. The vast majority of these books are in Turkish, while French and Arabic works remain at a very low rate. In terms of information sources, it was observed that participants predominantly utilize traditional sources such as mosques and family; the internet and social media serve as an important complementary source, whereas peer groups are less influential. These findings reveal that moral virtues take precedence over theological identity in the perception of Prophet Muhammad among Turkish youth living in France, that Turkish sources dominate sîra literacy, and that traditional institutions (mosques and family) still play a central role in knowledge acquisition. However, the fact that very few of the read works can be remembered by title and author suggests that the reading practice lacks depth. The increasing use of digital sources points to a future transformation in knowledge acquisition habits. The study provides important data for understanding the current dynamics of religious knowledge transmission among Turkish communities abroad and develops certain recommendations regarding sîra education, source reliability, and digital media usage

Keywords: Prophet Muhammad, Sîra, Perception, France, Youth.

GİRİŞ

Fransa, Avrupa kıtasında en kalabalık Müslüman nüfusa sahip ülke konumunda olup, İslam, ülke genelinde en yaygın ikinci din olarak istatistikî verilere yansımaktadır (INSEE, 2023). Göç hareketleri, İslam'ın kamusal alanda görünürlüğü, laiklik ilkesi ve ulusal kimlik tartışmaları gibi birbiriyle iç içe geçmiş meselelerin hâkim olduğu bu sosyo-politik zeminde, özellikle üçüncü kuşak Türk asıllı gençlerin dinî kimlik inşası ve bu süreçte Hz. Muhammed tasavvurunun oynadığı rol (Metin, 2022), akademik açıdan önemli bir inceleme sahası teşkil etmektedir.

Bu çalışma, Paris bölgesinde yaşayan 18-25 yaş arası Türk kökenli üniversite öğrencilerinin Hz. Muhammed algısını, siyer bilgi düzeylerini ve bilgi kaynaklarını üç temel boyutta ortaya koymayı hedeflemektedir: 1) Hz. Muhammed'i nasıl tanımladıkları ve onun kendileri için ne ifade ettiği, 2) Hz. Muhammed'in hayatı hakkında kitap okuma alışkanlıkları ve okunan eserlerin dilsel dağılımı, 3) Hz. Muhammed hakkındaki bilgilere hangi kaynaklar (aile, cami, kitaplar, internet/sosyal medya vb.) aracılığıyla ulaştıkları. Araştırma, alanında ilk nitelikli çalışmalardan biri olma iddiasını taşımakta olup, yurt dışında yaşayan Türk gençliğinin dini kimlik inşasında Hz. Muhammed algısının ve siyer bilgisinin rolünü anlamaya katkı sunmayı amaçlamaktadır.

[5] This study has been prepared as a part of an ongoing international cooperation project titled 'The Perception of Prophet Muhammad in the Context of Religious Identity Construction in a Multicultural Society: A Field Research on Turkish Students Living in France (The Case of Paris)', conducted by us and carried out jointly between Paris CNRS (Centre national de la recherche scientifique) and Eskişehir Osmangazi University, which has received Ethics Committee Approval (BAP Project Code: SUİ-2026-3920).

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ARAŞTIRMA VE BULGULAR

Yöntem

Araştırmanın veri seti, proje yürütücüsü Doç. Dr. İsmail Metin ve proje araştırmacısı Dr. Bayram Demirtaş tarafından üniversitede öğrenim gören veya üniversiteden mezun olmuş 18-25 yaş arası Türk asıllı 36 katılımcıyla yürütülen saha çalışmasından derlenmiştir. Veri toplama sürecinde, nitel araştırma desenlerinden biri olan yarı yapılandırılmış mülakat tekniği tercih edilmiş; görüşmeler her bir katılımcıyla yaklaşık 60 ila 90 dakika süren, yüz yüze ve derinlemesine oturumlar şeklinde gerçekleştirilmiştir. Katılımcıların kendilerini ifade etme biçimleri üzerindeki olası dilsel engelleri en aza indirmek amacıyla, görüşme dilini belirleme hususu katılımcıların tercihine bırakılmıştır. Bu esnek yaklaşım neticesinde, mülakatların büyük bir kısmı Türkçe yürütülmüş, belirli durumlarda ise Fransızca tercih edilmiştir.

Örneklem oluşturulurken istatistiksel genellenebilirlikten ziyade katılımcı profillerinin sosyo-demografik özellikler ve dinî aidiyet açısından çeşitliliğine öncelik verilmiştir. İlk aşamada DİTİB Fransa bünyesindeki camiler/dernekler ve araştırmacıların mevcut kişisel ağları aracılığıyla katılımcılara ulaşılmıştır. Sonrasında kartopu örnekleme modeli devreye sokularak ilk temaslar, katılımcıların arkadaş çevresi, akrabalık bağları, komşuluk ilişkileri ve tanıdıkları vasıtasıyla genişletilmiştir.

Görüşme verileri, katılımcıların izni doğrultusunda yazılı olarak kaydedilmiş, ardından ham metinler düzenlenerek analiz sürecine uygun biçime dönüştürülmüştür. Verilerin çözümlenmesinde içerik analizi yöntemi benimsenmiş; iletişim biçimleri, tematik eğilimler ve öne çıkan olay örgüleri belirlenerek belirli kategoriler altında sistematik bir biçimde sınıflandırılmıştır. Araştırmaya katılım gösteren tüm bireylerin kişisel bilgileri, etik ilkeler çerçevesinde gizli tutulmuş ve anonimlik ilkesine titizlikle riayet edilmiştir.



HARİTALAR. Alan araştırmasına katılan gençlerin Paris bölgesinde (Île-de-France) okuduğu/bitirdiği üniversiteleri ve bölümleri/fakülteleri gösteren haritalar (Görsel, araştırmacılar tarafından hazırlanmıştır.)

1. Hz. Muhammed'in Algılanma Biçimleri (1. Soru)

Katılımcıların Hz. Muhammed'i tanımlama biçimleri dört ana tema etrafında toplanmıştır.

Ahlaki ve İnsani Erdemler: Katılımcıların %61'i (22 kişi) Hz. Muhammed'i öncelikle ahlaki erdemlerle tanımlamaktadır. En çok vurgulanan erdemler sırasıyla merhamet (18 kez), dürüstlük/güvenilirlik (14 kez), adalet (11 kez), sabır (9 kez), tevazu (4 kez) ve hoşgörü/affediciliktir (3 kez). Bir katılımcı bu durumu şöyle ifade etmiştir: "Güzel ahlakın ve merhametin örneğidir. Bana doğru yaşamayı hatırlatır."

Pratik Yaşam Rehberliği: Katılımcıların %94'ü (34 kişi) Hz. Muhammed'i bir "örnek" veya "rehber" olarak tanımlamaktadır. "Örnek" kelimesi 36 cevabın 34'ünde doğrudan veya dolaylı olarak geçmektedir. Bu, onun yalnızca tarihsel bir figür olarak değil, günlük hayatta örnek alınabilir bir model olarak algılandığını göstermektedir. Bu durum, İslam geleneğindeki "Üsve-i Hasene/En Güzel Örnek"

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(Ahzâb, 33/21) anlayışının yurt dışında yaşayan Türk gençliği tarafından içselleştirildiğini ortaya koymaktadır: "Benim için Hz. Muhammed mutlaka takip edilmesi gereken bir örnektir. Mütevazı ve iyi niyetli olmamızı öğretiyor…"

Teolojik Kimlik: Katılımcıların %64'ü (23 kişi) Hz. Muhammed'i "Son Peygamber" ve "Allah'ın Elçisi" olarak tanımlamaktadır. Ancak bu vurgu, ahlaki erdemlerin gerisinde kalmaktadır. Katılımcılar için Hz. Muhammed, önce "güzel ahlaklı" bir şahsiyet, ardından "Allah'ın Elçisi"dir. Bu sıralama, modern ve rasyonel bir din anlayışının yansıması olarak değerlendirilebilir: "Hz. Muhammed, İslam dininin son peygamberi ve en büyük rehberidir. Allah'ın mesajını insanlara ulaştırmış…"

Duygusal Bağ ve Manevi Yakınlık: Katılımcıların %14'ü (5 kişi), Hz. Muhammed ile duygusal bir bağ kurduğunu ifade etmektedir. "Sığınak", "huzur", "liman" gibi metaforlar, onun yalnızca bir öğretici değil, aynı zamanda duygusal bir destek figürü olduğunu göstermektedir: "Benim için adaletin, merhametin ve güvenin zirvesidir. Hayat karmaşasında sığınabileceğim ahlaki bir limandır."

2. Siyer Okuma Alışkanlıkları (2. Soru)

Genel Okuma Durumu: Katılımcıların %80'i (24 kişi) Hz. Muhammed'in hayatı hakkında en az bir kitap okuduğunu belirtmiştir. Bu oran, dini bilgi ediniminde yazılı kaynakların önemli bir yer tuttuğunu göstermektedir.

Tablo 1. Katılımcıların Hz. Muhammed'in Hayatına İlişkin Kitap Okuma Durumu

Kategori	**Sayı**	**Yüzde**
Evet (Okumuş)	24	%80
Hayır (Okumamış)	6	%20

Dil Tercihi: Okunan kitapların büyük çoğunluğu Türkçe'dir (%53,3). Fransızca eserler %13,3 oranında kalırken, Arapça eser hiç okunmamıştır. Bu durum, Türkçenin yurt dışında yaşayan Türk gençliği için bir "din dili" olarak korunduğunu ve Arapça bilgisinin sınırlı olduğunu göstermektedir. Bir katılımcı bu tercihini şöyle açıklamıştır: "Türkçe Siyer kitapları okudum. Arapçam yok ve Batı dillerine tercüme edilmiş veya kaleme alınmış kitaplara güvenim yok."

Tablo 2. Katılımcıların Siyer Okumalarında Dil Tercihleri

Dil	**Sayı**
Sadece Türkçe	16
Sadece Fransızca	4
Türkçe ve Fransızca	2
Arapça	0

Hatırlama Düzeyi: Katılımcıların sadece %23'ü (7 kişi) okuduğu eserin hem adını hem yazarını hatırlayabilmiştir. Bu, okuma eyleminin derinlemesine ve etkileyici olmadığını, daha çok yüzeysel bir "bilgi tüketimi" olarak kaldığını düşündürmektedir: "Evet, gençken okumuştum ama kitabın ismini ya da yazarın ismini hatırlamıyorum."

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Tercih Çeşitliliği: Katılımcılar, hem Diyanet gibi resmi kurumların yayınlarına hem de popüler ve güncel dile sahip eserlere (Herkes için Siyer, Aile Reisi Olarak Peygamber Efendimiz) yönelmektedir. Bu, genç okuyucunun hem kurumsal otoriteye hem de anlaşılır, modern üsluba sahip eserlere ihtiyaç duyduğunu göstermektedir: "Evet, Diyanet'in Siyer kitabı[6] ile Bekir Develi ve Muhammed Emin Yıldırım'ın 'Herkes için Siyer' kitaplarını okudum."

3. Bilgi Kaynakları (3. Soru)

Katılımcılar, Hz. Muhammed hakkındaki bilgilerini birden fazla kaynaktan edindiklerini belirtmişlerdir. Hiçbir katılımcı tek bir kaynakla sınırlı kalmamıştır. En yaygın kaynaklar şu şekildedir:

- **Cami ve Kurumsal Dinî Eğitim:** %86,1 (31 kişi)
- **Aile:** %75,0 (27 kişi)
- **Kitap:** %41,7 (15 kişi)
- **İnternet ve Sosyal Medya:** %33,3 (12 kişi)
- **Dernek ve Sohbetler:** %16,7 (6 kişi)
- **Arkadaş:** %13,9 (5 kişi)

Katılımcıların büyük çoğunluğu, birden fazla kaynağı bir arada kullanmaktadır. En yaygın üçlü kombinasyonlar şunlardır: Aile + Cami + Kitap; Aile + Cami + İnternet; Aile + Cami + Arkadaş.

Cami ve Kurumsal Dinî Eğitim: Cami, %86,1 ile en yüksek frekansa sahip kaynaktır. Bu, Fransa'da yaşayan Türk topluluğunda caminin sadece ibadet yeri değil, aynı zamanda bir bilgi ve sosyalleşme merkezi olduğunu gösterir: "Küçükken camide öğrendim, büyüyünce sohbetlerde ve annemin anlattıklarından ama en çok internetten öğrendim."

Aile: Aile, %75 ile en sık zikredilen ikinci kaynaktır. Bu, dinî bilginin ilk ve en temel aktarım kanalının aile olduğunu gösterir. Özellikle anne ve baba figürleri, çocukluk döneminde ilk dinî bilgilerin aktarılmasında belirleyici rol oynamaktadır: "Genellikle önce aileyle, sonra cami ve dernekle."

İnternet ve Sosyal Medya: İnternet ve sosyal medya, %33,3 ile dördüncü sıradadır. Özellikle YouTube ve Instagram gibi platformlar, genç katılımcılar için önemli bilgi kaynaklarıdır. "Güvenilir internet kaynakları" vurgusu, katılımcıların dijital ortamda da kaynak eleştirisi yaptığını ve bilgi kirliliğine karşı duyarlı olduğunu gösterir: "Kitaplardan, YouTube'daki güvenilir siyer derslerinden ve Bünyamin D. Hoca'nın camideki derslerinden."

DEĞERLENDİRME

Araştırma bulguları, Paris bölgesinde yaşayan Türk kökenli genç Müslümanların Hz. Muhammed algısının dört katmanlı bir yapıdan oluştuğunu ortaya koymaktadır:

Tablo 3. Katılımcıların Hz. Muhammed Algısının Katmanları ve Tematik Dağılımı

Katman	Tema	Oran
1. En Dış Katman	Pratik Yaşam Rehberliği (Örnek, Rehber)	%94
2. Orta Katman	Ahlaki Erdemler (Merhamet, Dürüstlük, Adalet, Sabır)	%61
3. Derin Katman	Teolojik Kimlik (Son Peygamber, Allah'ın Elçisi)	%64
4. En Derin Katman	Duygusal Bağ ve Manevi Yakınlık	%14

[6] Katılımcı burada eser adını tam hatırlayamadı. Bununla ilgili Diyanet İşleri Başkanlığı ve Türkiye Diyanet Vakfı tarafından birçok eser yayımlanmıştır. Geniş bilgi için bkz: Çağlayan, İ. (2025). *Siyer yayıncılığı bağlamında Diyanet İşleri Başkanlığı*. Kitap Dünyası Yayınları.

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Bu katmanlı yapı, katılımcıların Hz. Peygamber ile kurduğu ilişkinin çok boyutlu ve zengin olduğunu göstermektedir. En dışta, onu günlük hayatta uygulanabilir bir "örnek" ve "rehber" olarak gören pratik bir yaklaşım yer almaktadır. Bunun altında, merhamet, dürüstlük, adalet ve sabır gibi erdemlerle tanımlanan ahlaki katman bulunur. Daha derinde, onu "Allah'ın Elçisi" ve "Son Peygamber" olarak konumlandıran teolojik kimlik vardır. En iç katmanda ise sevgi, huzur ve sığınak gibi duygusal bağlarla kurulan manevi bir ilişki söz konusudur.

Fransa gibi Müslümanların azınlıkta olduğu bir ülkede, Hz. Muhammed'in merhamet ve sabır gibi vasıfları, katılımcılar için bir kimlik inşası ve baş etme stratejisine dönüşmektedir. Ötekileştirme ve İslamofobi gibi zorlu sosyal koşullarda Müslüman kimliğini korumak için bu ahlaki modele sarılmak, bir tür direnç mekanizması olarak okunabilir. Katılımcılar, Hz. Muhammed'i hem "Allah'ın elçisi" (teolojik) hem de "güzel ahlaklı" (ahlaki) bir figür olarak tanımlamaktadır. Ancak ahlaki vurgunun daha baskın olması, modern bireyin dini kurallardan ziyade değerler üzerinden okuma eğilimini yansıtmaktadır.

Soru 2'deki bulgular, siyer okuma oranının yüksek (%80) olmasına rağmen, okunan eserlerin derinlemesine içselleştirilmediğini ve hatırlama düzeyinin düşük olduğunu göstermektedir. Bu durum, okuma eyleminin "bilgi edinme" amacından çok "dini görev bilinci" veya "kültürel aidiyet" duygusuyla yapıldığını düşündürmektedir. Ayrıca, Türkçe kaynakların baskın olması ve Fransızca kaynaklara güvensizlik, yurt dışında yaşayan Türk gençliğinin dilsel sınırlılığını ve Batı'daki oryantalist literatüre karşı mesafeli duruşunu ortaya koymaktadır.

Soru 3'teki bulgular, bilgi ediniminde cami ve ailenin hâlâ birincil kaynaklar olduğunu (%86,1 ve %75), ancak internet ve sosyal medyanın gençler için önemli bir tamamlayıcı kaynak haline geldiğini (%33,3) göstermektedir. Bu durum, geleneksel otorite yapıları varlığını sürdürürken modern bilgi kanallarının da dini bilgi ediniminde giderek daha fazla rol oynadığına işaret etmektedir. Özellikle YouTube'daki belirli kişilerin takip edilmesi, dijital platformlarda yeni nesil din anlatıcılarının oluştuğunu düşündürmektedir.

SONUÇ

Bu araştırma, Paris bölgesinde yaşayan Türk kökenli genç Müslümanların Hz. Muhammed algısının, siyer bilgi düzeylerinin ve bilgi kaynaklarının çok katmanlı ve karmaşık bir yapıya sahip olduğunu ortaya koymaktadır. Elde edilen bulgular beş ana sonuç etrafında toplanabilir:

1. Hz. Muhammed'in "Örnek" ve "Rehber" Olarak Algılanması: Katılımcıların tamamına yakını (%94), Hz. Muhammed'i öncelikle bir örnek ve rehber olarak konumlandırmaktadır. Merhamet, dürüstlük, adalet ve sabır gibi erdemler, onun algısının merkezinde yer almaktadır. Bu bulgu, "Üsve-i Hasene" anlayışının yurt dışında yaşayan Türk gençliği tarafından içselleştirildiğini göstermektedir.

2. Ahlaki Vurgunun Teolojik Kimlikten Baskın Olması: Katılımcılar için Hz. Muhammed, önce "güzel ahlaklı" bir şahsiyet, ardından "Allah'ın Elçisi"dir. Bu sıralama, modern bireyin din anlayışında etik değerlerin dogmatik kimlikten önce geldiğini göstermektedir. Fransa gibi laik ve çok kültürlü bir toplumda, dinin evrensel ahlaki ilkelerle ifade edilmesi, hem bireysel inanç hem de toplumsal uyum açısından daha işlevsel görünmektedir.

3. Yüksek Okuma Oranına Rağmen Sınırlı Okuma Derinliği: Siyer okuma oranı %80 gibi yüksek bir seviyede olmasına rağmen, katılımcıların büyük bir kısmı okuduğu eserin adını veya yazarını hatırlamamaktadır. Bu durum, okumanın derinlemesine olmadığını ve bilginin kalıcılığının sınırlı olduğunu göstermektedir. Ayrıca, Türkçe kaynakların baskın olması ve Fransızca kaynaklara güvensizlik, yurt dışında yaşayan Türk gençliğinin dilsel sınırlılığını ve Batı'daki oryantalist literatüre karşı mesafeli duruşunu yansıtmaktadır.

4. Geleneksel ve Dijital Kaynakların İç İçe Geçmesi: Bilgi ediniminde aile ve cami hâlâ birincil kaynaklar olmayı sürdürürken, internet ve sosyal medya giderek artan bir önem kazanmaktadır. Özellikle YouTube'daki belirli hocaların takip edilmesi, dijital platformlarda yeni nesil din otoritelerinin

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oluştuğunu göstermektedir. Bu durum, geleneksel otorite yapıları ile modern bilgi kanalları arasındaki karmaşık etkileşimi gözler önüne sermektedir.

5. Yurt Dışında Yaşayan Türk Gençliğinde Kimlik İnşası: Fransa gibi Müslümanlar açısından azınlık durumunda olunan bir ülkede, Hz. Muhammed'in merhamet ve sabır gibi vasıfları, katılımcılar için bir kimlik inşası ve baş etme stratejisine dönüşmektedir. Ötekileştirme ve İslamofobi gibi zorlu sosyal koşullarda Müslüman kimliğini korumak için bu ahlaki modele sarılmak, bir tür direnç mekanizması olarak okunabilir.

ÖNERİLER

Araştırma bulguları ışığında şu öneriler geliştirilebilir:

1. Eğitim Müfredatının Zenginleştirilmesi: Hz. Muhammed'in hayatı ve ahlaki vasıflarının, camilerde ve okullarda yürütülen eğitim faaliyetlerinde ve aile içi din eğitiminde daha somut örneklerle işlenmesi gerekmektedir. Özellikle okunan eserlerin derinlemesine anlaşılması ve içselleştirilmesi için okuma rehberleri ve tartışma grupları oluşturulabilir.

2. Dijital ve Görsel Medyanın Etkin Kullanımı: Gençlerin bilgi ediniminde önemli bir yer tutan dijital platformlarda (YouTube, Instagram, podcastler), Hz. Muhammed'in hayatını ve ahlaki mesajlarını içeren güvenilir ve ilgi çekici içeriklerin üretilmesi ve yaygınlaştırılması teşvik edilmelidir.

3. Fransızca Güvenilir Kaynakların Geliştirilmesi: Katılımcıların Fransızca kaynaklara güvenmemesi, bu alanda önemli bir eksiklik olduğunu göstermektedir. Fransa'daki Müslüman gençlere yönelik, oryantalist önyargılardan arındırılmış, akademik ve güvenilir Fransızca siyer kaynaklarının geliştirilmesi ve yaygınlaştırılması gerekmektedir.

4. Aile ve Cami İşbirliğinin Güçlendirilmesi: Aile ve cami, dinî bilgi aktarımında hâlâ en temel kaynaklar olarak işlev görmektedir. Bu iki kurum arasındaki iş birliğinin güçlendirilmesi, gençlerin dini kimlik inşasında daha tutarlı ve derinlikli bir bilgi aktarımına imkân tanıyacaktır.

5. Somut Örneklerle Bilgi Derinliğinin Artırılması: Katılımcıların genel farkındalık düzeyi yüksek olsa da somut örnek verebilme oranının sınırlı olması, bilgi derinliğinin artırılması ihtiyacını göstermektedir. Bu doğrultuda, Hz. Peygamber'in hayatından pratik ve günlük hayata uyarlanabilir örneklerin ön plana çıkarılması faydalı olacaktır.

6. Karşılaştırmalı Çalışmaların Yapılması: Bu çalışma, belirli bir zaman kesitinde 36 katılımcıyla sınırlıdır. Gelecek yapılacak araştırmalarda, farklı kuşaklar, farklı etnik kökenler ve farklı sosyo-ekonomik grupları kapsayan karşılaştırmalı çalışmaların yapılması, yurt dışında yaşayan Türk gençliğinin dini kimlik inşası sürecinin daha iyi anlaşılmasına katkı sağlayacaktır.

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ANADOLU TUNÇ DÖNEM İNSANLARININ SAĞLIK SORUNLARI
HEALTH ISSUES OF PEOPLE IN THE ANATOLIAN BRONZE AGE

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ÖZET

Anadolu, tarih öncesinden günümüze kadar kesintisiz yerleşime sahne olmuş ve farklı kültürlere ev sahipliği yapmış önemli bir coğrafyadır. Bu nedenle insan iskelet kalıntıları, geçmiş toplumların biyolojik yapısı, sağlık durumu, beslenme alışkanlıkları, yaşam biçimi ve çevresel koşullara uyum süreçlerinin değerlendirilmesinde temel veri kaynaklarını oluşturmaktadır. Bu verilerin yorumlanmasında paleopatolojik araştırmalar önemli bir yere sahiptir. Tunç Çağı, yazının kullanılmaya başlanması, ticaret ağlarının gelişmesi ve nüfus hareketliliğinin artmasıyla Anadolu'da önemli ekonomik, teknolojik ve toplumsal dönüşümlerin yaşandığı bir dönemdir. Bu süreçte yerleşimlerin büyümesi, topluluklar arası etkileşim ve göçlerin artması, toplumların biyolojik yapısını ve sağlık profillerini doğrudan etkilemiştir. Buna karşın Anadolu Tunç Çağı topluluklarına yönelik biyoarkeolojik ve paleopatolojik çalışmaların sayısı halen sınırlıdır. Bu bildiride, Anadolu Tunç Çağı insan iskeletleri üzerinde gerçekleştirilen paleopatolojik çalışmalar derlenerek dönemin sağlık profili biyoarkeolojik açıdan değerlendirilmiştir. Literatür verileri; dejeneratif eklem hastalıkları, travmatik lezyonlar, enfeksiyon hastalıkları, hematolojik kökenli kemik değişiklikleri ve metabolik hastalıkların farklı yerleşimlerde değişen sıklıklarda görüldüğünü ortaya koymaktadır. Ayrıca bu patolojik bulguların beslenme alışkanlıkları, fiziksel aktivite düzeyi, geçim ekonomisi, mesleki yüklenmeler ve çevresel koşullarla yakından ilişkili olduğu anlaşılmaktadır. Sonuç olarak paleopatolojik veriler, Anadolu Tunç Çağı topluluklarının yalnızca sağlık durumunun değil, aynı zamanda yaşam biçimi, çevresel adaptasyonu ve biyokültürel yapısının anlaşılmasına önemli katkılar sağlamaktadır. Bu çalışma, mevcut paleopatolojik bulguları bütüncül bir bakış açısıyla değerlendirerek Tunç Çağı Anadolu toplumlarının sağlık ve yaşam koşullarına ilişkin genel bir çerçeve sunmayı amaçlamaktadır.

Anahtar kelimeler: Anadolu, Tunç Çağ, paleopatoloji, sağlık

ABSTRACT

Anatolia is a significant region that has been continuously inhabited from prehistoric times to the present day and has been home to diverse cultures. Hence, human skeletal remains serve as fundamental data sources for assessing the biological structure, health status, dietary habits, lifestyle, and processes of adaptation to environmental conditions of past societies. Paleopathological research plays a significant role in the interpretation of this data. The Bronze Age is a period during which Anatolia underwent significant economic, technological, and social transformations, marked by the advent of writing, the development of trade networks, and increased population mobility. The growth of settlements, increased interaction between communities, and rising migration during this age directly influenced the biological structure and health profiles of these societies. Nevertheless, the number of bioarchaeological and paleopathological studies on Anatolian Bronze Age communities remains limited. In this paper, paleopathological studies conducted on Anatolian Bronze Age human skeletons have been compiled, and the health profile of the age has been evaluated from a bioarchaeological perspective. Data from the literature indicate that degenerative joint diseases, traumatic lesions, infectious diseases, bone changes of hematological origin, and metabolic diseases occur with varying frequencies in different locations. Furthermore, it is understood that these pathological findings are closely related to dietary habits, physical activity levels, subsistence economy, occupational stresses, and environmental conditions. In conclusion, paleopathological data make significant contributions to our understanding not only of the

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health status of Bronze Age communities in Anatolia but also of their lifestyle, environmental adaptation, and biocultural structure. This study aims to provide a general framework regarding the health and living conditions of Bronze Age Anatolian societies by evaluating existing paleopathological findings from a holistic perspective.

Key words: Anatolian, bronze age, paleopathology, health

GİRİŞ

İnsan vücudu yüzbinlerce yıl süren biyolojik ve kültürel etkileşimler sonrasında evrilmiş birçok özelliğe sahip olmuştur. Örneğin taş aletlerin keşfi, onları üretebilmek ve kullanabilmek için daha fazla çevikliğe ve yeteneğe yönelik seçilimi mümkün kılmıştır. Erken Paleolitik Dönem'de taş aletlerin yapılmaya başlanmasından sonra dişler daha küçük olma yönünde seçilime uğraması; yemeklerin pişirmeye başlanmasından sonra sindirim sistemlerinin de değişikliğe uğraması uyarlanma örnekleridir. Geç Paleolitik Dönem'de insanlar; dünyaya yayılmaya başlamalarıyla yeni mikroplarla, alışkın olmadıkları yiyeceklerle ve çok çeşitli iklimsel şartlarla karşıladıklarında, doğal seçilim, birbirinden yeni ayrılmış bu insanları farklı çevrelere uyarlamıştır (Lieberman, 2015). Ancak; Paleolitik Dönem avcı-toplayıcılarının sağlık durumları ile ilgili çok fazla bilgi bulunmamaktadır. Paleolitik Dönemi takip eden çiftçilik-endüstrileşme süreci; insanlar için konfor ve kolaylık sağlamış olsa da bu süreç, Paleolitik Dönem'de çok nadir görülen veya hiç görülmeyen yeni hastalıkları ve diğer sorunları da beraberinde getirmiştir. Çiçek hastalığı, çocuk felci ve veba gibi salgın hastalıklar *Tarım Devrimi*'nden sonra görülmeye başlamıştır. Neolitik Dönem, avcı-toplayıcı yaşam biçiminden tarım ve hayvancılığa dayalı yerleşik düzene geçişle karakterize önemli bir süreci ifade etmektedir. Bu süreçte insan toplulukları hareketli yaşamdan yerleşik düzene geçiş yapmışlardır. Bu dönüşüm, yalnızca ekonomik üretim biçimlerini değil, aynı zamanda çevreyle kurulan ilişkiyi, demografik yapıyı ve beslenme alışkanlıklarını da köklü biçimde değiştirmiştir. Bu değişim süreci beraberinde nüfusta büyüme, üretim kapasitesinde artış ve toplumsal yapıda önemli değişiklikleri de beraberinde getirmiştir. Son dönemlerde artan biyoarkeolojik ve paleopatolojik araştırmalar, bu sürecin insanların sağlığı üzerindeki etkilerinin çok da olumlu yönde olmadığını ortaya koymuştur. Bu araştırmalara ilişkin veriler, tarıma geçişle birlikte toplumların genel sağlık düzeyinin gerilediği ve birçok hastalığın da yaygınlaştığını göstermektedir. Avcı-toplayıcı insanlar neredeyse yenilebilir her şeyi yedikleri için hayatta kalmışlardır. Doğal olarak avcı-toplayıcıların besin türleri son derece çeşitlidir ve herhangi bir mevsimde düzinelerce farklı bitki türünü içermiştir (Hill vd., 1984:101-135). Buna karşın çiftçiler bol mahsul veren birkaç ana ürüne odaklanarak, nicelik için niteliği ve çeşitliliği feda etmişlerdir. Bu dönemde tüketilen kalorilerin çoğunu büyük bir ihtimalle mısır, pirinç, buğday ve patates oluşturuyordu. Arpa, darı, çavdar gibi ürünler muhtemelen çiftçiler için temel ürünlerdi. Kolay bir şekilde, bol miktarda yetiştirilebilen bu temel ürünler, kalori açısından zengindirler ve hasattan sonra uzun süre depolanabilmektedir. Ancak, bu ürünler avcı-toplayıcılar ve diğer primatlar tarafından tüketilen yabani bitkilere göre vitamin ve mineral açısından daha fakirdirler (Eaton vd., 1997: 207-216). Et, meyve ve diğer sebzeler gibi besinler olmadan, temel ürünlere fazla miktarda bağımlı olan çiftçilerin, besin eksikliklerine maruz kalmış olmaları muhtemeldir. Avcı-toplayıcıların aksine çiftçilerde C vitamini eksikliğinden iskorbüt, B1 vitamini eksikliğinden beriberi, B3 vitamini eksikliğinden pellegra, demir eksikliğinden anemi gibi hastalıklar görülmüştür (Cordain, 2002:280-281).

Pirinç ve buğday gibi tahıllarda vitamin, mineral, lif ve sağlıklı yağların büyük bölümü; nişastaca zengin olan iç kısmı (endosperm) çevreleyen dış katmanlarda ve embriyoda bulunur. Ancak, bitkilerin bu besleyici kısımları hızlı bozulmaktadır. Çiftçilerin, temel gıdalarını uzun süre saklamaları gerekmektedir. Bu nedenle, çiftçiler zamanla pirinç ve buğdayın kepek katmanlarını ayıklayarak tahılları rafine etmenin, yağ içeriğini azaltarak bozulmayı geciktirdiğini ve raf ömrünü uzattığını keşfetmişlerdir. Ancak bu işlem, tahılın vitamin, mineral ve lif içeriğinin önemli ölçüde azalmasına da neden olmuştur. Bu işleme teknolojileri ilk çiftçilerin yaşadığı dönemlerde mevcut değildi. Ancak zamanla pirinç ve buğdayın rafine edilmesi yaygınlaşmıştır. Bu işlem, tahılların raf ömrünü uzatırken besin değerlerini önemli ölçüde azaltmıştır. Örneğin, bir bardak esmer pirinç ile beyaz pirinç yaklaşık aynı miktarda kalori içermektedir. Buna karşılık esmer pirinç, üç ila altı kat daha fazla B vitamini içermektedir; ayrıca E vitamini, magnezyum, potasyum, fosfor ve lif bakımından da çok daha zengindir.

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Rafine edilmiş tahıllar ile bazı modern tarım çeşitleri, tam tahıllara kıyasla daha düşük lif içermektedir. Özellikle rafine etme işlemi sırasında kepek ayrıştırıldığı için lif miktarı önemli ölçüde azalmaktadır. Lif, besinlerin sindirim sistemi boyunca ilerlemesini düzenlemekte; mide boşalmasını ve karbonhidratların sindirim ile emilim hızını yavaşlatarak kan şekerinin daha dengeli yükselmesine ve daha uzun süre tokluk hissinin korunmasına yardımcı olmaktadır. Ayrıca bağırsak hareketlerini destekleyerek dışkının bağırsaklardan geçişini kolaylaştırmaktadır. Uzun süre gıda depolamanın bir diğer riski ise küf ve diğer mikroorganizmalarla meydana gelen kirlenmedir. Örneğin aflatoksinler, uygun olmayan koşullarda depolanan tahıllar, sert kabuklu yemişler ve yağlı tohumlarda gelişebilen bazı küf türleri tarafından üretilen toksik maddelerdir. Bu toksinler karaciğere zarar verebilir; uzun süre veya yüksek miktarda maruz kalınması durumunda karaciğer kanseri riskini artırabilir ve çeşitli sağlık sorunlarına yol açabilir. Avcı-toplayıcılar bir veya iki günden fazla yiyecek depolamadıkları için, bu toksinlere neredeyse hiç maruz kalmadıkları düşünülmektedir (Lieberman, 2015:274)

Çiftçilerin beslenme biçiminin yol açtığı bir diğer önemli sağlık sorunu ise nişasta bakımından zengin besinlerin aşırı tüketimidir. Avcı-toplayıcılar; meyveler, sebzeler ve çeşitli yabani bitkiler sayesinde daha dengeli miktarda lif ve karmaşık karbonhidrat tüketirken; tarımla birlikte insanlar tahıllar, yumru kökler ve diğer nişasta bakımından zengin bitkilere daha fazla bağımlı hâle gelmiştir. Bu durum; beslenme çeşitliliğini azaltmış, günlük enerji alımında nişastanın payını önemli ölçüde artırmıştır. Nişastalı besinler önemli bir enerji kaynağı olsa da özellikle rafine edilmiş tahılların aşırı tüketimi çeşitli sağlık sorunlarını ortaya çıkarmıştır. Diş çürükleri bu sağlık sorunlarından biridir. Ağızdaki bakteriler nişasta ve şekerleri parçalayarak diş minesini aşındıran asitler üretmektedir. Arkeolojik çalışmalardan ele geçen iskelet kalıntıları, diş çürüklerinin avcı-toplayıcı toplumlarda oldukça nadir olduğunu, ancak tarımın başlaması ve nişastaca zengin beslenmenin yaygınlaşmasıyla ilk çiftçiler arasında belirgin biçimde arttığını göstermektedir. Dişin taç kısmında başlayan ve köke kadar ilerleyen çürükler, şiddetli ağrıya neden olmanın yanı sıra diş pulpasına ve çevre dokulara yayılan enfeksiyonlara yol açmaktadır. Tedavi edilmediğinde ise bu enfeksiyonlar kana karışarak yaşamı tehdit eden ciddi sorunlara neden olabilmektedir (Hillson, 2008: 111-135).

Daha fazla sayıda besin çeşitliliği ve daha düzenli bir yaşam şekli, çiftçi insanların daha büyük aileler kurabilmesine ve nüfusun hızla artmasına olanak sağlamıştır. Ancak; nüfusun büyümesi, insanların daha kalabalık ve yerleşik düzende yaşamaya başlamasıyla birlikte bulaşıcı hastalıkların ortaya çıkması ve yayılması için elverişli koşullar oluşturmuştur. Bu doğrultuda, Tarım Devrimi'nin yol açtığı en önemli evrimsel uyumsuzluklardan biri enfeksiyon hastalıklarının yaygınlaşması olmuştur. Bu hastalıklar tarih boyunca milyonlarca insanın ölümüne neden olmuş ve günümüzde de küresel ölçekte önemli bir sağlık sorunu olmaya devam etmektedir. Salgın hastalıkların ortaya çıkması ve yayılabilmesi için gerekli koşullardan biri de yüksek nüfus yoğunluğuna sahip kalıcı yerleşim alanlarının oluşmasıdır. Çiftçiler; değirmenler, sulama sistemleri ve diğer ortak kaynaklardan yararlanmak ve ticareti kolaylaştırmak için çoğunlukla köylerde yaşamaya başlamışlardır. Bu ekonomik ve toplumsal avantajlar, tarımın başlamasıyla birlikte gerçekleşen hızlı nüfus artışıyla birleşerek yerleşimlerin giderek büyümesine ve daha yoğun hâle gelmesine olanak sağlamıştır. Natufyan Dönemi'nde yaklaşık 10 evden oluşan küçük mezralar, Neolitik Çağ'da 50 veya daha fazla ev içeren köylere dönüşmüş; yaklaşık 7.000 yıl önce ise nüfusu bin kişiyi aşan küçük kasabalar ortaya çıkmaya başlamıştır. Nüfus arttıkça yerleşimlerin yoğunluğu da yükselmiştir. Avcı-toplayıcı topluluklar, kaynaklara olan bağımlılıkları nedeniyle genellikle kilometrekare başına bir kişiden daha az nüfus yoğunluğunda yaşarken, tarım toplumlarında bu yoğunluk çok daha yüksek seviyelere ulaşmıştır (Zimmermann vd., 2009:357-380). Daha büyük ve yoğun topluluklarda yaşamak sosyal açıdan zenginleştirici ve ekonomik olarak avantaj sağlayabilir; ancak bu yoğunluklar aynı zamanda ölümcül olabilecek sağlık risklerini de beraberinde getirmiştir. Çok sayıda bulaşıcı hastalık türü söz konusudur ve bu hastalıkların nedeni, konak canlılara girerek onların kaynaklarını kullanan, çoğalan ve ardından yeni konaklara yayılan patojenlerdir. Bir enfeksiyonun bir popülasyonda kalıcı olarak varlığını sürdürebilmesi; hastalığın yayılabileceği yeterli sayıda konağın bulunması, patojenin bir konaktan diğerine geçebilme yeteneği ve enfekte olan konağın hastalık sonrasında hayatta kalma oranı gibi çeşitli faktörlere bağlıdır (Ewald, 1994).

Köyler ve kasabalar, çok sayıda potansiyel konağı birbirine yakın şekilde bir araya getirerek bulaşıcı hastalıkların yayılması için elverişli ortamlar oluşturmuştur. Bu yoğun yerleşimler, patojenlerin insan toplulukları içinde daha kolay aktarılmasına ve varlığını sürdürmesine olanak sağlamıştır. Ticaretin de

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bulaşıcı hastalıkların yayılmasını kolaylaştıran bir diğer önemli etken olduğu bilinmektedir. Tarım toplumları üretim fazlası sayesinde düzenli olarak mal alışverişi yapmaya başlamışlardır; ancak, bu hareketlilik yalnızca ürünlerin değil, mikroorganizmaların da bir topluluktan diğerine taşınmasına yol açmıştır. Bu koşullar, tarımın yaygınlaşmasıyla birlikte verem, cüzzam, frengi ve veba gibi birçok bulaşıcı hastalığın insan toplulukları arasında daha büyük ölçekte yayılmasına zemin hazırlamıştır (Barnes, 2005). Bu durum, avcı-toplayıcıların hiç hastalanmadığı anlamına gelmez. Ancak çiftçilikten önce insanlar çoğunlukla diğer memelilerle temas, kirlenmiş yiyecek ve su kaynakları yoluyla bulaşan bağırsak parazitleri ile uçuk gibi hastalıklara neden olan bazı virüs ve bakterilerin yol açtığı enfeksiyonlarla karşı karşıyaydı (Armelagos vd., 1991:9-22). Büyük olasılıkla sıtma ve frambezi gibi bazı hastalıklar avcı-toplayıcı topluluklarda da görülüyordu; ancak bu hastalıkların yaygınlığı ve sürekli dolaşımda kalma ihtimali, çiftçi toplumlarına kıyasla çok daha düşüktü. Bunun temel nedenlerinden biri, avcı-toplayıcı grupların düşük nüfus yoğunluklarına ve hareketli yaşam biçimlerine sahip olmalarıydı. Nüfus yoğunluğu düşük olduğunda, birçok bulaşıcı hastalık kendini sürdürebilecek yeterli sayıda konağı bulmakta zorlanmaktadır. Bu nedenle Neolitik öncesi dönemde, daha sonraki tarım toplumlarında görülen türden kalıcı ve büyük ölçekli salgınların ortaya çıkması çok daha zordu. Çiçek hastalığı gibi bazı eski viral hastalıkların kökeni ise insanlarla hayvanlar arasındaki uzun süreli etkileşimlerle ilişkilendirilmektedir. Ancak bu tür hastalıkların geniş insan toplulukları arasında kalıcı biçimde yayılması, büyük ve yoğun yerleşimlerin ortaya çıkmasından sonra çok daha mümkün hâle gelmiştir (Li vd., 2003).

Yetersiz sanitasyon, tarımla birlikte ortaya çıkan evrimsel uyumsuzluklarla ilişkili sağlık sorunlarının önemli nedenlerinden birini oluşturmaktadır. Küçük ve geçici kamplarda yaşayan avcı-toplayıcı topluluklar, hareketli yaşam biçimleri sayesinde atıklarını çevreye daha seyrek ve dağınık biçimde bırakıyorlardı. Ancak insanlar kalıcı yerleşimlere geçtiklerinde, daha fazla miktarda atık biriktirmeye ve yaşadıkları alanları kirletmeye başladılar. Kalıcı tuvaletler ve atık alanları, insan dışkısının su kaynaklarına ve toprağa karışmasına yol açarak hastalıkların yayılma riskini artırmıştır. Aynı zamanda biriken çöpler; fareler, sıçanlar ve bazı kuş türleri gibi insan yerleşimlerinden faydalanan hayvanlar için uygun beslenme ve barınma alanları oluşturmuştur. Bu tür hayvanlar, insan faaliyetleriyle oluşan güvenli ortamlarda doğal avcılardan korunarak çoğalma avantajı elde etmiştir. İnsanlar kapalı kanalizasyon sistemleri ile septik alanlar ve diğer ortak sanitasyon altyapılarını inşa etmeye başlayana kadar, kalıcı köy yaşamı, birçok bulaşıcı hastalığın ortaya çıkması ve yayılması için uygun bir ortam oluşturmuştur. Atıkların güvenli biçimde uzaklaştırılamaması, su ve toprağın kirlenmesine yol açarak insan sağlığı üzerinde önemli riskler meydana getirmiştir (Lieberman, 2015:283).

TUNÇ ÇAĞI İLE ANADOLU İNSANLARININ YAŞAMINDA MEYDANA GELEN DEĞİŞİMLER

Anadolu'da Kalkolitik Dönem'den Tunç Çağı'na geçiş, insanların yaşam biçimlerinde zaman içerisinde önemli değişimlerin meydana geldiği bir süreçtir. Bu süreçte teknolojik, ekonomik ve toplumsal alanlarda yaşanan dönüşümlerin birbirini etkileyerek ilerlediği görülmektedir. Özellikle Erken Tunç Çağı'nda Anadolu'nun farklı bölgelerinde kentleşmenin gelişmesi, üretimde uzmanlaşmanın artması ve bölgeler arasındaki ilişkilerin güçlenmesi dikkat çekmektedir (Çevik, 2013). Bu dönemde metal teknolojisindeki gelişmelerin yanı sıra yerleşimlerin büyümesi, üretim faaliyetlerinin çeşitlenmesi, zanaatlarda uzmanlaşma ve bölgeler arası ticaretin gelişmesi de insanların günlük yaşamını etkileyen değişimler arasında yer almaktadır (Massa vd., 2017; Derin & Erdem, 2024). Bununla birlikte, söz konusu gelişmeler Anadolu'nun tüm bölgelerinde aynı şekilde ve aynı zamanda gerçekleşmemiş; bölgesel farklılıklar, ekonomik faaliyetlerin ve toplumsal yapının şekillenmesinde etkili olmuştur (Çevik, 2013).

Madencilik ve Metal Teknolojisindeki Gelişmeler

Kalkolitik Dönem'den Tunç Çağı'na geçiş sürecinde öne çıkan gelişmelerden biri metal teknolojisindeki ilerlemedir. Anadolu'da bakır ve diğer metallerin kullanımı Kalkolitik Dönem'den itibaren bilinmekle birlikte, metal üretimine yönelik tekniklerin özellikle Geç Kalkolitik ve Erken Tunç Çağı'nda daha da geliştiği görülmektedir (Stronach, 1957). Erken Tunç Çağı'na gelindiğinde metal üretimi daha fazla bilgi ve uzmanlık gerektiren bir faaliyet hâline gelmiştir. Batı Anadolu'daki Yassıtepe Höyüğü'nde Erken Tunç Çağı I dönemine tarihlenen pota ve cürufların bulunması, yerleşimde metal

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üretiminin gerçekleştirildiğini göstermektedir (Derin & Erdem, 2024). Demircihüyük'te yapılan çalışmalar da metal üretiminin belirli bir teknik bilgi birikimine dayandığını ve yerleşimin farklı metalürjik ağlarla bağlantılı olduğunu ortaya koymaktadır. Bu durum, Anadolu'nun farklı bölgeleri arasında hammadde ve teknolojinin dolaşımda olduğunu düşündürmektedir (Massa vd., 2017). Metal teknolojisindeki bu gelişmeler, günlük yaşamda metal alet ve silahların kullanımının yaygınlaşmasının yanı sıra metal işçiliğinin de belirli bilgi ve becerilere sahip zanaatkârların uzmanlaştığı bir faaliyet alanına dönüşmesine zemin hazırlamıştır. Özellikle cevherin çıkarılması ve işlenmesi ile metal nesnelerin üretilmesi, belirli bir bilgi ve deneyim gerektiren faaliyetlerdi. Üretimdeki bu uzmanlaşmanın, toplum içinde farklı meslek ve uğraşların gelişmesine katkı sağlamış olabileceğini düşündürmektedir. Böylece bazı bireylerin zamanlarının bir bölümünü tarım ve hayvancılığın yanı sıra metal işçiliği ve diğer zanaat faaliyetlerine ayırdığına işaret etmektedir (Derin & Erdem, 2024).

Tarım ve Hayvancılık

Kalkolitik Dönem'den Tunç Çağı'na geçiş sürecinde tarım ve hayvancılık, Anadolu topluluklarının temel geçim kaynakları olmayı sürdürmüştür. Bununla birlikte, ekonomik faaliyetlerin niteliği ve ağırlığı bölgeden bölgeye değişmiştir. Hayvancılığın öne çıktığı bölgelerin yanı sıra, tarıma elverişli alanlarda tahıl üretiminin de önemli bir yer tuttuğu görülmektedir. Bu farklılıklar, toplulukların geçim biçimlerinin büyük ölçüde yaşadıkları çevrenin koşullarına göre şekillendiğini göstermektedir. Üretimin artmasıyla birlikte elde edilen ürünlerin depolanması ve gerektiğinde yeniden dağıtılması da önem kazanmış, böylece üretim ve tüketim arasındaki ilişkiler daha düzenli bir yapıya kavuşmuştur (Yurtsever Beyazıt, 2019).

Yerleşimlerin Büyümesi ve Kentleşme

Kalkolitik Dönem'den Tunç Çağı'na geçişle birlikte Anadolu'daki bazı yerleşimlerin büyüdüğü ve özellikle Erken Tunç Çağı'nda bazı bölgelerde daha büyük ve merkezi yerleşimlerin ortaya çıktığı görülmektedir. Bununla birlikte, bu gelişme Anadolu'nun her bölgesinde aynı şekilde yaşanmamıştır. Bazı bölgelerde büyük yerleşimler ve daha merkezi bir yapı görülürken, bazı bölgelerde küçük yerleşimlerin varlığını sürdürdüğü anlaşılmaktadır. Bu nedenle Erken Tunç Çağı Anadolu'sunda tek tip bir yerleşim ya da toplumsal yapıdan söz etmek mümkün değildir (Çevik, 2013). Bu bölgesel farklılıklar, Anadolu'nun çeşitli kesimlerindeki yerleşimlerde izlenebilmektedir. Batı Anadolu'da Liman Tepe, Erken Tunç Çağı boyunca daha merkezi ve örgütlü bir yerleşim yapısının geliştiğini gösteren önemli örneklerden biridir. Yerleşimdeki mimari düzenleme ve savunma sistemi, kıyı Batı Anadolu'da belirli merkezlerin diğer yerleşimlerden ayrışmaya başladığına işaret etmektedir (Şahoğlu, 2005). Benzer şekilde, Batı ve Orta Anadolu'da Küllüoba ve Seyitömer Höyük gibi merkezlerde Erken Tunç Çağı'nın ilerleyen evrelerinde daha büyük yerleşimlerin, depolama alanlarının ve merkezi yapıların ortaya çıktığı bilinmektedir. Buna karşılık, Anadolu'nun farklı kesimlerinde küçük ölçekli yerleşimlerin varlığını sürdürmesi, söz konusu dönüşümün tüm bölgelerde aynı düzeyde gerçekleşmediğini göstermektedir. Bu durum, Erken Tunç Çağı Anadolu'sunda yerleşimlerin büyüklüğü ve örgütlenme biçiminin bölgesel koşullar, ekonomik ilişkiler ve toplumsal yapılanmalar doğrultusunda farklılaştığını ortaya koymaktadır (Özdoğan, 2023).

Evler ve Günlük Yaşam

Günlük yaşamda meydana gelen değişimler, insanların yaşadığı mekânlara ve yerleşimlerin mimari özelliklerine de yansımıştır. Kalkolitik Dönem'in sonlarında Anadolu'nun farklı bölgelerinde kerpiç, ahşap ve diğer yapı malzemelerinin kullanıldığı çeşitli mimari uygulamalar bilinmektedir. Örneğin, Çaltılar Höyük'te Geç Kalkolitik Dönem'e ait mimari kalıntılar, yerleşimde farklı yapı tekniklerinin kullanıldığını göstermektedir (Aykurt & Böyükulusoy, 2025). Erken Tunç Çağı'nda ise bazı yerleşimlerde barınma alanlarının yanı sıra üretim faaliyetleriyle ilişkili mekânların da bulunduğu anlaşılmaktadır. Örneğin, Yassıtepe Höyüğü'nde metal üretimine işaret eden buluntuların ele geçirilmesi, yerleşimin yalnızca bir yaşam alanı olmadığını, aynı zamanda üretim faaliyetlerinin de yürütüldüğü bir merkez olduğunu düşündürmektedir (Derin & Erdem, 2024). Bu durum, yerleşimlerdeki mekânların yalnızca barınma amacıyla kullanılmadığını; üretim, depolama ve çeşitli zanaat faaliyetlerinin de günlük yaşamın bir parçası olduğunu göstermektedir.

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Toplumsal Farklılaşma

Üretimin çeşitlenmesi, zanaatlarda uzmanlaşmanın artması ve bölgeler arasındaki ilişkilerin güçlenmesi, toplumların yapısında da bazı değişimlere yol açmış olabileceğini düşündürmektedir. Erken Tunç Çağı'nda Anadolu'nun bazı bölgelerinde daha merkezi yerleşimlerin ve kentleşme eğilimlerinin ortaya çıktığı görülmektedir. Ekonomik kaynakların ve üretimin belirli merkezlerde toplanması, bu süreçte toplumsal farklılaşmanın da artmasına neden olmuş olabilir. Bununla birlikte bu durum Anadolu'nun her bölgesinde aynı şekilde gelişmemiştir. Bazı bölgelerde büyük ve merkezi yerleşimler öne çıkarken, bazı yerlerde daha küçük topluluklar yaşamaya devam etmiştir (Çevik, 2013).

Savaş, Silahlar ve Savunma

Bakır ve tunçtan yapılan silahların kullanılmasıyla metal, savaş araçlarının üretiminde daha önemli bir bulmuştur. Metal türleri ve üretim tekniklerindeki gelişmeler, Erken Tunç Çağı'ndaki teknolojik değişimin önemli unsurlarından biri olarak değerlendirilmektedir. Ancak; silahların ve savunma sistemlerinin yaygınlaşması, bu dönemde yaşayan toplulukların sürekli bir savaş ortamı içerisinde bulunduğu şeklinde düşünülmemelidir. Dönemin toplulukları arasındaki ilişkilerin yalnızca çatışma üzerinden şekillenmediği; ticaret, kültürel etkileşim ve karşılıklı iş birliği gibi farklı etkileşim biçimlerinin de bu ilişkilerde önemli bir rol oynadığı anlaşılmaktadır (Stronach, 1957).

İnsan Sağlığı ve Yaşam Koşulları

Kalkolitik Dönem'den Tunç Çağı'na geçiş sırasında yaşanan ekonomik ve teknolojik değişimler, insanların günlük yaşamını ve dolayısıyla sağlık koşullarını da etkilemiştir. Yerleşimlerin büyümesi ve nüfus yoğunluğundaki artışın, bireyler arasındaki temasın artmasına bağlı olarak bulaşıcı hastalıkların yayılımı açısından elverişli koşullar oluşturmuş olabileceği düşünülmektedir. Bunun yanı sıra tarımsal üretimin yaygınlaşması ve beslenme alışkanlıklarındaki değişimler, insan iskeletlerinde ve özellikle dişlerde farklı patolojik izlerin ortaya çıkmasına neden olabilmektedir (Atamtürk & Duyar, 2010; Erdal, 2004). Örneğin, Erken Tunç Çağı'na tarihlenen Resuloğlu topluluğu üzerinde gerçekleştirilen dental antropolojik çalışmalar, diş çürüğü, diş taşı, mine hipoplazisi, apse ve alveol kemik kaybı gibi bulgular üzerinden dönemin beslenme biçimi ve sağlık koşullarına ilişkin önemli veriler sunmaktadır (Atamtürk ve Duyar, 2010). Benzer şekilde, Kültepe'den elde edilen insan iskeletleri üzerinde gerçekleştirilen çalışmalar, bireylerin beslenme biçimleri ve fiziksel aktivitelerinin biyolojik kalıntılar üzerinden değerlendirilebileceğini göstermektedir (Kale vd., 2024). Bu açıdan insan iskeletleri ve dişler üzerinde gerçekleştirilen paleopatolojik ve dental antropolojik incelemeler, geçmiş toplumların yaşam koşullarının ve sağlık profillerinin değerlendirilmesinde önemli bir veri kaynağı oluşturmaktadır. Dolayısıyla Kalkolitik Dönem'den Tunç Çağı'na geçiş sırasında ortaya çıkan ekonomik, teknolojik ve toplumsal dönüşümlerin insan bedeni üzerindeki olası yansımaları, iskelet ve diş kalıntıları üzerinden daha ayrıntılı biçimde değerlendirilebilmektedir.

ESKİ ANADOLU TOPLUMLARININ SAĞLIK YAPISI

Anadolu; Afrika, Avrupa ve Asya arasındaki stratejik konumu nedeniyle tarih boyunca çok sayıda göç, kültürel etkileşim ve biyolojik çeşitliliğe sahne olmuştur. Bu durum, yalnızca kültürel kalıntılara değil, insan sağlığı ve hastalık örüntülerine de yansımıştır. Özellikle Neolitik Dönem'de tarıma geçişle birlikte ortaya çıkan yerleşik yaşam, nüfus yoğunluğunun artması ve hastalıkların yayılımı paleopatolojik kayıtlarda belirgin değişimlere yol açmıştır. Bu bağlamda, Anadolu'daki iskelet serileri; enfeksiyon hastalıklarından travmatik yaralanmalara, beslenme yetersizliklerinden, doğuştan gelen anomalilere kadar geniş bir patolojik yelpazeyi belgelemektedir. Ayrıca; Anadolu paleopatolojisi üzerine yapılan çalışmalar, aynı zamanda sosyal eşitsizliklerin ve kültürel farklılıkların sağlık üzerindeki etkilerini de görünür kılmaktadır.

Dünya genelinde **Paleolitik Dönem** insanlarına ait iskelet kalıntıları üzerinde gerçekleştirilen paleopatolojik çalışmaların sınırlı olduğu görülmektedir. Anadolu'da Paleolitik Dönem'e ait paleopatolojik araştırmalar, bu döneme ait iskelet kalıntılarının az sayıda ele geçirilmesi nedeniyle

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oldukça sınırlıdır (Sağır ve Sağır, 2013). Buna karşın mevcut bulgular, Paleolitik Dönem toplumlarında en yaygın paleopatolojik bulguların travmalar olduğunu göstermektedir (Zivanovic, 1982, s. 156–159).

Paleolitik Dönem'den **Neolitik Dönem**'e geçiş, insanlık tarihindeki en önemli biyokültürel dönüşümlerden biri olarak kabul edilmektedir. Avcı-toplayıcı yaşam biçimi yerini, tarım ve hayvancılığa dayalı yerleşik yaşama bırakmasıyla birlikte beslenme alışkanlıkları, nüfus yoğunluğu, çalışma biçimleri ve çevresel koşullar önemli ölçüde değişmiştir. Bu değişimler yalnızca toplumsal ve ekonomik yapıyı değil, insan sağlığını ve hastalık örüntülerini de etkilemiştir. Paleopatolojik araştırmalar; Neolitik yaşam biçimiyle birlikte enfeksiyon hastalıklarının, beslenme yetersizliklerinin ve fiziksel aktiviteye bağlı iskelet değişikliklerinin görülme sıklığında önemli farklılıklar ortaya koymuştur (Larsen, 1995:185-203).

Neolitik Dönem'de yerleşik yaşamın ve tarıma dayalı ekonominin temellerinin atılmasının ardından, **Kalkolitik Dönem**'de toplumsal ve ekonomik örgütlenme daha karmaşık bir yapıya ulaşmıştır. Tarımsal üretimin artması, hayvancılığın gelişmesi, nüfus yoğunluğunun artması, iş bölümünün belirginleşmesi ve bakırın işlenmeye başlanması yaşam biçiminde önemli değişikliklere neden olmuştur. Bu değişimler bireylerin sağlık durumunu da etkilemiştir ve beslenme alışkanlıkları, çalışma yükü, enfeksiyonel hastalıklara ve travmalara maruz kalma durumlarında artışlar gözlenmiştir. Paleopatolojik araştırmalar, Kalkolitik Dönem topluluklarında Neolitik Dönem'e kıyasla yaşam biçimindeki bu dönüşümlerin iskeletlere de yansıdığını göstermiştir (Larsen, 1995; Roberts ve Manchester, 2010; Ortner, 2003).

Kalkolitik Dönem'den **Tunç Çağı**'na geçiş, insan topluluklarının ekonomik, teknolojik ve sosyal yapılarında önemli dönüşümlerin yaşandığı bir süreçtir. Bu süreçte madencilik teknolojisindeki ilerlemeler yalnızca üretim biçimlerini değiştirmekle kalmamış, aynı zamanda toplumsal iş bölümünü, nüfus hareketlerini ve yaşam biçimlerini de etkilemiştir (Renfrew ve Bahn, 2016). Yerleşimlerin büyümesi, nüfus yoğunluğunun artması ve topluluklar arasındaki hareketliliğin çeşitlenmesi, bireylerin yaşam koşullarını ve sağlık profillerini de etkilemiştir. Bu dönemde beslenme biçimleri, fiziksel aktivite düzeyi, mesleki yüklenmeler, travmalar ve enfeksiyon hastalıkları gibi unsurlar, insan iskelet kalıntıları üzerinden değerlendirilebilen önemli ipuçları hâline gelmiştir (Larsen, 2002; Roberts ve Manchester, 2010).

TUNÇ DÖNEM ANADOLU TOPLUMLARI

Tunç Çağı, Anadolu'da tarım ve hayvancılığın yanı sıra madencilik, metal işçiliği ve ticaret faaliyetlerinin geliştiği; yerleşimlerin ve toplumsal örgütlenmenin çeşitlendiği bir dönemdir (Yener, 2000; Stech, 1999). Bu ekonomik ve sosyal değişimler, bireylerin beslenme biçimleri, fiziksel aktiviteleri ve yaşam koşulları üzerinde etkili olmuş ve dolayısıyla sağlık profillerine de yansımıştır. İnsan iskeletleri üzerinde gerçekleştirilen paleopatolojik çalışmalar; travmalar, dejeneratif eklem hastalıkları, enfeksiyonlar, metabolik hastalıklar ve dental patolojiler gibi sağlık sorunlarının yanı sıra Tunç Çağı topluluklarının yaşam biçimleri ve çevresel koşulları hakkında da önemli bilgiler sunmaktadır (Larsen, 2002; Ortner, 2003). Bu doğrultuda, Anadolu'nun farklı bölgelerinde Tunç Çağı'na tarihlenen iskelet topluluklarında tespit edilen başlıca paleopatolojik bulgular aşağıda değerlendirilmiştir.

Seyitömer Höyük:

Kütahya ili Seyitömer Höyük kazısından Orta Tunç Çağı'na tarihlendirilen 64 bireyin beşini bebek, 13'ünü çocuklar oluşturmaktadır. 46 erişkin bireyin 15'ini kadınlar, 29'unu erkekler oluşturmaktadır. Cinsiyeti belirlenemeyen iki birey de topluluğun %3,12'sini oluşturmaktadır. Seyitömer topluluğunda, çoğunun orta erişkin yaşlarda olduğu 24 bireyde (%37,5) paleopatolojik lezyonlar belirlenmiştir. Travmalar, doğuştan anomalilerden spina bifida occulta, aneminin belirtileri olan cribra orbitalia ve porotic hyperostosis, enfeksiyon, omurlardaki dejeneratif eklem hastalıklarının belirtileri olan osteofit ve schmorl nodülleri ile osteoartrit topluluk genelinde gözlenen patolojik olgulardır (Özdemir, 2011).

Seyitömer Höyük insanlarında beş bireyde (%7,81) ***kırık ve kafatası travmaları*** olgularıyla karşılaşılmıştır. Kafatası travmaları üç erkek ve bir çocuk bireyde gözlenirken, kırık bir erkek bireyde belirlenmiştir. Kırığa, 30 yaşlarında erkek bir bireyin costae kemiğinde rastlandığı ifade edilerek, bu kırık sonucunda kemikte enfeksiyon meydana geldiği belirtilmiştir. Aynı bireyin kafatasında sağ

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parietalde linea temporalisin sonlandığı yerde kafatası travmasına rastlanmıştır. Seyitömer topluluğunda gözlenen yaralanmaların gerek lezyonun derecesi gerekse iskeletlerdeki görülme sıklığına göre savaş veya kavgadan kaynaklanmadığı sonucunu ortaya konmuştur. Buna karşılık hem kafatasındaki hem de vücuttaki yaralanma izlerinin iyileşmiş olmasından ve laboratuvar ortamında yapılan patolojik analizlerden yola çıkılarak bu bireydeki travmanın düşme ve çarpma gibi kazalardan meydana gelmiş olabileceği ifade edilmiştir. Yine Seyitömer topluluğunda 64 bireyin yedisinde ***porotic hyperostisis*** (%10,93) lezyonuna rastlanmıştır. Sekiz kadın, dokuz erkek ve beş çocuk olmak üzere 22 kafatası ***cribra orbitalia*** açısından değerlendirilmiş ve bunlardan üç erkek ile bir çocuğun kafatasında (%18,18) bu olgu rapor edilmiştir. Literatürde, kalıtsal nedenlerden kaynaklanan anemide kafatası dışındaki kemiklerde de hastalığın bıraktığı izler saptanmakta, yüz kemiklerinin genişlemesi ve uzun kemiklerin metafizlerinde şişkinlikler gözlendiği belirtilmiştir. Seyitömer topluluğunda bu lezyonların hem erişkinlerde hem de çocuklarda gözlenmesi ve hafif düzeyde seyretmesi, kalıtsal nedenlerden çok sonradan kazanılan nedenlere bağlanmıştır. Ayrıca, kalıtsal hastalıklardan geliştiğini yansıtacak, bahsedilen herhangi bir olguya rastlanmaması, Seyitömer topluluğunda aneminin, kanda hemoglobin düzeyinin normal değerlerden daha az olması durumunda ortaya çıkan demir eksikliğinden kaynaklandığına işaret edilmiştir (Özdemir, 2011).

Seyitömer Höyük topluluğunda ikisi kadın, dördü erkek olmak üzere altı bireyde ***non-spesifik enfeksiyon*** gözlenmiştir. 30 yaşlarındaki *birey 6 envanter numaralı* kadının sağ humerusunda caput humerinin şeklini kaybettirecek ve scapulada cavitas glenoidalisi etkileyecek derecede enfeksiyon gözlenmiştir. Aynı bireyin sol coxasında facies auricularisin posteriorunda ve tuber iliacada enfeksiyon gözlenmiştir. *Birey 9 envanter numaralı* 20 yaşlarındaki diğer kadının sol humerusunda caput humerinin altında medialde enfeksiyon belirlenmiştir. Seyitömer Höyük erkeklerinde ise, *26 envanter numaralı* 32 yaşlarında bir bireyin sağ ve sol humerusları ile sağ ve sol claviculalarında; 28 yaşlarında *birey 37 envanter numaralı* bireyin sol humerusunda; 47+ yaşlarında *birey 49 envanter numaralı* bireyin sağ humerusunda enfeksiyon gözlenmiştir. Ayrıca 34 yaşlarında *birey 51 envanter numaralı* bireyin sağ ve sol humeruslarında osteomyelit tespit edilmiştir. Seyitömer bireylerindeki non-spesifik nedenlere dayandırılabilecek enfeksiyonların %8,77'si (n:57/6) **periostit,** %1,7'sinin (n:57/1) **osteomyelit** olduğu belirtilmiştir. Yine bu toplulukta bir kadın, beş erkek sacrumu değerlendirmeye alınmış, bunlardan iki erkek sacrumunda ***spina bifida*** (%33,3) tespit edilmiştir. Seyitömer Höyük topluluğu genel olarak değerlendirildiğinde, toplam 55 boyun omurundan birinde (%1,8), 83 sırt omurundan altısında (% 7,22) ve 56 bel omurundan dokuzunda (% 16,07) ***osteofit*** gözlenmiştir. Toplam 194 omurdan 16'sında (%8,24) bu lezyona rastlanılmıştır. ***Schmorl nodülü*** ise toplam 55 boyun omurunun dört tanesinde (%7,27), 83 sırt omurunun sekizinde (%9,63), 56 bel omurunun altısında (%10,71) rapor edilmiştir. Genel olarak bakıldığında bu oranının 194 omurun 18'inde (%9,27) olduğu bildirilmiştir. Bu lezyonlar, omurganın ağırlık taşıma işlevinin bir sonucu olarak ortaya çıkan strese dayandırılmıştır. Halk arasında 'kireçlenme' olarak bilinen ***osteoartrit***, Seyitömer Höyük topluluğunda 45+ yaşlarında erkek bireyin sağ ve sol calcaneusları ve sağ ve sol patellaları ile 20 yaşlarında erkek bir bireyin parmak kemiklerinde gözlenmiştir. Seyitömer Höyük topluluğunda gerek görülme sıklığının azlığı gerekse görülme şiddetinin hafif olması nedeniyle osteoartitirin gelişmesine neden olabilecek faktörlere ilişkin bir yorum yapılamadığı ifade edilmiştir (Özdemir, 2011).

Salat Tepe Höyüğü:

Diyarbakır ili, Bismil ilçesi sınırları içerisinde yer alan Salat Tepe Höyüğü, Salat Çayının kuzey terası üzerine kurulmuş önemli bir yerleşim alanıdır. 2009-2010 yılları kazı sezonunda ele geçirilen, üç kadın (%30), üç erkek (%30), iki bebek (%20) ve iki cinsiyeti belirlenemeyen olmak üzere 10 birey hem paleodemografik hem paleopatolojik açıdan incelenmiştir (Başoğlu vd., 2013). Paleopatolojik çalışmalar sonucunda; bir kadın bireyin bel omurlarında vertebra disklerinin üst ve alt yüzeylerinin fıtıklaşması olarak tanımlanan ***schmorl nodülü*** tespit edilmiştir. Kadın bireylerin birinde el parmak kemiklerinde eklem yüzeyinin bozulması şeklinde ortaya çıkan ***osteoartrit*** belirlenmiştir. *M66 numaralı* kadın bireyin sağ tibiasında ve sağ fibulada ***periostit*** tespit edilmiştir. Ayrıca; sol acetabulumda periostit başlangıcına rastlanmıştır. *M66 numaralı* kadın bireyde ve *M60 numaralı* bebek kafatasında ***porotic hyperostosis ve cribra orbitalia***'nın varlığı rapor edilmiştir. Ayrıca Salat Tepe Höyük insanlarında *M68 numaralı* erkek bireyin parmak kemiklerinde ***osteoartrit***, *M66 numaralı* kadın bireyde bel omurlarında

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osteofit, ileri derecede ***schmorl nodülü*** ve vertebra gövdelerinde incelme tespit edilmiştir (Başoğlu vd., 2013).

Salat Tepe Höyük'te 2011 ve 2012 yılı kurtarma kazılarından ele geçirilen iskeletlerin paleoantropolojik değerlendirilmesi ise Başoğlu ve Erkman (2015) tarafından yapılmıştır. Çalışma kapsamında Salat Tepe Höyük Orta Tunç Çağı tabakalarından açığa çıkarılmış 7 mezardan ele geçirilen 12 birey incelenmiştir. İki erkek bireyin ve iki bebeğin kafatasında ***porotic hyperostosis*** ve ***cribra orbitalia*** rapor edilmiştir. Bu lezyonlar, beslenme bozuklukları, bazı enfeksiyon ve metabolik hastalıklar sonucu edinilen anemiye bağlanmıştır. Salat Tepe Höyük insanlarından bir erkek bireyin ayak parmak kemiklerinde, başka bir erkek bireyin sol femurunun distal ucunda, sağ ve sol tibialarının proximal uçlarında, sol fibulanın proximal ucunda ve ayak parmak kemiklerinde ***osteoartrit*** tespit edilmiştir. Ayrıca bu toplulukta bir erkek ve bir kadın bireyin bel omurlarında ***schmorl nodülü*** ve ***osteofit*** belirlenmiştir. Başka bir erkek bireyin thoracal vertebralarında da deformasyon gözlenmiştir. Bu bireylerin genç olmasından bu oluşumlar; ağır fiziksel aktivite ve yaşam koşullarına bağlanmıştır. 2011 ve 2012 yılları kazı çalışmalarından çıkarılan iskeletlerin sayısının azlığı ve korunma durumunun kötü olmasının popülasyon genelinde antropolojik inceleme ve değerlendirmeyi zorlaştırdığı; elde edilen değerlerin toplum genelini yansıtmadığı, ancak Tunç Çağ antropolojik çalışmalarına ilişkin verilerin azlığı göz önünde bulundurulduğunda elde edilen bilgilerin önem arz ettiği, sonuç olarak bu topluluğun bireylerinin patolojik olgularına göre zor bir yaşam sürdükleri rapor edilmiştir (Başoğlu & Erkman, 2015).

Ovaören Höyük:

Nevşehir ili, Gülşehir ilçesi Ovaören Höyüğü'nden 2012 yılı kazı çalışmalarından çıkarılan Erken Tunç Çağ tarihli 13 birey Başoğlu ve Şener (2015) tarafından incelenmiştir. Bireylerin genel sağlık durumlarını ortaya koymak amacıyla yapılan paleopatolojik analizler sonucunda, vücut kemiklerinde artrit, porotic yapılar, omurlarda osteofit ve schmorl nodülü gibi lezyonlar belirlenmiştir. *M8 numaralı* küp mezardan çıkarılan genç erişkin erkek bireyin kafatasında ***porotic hyperostosis*** ve ***cribra orbitalia*** tespit edilmiş, bu lezyonların kafatası ile sınırlı kalması, diploe kalınlaşmasının olmayışı ve hafif düzeyde seyretmesinden dolayı demir eksikliği sonucu edinilen anemiye bağlanmıştır. *M6 numaralı* basit toprak mezardan çıkarılan genç erişkin kadın bireyde porotic hyperostosis kafatasının yanı sıra kalça kemiklerinde de gözlenmiştir. *M2 numaralı* taş sanduka mezarda bulunan erişkin erkeğin cervical ve lumbar vertebralarında, *M3 numaralı* taş sanduka mezarda bulunan genç erişkin erkek bireyin lumbar vertebralarında ***schmorl nodülü*** ve ***osteofit*** olgusu tespit edilmiştir. *M2 numaralı* taş sanduka mezardan çıkarılan erişkin kadın bireyin ayak parmak kemiklerinde ve *M3 numaralı* taş sanduka mezardan ele geçirilen diğer genç erişkin erkek birey ve *M8 numaralı* küp mezardan çıkarılan genç erişkin erkeğin sağ tibia ve patellasında ***osteoartrit*** rapor edilmiştir. Yine *M2 numaralı* taş sanduka mezardan ele geçirilen erişkin erkek bireyin sağ fibulasının proksimal ve distal uçlarında osteoartrit tespit edilmiştir. Ayrıca; *M3 numaralı* taş sanduka mezardan çıkarılan genç erişkin kadın bireyde ileri derecede vertebral osteoartrit sonucu thorocal vertebralarında kaynaşma söz konusudur. İki omur birey hayatta iken kaynaşıp (***ankylosis***) bir blok oluşturmuştur. Boyun ve sırt omurlarındaki bu tür kaynaşmaların genelde bireyin hayatta iken sırtında devamlı ağır yük taşıma alışkanlığının neden olduğu, Ovaören Höyük insanlarında da bu tür dejeneratif eklem rahatsızlıkların genç bireylerde gözlenmiş olması ağır fiziksel aktivite, ağır yaşam koşulları ve bu eklemlerin çok kullanılmasına bağlanmıştır (Başoğlu ve Şener, 2015).

Kızılin Mağarası:

Burdur ili, Çatağıl Köyü'nde İnsuyu Mağarası'nın kuzeyinde yer alan Kızılin Mağarası'ndan 2009 yılı kazı çalışmalarından ele geçirilen bir çocuk, üç erişkin olmak üzere dört birey incelenmiştir. Bu bireylerin birinin erkek, ikisinin kadın ve birinin çocuk olduğu rapor edilmiştir. Bu bireylerin iskelet kalıntılarında, sadece bir bireyin kalça kemiği ve sağrı kemiği arasındaki kaynaşma dışında herhangi bir patolojik oluşuma ve anomaliye rastlanmamıştır. Araştırmacılar tarafından, artiritin özellikle omurgayı tutan ***ankilozan spondilit*** denilen türünde, bu iskelet kalıntısında görülen kalça ve sağrı kemiği arasındaki kaynaşmaya benzer bir oluşum görülebildiği ifade edilmiştir. Ancak, mevcut diğer iskelet kalıntılarının incelenmesi sonucunda adı geçen rahatsızlıklarla ilişkilendirilebilecek başka bir belirtiye

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rastlanmadığından, bu oluşumun hangi hastalığa bağlı olarak ortaya çıktığını belirlemenin mümkün olmadığı belirtilmiştir (Yaşar vd., 2012).

Ağızören Nekropolü:

Kütahya ili Merkez ilçesi Ağızören Köyü'nden ele geçirilen 18 birey üzerinde gerçekleştirilen çalışmada; *2 numaralı* mezardan çıkarılan kadının sağ femurunda ***kalça çıkığı***ndan kaynaklandığı düşünülen bir deformasyon tespit edilmiştir. Bu bireyin caput femoris'inin tamamen deforme olduğu, femur proximalinde yeni bir eklem yüzeyi meydana geldiği rapor edilmiştir. Ağızören bireylerinde saptanan bir diğer rahatsızlık çeşitli mikroorganizmalar nedeniyle meydana gelen ***non-spesifik enfeksiyonlar***dır. *M7A envanter numaralı* bireyin femurunda ***periostit***, caput humeri'sinde ***osteoartirit*** belirtileri tespit edilmiştir. *M4A ve M4B envanter numaralı* bireylerin tibia kemiklerinde de periostit lezyonu belirlenmiştir ve bu bireylerde büyük oranda kalıtımsal olduğu kabul edilen ***Perthes's hastalığı*** rapor edilmiştir. Yine 4 numaralı mezardan çıkarılan *M4C numaralı* bireyin bacak kemiklerinde periostit belirlenmiştir (Açıkkol vd., 2003).

Küçükhöyük:

Bilecik ili, Küçükhöyük'te gerçekleştirilen kazı çalışmalarından; 36 bebek ve çocuk, 39 kadın, 43 erkek, 24 cinsiyeti belirlenemeyen birey olmak üzere 142 birey Açıkkol (2000) tarafından incelenmiş ve Küçükhöyük bireylerinin demir eksikliğinden kaynaklanan anemi, kemik zarı iltihabı, beyin tümörü ve osteofit rahatsızlıklarına maruz kaldıkları ifade edilmiştir. Yapılan değerlendirmede Küçükhöyük'te görülen en önemli bulgunun yaşlı bir erkekte tespit edilen ***trepenasyon*** olduğu ortaya konmuştur. Ağızören bireylerinde göz çukurları incelenebilen yedi bireyden, yaşı belirlenemeyen erişkin bir kadının sağ orbit tavanı ile 10 yaşlarında bir çocuğun her iki orbit tavanında ***cribra orbitalia*** saptanmıştır. Cribra orbitalia ile paralellik gösteren ***porotic hyperostosis*** 20 bireye ait kafatası kemiklerinde incelenebilmiştir. Ancak bireylerin hiçbirinde bu lezyona rastlanmamıştır. Küçükhöyük topluluğunda porotic hyperostosise rastlanmaması, gözlenen cribra orbitalianın yetersiz demir alımından kaynaklı olabileceğine bağlanmıştır. Küçükhöyük topluluğunda cinsiyeti belirlenemeyen izole bir erişkin bireye ait fibula ve tibia kemiklerinde ***periostit*** lezyonu tespit edilmiştir. Bu bireye ait bir lumbar vertebra gövdesinde de ***osteofit*** oluşumu gözlenmiştir. Yine bu toplulukta rapor edilen diğer patolojik olgu, 62 yaşlarında iki erkek kafataslarının endocranialinde yaşlılık nedeniyle olabileceği düşünülen çukur yapılardır. Ayrıca üç kadın bireyin parietal kemiklerinde ***tümör*** izine rastlanmıştır (Açıkkol, 2000).

Çavlum Nekropolü:

Eskişehir ili, Alpu Ovasında yer alan Çavlum nekropolünün Orta Tunç katmanından çıkarılan 111 birey antropolojik olarak değerlendirilmiştir (Sevim vd., 2004). Bu bireylerin 35'inin erkek, 30'unun kadın olduğu, bebek ve çocukların populasyonun %36,93'ünü oluşturduğu ortaya konmuştur. Çavlum topluluğunda tespit edilen en önemli patolojik bulgunun ***trepenasyon*** olduğu rapor edilmiştir. Çavlum trepenasyonun *M68* envanter numaralı iskeletin kafatasına uygulandığı, bu bireyin 25-27 yaşlarında erkek bir birey olduğu ifade edilerek, olguya ilişkin detaylı bilgiye çalışma kapsamında yer vermişlerdir. Ayrıca; Çavlum bireylerinden bir kadın iki erkek ve bir çocuk bireyde ***porotic hyperostosis***, bir kadın üç erkek bireyde ***schmorl nodülü***, üç erkek bireyin kafatasında ***diploe kalınlaşması***, bir kadın iki çocuk bireyin kafatasında ***kültürel kafa deformasyonu***, bir kadın ve iki erkek bireyde ***enfeksiyon***, bir erkek bireyde ***travma***, bir kadın bireyde ***kemik kisti***, bir erkek bireyde ***osteoartrit***, bir kadın bireyde ***osteofit*** ve bir erkek bireyde ***Perthes hastalığı*** rapor edilmiştir (Sevim vd., 2004).

Birecik Barajı Eski Tunç Mezarlığı:

1996 yılında Gaziantep ilinin Nizip ilçesi yakınlarındaki Birecik Barajı çalışmalarında tesadüfen bir mezarlık alanı tespit edilmiştir. Oldukça hasarlı olarak ele geçirilen iskelet kalıntılarına ilişkin çalışmalardan dokuz çocuk, üç genç erişkin, 12 kadın, 15 erkek, 23 cinsiyeti belirlenemeyen bireye ait iskelet kalıntıları tespit edilmiştir. İncelemelerde; genellikle yaşlı bireylerin bel ve sırt omurlarında günlük yaşamdaki fiziksel strese bağlı olarak ortaya çıkan ***osteofit*** ve ***schmorl nodülleri***, enfeksiyonel rahatsızlıklara bağlı olarak gelişen doku bozuklukları rapor edilmiştir. Birecik Barajı Eski Tunç Mezarlığı'ndan çıkarılan iskeletlerde, premortem olarak ve insanlar tarafından yapıldığı anlaşılan

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belirgin ***kesik izleri*** tespit edilmiştir. Bu izlere toplam 62 bireyin 13'ünde (%20,97) rastlanmıştır. Bu izler; gömü ritüeli ve kanibalizme dayandırılmıştır (Sevim vd., 1999).

Çiledir Höyük:

Kütahya ili Çiledir Höyük kurtarma kazısından 2009 ve 2010 yıllarında ele geçirilen iskeletler değerlendirmeye alınmış ve altı birey rapor edilmiştir. Eski Tunç Dönemi, Çiledir Höyük bireylerinde; *B5/29 numaralı* bireyin frontalinin sol tarafında kesici âletle yapılmış bir ***travma*** olgusu, sol orbitalinde anemi olarak kabul edilen ***cribra orbitalia'***nın varlığı ve tibiasında non-spesifik ***enfeksiyon*** tespit edilmiştir. *B5/27-20 numaralı* bireyin sol frontalinden squamosasına kadar ince bir çizgi hâlinde uzanan bir ***travma*** izi ile nasal kısımdan başlayıp sol frontale kadar devam eden bir kırık gözlenmiş ve frontalde oluşan bu kırığın travmayla bağlantılı olduğu belirtilmiştir. Ayrıca bireyin iki orbitalinde de ***cribra orbitalia*** tespit edilmiştir (Surul vd., 2011).

Çankırı Salur Höyük:

Çankırı ili, Orta ilçesinde yer alan Salur Höyük'te gerçekleştirilen kazı çalışmalarında ele geçirilen 41 bireye ait iskelet kalıntıları değerlendirilmiş ve bu bireylerin %2,44'ünün bebek (n: 1), %9,76'sının çocuk (n: 4), %26,83'ünün kadın (n: 11), %48,78'inin erkek (n: 20) ve %12,2'sinin cinsiyeti belirlenemeyen bireyler (n: 5) olduğu belirtilmiştir. Salur Höyük insanlarında; *S5/M11 A numaralı* erişkin bir erkek bireyde, sol femurda ***pozisyon bozukluğu***, halux gövdesinde şişkinlik, sağ femurun distalinde az derecede gelişim gösteren ***porotic yapı***; *S/M10 C numaralı* diğer bir erişkin erkeğe ait metatarsalde eğrilik; *S5 / M9 B* numaralı erişkin bir erkek bireyde sağ humerus gövdesinde ***osteomyelit***; *S5/M14 A* numaralı erişkin bir erkek bireyde sol humerusta proksimal gövdede eğrilik, kafatasının iç kısmında parietal bölgede doku bozukluğu ve aynı bireyin bir thoracal vertebrasında ***schmorl nodülü***; *S1/M6 A* numaralı erişkin bir kadın bireyde bir thoracal vertebrada ***osteofit***; *S7/M12 A numaralı* erişkin bir erkek bireyin bir cervical vertebrasında ***osteofit*** oluşumları rapor edilmiştir (Yiğit vd., 2010).

SONUÇ

Anadolu, tarih öncesi dönemlerden itibaren farklı kültürlerin ve yaşam biçimlerinin şekillendiği önemli bir coğrafya olmuştur. Bu süreç içerisinde yaşamış topluluklara ait insan iskeletleri, geçmiş toplumların biyolojik yapılarının, sağlık durumlarının, beslenme alışkanlıklarının, fiziksel aktivitelerinin ve çevresel koşullarla olan ilişkilerinin anlaşılmasında önemli bir veri kaynağı oluşturmaktadır. Bu bağlamda paleopatolojik incelemeler, geçmiş toplumların sağlık yapılarının değerlendirilmesinde önemli bir araştırma alanı sunmaktadır.

Çalışma kapsamında, Anadolu'da Tunç Çağı'nda yaşamış topluluklara ait insan iskeletleri üzerinde gerçekleştirilen paleopatolojik araştırmalar değerlendirilerek, söz konusu topluluklarda görülen başlıca sağlık sorunlarının ortaya konulması amaçlanmıştır. İncelenen çalışmalar, Tunç Çağı Anadolu topluluklarında travmatik lezyonlar, dejeneratif eklem hastalıkları, enfeksiyon hastalıkları, metabolik ve kan hastalıklarına bağlı kemik değişikliklerinin farklı sıklıklarda görüldüğünü ortaya koymaktadır. Elde edilen bulgular, Tunç Çağı toplumlarının sağlık durumlarının yalnızca biyolojik faktörlerle değil, aynı zamanda yaşam biçimi, beslenme alışkanlıkları, fiziksel aktivite düzeyi, mesleki faaliyetler ve çevresel koşullardan da etkilendiğini göstermektedir. Özellikle tarımsal faaliyetler, hayvancılık, ağır fiziksel iş yükü ve tekrarlayan mekanik streslerin iskelet sistemi üzerinde çeşitli dejeneratif değişikliklerin ve travmatik lezyonların oluşumunda etkili olduğunu düşündürmektedir. Tunç Çağı boyunca Anadolu'da farklı ekonomik ve kültürel yapılara sahip toplulukların yaşamış olması, sağlık sorunlarının topluluklar arasında farklılık göstermesine neden olmuş olabilir. Bununla birlikte mevcut araştırmaların bazı bölgeler ve dönemler açısından sınırlı olması, elde edilen sonuçların Anadolu'nun tamamına genellenmesini güçleştirmektedir. Ayrıca iskelet topluluklarının korunma durumu, örneklem büyüklüğü ve araştırmacılar tarafından kullanılan paleopatolojik kayıt ve değerlendirme yöntemlerindeki farklılıklar, topluluklar arasında doğrudan karşılaştırma yapılmasını sınırlandıran önemli faktörlerdir.

Sonuç olarak, Anadolu Tunç Çağı toplumlarına ait iskeletler üzerinde gerçekleştirilen paleopatolojik çalışmalar, bu toplulukların karşılaştıkları sağlık sorunlarının belirlenmesinin yanı sıra yaşam biçimleri, beslenme düzenleri, fiziksel aktiviteleri ve çevresel koşulları hakkında da önemli bilgiler sunmaktadır. Bununla birlikte Anadolu Tunç Çağı'nın farklı dönem ve bölgelerinin paleopatolojik açıdan daha

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kapsamlı biçimde araştırılmasına ihtiyaç bulunmaktadır. Gelecekte yapılacak çalışmaların daha geniş örneklem gruplarını kapsaması, standart paleopatolojik değerlendirme yöntemlerinin kullanılması ve radyolojik, histolojik, izotopik ve biyomoleküler analizler gibi farklı yöntemlerle desteklenmesi, Tunç Çağı Anadolu toplumlarının sağlık yapısının ve yaşam koşullarının daha bütüncül biçimde anlaşılmasına önemli katkılar sağlayacaktır.

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BUĞDAY KAPÇIĞI KULLANILARAK KAPLAMALI POLYESTER TEKSTİL YÜZEYLERİNİN GÜÇ TUTUŞURLUK ÖZELLİKLERİNİN GELİŞTİRİLMESİ

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ÖZET

Tekstil materyallerinin yanma davranışı, özellikle ev tekstili ve teknik tekstil uygulamalarında ürün güvenliğini doğrudan etkileyen önemli özelliklerden biridir. Doğal ve sentetik polimer esaslı tekstil materyallerinin bir bölümü kolay tutuşabilmekte; bazı sentetik lifler ise yanma sırasında erime ve alevli damlama davranışı gösterebilmektedir. Tekstil yüzeylerine güç tutuşurluk özelliği kazandırmak amacıyla çeşitli kimyasal maddeler kullanılmakla birlikte, bu kimyasalların çevre ve insan sağlığı üzerindeki olası etkileri doğal, yenilenebilir ve atık kaynaklı alternatif malzemelere yönelik araştırmaları artırmıştır (Costes et al., 2017; Morgan, 2016; Yang et al., 2018).

Bu çalışmada, buğday üretimi sırasında ortaya çıkan lignoselülozik bir tarımsal yan ürün olan buğday kapçığının kaplamalı polyester tekstil yüzeylerinin güç tutuşurluk davranışına etkisi araştırılmıştır. Deneylerde %100 güç tutuşur polyester iplikten dokunmuş, bezayağı örgü yapısına sahip ve 400 g/m² gramajlı kumaş kullanılmıştır. Buğday kapçıkları ayıklama, öğütme ve eleme işlemleri sonrasında farklı partikül boyutlarına ayrılmış; akrilik ve poliüretan binder sistemleriyle hazırlanan kaplama patlarına ilave edilmiştir. Kaplama uygulamaları laboratuvar mini-ramında boşlukta bıçak yöntemiyle gerçekleştirilmiştir.

Yanma davranışı NF P 92-504 test yöntemi esas alınarak değerlendirilmiştir (French Standard, 1995). Akrilik binderli kontrol numunesi 2. alev temasında tutuşmuş ve tutuşma süresi 10 s olarak kaydedilmiştir. 125-250 µm kapçık içeren numune 3. alev temasında 15 s'de, 63-125 µm kapçık içeren numune ise 5. alev temasında 25 s'de tutuşmuştur. Partikül boyutunun 45-63 µm ve <45 µm seviyelerine düşürülmesi tutuşma süresini 20 s'ye geriletmiş, dolayısıyla en iyi sonuç 63-125 µm aralığında elde edilmiştir. Aynı partikül boyutu poliüretan binder ile denendiğinde tutuşma 6. alev temasında gerçekleşmiş ve tutuşma süresi 30 s'ye ulaşmıştır.

Buğday kapçığı ilavesi katkısız kaplamaya göre tutuşmayı geciktirmiş, erime ve alevli damlama eğilimini azaltmış ve yanma morfolojisini değiştirmiştir. Sonuçlar, partikül boyutu ile binder türünün performans üzerinde belirleyici olduğunu; özellikle 63-125 µm partikül boyutu ve poliüretan binder kombinasyonunun bu çalışma kapsamındaki en yüksek tutuşma gecikmesini sağladığını göstermiştir.

Anahtar Kelimeler: Güç tutuşurluk, buğday kapçığı, polyester kumaş, doğal malzeme, kaplama, NF P 92-504.

GİRİŞ

Tekstil materyalleri günlük yaşamda giyimden ev tekstiline, ulaşımdan koruyucu ürünlere kadar oldukça geniş bir kullanım alanına sahiptir. Kullanım alanlarının çeşitlenmesiyle birlikte tekstil ürünlerinden yalnızca estetik ve mekanik özellikler değil, aynı zamanda kullanım güvenliğini artıran fonksiyonel özellikler de beklenmektedir. Güç tutuşurluk bu özelliklerin başında gelmektedir. Özellikle ev tekstillerinde kullanılan malzemelerin yangın sırasında tutuşması, alevin ilerlemesine katkıda bulunması veya eriyerek alevli damlalar oluşturması yangının başka malzemelere taşınmasına neden olabilmektedir (Morgan, 2016; Yang et al., 2018).

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Tekstil materyalinin yanma davranışı lifin kimyasal yapısı ve termal özellikleriyle doğrudan ilişkilidir. Pamuk gibi bazı doğal polimerler erimeden yanarken, polyester gibi termoplastik sentetik lifler ısı etkisi altında eriyebilmekte, büzülebilmekte ve damlama gösterebilmektedir. Tekstil materyallerine güç tutuşurluk kazandırmak amacıyla yapısı itibarıyla güç tutuşur liflerin kullanılması, polimer yapısının kimyasal olarak değiştirilmesi, lif çekimi sırasında alev geciktirici katkıların polimere ilave edilmesi veya kumaş yüzeyinin alev geciktirici kimyasallarla işlem görmesi gibi farklı yaklaşımlar uygulanmaktadır. Bunlar içerisinde yüzey işlemleri ve kaplama uygulamaları, uygulanabilirlik ve maliyet açısından yaygın yöntemler arasında yer almaktadır (Uddin, 2019).

Bir polimerik malzemenin yanması; materyalin ısınması, makromoleküllerin termal olarak parçalanması, oluşan yanıcı gazların oksidasyonu sonucunda tutuşmanın gerçekleşmesi ve açığa çıkan enerjinin yeni piroliz reaksiyonlarını desteklemesiyle yanmanın devam etmesi şeklinde ilerleyen bir süreçtir (Horrocks & Price, 2001). Alev geciktirici sistemler bu döngünün farklı aşamalarına müdahale edebilmektedir. Yüzeyde kömürleşmiş, şişmiş veya camsı bir bariyer tabakasının oluşması, ısının malzeme içerisine geri aktarılmasını sınırlandırarak yeni parçalanma reaksiyonlarının azaltılmasına katkı sağlayabilmektedir (Hautamaki, 2017; Kilinc, 2013).

Geleneksel güç tutuşurluk uygulamalarında kullanılan bazı kimyasalların çevre ve insan sağlığı üzerindeki olumsuz etkilerinin ortaya çıkması, bu alanda daha sürdürülebilir alternatiflerin araştırılmasına neden olmuştur. Bu doğrultuda doğal kaynaklı ve biyobazlı maddelerin alev geciktirici sistemlerde değerlendirilmesine yönelik çalışmalar giderek önem kazanmıştır (Costes et al., 2017). Aynı zamanda tarımsal üretim sonucunda ortaya çıkan atıkların katma değerli ürünlere dönüştürülmesi, çevresel sürdürülebilirlik açısından önemli bir yaklaşım olarak değerlendirilmektedir (Sadh et al., 2018; Väisänen et al., 2016).

Buğday kapçığı, buğday tanesinin dış kısmında bulunan koruyucu bir yapı olup buğdayın yaklaşık %15-20'sini oluşturan lignoselülozik bir yan üründür (Bledzki et al., 2010a). Yapısında selüloz, hemiselüloz ve ligninin yanı sıra silisyum ve potasyum gibi inorganik bileşenlerin de bulunduğu bildirilmiştir (Bledzki et al., 2010a). Bledzki ve arkadaşları tarafından gerçekleştirilen çalışmada buğday kapçığının kimyasal ve yüzey özellikleri ayrıntılı olarak incelenmiş ve kapçığın polimer kompozitlerde doğal dolgu malzemesi olarak kullanılabilirliği değerlendirilmiştir (Bledzki et al., 2010a).

Buğday kapçığının farklı alanlarda değerlendirilmesine ilişkin çalışmalar bulunmasına rağmen, tez çalışmasının gerçekleştirildiği dönemde kapçığın tekstil yüzeylerinde doğrudan güç tutuşurluk katkısı olarak kullanımına yönelik bir çalışmaya rastlanmamıştır. Bu nedenle çalışmada, ülkemizde kolaylıkla temin edilebilen buğday kapçığının tekstil sektöründe doğal bir güç tutuşurluk katkısı olarak kullanılabilirliği araştırılmıştır. Çalışma öncesinde gerçekleştirilen LOI incelemelerinde de kapçığın alev uzaklaştırıldığında belirli oksijen konsantrasyonlarında sönme davranışı göstermesi, kaplama sistemlerinde değerlendirilmesi için başlangıç noktası oluşturmuştur.

Bu çalışmanın amacı, farklı partikül boyutlarına getirilen buğday kapçığının polyester tekstil yüzeylerinde kaplama katkısı olarak kullanılması ve bu katkının kumaşın tutuşma ve yanma davranışı üzerindeki etkisinin belirlenmesidir. Bu kapsamda buğday kapçığının partikül boyutu ile kaplama sisteminde kullanılan binder türünün etkileri karşılaştırılmış; özellikle tutuşma süresi, kendi kendine sönme, erime ve alevli damlama davranışlarındaki değişimler değerlendirilmiştir.

Çalışma kapsamında doğal bir kaynağın değerlendirilmesi, kapçık ilavesiyle tutuşmanın geciktirilmesi, partikül boyutu ile kaplama reçetesinin performans üzerindeki etkisinin belirlenmesi ve uygun formülasyon koşullarının ortaya konulması hedeflenmiştir. Bu yaklaşım, tarımsal bir yan ürünün daha sürdürülebilir güç tutuşurluk uygulamalarında değerlendirilmesine yönelik bir seçenek olarak ele alınmıştır.

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Buğday Kapçığının Kimyasal ve Elementel İçeriği

Buğday kapçığının seçilme gerekçesi, lignoselülozik yapısı ile mineral içeriğinin birlikte değerlendirilmesine dayandırılmıştır. Aşağıda verilen literatür verileri Çizelge 1'de özetlenmiştir (Bledzki et al., 2010b).

Çizelge 2.1: Numunenin kimyasal ve elementel içeriği (Bledzki et al., 2010b).

Kimyasal içerik	% (a/a)	Elementel içerik	% (a/a)
Selüloz	33,37	Silisyum (Si)	2,80
Hemiselüloz	19,76	Potasyum (K)	1,72
Lignin	11,47	Kalsiyum (Ca)	1,07
Kül (mineral madde)	16,11	Magnezyum (Mg)	0,42
Ekstraktif maddeler	2,08	Sodyum (Na)	0,17
Diğerleri	11,24	Demir (Fe)	0,08

MATERYAL VE YÖNTEM

Materyaller

Çalışmada substrat olarak %100 güç tutuşur polyester iplikten dokunmuş kumaş kullanılmıştır. Kumaş dokuma sonrasında ham halde kullanılmış; bezayağı örgü yapısında, çözgü yönünde 33,5 tel/cm ve atkı yönünde 36,5 tel/cm sıklığa, 400 g/m² gramaja sahip olduğu belirlenmiştir. Buğday kapçıkları Sivas ili, Şarkışla ilçesi, Oluktaş köyü, Dangaz mevkiinden toplanan Betosa buğdaylarından elde edilmiştir. Toplanan buğdaylar üç gün süreyle güneşte kurutulmuş; kapçıklar ayıklama, öğütme ve eleme işlemleri sonrasında farklı partikül boyutlarına ayrılmıştır.

Sunumda kapçıkların eleme sonrası >250 µm, 125-250 µm, 63-125 µm ve 63-45 µm aralıklarında ayrıldığı belirtilmiştir. Deney tasarımında ise performans karşılaştırmaları 125-250 µm, 63-125 µm, 45-63 µm ve <45 µm grupları üzerinden yapılmıştır.

Kaplama sistemlerinde akrilik binder olarak Tubicoat HC04 (poliakrilat), poliüretan binder olarak Ruco-Coat PU 8521 (alifatik polyester poliüretan dispersiyonu) kullanılmıştır. Kaplama patında Tubivis Star ve sodyum alginat kıvamlaştırıcı, Dispersant K 850 ise dispergatör olarak değerlendirilmiştir.

Buğday Kapçığının Hazırlanması ve Kaplama Patının Oluşturulması

Toplanan buğday kapçıkları yabancı maddelerden ayrıldıktan sonra öğütülmüş ve farklı partikül boyutlarını elde etmek amacıyla elenmiştir. Hazırlanan kapçıklar kaplama patına ilave edilinceye kadar ayrı olarak muhafaza edilmiştir.

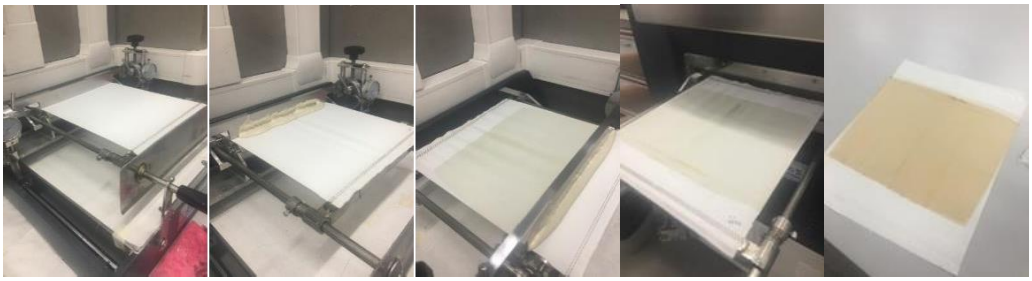
Stok kaplama patı 500 rpm karıştırma hızında hazırlanmıştır. Binder ile suyun bir bölümü karıştırıldıktan sonra dispergatör eklenmiş, ardından kıvamlaştırıcı kontrollü olarak ilave edilmiştir. Karışımın viskozitesi 5000-6000 cP aralığına ulaşıncaya kadar kıvamlaştırıcı ilavesine devam edilmiştir. Hedef viskozite sağlandıktan sonra kalan su eklenerek karışım tamamlanmıştır.

Buğday kapçığı içeren denemelerde hazırlanan stok pat esas alınmıştır. Örneğin %20 buğday kapçığı içeren 250 g'lık bir kaplama patı hazırlamak için 200 g stok kaplama patı ile 50 g buğday kapçığı 10 dakika karıştırılmıştır.

Hazırlanan kaplama patları kumaş yüzeyine laboratuvar tipi mini-ram kullanılarak boşlukta bıçaklı kaplama yöntemiyle uygulanmış ve kaplanan numuneler belirlenen şartlarda kurutulmuştur. Birden

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fazla kaplama katı uygulanan numunelerde kaplama ve kurutma işlemleri kat sayısına bağlı olarak tekrarlanmıştır.



(a) (b) (c) (d) (e)

Şekil 1. Kaplama işleminin yapılması.

Kaplama Patı Reçetesi ve Hazırlama Aşamaları

Kaplama patı toplam 1000 g stok pat esasına göre hazırlanmıştır. Karıştırma işlemi 500 rpm'de yürütülmüş, viskozite 5000-6000 cP aralığında tutulmuştur. Hazırlanan stok pat, farklı partikül boyutlarındaki buğday kapçıklarının ilave edildiği 250 g'lık deneme patlarının hazırlanmasında kullanılmıştır.

Çizelge 2. Stok kaplama patı reçetesi

Kimyasal	Miktar
Binder	100 g (%10)
Dispergatör	10 g (%1)
Kıvamlaştırıcı	40-50 g (viskoziteye göre)
Su	840-850 g (kıvamlaştırıcı miktarına göre)

Hazırlama sırasında binderin tamamı ve suyun 100 mL eksiği 5 dakika karıştırılmış, dispergatör ilavesinden sonra 2 dakika daha karıştırmaya devam edilmiştir. Kıvamlaştırıcı önce 3 g'lık ilaveler halinde ve her ilaveden sonra 10 dakika karıştırılarak eklenmiş; viskozite 4000 cP seviyesine ulaştıktan sonra ilave miktarı 1 g'a düşürülmüştür. Hedef viskoziteye ulaşıldığında eksik su tamamlanmış ve sistem 5 dakika daha karıştırılmıştır. %20 buğday kapçığı içeren 250 g'lık deneme patı için 200 g stok pat ve 50 g buğday kapçığı 10 dakika karıştırılmıştır.

Deney Tasarımı

Buğday kapçığı ilaveli kaplamaların güç tutuşurluk davranışını karşılaştırmak amacıyla iki deney grubu tanımlanmıştır. İlk grupta akrilik binder sabit tutularak partikül boyutu etkisi, ikinci grupta ise seçilen partikül boyutlarında binder türü karşılaştırılmıştır.

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Çizelge 3: Akrilik binderli sistemlerde partikül boyutu etkisinin değerlendirilmesi

Numune	Binder	Partikül boyutu	Kapçık ilavesi (%)	Binder (%)	Diğer katkılar (%)	Su (%)
Kontrol	Akrilik	Yok	0	10	10 (dispergatör + kıvamlaştırıcı)	80
WH-1	Akrilik	125-250 µm	20	10	10 (dispergatör + kıvamlaştırıcı)	60
WH-2	Akrilik	63-125 µm	20	10	10 (dispergatör + kıvamlaştırıcı)	60
WH-3	Akrilik	45-63 µm	20	10	10 (dispergatör + kıvamlaştırıcı)	60
WH-4	Akrilik	<45 µm	20	10	10 (dispergatör + kıvamlaştırıcı)	60

Çizelge 4: Seçili partikül boyutlarında binder türü karşılaştırması.

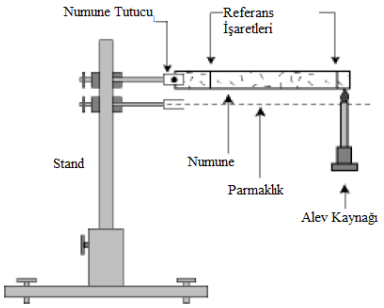
Numune	Binder	Partikül boyutu	Kapçık ilavesi (%)	Binder (%)	Diğer katkılar (%)	Su (%)
Akrilik	Akrilik	125–250 µm / 63–125 µm	20	10	10 (dispergatör + kıvamlaştırıcı)	60
PU	Poliüretan	125–250 µm / 63–125 µm	20	10	10 (dispergatör + kıvamlaştırıcı)	60

NF P 92-504 Test Yöntemi

NF P 92-504, sert bir yüzeye yapıştırılması amaçlanmayan malzemeler için kullanılan alev yayılma hızı test yöntemidir (French Standard, 1995). Numune test sırasında dikey ve gergin olarak yerleştirilmiştir. Numuneye 45° açıyla 5 s süreyle propan alevi uygulanmış; alev uzaklaştırıldıktan sonra kumaş yüzeyindeki devam eden alevlenme süresi kaydedilmiştir. Numuneden ayrılarak zemine düşen alevli

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damlamalar ve parçacıklar ayrıca değerlendirilmiştir. Yalnız eriyerek düşen, alev taşımayan damlamalar alevli damlama olarak kabul edilmemiştir



Şekil 2. gösterimi.



Ş

BULGULAR VE TARTIŞMA

Buğday kapçığı ilavesi, katkısız kaplamaya göre tutuşmanın daha geç gerçekleşmesine ve yanma davranışının değişmesine neden olmuştur. Katkısız numunede erime, sılaşma ve yanıcı damlama eğilimi daha belirgin iken, buğday kapçığı içeren kaplamalarda tutuşma gecikmiş ve yanma morfolojisi farklılaşmıştır.

Çizelge 5. Farklı buğday kapçığı boyutlarının NF P 92-504 testindeki yanma davranışına etkisi.

Deneme No	Binder	Partikül boyutu	İlk tutuşma	Tutuşma süresi (s)	Kendi kendine sönme
10 (Kontrol)	Akrilik	Yok	2. alev temasında	10	Hayır
5	Akrilik	125-250 µm	3. alev temasında	15	Hayır
13	Akrilik	63-125 µm	5. alev temasında	25	Hayır
14	Akrilik	45-63 µm	4. alev temasında	20	Hayır
15	Akrilik	<45 µm	4. alev temasında	20	Hayır

Kontrol numunesi ikinci alev temasında ve toplam 10 s sonunda tutuşmuştur. 125-250 µm partikül boyutunda tutuşma üçüncü alev temasına ve 15 s'ye, 63-125 µm partikül boyutunda ise beşinci alev temasına ve 25 s'ye kadar gecikmiştir. Partikül boyutunun 45-63 µm ve <45 µm seviyelerine düşürülmesi ek bir avantaj sağlamamış; her iki numunede tutuşma dördüncü alev temasında ve 20 s sonunda gerçekleşmiştir. Bu sonuç, çalışılan koşullarda 63-125 µm aralığının en yüksek tutuşma gecikmesini sağladığını göstermektedir.

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Binder Türünün Etkisi

Çizelge 6: 63-125 µm buğday kapçığı içeren akrilik ve poliüretan sistemlerin karşılaştırılması.

Deneme No	Binder	Partikül boyutu	İlk tutuşma	Tutuşma süresi (s)	Kendi kendine sönme
13	Akrilik	63-125 µm	5. alev temasında	25	Hayır
17	Poliüretan	63-125 µm	6. alev temasında	30	Hayır

Akrilik binderli numuneler içinde en iyi sonuç 63-125 µm partikül boyutunda elde edildiğinden binder karşılaştırması bu aralık üzerinden yapılmıştır. Poliüretan binderli numune altıncı alev temasında tutuşmuş ve tutuşma süresi 30 s olarak ölçülmüştür. Buna karşılık aynı partikül boyutundaki akrilik sistemde tutuşma beşinci alev temasında ve 25 s'de gerçekleşmiştir. Böylece poliüretan binder, bu deney grubunda akrilik bindere göre tutuşmayı 5 s daha fazla geciktirmiştir. Her iki numunede de kendi kendine sönme gözlenmemiştir.

Katkısız kaplamada belirgin erime ve alevli damlama görülürken, buğday kapçığı ilavesiyle erime davranışında azalma/değişim ve karbonlaşmaya daha yakın bir yanma morfolojisi gözlenmiştir. Bu bulgu, kapçık ilavesinin yalnızca tutuşma süresini değil, malzemenin termal bozunma ve yanma biçimini de etkilediğini düşündürmektedir. Tezdeki yanma sonrası görüntüler ve gözlemler de kapçık içeren numunelerde en yönünde alev yayılımının sınırlandığını, eriyik damlamaların azaldığını ve yanma bölgesinde erime yerine karbonlaşma davranışının öne çıktığını göstermektedir.

SONUÇ VE TARTIŞMA

Çalışma sonucunda buğday kapçığının polimer kaplamalı polyester kumaşların yanma davranışını değiştirdiği ve tutuşmayı geciktirdiği belirlenmiştir. Bununla birlikte buğday kapçığı tek başına tam bir kendi kendine sönme davranışı sağlamamıştır. Partikül boyutunun önemli bir parametre olduğu; 125-250 µm'den 63-125 µm'ye geçildiğinde belirgin bir iyileşme sağlandığı, ancak partikül boyutunun daha fazla küçültülmesinin ek bir güç tutuşurluk avantajı oluşturmadığı görülmüştür. Binder türünün de katkının performansını etkilediği ve 63-125 µm partikül boyutunda poliüretan binderli sistemin akrilik binderli sisteme göre 5 s daha uzun tutuşma süresi verdiği belirlenmiştir.



Şekil 2. Buğday kapçığı katılmamış yanma sonrası görüntüsü.



Şekil 3. Buğday kapçığı katılmış kaplamalı kumaşın kaplamalı kumaşın yanma sonrası sonrası görüntüsü.

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Sonuçlar, buğday kapçığının geliştirilecek formülasyonlarla konvansiyonel alev geciktiricilere destek olabilecek biyobazlı bir katkı olarak değerlendirilebileceğini göstermektedir. İlerleyen çalışmalarda kapçığın farklı biyobazlı güç tutuşurluk malzemeleriyle birlikte kullanılarak sinerjik etkinin incelenmesi ve kapçık üzerinde kimyasal modifikasyon uygulanarak sönme davranışının geliştirilmesi önerilmektedir.

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LENGTH PREDICTION OF *Atherina boyeri* BASED ON MORPHOMETRIC MEASUREMENTS: AN ARTIFICIAL NEURAL NETWORK AND SUPPORT VECTOR REGRESSION APPROACH

MORFOMETRİK ÖLÇÜMLERE DAYALI *Atherina Boyeri'NİN* BOY TAHMİNİ: YAPAY SİNİR AĞLARI VE DESTEK VEKTÖR REGRESYONU YAKLAŞIMI

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ABSTRACT

Atherina boyeri is an invasive fish species that has successfully established populations in many inland waters due to its high ecological adaptability and rapid population growth. Understanding its growth characteristics and accurately estimating body length are important for biological assessments, stock evaluation, and fisheries management. In this study, growth characteristics of *A. boyeri* collected from Sır Dam Lake were investigated, and the predictive performances of Artificial Neural Network (ANN) and Support Vector Regression (SVR) models were evaluated for estimating fish length using morphometric measurements. A total of 324 specimens were examined, and total weight (W), total length (TL), fork length (FL), standard length (SL), and sex were recorded for each individual. Length–weight relationships were first analyzed to determine growth patterns, after which ANN and SVR models were developed using morphometric variables. Model performance was assessed using the coefficient of determination (R^2), mean squared error (MSE), root mean squared error (RMSE), and mean absolute error (MAE). The sampled fish had total weights ranging from 0.88 to 8.16 g, while total length, fork length, and standard length varied between 50.22–108.12 mm, 49.50–103.35 mm, and 46.45–99.16 mm, respectively. Both machine learning models successfully described the relationships among morphometric variables and produced reliable predictions of fish length, with differences observed in their predictive performance according to the evaluation metrics. The results demonstrate that ANN and SVR provide effective alternatives for modeling fish growth and estimating length from morphometric measurements, offering practical tools that can support fisheries research, biological monitoring, and sustainable management of aquatic resources.

Keywords: *Atherina boyeri*; Morphometric Measurements; Artificial Neural Networks; Support Vector Regression; Fish Length Prediction; Length–Weight Relationship.

ÖZET

Atherina boyeri, yüksek adaptasyon yeteneği ve hızlı popülasyon artışı sayesinde birçok iç su ekosisteminde başarılı bir şekilde yayılım gösteren istilacı bir balık türüdür. Türün büyüme özelliklerinin belirlenmesi ve vücut uzunluğunun doğru tahmin edilmesi, biyolojik değerlendirmeler, stok analizleri ve balıkçılık yönetimi açısından önemli bir yere sahiptir. Bu çalışmada, Sır Baraj Gölü'nden örneklenen *A. boyeri* bireylerinin büyüme özellikleri incelenmiş ve morfometrik ölçümler kullanılarak balık uzunluğunun tahmininde Yapay Sinir Ağları (YSA) ve Destek Vektör Regresyonu (SVR) modellerinin performansları değerlendirilmiştir. Araştırma kapsamında toplam 324 birey incelenmiş; her birey için toplam ağırlık (W), toplam boy (TB), çatal boy (ÇB), standart boy (SB) ve cinsiyet bilgileri kaydedilmiştir. Öncelikle boy-ağırlık ilişkileri analiz edilerek büyüme özellikleri

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belirlenmiş, ardından morfometrik değişkenler kullanılarak YSA ve SVR modelleri oluşturulmuştur. Modellerin performansı belirleme katsayısı (R^2), ortalama kare hata (MSE), karekök ortalama kare hata (RMSE) ve ortalama mutlak hata (MAE) ölçütleri kullanılarak değerlendirilmiştir. İncelenen bireylerde toplam ağırlık 0,88–8,16 g, toplam boy 50,22–108,12 mm, çatal boy 49,50–103,35 mm ve standart boy ise 46,45–99,16 mm arasında değişmiştir. Her iki makine öğrenmesi modeli de morfometrik değişkenler ile balık boyu arasındaki ilişkiyi başarılı bir şekilde modellemiş ve yüksek doğrulukta tahminler üretmiştir. Elde edilen bulgular, morfometrik ölçümlerin balık boyunun tahmininde güvenilir göstergeler olduğunu ve YSA ile SVR yöntemlerinin büyüme özelliklerinin modellenmesinde geleneksel istatistiksel yaklaşımlara etkili alternatifler sunduğunu göstermektedir. Bu modellerin biyolojik değerlendirmeler, balıkçılık araştırmaları ve sürdürülebilir su ürünleri yönetimi çalışmalarında yararlı araçlar olarak kullanılabileceği değerlendirilmektedir.

Anahtar Kelimeler: *Atherina boyeri*; Morfometrik Ölçümler; Yapay Sinir Ağları; Destek Vektör Regresyonu; Boy Tahmini; Boy-Ağırlık İlişkisi.

1. GİRİŞ

Balık popülasyonlarının büyüme özelliklerinin ortaya konulması, populasyon dinamiğinin anlaşılması ve stokların sürdürülebilir şekilde yönetilebilmesi açısından büyük önem taşımaktadır. Bu kapsamda boy ve ağırlık verileri, büyüme parametrelerinin hesaplanması, stok yapısının değerlendirilmesi ve populasyon özelliklerinin belirlenmesinde en yaygın kullanılan biyometrik değişkenler arasında yer almaktadır (King, 2007; Froese, 2006).

Atherina boyeri Risso, 1810, doğal yayılışı deniz ve acısu ekosistemlerini kapsayan küçük pelajik bir balık türüdür. Geniş çevresel toleransı sayesinde doğal dağılım alanı dışındaki birçok göl ve baraj gölüne de yayılmıştır (Iveša ve ark., 2021). Türün kısa yaşam döngüsü, yüksek üreme kapasitesi ve farklı çevresel koşullara uyum sağlayabilmesi, yeni habitatlarda hızla yayılış göstermesine olanak sağlamaktadır (Kottelat & Freyhof, 2007). Günümüzde *A. boyeri*, Avrupa ve Akdeniz havzasındaki birçok iç su ekosisteminde yayılış gösteren ve ekolojik etkileri nedeniyle ilgi gören türlerden biri olarak kabul edilmektedir (Economidis ve ark., 2000; Leonardos, 2008).

Balık biyolojisi çalışmalarında morfometrik özellikler arasındaki ilişkilerin belirlenmesinde çoğunlukla regresyon temelli istatistiksel yöntemler kullanılmaktadır. Özellikle boy-ağırlık ilişkileri, bireylerin büyüme özelliklerinin değerlendirilmesinde en yaygın yaklaşımlardan biridir (Froese, 2006). Bununla birlikte, biyolojik sistemlerde değişkenler arasındaki ilişkiler çoğu zaman doğrusal bir yapı göstermemektedir. Bu nedenle doğrusal varsayımlara dayanan geleneksel istatistiksel modeller, karmaşık biyolojik süreçlerin modellenmesinde bazı durumlarda yetersiz kalabilmektedir (Lek ve ark., 1996; Heit ve ark., 2024).

Son yıllarda makine öğrenmesi yöntemleri, doğrusal olmayan ilişkilerin modellenmesinde farklı disiplinlerde yaygın olarak kullanılmaya başlanmıştır. Özellikle Yapay Sinir Ağları (Artificial Neural Networks, ANN) ve Destek Vektör Regresyonu (Support Vector Regression, SVR), çok değişkenli veri yapılarının analizinde ve yüksek doğrulukta tahmin modellerinin geliştirilmesinde başarılı sonuçlar vermektedir (Vapnik, 1995; Haykin, 2009; Benzer & Benzer, 2024; Benzer ve ark., 2025). Bu doğrultuda, makine öğrenmesi yöntemlerinin morfometrik verilere dayalı tahmin çalışmalarındaki performansının değerlendirilmesi, balık biyolojisi araştırmaları açısından önem taşımaktadır.

Bu çalışmada, Sır Baraj Gölü'nden örneklenen *Atherina boyeri* bireylerinin büyüme özellikleri incelenmiş ve morfometrik ölçümler kullanılarak balık boyunun tahmininde Yapay Sinir Ağları ile Destek Vektör Regresyonu modellerinin performansı değerlendirilmiştir. Elde edilen sonuçların, balık biyolojisinde makine öğrenmesi uygulamalarına katkı sağlaması ve morfometrik verilere dayalı tahmin çalışmalarına alternatif bir yaklaşım sunması amaçlanmıştır.

2. MATERYAL VE YÖNTEM

Araştırmanın materyalini, Sır Baraj Gölü'nde faaliyet gösteren ticari balıkçılardan temin edilen *Atherina boyeri* (Risso, 1810) bireyleri oluşturmuştur. Örnekler uygun muhafaza koşullarında laboratuvara

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taşınmış ve morfometrik ölçümleri gerçekleştirilmiştir. Çalışmada toplam 324 birey değerlendirilmiştir. Her bireyde toplam boy (Total Length, *TL*), çatal boy (Fork Length, *FL*), standart boy (Standard Length, *SL*) ve toplam ağırlık (*W*) ölçülmüştür. Boy ölçümleri 0,01 mm hassasiyetindeki dijital kumpas, ağırlık ölçümleri ise 0,01 g hassasiyetindeki dijital terazi kullanılarak gerçekleştirilmiştir. Ayrıca bireylerin cinsiyetleri belirlenerek kayıt altına alınmıştır. Morfometrik ölçümler, balık biyolojisi çalışmalarında yaygın olarak kullanılan standart yöntemlere göre gerçekleştirilmiştir (Hubbs & Lagler, 1958; Froese, 2006).

Örneklenen bireylerin büyüme özelliklerini belirlemek amacıyla toplam boy, çatal boy ve standart boy için ayrı ayrı boy-ağırlık ilişkileri aşağıdaki eşitlik kullanılarak hesaplanmıştır (Ricker, 1975; Froese, 2006).

$$W=a\,L^{b}$$

Bu eşitlikte *W* bireyin ağırlığını (g), *L* boyunu (mm), *a* regresyon sabitini ve *b* büyüme katsayısını ifade etmektedir. Büyüme tipi, b = 3 olması durumunda izometrik, b < 3 olması durumunda negatif allometrik ve b > 3 olması durumunda ise pozitif allometrik büyüme olarak değerlendirilmiştir (Ricker, 1975).

Balık boyunun tahmin edilmesinde, doğrusal olmayan ilişkilerin modellenmesinde yaygın olarak kullanılan Yapay Sinir Ağları (Artificial Neural Networks, ANN) (Haykin, 2009) ve Destek Vektör Regresyonu (Support Vector Regression, SVR) (Vapnik, 1995) algoritmalarından yararlanılmıştır. Modellerde bireylere ait ağırlık ve cinsiyet bilgileri giriş değişkeni olarak tanımlanmış, toplam boy (TL), çatal boy (FL) ve standart boy (SL) ise ayrı ayrı çıktı değişkenleri olarak modellenmiştir. Böylece her bir boy parametresi için bağımsız tahmin modelleri oluşturulmuştur. Veri seti, modellerin eğitim ve doğrulama performansını değerlendirmek amacıyla %70 eğitim ve %30 test olacak şekilde iki gruba ayrılmıştır (James ve ark., 2021). ANN modeli doğrusal olmayan ilişkilerin öğrenilmesinde, SVR modeli ise yüksek boyutlu veri yapılarında regresyon performansının değerlendirilmesinde kullanılmıştır (Vapnik, 1995; Haykin, 2009; Benzer & Benzer, 2024; Benzer ve ark., 2025).

Bu hesaplamalarda ANN için tek gizli katmanlı bir ağ, SVR için RBF çekirdeği ve her iki modelde standartlaştırılmış giriş değişkenleri kullanıldı. Analizin tekrarlanabilirliği için veri bölme işlemi sabit rastgelelik değeriyle gerçekleştirildi.

Modellerin performansı; belirleme katsayısı (R^2), ortalama mutlak hata (Mean Absolute Error, MAE), ortalama karesel hata (Mean Squared Error, MSE) ve hata kareleri ortalamasının karekökü (Root Mean Squared Error, RMSE) kullanılarak değerlendirilmiştir. R^2, model tarafından açıklanabilen varyansın oranını gösterirken, MAE tahmin edilen değerler ile gerçek değerler arasındaki ortalama mutlak sapmayı ifade etmektedir. MSE, tahmin hatalarının karelerinin ortalamasını gösteren bir hata ölçütü olup büyük hatalara daha duyarlıdır. RMSE ise MSE'nin karekökü alınarak hesaplanmakta ve hata miktarını ölçülen değişken ile aynı birimde ifade etmektedir. Modellerin karşılaştırılmasında yüksek R^2 ile düşük MAE, MSE ve RMSE değerleri daha başarılı tahmin performansı olarak değerlendirilmiştir (Willmott & Matsuura, 2005; Chai & Draxler, 2014).

3. BULGULAR

Çalışmada toplam 324 adet *Atherina boyeri* bireyi değerlendirilmiştir. İncelenen bireylerin ağırlıkları 0,88–8,16 g arasında değişmiş ve ortalama ağırlık 3,27 ± 1,44 g olarak belirlenmiştir. Toplam boy değerleri 50,22–108,12 mm arasında değişirken ortalama toplam boy 78,43 ± 13,47 mm olarak hesaplanmıştır. Çatal boy değerleri 49,50–103,35 mm arasında değişmiş ve ortalama çatal boy 75,74 ± 12,05 mm olarak bulunmuştur. Standart boy değerleri ise 46,45–99,16 mm arasında değişmiş ve ortalama standart boy 69,90 ± 11,44 mm olarak belirlenmiştir (Tablo 1).

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Tablo 1. *Atherina boyeri* bireylerine ait tanımlayıcı istatistikler

Değişken	n	Minimum	Maksimum	Ortalama ± SS
Ağırlık (W, g)	324	0,88	8,16	3,27 ± 1,44
Toplam Boy (TB, mm)	324	50,22	108,12	78,43 ± 13,47
Çatal Boy (CB, mm)	324	49,50	103,35	75,74 ± 12,05
Standart Boy (SB, mm)	324	46,45	99,16	69,90 ± 11,44

SS: Standart Sapma

Atherina boyeri bireylerinin büyüme özelliklerini belirlemek amacıyla toplam boy, çatal boy ve standart boy ile ağırlık arasındaki ilişkiler ayrı ayrı incelenmiştir. Boy-ağırlık ilişkileri, logaritmik dönüşüm uygulanarak (W=aL^b) eşitliği üzerinden hesaplanmıştır. Her bir boy ölçümü için elde edilen regresyon denklemleri, regresyon katsayıları ve büyüme tipleri Tablo 2'de sunulmuştur.

Tablo 2. *Atherina boyeri* bireylerinde toplam boy, çatal boy ve standart boy için hesaplanan boy-ağırlık ilişkisi parametreleri.

Boy parametresi	n	Regresyon denklemi	a	b	R^2	Büyüme tipi
TB	324	$W = 0{,}00004027 \times TB^{2{\cdot}5767}$	0,00004027	2,5767	0,9303	A−
ÇB	324	$W = 0{,}00001738 \times CB^{2{\cdot}7910}$	0,00001738	2,7910	0,9403	A−
SB	324	$W = 0{,}00002729 \times SB^{2{\cdot}7378}$	0,00002729	2,7378	0,9479	A−

Toplam boy, çatal boy ve standart boy değerlerinin tahmini için Yapay Sinir Ağları ve Destek Vektör Regresyonu modelleri ayrı ayrı oluşturulmuştur. Veri setinin %70'i model eğitimi, %30'u ise bağımsız test işlemi için kullanılmıştır. Her modelin test veri setindeki performansı R^2, MAE, RMSE ve MSE ölçütleriyle değerlendirilmiştir. Elde edilen sonuçlar Tablo 3'te verilmiştir.

Tablo 3. ANN ve SVR modellerinin test veri setindeki tahmin performansları.

Tahmin edilen değişken	Model	R^2	MAE (mm)	RMSE (mm)	MSE (mm^2)
Toplam Boy (TB)	ANN	0,9457	2,4346	2,9209	8,5317
	SVR	0,8852	3,0674	4,2456	18,0248
	LR	0,9648	1,9601	2,3522	5,5328
Çatal Boy (CB)	ANN	0,9544	1,9062	2,3453	5,5006
	SVR	0,9179	2,3873	3,1469	9,9030
	LR	0,9762	1,2898	1,6947	2,8718
Standart Boy (SB)	ANN	0,9803	1,1876	1,4835	2,2008
	SVR	0,9511	1,8662	2,3355	5,4547
	LR	0,9820	1,1049	1,4177	2,0098

LR: Doğrusal Regresyon (*Linear Regression*); **ANN:** Yapay Sinir Ağları (*Artificial Neural Networks*); **SVR:** Destek Vektör Regresyonu (*Support Vector Regression*);

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ANN modelinde R^2 değerleri 0,9457 ile 0,9803 arasında değişmiştir. En yüksek belirleme katsayısı standart boy tahmininde (R^2 = 0,9803) elde edilirken, bu modele ait MAE, RMSE ve MSE değerleri sırasıyla 1,1876 mm, 1,4835 mm ve 2,2008 mm² olarak hesaplanmıştır. En düşük R^2 değeri ise toplam boy tahmininde (R^2 = 0,9457) belirlenmiştir.

SVR modelinde R^2 değerleri 0,8852 ile 0,9511 arasında değişmiştir. En yüksek tahmin performansı standart boy modelinde (R^2 = 0,9511) elde edilmiş olup, bu modele ait MAE, RMSE ve MSE değerleri sırasıyla 1,8662 mm, 2,3355 mm ve 5,4547 mm² olarak hesaplanmıştır. En düşük R^2 değeri ise toplam boy tahmininde (R^2 = 0,8852) elde edilmiştir.

Modeller birlikte değerlendirildiğinde, ANN modeli üç boy değişkeninin tamamında SVR modeline göre daha yüksek R^2 ve daha düşük hata değerleri üretmiştir. Her iki makine öğrenmesi algoritmasında da en yüksek tahmin performansı standart boy için elde edilmiştir.

Tablo 3'te verilen performans ölçütleri incelendiğinde, tüm modellerin morfometrik ölçümlerden balık boyunun tahmininde yüksek doğruluk sağladığı görülmektedir. Doğrusal Regresyon (LR) modeli, üç boy parametresinin tamamında en yüksek R^2 değerlerini ve en düşük hata ölçütlerini göstermiştir. ANN modeli, LR modeline yakın tahmin performansı sergilerken, SVR modeli diğer modellere göre daha düşük belirleme katsayıları ve daha yüksek hata değerleri üretmiştir.

4. TARTIŞMA

Bu çalışmada, *Atherina boyeri* bireylerine ait morfometrik ölçümler kullanılarak balık boyunun tahmininde doğrusal regresyon, Yapay Sinir Ağları ve Destek Vektör Regresyonu modellerinin performansları değerlendirilmiştir. Üç model de yüksek tahmin doğruluğu göstermiştir. Doğrusal regresyon modeli en yüksek belirleme katsayılarını ve en düşük hata değerlerini üretirken, ANN modeli benzer performans sergilemiş, SVR modeli ise diğer modellere göre daha düşük tahmin başarısı göstermiştir. Elde edilen sonuçlar, mevcut veri setinde doğrusal regresyon modelinin öne çıktığını göstermekle birlikte, ANN ve SVR algoritmalarının doğrusal olmayan veri yapılarının modellenmesinde önemli alternatif yöntemler olmaya devam ettiğini desteklemektedir (Haykin, 2009; Vapnik, 1995; Benzer & Benzer, 2024; Benzer ve ark., 2025).

5. SONUÇ

Bu çalışmada, *Atherina boyeri* bireylerinin boy-ağırlık ilişkileri belirlenmiş ve morfometrik ölçümler kullanılarak balık boyunun tahmininde doğrusal regresyon, Yapay Sinir Ağları ve Destek Vektör Regresyonu modellerinin performansları karşılaştırılmıştır. Elde edilen sonuçlar, üç yöntemin de yüksek tahmin doğruluğu sağladığını, ancak mevcut veri setinde doğrusal regresyon modelinin en yüksek performansı gösterdiğini ortaya koymuştur. Bununla birlikte, makine öğrenmesi algoritmaları da düşük hata değerleri ve yüksek belirleme katsayıları ile güvenilir tahminler üretmiştir. Bu bulgular, morfometrik ölçümlerin balık boyunun tahmininde etkin bir şekilde kullanılabileceğini göstermekte olup, daha geniş veri setleri ve farklı makine öğrenmesi algoritmaları ile gerçekleştirilecek çalışmaların bu alandaki bilgi birikimine katkı sağlayacağı düşünülmektedir.

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PROGRAMMABLE DAMAGE LOCALIZATION THROUGH SPATIAL TOOLPATH ENGINEERING IN 3D PRINTING

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ABSTRACT

Additive manufacturing enables the fabrication of components with complex geometries. However, the mechanical response of printed parts is generally optimized to maximize strength rather than to control where damage initiates. This study introduces a proof-of-concept approach for programmable damage localization through spatial toolpath engineering in material extrusion-based 3D printing. The proposed concept is based on locally modifying raster orientations within predefined regions of a tensile specimen while maintaining identical material, geometry, printing parameters, and infill density. Initially, homogeneous specimens with raster orientations of 0°, 45°, and 90° are manufactured by 3D printing to establish a reference database describing the influence of raster orientation on tensile behavior. Subsequently, heterogeneous specimens incorporating a localized raster-modified region are produced to investigate whether damage initiation can be intentionally directed to a predetermined location. Tensile tests are conducted to evaluate mechanical performance and fracture behavior, and the effectiveness of spatial toolpath engineering for damage localization is assessed by comparing homogeneous and heterogeneous specimens. The proposed methodology demonstrates the feasibility of using raster orientation as a design parameter for controlling the spatial distribution of damage rather than solely improving structural strength. This work provides a foundation for programmable mechanical behavior in additively manufactured structures and establishes a new perspective for damage-aware design in 3D printing.

Keywords: 3D Printing, Damage Localization, Raster Orientation, Additive Manufacturing, Toolpath Engineering.

INTRODUCTION

Additive Manufacturing (AM) has become one of the most rapidly evolving manufacturing technologies due to its capability to fabricate complex geometries with minimal material waste and high design flexibility. Among various AM processes, material extrusion-based 3D printing has gained widespread attention in engineering applications because of its low cost, and ability to produce functional polymer components (Tümer, 2021). Consequently, numerous studies have focused on improving the mechanical performance of printed parts by optimizing process parameters such as layer thickness, printing speed, build orientation, infill density, and raster orientation (Doshi et al., 2022; Rathod et al., 2026).

Raster orientation is recognized as one of the most influential process parameters affecting the tensile behavior of material extrusion components (Elwasli et al., 2026). By altering the deposition direction of adjacent filaments, the stress transfer mechanism, inter-road bonding, and fracture behavior of printed parts can be significantly modified. Previous studies have primarily investigated the effect of uniform raster orientations on global mechanical properties, including tensile strength, elastic modulus, and failure strain (Khodabandeh et al., 2026). Although these studies provide valuable information for mechanical optimization, they generally consider raster orientation as a parameter for maximizing structural performance rather than controlling the location of damage initiation (Amor & Souissi, 2025).

In many engineering applications, however, failure at a predetermined location can be desirable for improving structural safety, simplifying inspection, or facilitating component replacement. Inspired by this concept, the present study explores the possibility of using raster orientation not merely as a strengthening parameter but as a design variable for spatially programming the mechanical response of

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3D-printed structures. Instead of optimizing the entire component for maximum strength, the proposed approach aims to intentionally influence where damage initiates through localized modification of the printing toolpath.

Therefore, this study presents a proof-of-concept methodology for programmable damage localization through spatial toolpath engineering in material extrusion-based 3D printing. In the first stage, homogeneous tensile specimens with raster orientations of 0°, 45°, and 90° are fabricated to establish the relationship between raster orientation and tensile behavior. These results provide a reference database for the subsequent development of heterogeneous specimens containing localized raster-modified regions designed to investigate controlled damage initiation. The proposed methodology introduces a new perspective in additive manufacturing by employing toolpath engineering as a means of programming the spatial distribution of damage rather than solely enhancing mechanical performance.

MATERIALS AND METHODS

Commercial PLA filament was employed throughout the study. All specimens were fabricated using a Bambu Lab H2D Pro material extrusion 3D printer equipped with a 0.4 mm nozzle. To eliminate the influence of material-related variables, the same filament spool and same printing parameters were used for all specimens (Tablo 1).

Table 1. Printing parameters for tensile test specimens.

Parameter	**Value**
Printer	Bambu Lab H2D Pro
Material	eSUN PLA+
Nozzle diameter	0.4 mm
Layer height	0.20 mm
Infill density	100%
Infill pattern	Rectilinear
Number of specimens	15
Printing orientation	Flat
Variable parameter	Raster orientation (0°, 45°, 90°)

Tensile specimens were designed according to the selected standard geometry and printed in the flat orientation on the build platform. All specimens possessed identical dimensions to ensure that only the influence of toolpath orientation on the mechanical response was investigated.

Three homogeneous raster configurations were selected to establish the relationship between raster orientation and tensile behavior. Raster orientations of 0°, 45°, and 90° were assigned to the entire gauge section of the tensile specimens (Table 2). Three specimens were fabricated for each configuration, resulting in a total of nine specimens. To isolate the effect of raster orientation, all process parameters were maintained constant throughout the study. The only variable was the raster orientation assigned during slicing.

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Table 2. Experimental groups based on homogeneous and heterogeneous raster architectures.

Group	Raster orientation	Number of specimens
G0	0°	3
G45	45°	3
G90	90°	3
G45–0–45	45°–0°–45°	3
G45–90–45	45°–90°–45°	3

The proposed methodology consists of two sequential stages. In the first stage, homogeneous tensile specimens with raster orientations of 0°, 45°, and 90° are fabricated to establish the relationship between raster orientation and tensile behavior (Figure 1). Mechanical properties obtained from these specimens constitute a reference database for evaluating the influence of raster orientation on damage initiation.

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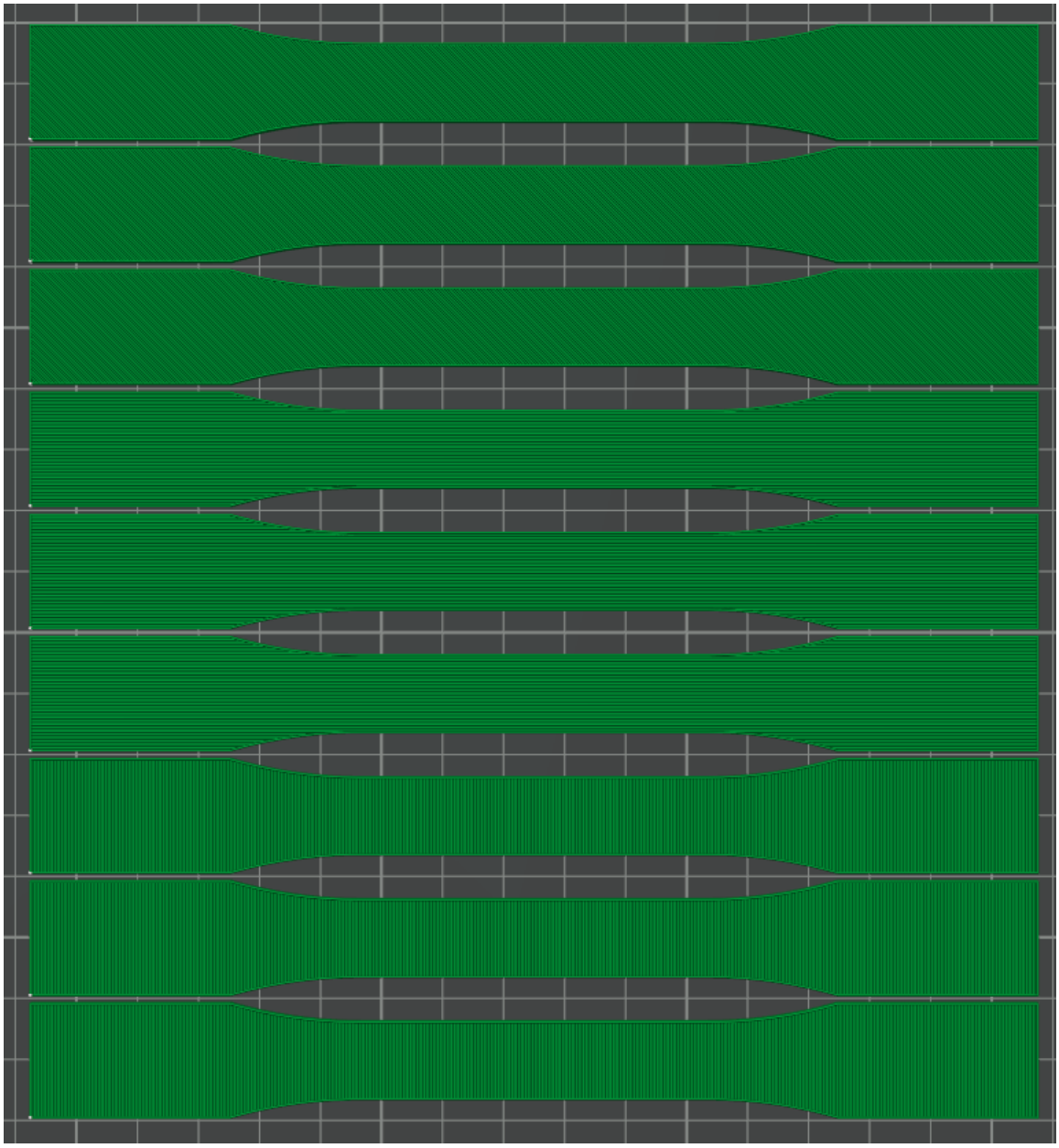


Figure 1. Representative raster orientations used in the study: (a) 45°, (b) 0°, and (c) 90°.

In the second stage, heterogeneous tensile specimens incorporating spatially modified raster orientations were designed to investigate the feasibility of programmable damage localization. As illustrated in Figure 2, two heterogeneous raster architectures were proposed: a 45°–0°–45° configuration, in which the central region represents a mechanically weaker corridor, and a 45°–90°–45° configuration, in which the central region represents a mechanically stronger corridor. By maintaining identical material, specimen geometry, printing parameters, and infill density while locally modifying only the raster orientation, the influence of spatial toolpath engineering on damage initiation and localization can be systematically evaluated.

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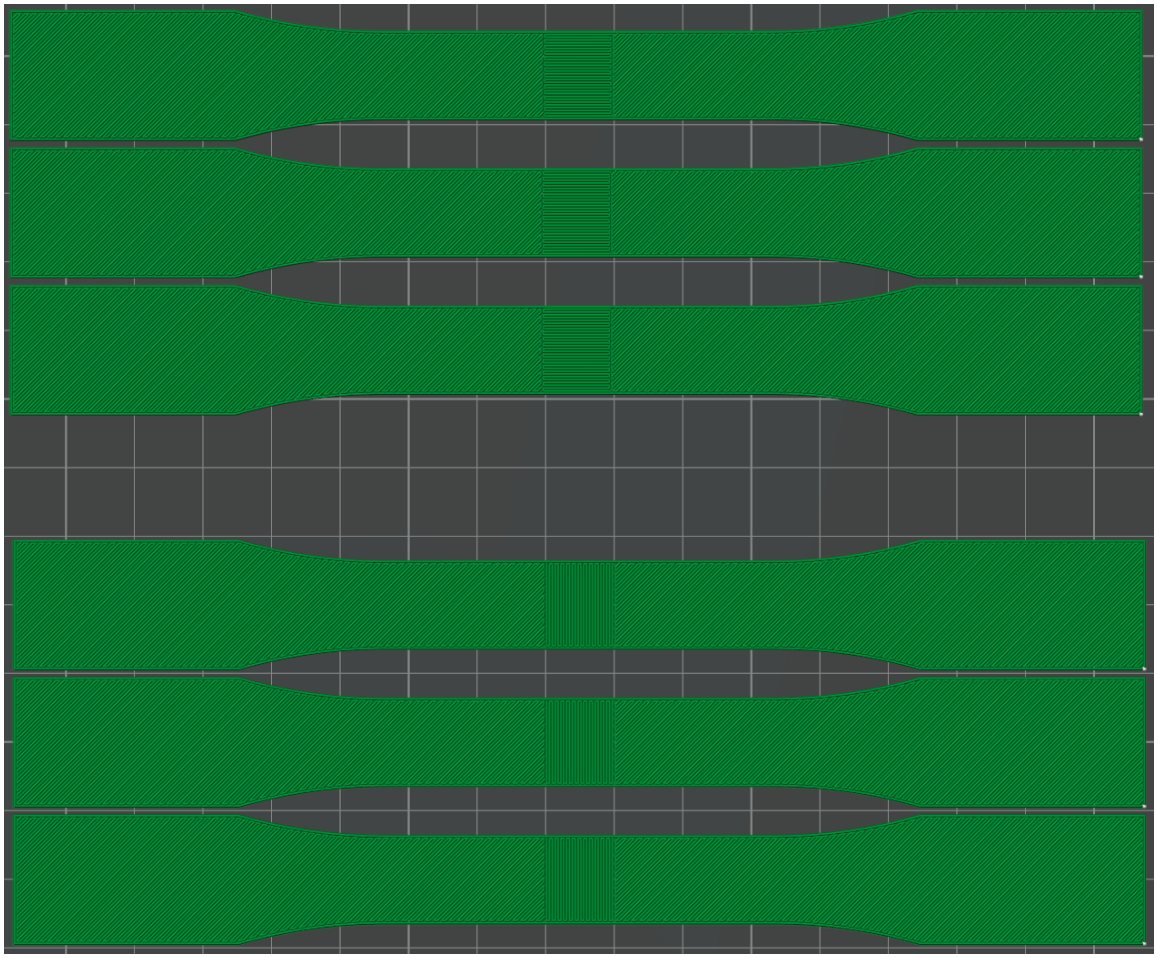


Figure 2. Representative heterogeneous raster architectures with localized raster-modified regions used for programmable damage localization

FINDINGS

Homogeneous tensile specimens with raster orientations of 0°, 45°, and 90° were successfully fabricated using material extrusion-based 3D printing. All specimens were produced under identical printing conditions, including material, layer height, infill density, and printing orientation, while raster orientation was maintained as the only variable. Representative photographs of the fabricated specimens are presented in Figure 3.

Visual inspection confirmed that the specimens exhibited consistent geometry and satisfactory surface quality without noticeable manufacturing defects. The rectilinear raster orientations generated during slicing were successfully reproduced in the printed specimens, indicating reliable control of the toolpath during fabrication.

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Figure 3. Fabricated tensile specimens with homogeneous raster orientations of 0°, 45°, and 90°.

The engineering stress–strain curves of all specimen groups are presented in Figure 4, while the corresponding ultimate tensile strength values are summarized in Table 3. Among the homogeneous specimens, G90 exhibited the highest average ultimate tensile strength (43.47 ± 0.47 MPa), followed by G45 (37.15 ± 0.54 MPa) and G0 (33.61 ± 0.47 MPa). These results demonstrate that raster orientation markedly influences the tensile response of material extrusion-based PLA specimens.

Table 3. Ultimate tensile strength of homogeneous and heterogeneous raster architectures.

Group	Raster Architecture	R1 (MPa)	R2 (MPa)	R3 (MPa)	Mean ± SD (MPa)
G0	0°	33.61	34.08	33.14	33.61 ± 0.47
G45	45°	36.52	37.46	37.46	37.15 ± 0.54
G90	90°	43.94	43.00	43.47	43.47 ± 0.47
G45-0-45	45°–0°–45°	25.77	24.08	25.21	25.02 ± 0.86
G45-90-45	45°–90°–45°	16.38	15.63	16.24	16.09 ± 0.40

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The heterogeneous raster architectures exhibited considerably lower tensile strengths than the homogeneous specimens. The G45–0–45 specimens achieved an average ultimate tensile strength of 25.02 ± 0.86 MPa, whereas the G45–90–45 specimens exhibited the lowest average value of 16.09 ± 0.40 MPa. Although the central region of the G45–90–45 configuration contained the mechanically stronger raster orientation identified in the homogeneous tests, its overall tensile performance was substantially reduced.

The stress–strain responses shown in Figure 4 further reveal that the heterogeneous specimens displayed distinct deformation behavior compared with the homogeneous groups. The introduction of localized raster transitions altered the load-carrying response of the specimens, suggesting that the interfaces between adjacent raster architectures play a significant role in the tensile behavior. These observations demonstrate that the mechanical response of material extrusion components cannot be explained solely by the strength of the individual raster orientations but is also affected by the spatial arrangement of raster architectures.

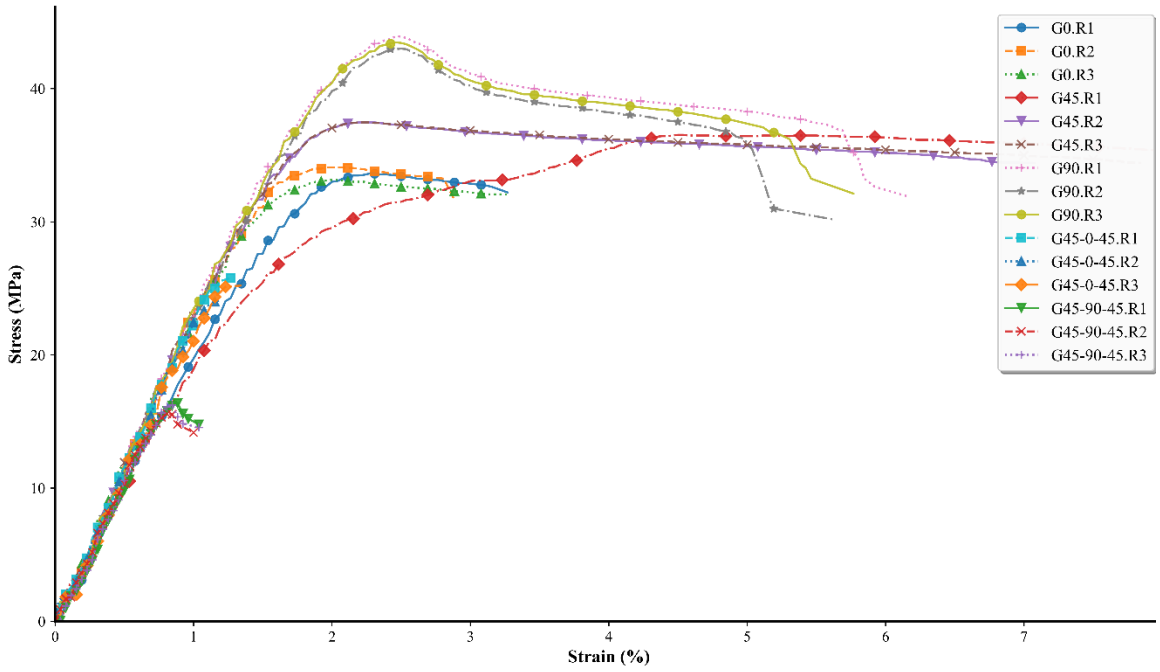


Figure 4. Engineering stress–strain curves of homogeneous and heterogeneous tensile specimens with different raster architectures.

Visual examination of the fractured specimens revealed that all G45–0–45 and G45–90–45 specimens failed at one of the transition regions between adjacent raster architectures. No heterogeneous specimen fractured entirely within the central homogeneous corridor. This repeatable fracture location demonstrates that the raster-transition regions acted as mechanically critical zones under tensile loading.

The consistent fracture of all heterogeneous specimens at the raster-transition regions provides direct experimental evidence that spatial toolpath modification can be used to localize failure within predefined regions. Future work will focus on clarifying the detailed fracture mechanisms and damage evolution within these transition zones.

CONCLUSION AND DISCUSSION

This study presented a proof-of-concept approach for programmable damage localization through spatial toolpath engineering in material extrusion-based 3D printing. Homogeneous tensile specimens with raster orientations of 0°, 45°, and 90° were first fabricated to establish the influence of raster orientation on tensile behavior. The experimental results demonstrated that raster orientation strongly affected the

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mechanical performance of the printed PLA specimens, with the 90° raster orientation exhibiting the highest ultimate tensile strength, followed by the 45° and 0° orientations.

Based on these reference data, heterogeneous raster architectures incorporating localized raster-modified regions were designed and experimentally evaluated. Both heterogeneous configurations exhibited considerably lower tensile strengths than the homogeneous specimens, indicating that introducing spatial variations in raster architecture substantially alters the global mechanical response. The reduction in tensile strength suggests that the mechanical behavior of heterogeneous structures cannot be predicted solely from the tensile performance of their individual homogeneous raster orientations.

A particularly significant finding of this study is that all heterogeneous specimens fractured at the transition regions between adjacent raster architectures rather than within the homogeneous raster regions themselves. This consistent fracture behavior indicates that the interfaces created by changes in raster orientation represent mechanically critical regions governing damage initiation under tensile loading. The results indicate that damage localization is governed not only by the mechanical properties of the individual raster orientations but also by the spatial arrangement and transitions between adjacent raster architectures.

The obtained findings demonstrate that spatial toolpath engineering provides a practical means of modifying the mechanical response of material extrusion components. Rather than considering raster orientation only as a parameter for maximizing mechanical performance, the present work highlights its potential as a design variable for controlling where damage preferentially initiates. This concept introduces a new perspective in additive manufacturing by enabling damage-aware structural design through localized toolpath modification.

Future work will focus on detailed fracture surface analysis, digital image correlation (DIC), and microscopic characterization of the transition regions to better understand the mechanisms responsible for damage initiation. In addition, different transition geometries, corridor widths, and raster combinations will be investigated to establish quantitative design guidelines for programmable damage localization in additively manufactured structures.

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THE EFFECT OF SEISMIC LOADS ON AN ONSHORE WIND TURBINE TOWER

SİSMİK YÜKLERİN KARADAKİ BİR RÜZGAR TÜRBİN KULE YAPISINA ETKİSİ

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ABSTRACT

The use of wind energy which is a renewable energy source is gradually increasing. Wind turbines are used to generate electricity from wind energy. The wind turbine tower structure is the load-bearing element of the system and must be able to withstand the loads acting on the system. Determining the behavior of thin and delicate wind turbine tower structures when subjected to seismic loads is crucial. Especially in wind turbine towers built in seismically active regions, large inertial forces can occur during earthquakes. To determine the structural responses that may occur in these structures during strong ground motions, an onshore wind turbine tower structure was modeled as three dimensions using the finite element method and dynamic analyses were performed. During the dynamic analyses, the time-history analysis method was used, and earthquake records with different characteristics were applied to the system. As a result of the analyses, the obtained structural responses were compared and evaluated.

Keywords: Onshore wind turbine tower, Seismic loads, Earthquake

ÖZET

Yenilenebilir enerji kaynaklarından olan rüzgar enerjisinin kullanımı giderek artmaktadır. Rüzgar enerjisinden elektrik üretmek amacı ile rüzgar türbinleri kullanılmaktadır. Rüzgar türbin kule yapısı sistemin taşıyıcı elemanı olup sisteme etkiyen yüklere karşı dayanım gösterebilmesi gereklidir. Ince ve narin olan rüzgar türbin kule yapılarının sismik yüklere maruz kalması durumunda göstereceği davranışın belirlenmesi oldukça önemlidir. Özellikle sismik hareketliliğin bulunduğu bölgelere inşa edilen rüzgar türbin kule yapılarında deprem sırasında büyük atalet kuvvetleri meydana gelebilmektedir. Kuvvetli yer hareketleri sırasında bu yapılarda oluşabilecek yapısal tepkilerin belirlenebilmesi amacı ile karadaki bir rüzgar türbin kule yapısı üç boyutlu olarak sonlu elemanlar yöntemi ile modellenerek dinamik analizler gerçekleştirilmiştir. Dinamik analizler gerçekleştirilirken zaman tanım alanı yöntemi kullanılarak sisteme farklı özelliklere sahip deprem kayıtları uygulanmıştır. Analizler sonucunda, elde edilen yapısal tepkiler karşılaştırılarak değerlendirilmiştir.

Anahtar Kelimeler: Karadaki rüzgar türbin kulesi, Sismik Yükler, Deprem

INTRODUCTION

The capacities of wind turbines depend on the characteristics of the region where the turbine is constructed, the geographical conditions, and meteorological situations (Jung and Schindler, 2023). Onshore wind turbine tower structures can be built as concrete towers, steel lattice structures, precast concrete structures, steel tabular systems, and hybrid systems (Pons et. al, 2017).

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Large rotor blades are used for more benefit of wind loads. However, high-tower building systems are used (Oliveira et al., 2018). The nacelle is placed on top of the tower. The blades move due to the wind load and provide energy to the generators (Márquez et al., 2012).

Because of the increasing utilize of wind generators in recent years, their production capacities also increased. Because of the increase in the size of the generators, it is also necessary to providing their resistance to dynamic loads. Dynamic loads can cause fatigue, vibration, and stress and lead to generator failures. These factors are important in terms of the system's production, design, and installation (Hernandez-Estrada et al., 2021).

A large number of material are necessary in the course of the construction of wind turbine structure plants. These materials include steel, copper, dysprosium, neodymium, concrete, and fiberglass. Steel material production requires intensive-energy processes and by using blast furnaces, metallurgical coal is burned. Carbondioxide is also composed of during concrete production. Because these situations can be ignored compared to fossil fuels that continuously produce carbondioxide (Desalegn et al., 2023).

In 07.08.2015, Typhoon Taichung occurred in Taiwan. During this typhoon, 2 MW capacity onshore wind turbine towers collapsed. Wind turbines were examined by Chou et al. (2018). In 2010, 0.6 MW capacity wind turbine located on Jeju Island failured. A fire that started in the turbine body spread. Due to the rotation of the turbine blades, the generator body connection separated and fell. In addition, the tower inclined because of the vibrations that occurred in the tower. The collapse behavior of a wind turbine having this capacity was investigated by Lee et al. (2020).

The structures of the wind turbine tower can be subjected to various environmental loads. These environmental loads include seismic loads and wind loads. In the case of increased wind loads, the structure behavior may show negative effects. Seismic loads also significantly influence the behavior of tower structures.

Zhao et al. (2020), investigated the vibration response of a onshore wind turbine tower structure with 1.5 MW capacity. The vibration features of the turbine were examined under different situations. Campbell diagrams were generated depend on the obtained natural frequency values. These diagrams were utilized to investigate the resonance case of the system. However, the relationship between the operating conditions of the wind turbine system and modal parameters were investigated. Wang et al. (2026) determined the reliability of offshore wind turbine tower structures under earthquake effects occurring on land and at sea. Because offshore earthquakes have a longer duration and higher intensity, it was determined that greater responses occur in the structure of onshore wind turbines as a result of these earthquakes. As a result of the fragility analyses, It was shown that earthquakes occurring at sea cause greater damage than those occurring on land. da Silva Medeiros and de Lima (2025) investigated soil-structure interaction by evaluating onshore wind turbine tower structures. According to the results obtained, it was determined that considering the soil conditions is important in determining structural responses. Furthermore, the essentiality of considering displacement and stress values in soil-structure interaction studies has been emphasized. Nezamolmolki and Shooshtari (2016), performed a frequency analysis of a wind turbine tower. In the design of a 3-bladed wind turbine structure, it was determined that the hinge slip effect could affect the natural frequency values of the tower. However, Displacement values were evaluated by considering the values of different design load. Luo et al. (2025) investigated fatigue reliability considering a lattice tubular hybrid tower. Sorge et al. (2024), determined the optimum design parameters of the hinge-spring-friction device for onshore wind turbines using an optimization algorithm. Korkmaz (2008) conducted pushover analyses and the time-history analyses using the different seismic records, considering a wind turbine tower structure.

The main purpose of this study is to determine the behaviour of the onshore wind türbine tower structure under the seismic loads. For this purpose, the structure of wind turbine tower with height of 45m was modeled and the values of structural response were determined by applying seismic loads with different characteristics. The obtained values were compared.

MATERIAL and METHOD

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In this study, a onshore structure with a height of 45 m, a base width of 8 m, and a top width of 1.75 m was modeled as three dimensions using ANSYS finite element program (ANSYS, 2026). The system is made of steel material. Figure 1 shows the finite element model of the tower.

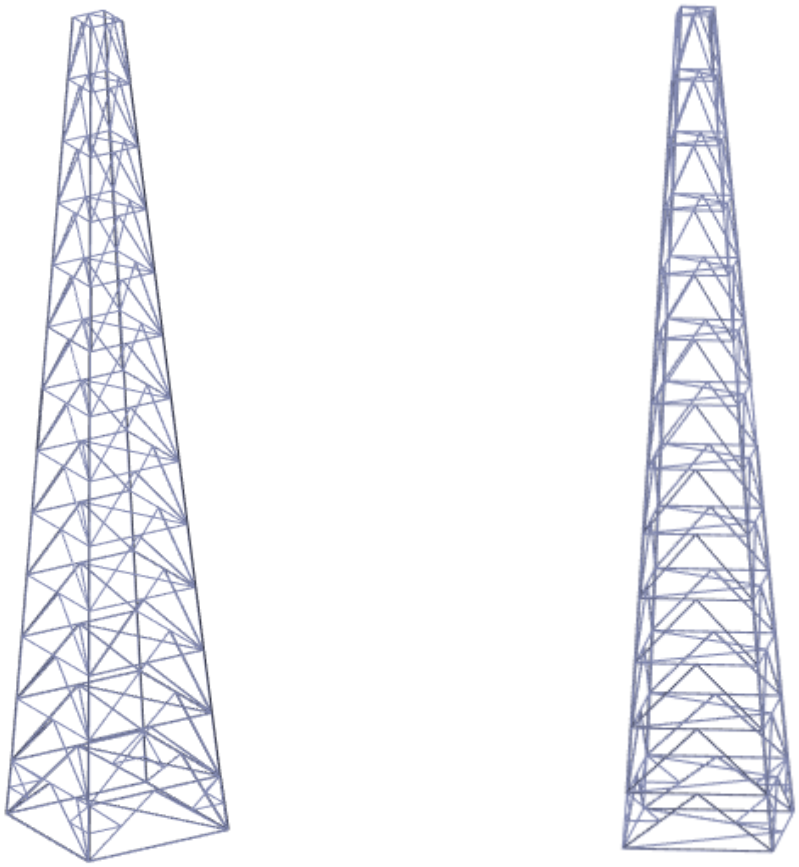


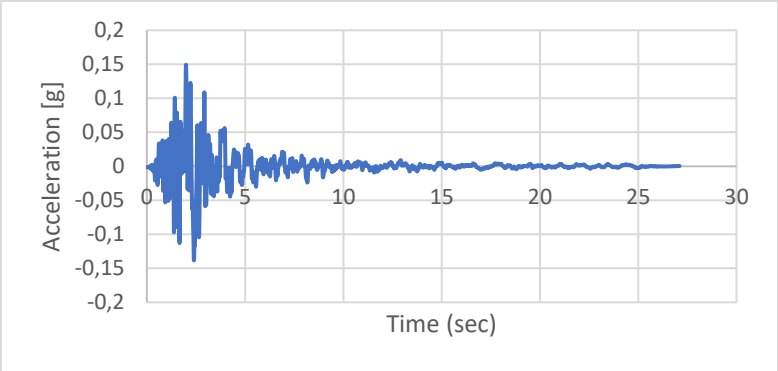
Figure 1. Onshore structure model

Dynamic analyses were performed on the onshore tower structure by applying time-dependent acceleration records with different characteristics. Table 1 shows the characteristics of earthquakes. The Coyote Lake earthquake (Mw=5.74) occurred in 1979, and the Imperial Valley-06(179) (Mw=6.53) and Imperial Valley-06(183) (Mw=6.53) earthquakes also occurred in 1979. Anza earthquake had a magnitude of 5.19 and took place in 1980. Cape Mendocino earthquake with a magnitude of 7.01 and occurred in 1992. The time-dependent characteristics of earthquakes are shown in Figure 2 (PEER, 2026).

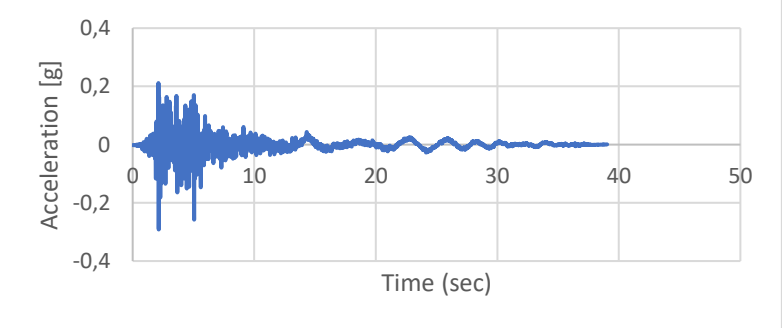
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Table 1. The features of earthquakes (PEER, 2026)

Earthquake Number	Record Sequence Number	Earthquake Name	Year	Station Name	Earthquake Magnitude (Mw)	PGA (g)	Vs30 (m/s)
1	150	Coyote Lake	1979	Gilroy Array #6	5.74	0.149	663.31
2	179	Imperial Valley-06	1979	El Centro Array #4	6.53	0.291	208.91
3	183	Imperial Valley-06	1979	El Centro Array #8	6.53	0.467	206.08
4	225	Anza (Horse Canyon)-01	1980	Anza - Pinyon Flat	5.19	0.047	724.89
5	825	Cape Mendocino	1992	Cape Mendocino	7.01	0.738	567.78

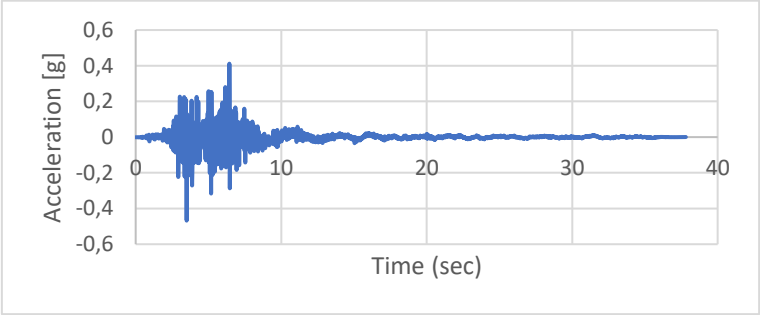


Coyote Lake Earthquake (RSN-150)

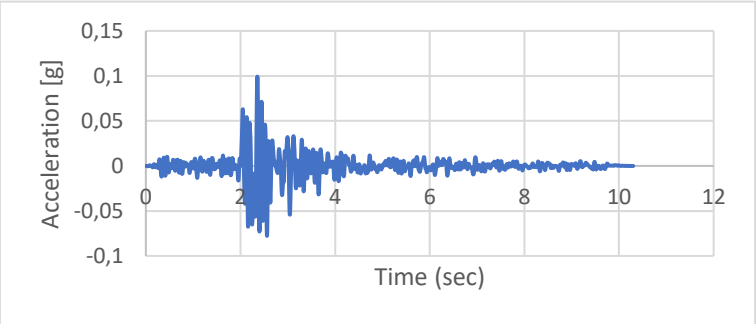


Imperial Valley-06 Earthquake (RSN-179)

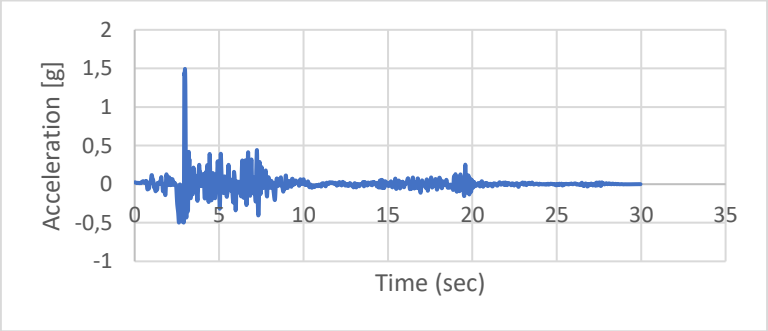
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Imperial Valley-06 Earthquake (RSN-183)



Anza (Horse Canyon)-01Earthquake (RSN-225)



Cape Mendocino Earthquake (RSN-825)

Figure 2. Acceleration-time values of the earthquakes.

RESEARCH and FINDINGS

Modal analyses were performed considering the onshore structure. As a result of the modal analyses, the values of frequency, period, and mode shapes were determined. The mode shapes are shown in Figure 3. The frequency values obtained from the modal analysis results are 2.917 Hz, 2.926 Hz, 3.721 Hz and 3.734 Hz. The period values are 0.343 sec, 0.342 sec, 0.269 sec ve 0.268 sec.

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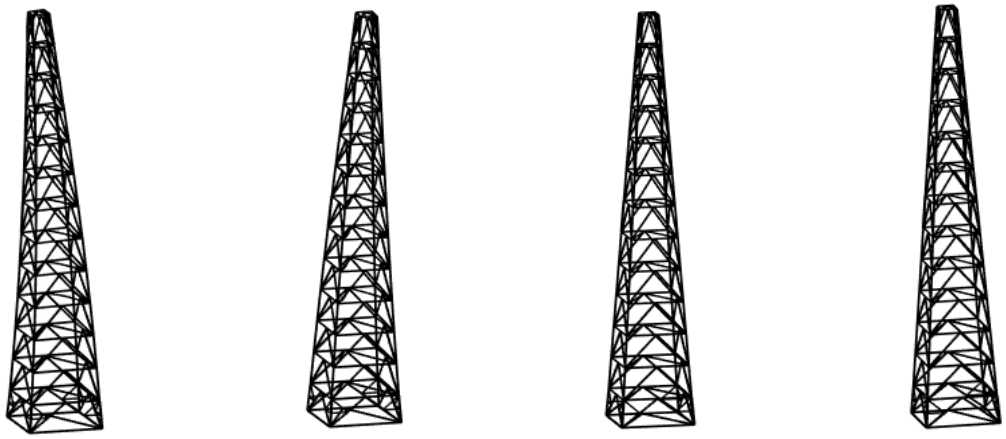


Figure 3. Mode shapes of the onshore tower

In this study, a time-history analysis method was applied to a steel wind turbine tower structure with a height of 45 m, using 5 time-dependent acceleration values, in order to determine the structural behavior of an onshore structure under seismic loads. The earthquakes that applied to the structure were Coyote Lake (RSN-150), Imperial Valley-06 (RSN-179), Imperial Valley-06(RSN-183), Anza (Horse Canyon)-01(RSN-225) and Cape Mendocino (RSN-825) earthquakes with different characteristics. The maximum effective ground acceleration values of the Coyote Lake (RSN-150), Imperial Valley-06 (RSN-179), Imperial Valley-06 (RSN-183), Anza (Horse Canyon)-01(RSN-225) and Cape Mendocino (RSN-825) earthquakes are 0.149 g, 0.211g, 0.411g, 0.99 g and 1.493 respectively. The moment magnitudes are 5.74, 6.53, 6.53, 5.19 and 7.01 respectively.

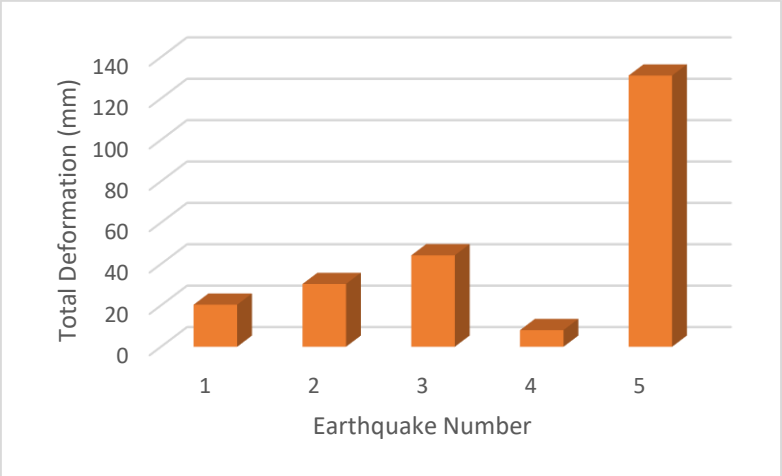


Figure 4. The displacement values obtained from time history analyses.

Figure 4 shows the displacement values obtained from the analyse results. In Anza (Horse Canyon)-01(RSN-225) earthquake, the smallest displacement value is obtained as 8.04 mm and the value of the largest displacement was obtained as 131.07 mm for Cape Mendocino (RSN-825) earthquake. The displacement values for Coyote Lake (RSN-150) earthquake, Imperial Valley-06 earthquake (RSN-179) and Imperial Valley-06 (RSN-183) earthquake are 20.33 mm, 30.32 mm and 44.17 mm respectively.

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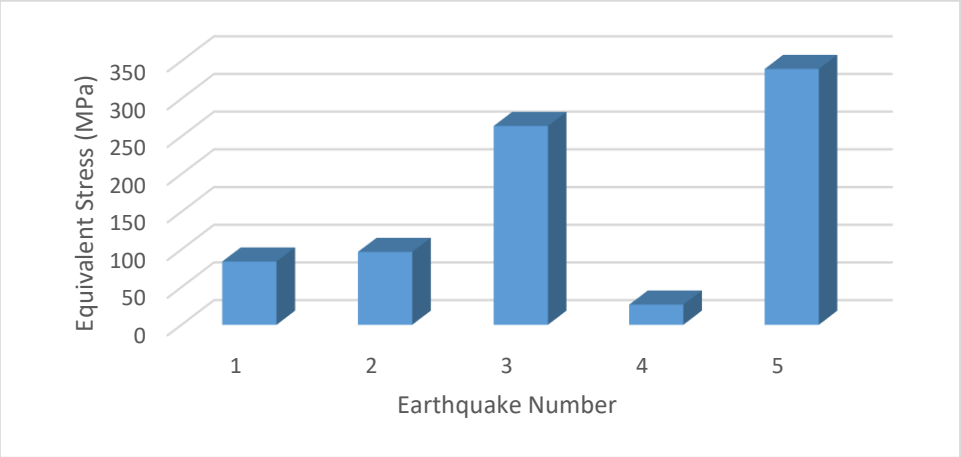


Figure 5. Stress values obtained as a result of dynamic analyses.

Figure 5 shows the stress values determined as a result of time history analyses. The highest value of stress was obtained as 339.41 MPa in Cape Medocino (RSN-825) earthquake, while the lowest value of stress was determined as 26.70 MPa in Anza (Horse Canyon)-01(RSN-225). The values of the stress obtained for Coyote Lake earthquake (RSN-150), Imperial Valley-06 earthquake (RSN 179) and Imperial Valley-06 earthquake (RSN 183) are 83.95 MPa, 96.65 MPa and 263.73 MPa respectively.

CONCLUSION

In this study, a wind turbine tower was designed considering an onshore environment.Dynamic analyses were performed to determine the response of onshore tower structure under seismic loads. Time history analysis method was used during dynamic analyses. Five different types of seismic motion recordings were applied to the system. The earthquakes that were applied to the onshore structure are Coyote Lake (RSN-150), Imperial Valley-06 (RSN-179), Imperial Valley-06 (RSN-183), Anza (Horse- Canyon)-01(RSN-225) and Cape-Mendocino (RSN-825) earthquakes. Under the effect of these earthquakes, the largest displacement and stress values were obtained from the Cape Mendocino (RSN-825) earthquake, while the smallest displacement and stress values were obtained by applying the Anza (Horse-Canyon)-01 (RSN-225) earthquake to the structure. The structural response values obtained vary depending on differences in earthquake characteristics (magnitude, effective ground acceleration, ground velocity). When examining the behavior of an onshore structure under dynamic loads, considering different earthquake characteristics are of great importance for determining the structural behavior.

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THE IMPACT OF TRAUMA ON MEMORY AND IDENTITY IN RICHARD POWERS' *BEWILDERMENT*

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ABSTRACT

This paper critically explores the theme of trauma, grief, memory, identity, and the connection between parent- child relationship. The character Theo Byrne, an astrobiologist the father of Robin presents the emotional sufferings of loss and trauma from the novel *Bewilderment*. After the death of his wife, Alyssa, Theo struggles with grief while trying to feel and support Robin, whose expressive complications become regularly difficult to manage. Their experiences reveal how trauma can influence memory, activities, relationships, and observations of reality.

Integrating perspectives from trauma scholarships, memory studies, and psychological methods, this research conceptualizes trauma as an experience that reshapes both memory and identity. Theo constantly returns to memories of Alyssa, displaying how pain keeps the past emotionally present. It is seen that the emotional struggles of Robin force Theo to confront his pain and reconsider his understanding of reality. The novel, therefore, reflects memory not simply as a record of the past but as an active force that influences the present.

Bewilderment focuses on the complications of accepting loss and finding emotional curing by analysing the relationship of grief, memory, trauma, and parent-child connection with reference to the protagonist of the story.

In brief, this research article critically analyses that Powers presents trauma as an experience that changes identity and human relationships. It is studied that compassion, emotional connection, and acceptance are the best possible ways for healing. The present study contributes to contemporary literary scholarship by discussing the significance of trauma, memory, and emotional flexibility in understanding human involvement.

Keywords: Trauma Studies, Memory, Grief, Identity, Healing, Parent-Child Relationship, Emotional Trauma.

Introduction

Trauma and grief have a significant influence on the ways individuals understand memory, identity, relationships, and reality. Contemporary literature often explores these experiences by showing how personal loss continues to affect individuals long after a traumatic event has occurred. Richard Powers' *Bewilderment* presents a powerful exploration of grief, trauma, memory, and the emotional relationship between parents and children. The novel centres on Theo Byrne as a single father who struggles to raise his son Robin after the death of his wife, Alyssa.

The grief of the protagonist reflects his understanding of the world and affects his relationship with Robin. Without the mother, Robin experiences emotional and behavioural difficulties which make Theo confront his own unresolved trauma. The novel connects trauma with memory by showing how Theo repeatedly returns to memories of Alyssa and how the past continues to influence his present life. Memory, thus, becomes a vital part of Theo's emotional experience and his struggle to accept loss.

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Through Theo and Robin, Powers shows their unresolved grief which can affect their behaviour, relationships, identity, and perceptions of reality. The novel also suggests that healing does not require forgetting painful experiences. The study finds that healing involves accepting loss, understanding traumatic memories, and maintaining emotional connections with others. By focusing on compassion, love, and acceptance, *Bewilderment* presents healing as a gradual process through which individuals learn to live with the memories of the past while continuing to build meaningful relationships in the present.

Trauma and Grief in *Bewilderment*

The story shows that trauma and grief are closely connected with the death of Alyssa, which creates an emotional rupture in the Byrne family. The grief of the protagonist is evident when he reflects on Robin's vulnerability and admits, "Alyssa would've propelled the three of us forward on her own bottomless forgiveness and bulldozer will. Without her, I was flailing" (Powers 34). His expression reveals that Alyssa's death is not simply a moment of sadness but a traumatic disruption of Theo's identity, confidence, and ability to protect his son. This condition of the person who is suffering from the trauma can be understood through Caruth's trauma theory, which argues that "trauma is an overwhelming experience that cannot be fully assimilated when it occurs and therefore returns belatedly to affect the survivor" (Caruth 4–17).

The feeling of "flailing" of the protagonist depicts that his inability to immediately assimilate the loss and his continuing dependence on Alyssa's presence. In the same way, Judith Herman describes that traumatic events can destroy an individual's sense of safety, control, and connection with others (Herman 33), which is reflected in Theo's struggle to maintain his role as a father after Alyssa's death.

The trauma of Robin is released through his sensitivity, anger, and unusual behaviour, particularly when Theo worries about protecting him from "his own imagination" and from the bullying of "carnivorous third-graders." His behaviour can be seen through Dominick LaCapra's concept of "acting out," in which the traumatic past repeatedly intrudes upon the present and the individual becomes caught in the compulsive repetition of traumatic experience (LaCapra 21).

Powers marks both father and son as struggling with the continuing effects of Alyssa's death while questioning institutional attempts to understand Robin only through diagnosis. Their story of grief shows it is an ongoing traumatic experience that reshapes identity, behaviour, and family relationships.

Trauma and Memory

According to Richard Powers's *Bewilderment*, Memory is one means through which trauma operates in Theo repeatedly remembers Alyssa, and these memories prevent her from becoming merely a figure from the past; instead, she remains emotionally present in his life and in Robin's. This is found when Theo observes Robin: "He squinted, sending all kinds of places—Gatlinburg, Pigeon Forge, Chicago, Madison—back to wilderness. I'd done the same thing, on my own worst nights after Alyssa died. But in the mind of this child, the one who'd kept me going, the wish seemed unhealthy" (Powers 26). Theo's admission, "I'd done the same thing, on my own worst nights after Alyssa died," establishes a direct connection between his traumatic grief and Robin's imagination. In the words of Cathy Caruth, "traumatic experience is not completely assimilated when it occurs but returns through recurring memories, images, and emotional responses" (Caruth 4–5). Theo recognizes his own post-traumatic response in Robin, suggesting that trauma is reflected across generations through emotional identification. His concern that Robin's wish to return the world to wilderness is "unhealthy" also demonstrates his anxiety about how grief may affect his son. It is learnt through Dominick LaCapra's concept of "acting out," in which the traumatic past continues to intrude upon the present rather than remaining safely confined to the past (LaCapra 21). Robin's desire to erase civilization and return places such as "Chicago" and "Madison" to wilderness can therefore be interpreted as an imaginative response to a world that has become threatening and emotionally unstable. It is marked that Theo's statement that Robin was "the one who'd kept me going" reveals the reciprocal nature of their grief: Theo is seen that he banks upon Robin for emotional survival, while Robin is also affected by the unresolved trauma surrounding Alyssa's death. Here, it is summed up that Powers presents memory as an active

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psychological force through which trauma passes between father and son, shaping their imagination, behaviour, identity, and understanding of loss.

Trauma and Identity

It is analysed that Trauma changes how individuals understand themselves and reconstruct their identities. In Richard Powers's *Bewilderment*, Theo's identity is transformed by the death of Alyssa. Before her death, he was a scientist and husband who shared parenting responsibilities, but after her death he becomes a single father responsible for a child whose emotional needs he does not always understand. Theo expresses his fear of fatherhood in the following words, "Everything about parenting terrified me, long before the day Alyssa burst into my office in Sterling Hall and shouted, 'Ready or not, Professor—company's coming!' I hugged her, to an ovation from my amused colleagues. But that was the last time I executed my paternal responsibilities with unambiguous success" (Powers 33). This study depicts how trauma and identity are interconnected. The theory of trauma by Judith Herman's trauma highlights "traumatic experiences can disrupt an individual's sense of safety, identity, and relationships" (Herman 33). Theo's loss of Alyssa, thus, destabilizes his understanding of himself as a father, leaving him anxious about whether he can adequately care for Robin. His scientific knowledge offers him with intellectual confidence, but it cannot give him an easy solution to emotional suffering. This is deeply connected to Cathy Caruth's theory of trauma, according to which trauma exceeds ordinary understanding and continues to shape the survivor's sense of self after the traumatic event (Caruth 4–5). Robin's identity is influenced by trauma. His unusual behaviour causes institutions to categorize him through psychological diagnoses, but Powers presents him as a complex individual whose sensitivity is also a strength. His concern for animals, endangered species, and the environment demonstrates his capacity for empathy. Dominick LaCapra's distinction between "acting out" and "working through" is useful here because Robin's emotional and behavioural responses can be understood as ways of expressing experiences that he cannot fully articulate (LaCapra 21). Rather than accepting institutional definitions of Robin, Powers marks his identity develops through his relationship with Theo, his connection to Alyssa, his sensitivity toward nature, and his emotional response to suffering. In sum, *Bewilderment* challenges fixed medical and social definitions of identity and demonstrates, through trauma theory, that identity is continually reconstructed through loss, memory, relationships, and emotional experience.

The Parent-Child Relationship

The relationship between Theo and Robin is at the core of Richard Powers's *Bewilderment*. It is found that their relationship is shaped by love but also by misunderstanding, grief, and fear. Theo wishes to protect Robin, yet he does not always understand his son's emotional world. Theo observes, "We followed one of the winding footpaths through the green. Robin nudged us toward the steps. My heart sank when I realized what he had in mind. The butcher-paper banner stuck out of his backpack like a space suit antenna" (Powers 258). Theo's reaction, "My heart sank," reveals his anxiety about Robin's behaviour and his fear that his son may once again be judged or rejected by others. At the same time, Robin's decision to carry the banner demonstrates his developing sense of social and environmental responsibility. Theo's difficulty becomes especially clear when Robin's behaviour creates problems at school, where teachers and authorities look for solutions based on conventional ideas of discipline and medication. Theo truly believes that his son requires understanding rather than simple correction as Judith Herman's trauma theory says, "trauma can affect an individual's sense of safety, relationships, and ability to respond to the world" (Herman 33). The father-son relationship consequently becomes a space where both characters experience and process trauma. Theo must learn to understand Robin, while Robin depends on Theo for emotional security after losing his mother. Their relationship is also strengthened through storytelling and imagination. Theo uses his scientific knowledge to create imaginary worlds for Robin. Thus, it is seen that stories provide an emotional space in which father and son can communicate. The imagined planets become more than scientific exercises; they provide a way for Theo to enter Robin's imaginative world. Cathy Caruth's trauma theory is relevant because trauma often creates difficulty in fully communicating or understanding experience (Caruth 4–5). Similarly, Theo struggles to access Robin's inner emotional world despite his scientific intelligence. The parallel between outer space and the human mind is therefore significant: Theo searches for life on distant

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planets while struggling to understand the emotional world of his own son. Dominick LaCapra's concept of "working through" trauma is also relevant because Theo gradually attempts to confront his grief and difficulties through his relationship with Robin (LaCapra 21). Thus, *Bewilderment* suggests that understanding another human being can be as difficult as discovering life on another planet. Scientific knowledge cannot completely remove emotional uncertainty; compassion, attention, and emotional connection become equally important forms of knowledge.

The Memory of Alyssa and Emotional Continuity

It is seen that Alyssa is physically absent, her presence dominates Richard Powers's *Bewilderment*. She continues to influence Theo and Robin through memory, values, language, and behaviour. This continuing presence becomes particularly intimate in the scene where Robin recognizes his mother through smell: "The animal writhed into a ball in my hand. I fanned the air above it toward Robin's nose. / 'Holy crow!' / 'What does it smell like?' / 'Like Mom!"(Powers 20). Theo explains that the smell is "Almond extract," which reminds him of Alyssa when she was baking, and Robin responds with wonder: "He pressed my palm to his nose, traveling. That is so wild." This moment demonstrates how memory operates through the senses and how Alyssa remains emotionally present through ordinary experience. It is seen that Cathy Caruth's theory of trauma which suggests, "traumatic loss continues to return through unexpected memories and sensory experiences" (Caruth 4–5). The smell of almond extract becomes a sensory bridge between the present and Alyssa's absence, allowing both Theo and Robin to experience a moment of connection with her. The scene also supports Marianne Hirsch's concept of postmemory, in which the emotional experiences of the previous generation can become deeply internalized by the next generation (Hirsch 103–104). Although Robin is not simply remembering an event he never experienced, his response shows how his mother's identity continues to shape his emotional world. Her concern for animals and her values also become part of Robin's identity, while Theo continues to measure his life against the life they shared. The experimental treatment involving Alyssa's recorded emotional states intensifies this relationship between memory and identity by giving Robin access to neurological patterns associated with his mother's emotions. The treatment raises vital questions about whether another person's emotional experience can become part of one's identity and whether technology can reproduce the presence of someone who has died. From LaCapra's perspective on acting out and working through, the procedure can be seen as an attempt to remain connected to the traumatic past rather than accepting its irreversibility (LaCapra 21). Although the treatment initially appears to offer Robin a way to regulate his emotions and recover a connection with Alyssa, it ultimately makes grief more complicated because it creates an artificial closeness with the dead. In sum, the novel bears a message that technology cannot truly eliminate the distance created by death. It is found that *Bewilderment* emphasizes the importance of accepting loss while allowing memory, love, and emotional inheritance to preserve the continuing presence of those who are gone.

Healing Through Compassion and Connection

Bewilderment does not depicts healing as a simple or complete process. Theo cannot erase his memories of Alyssa, and Robin cannot simply forget the loss of his mother. It is seen that healing depends on their ability to remain connected. Compassion becomes important as Theo gradually recognizes that understanding Robin requires more than discipline or diagnosis; he must listen to his son and accept his differences. This is reflected in Robin's declaration, "You know how people sometimes worry: Is that person mad at me? Well, if anyone's ever wondering, I'm good with the whole world" (Powers 249). Robin's words demonstrate his capacity for acceptance and compassion despite the emotional difficulties he experiences. His invented gesture, which he uses to communicate "All Is Good," (Powers 251) further becomes a symbol of emotional reassurance between father and son. The study draws a conclusion that imagination can support healing. The stories of Theo create a shared space where father and son can communicate without the pressures of school, medicine, or social expectations. It is understood through Dominick LaCapra's concept of "working through," in which trauma is not erased but gradually confronted and integrated into life (LaCapra 21). It is concluded that Judith Herman says that recovery from trauma involves rebuilding connection and developing a sense of safety and trust (Herman 33). The vitality of empathy is treated as a central to the novel's representation of healing, particularly through Robin's concern for other living beings and Theo's growing acceptance of his son.

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In brief, healing involves accepting vulnerability rather than attempting to control or eliminate it. Theo must accept that he cannot control everything that happens to Robin and that Alyssa cannot be brought back. His relationship with Robin becomes the means through which he continues to live with his grief, while Robin's compassion demonstrates that emotional vulnerability can coexist with hope, acceptance, and connection.

Conclusion

Richard Powers' *Bewilderment* reflects on trauma as a complex experience that affects memory, identity, relationships, and perceptions of reality. Through Theo and Robin, Powers demonstrates how the death of Alyssa continues to influence the emotional lives of those who survive her. Theo's grief changes his identity as a husband and father, while Robin's emotional difficulties reveal the complicated ways in which children experience and express loss.

The novel also establishes a strong connection between trauma and memory. Theo's memories of Alyssa keep the past emotionally present, while Robin's experience with neurological technology makes the relationship between memory, emotion, and identity even more complicated. Powers uses speculative science not simply to imagine technological possibilities but to question whether technology can truly reproduce human emotional experience.

The parent-child relationship provides the central space for emotional healing. Theo gradually learns that understanding Robin requires compassion, patience, and acceptance. Their relationship demonstrates that healing does not mean forgetting the past. Instead, it means learning to live with painful memories while maintaining meaningful relationships in the present.

Furthermore, the novel expands personal trauma into a larger ecological and social context. Robin's concern for endangered species connects his personal grief with the suffering of the natural world. His empathy suggests that emotional sensitivity, although treated by some institutions as a weakness, can also become a moral strength.

It is seen that *Bewilderment* portrays trauma changes individuals but does not have to completely define them. Memory can preserve pain, but it can also preserve love and connection. Through Theo and Robin, Powers presents compassion, acceptance, imagination, and emotional connection as important possibilities for healing. The study critically offers a significant contribution to contemporary literary discussions of trauma, memory, identity, family, and emotional resilience.

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WHO DECIDES WHAT IS SCIENTIFICALLY VALID? LEARNERS' EPISTEMIC ENGAGEMENT WITH GENERATIVE AI IN SCIENCE EDUCATION

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ABSTRACT

The development of generative AI is changing the way in which the learners access, interpret, and engage with scientific information. Generative AI can generate accurate scientific information but raises serious questions about who is responsible for determining the scientific validity of knowledge generated by AI systems. This paper explores learners' relationships with generative AI in the field of science education through a qualitative synthesis of existing research literature. The study focuses on synthesizing findings from empirical research on learners' interactions with AI-generated content, including identifying fundamental factors influencing trust in AI, challenging AI-generated claims and information, looking for evidence, evaluating sources, and determining the information's scientific validity. To find recurrent themes, connections, and conflicts throughout the literature, a thorough search of peer-reviewed research publications was conducted. This was followed by a qualitative thematic synthesis. The results show how students progress from accepting knowledge generated by AI to questioning, verifying, assessing, and occasionally even changing it. Much emphasis is placed on the significance of prior knowledge in science, epistemic beliefs, attitudes toward AI authority, and understanding of the nature of scientific knowledge and shaping learners' behaviour toward AI generated information. The paper argues that in order to successfully employ generative AI in science education, educators have to move away from the notion of learners as mere users of AI technologies and instead hold the view of them as epistemic agents who actively question, evaluate, and validate knowledge and assess the information they acquire from AI sources. The study highlights implications for science education, scientific literacy, and AI literacy, emphasising the need to prepare learners not merely to obtain answers from AI but to critically determine the validity, credibility, and evidentiary basis of AI-generated scientific claims.

Keywords: Generative Artificial Intelligence, Epistemic Engagement, Science Education, Scientific Knowledge, Scientific Literacy, AI Literacy

1. INTRODUCTION

The rapid development of generative artificial intelligence (GenAI) is transforming how learners access, interpret, and engage with scientific information. Tools such as ChatGPT can generate fluent, confident, and often scientifically accurate responses to almost any prompt, and their presence in science classrooms has grown quickly and largely without coordinated pedagogical planning. A systematic review of GenAI in science education identified a persistent dissonance between what these tools offer and what science education aspires to teach, including the epistemic understanding of science that learners are expected to develop. The technology is neither a neutral resource nor simply a threat; it is an epistemic actor in the classroom whose influence on how learners come to know science must be examined directly.

The central concern of this paper is not whether GenAI can produce accurate scientific information, but who decides whether the knowledge it generates is scientifically valid. AI-generated scientific claims arrive with the surface features of authoritative knowledge, yet without the evidentiary grounding,

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methodological transparency, or connection to the material world that ordinarily justifies scientific claims (Cooper, 2023) (Tang, 2024). Learners cannot assume that a fluent, confident answer is warranted, and teachers cannot monitor every interaction. The question of who is responsible for determining whether AI-generated knowledge can be trusted is therefore not an abstract philosophical puzzle but a practical problem at the heart of science education.

Evidence from the earliest empirical work suggests the problem is real. Students have been found to treat GenAI as a "superior knower," a source of knowledge whose authority is accepted with little critical reflection (Jose, 2025). Physics undergraduates trusted ChatGPT's answers even when those answers were demonstably inaccurate (Ding, 2023), and secondary students described an "initial trust under the halo of technical authority" when first encountering AI output in science learning (Zhou, 2026). At the same time, a smaller body of studies shows learners questioning, verifying, and evaluating AI-generated content, sometimes revising or rejecting it. Understanding when and why learners move between acceptance and critical evaluation, and which factors govern that movement, is essential if GenAI is to support rather than undermine scientific learning.

Three bodies of theory frame this question. Research on epistemic beliefs and epistemic stances describes how learners justify knowledge claims, from absolutist positions that require no justification, through multiplist positions based on personal preference, to evaluativist positions that weigh evidence and inquiry procedures (Wu, 2025). Work on epistemic agency examines learners' capacity to actively engage in knowledge formation and validation, a capacity that AI systems may either support or supplant. And the nature of science (NOS) tradition asks what learners understand about how scientific knowledge is produced, justified, and revised, an understanding increasingly tested against AI systems that simulate scientific discourse (Cheung, 2026). Together these literatures supply the vocabulary and the criteria for judging whether learners can determine the validity of AI-generated scientific claims.

Existing reviews of GenAI in education do not yet answer this question. Much of the empirical literature has focused on cognitive and affective outcomes, such as performance, motivation, and attitudes, without characterising GenAI's epistemic outcomes in science (Cheung, 2026). Systematic reviews of the broader field repeatedly flag a paucity of research in school-level (K-12) education relative to higher education (Yusuf, 2024) and call explicitly for more empirical evidence at primary and secondary levels (Dimeli, 2025). No existing synthesis, to our knowledge, organizes the literature around learners' epistemic engagement with AI-generated scientific content, that is, around how learners trust, question, verify, and evaluate such content and how they determine its scientific validity.

This paper addresses that gap through a qualitative thematic synthesis of empirical research on learners' interactions with AI-generated scientific content. The research objectives and questions guiding the review are set out below, and the paper argues that answering them requires reconceiving learners not as users of AI technologies but as epistemic agents who actively question, evaluate, and validate the knowledge they encounter. The method section describes the search and synthesis procedures; the results and analysis section presents the synthesized findings; the discussion section returns to the validity question and its implications; and the conclusion draws the argument together.

1.1 RESEARCH QUESTIONS

The review is guided by three research questions:

- **RQ1.** How do learners trust AI-generated scientific content, challenge AI-generated claims and information, look for evidence, evaluate sources, and determine its scientific validity in science education?
- **RQ2.** Which factors shape learners' epistemic engagement with AI-generated scientific content?
- **RQ3.** What does the evidence imply for who determines the scientific validity of AI-generated knowledge, and for the design of science education in the age of generative AI?

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2. METHOD

2.1 RESEARCH DESIGN

This research relied on the technique of qualitative thematic synthesis based on the process indicated by Thomas and Harden which allows combining the results of many qualitative or mixed-methods studies in a way that secures the relationship of the results obtained to the studies performed (Thomas, 2008). The reason for choosing thematic synthesis was the need for the analysis of pervasive themes, connections, controversies on the topic of learners' epistemic engagement with AI-generated scientific messages, as well as the method of thematic synthesis being the one that enables to proceed from the mere description of the findings of individual studies to the interpretations of such findings focusing on the conditions of acceptance, questioning, verification, and rejection of claims made by AI in the scientific field.

2.2 SEARCH STRATEGY

A systematic literature search was performed in Databases such as ERIC, Scopus, Web of Science. The search was comprised of three blocks of terms which were integrated together with the Boolean operators. The three groups of terms used in the search include: (a) Generative AI (e.g., "generative AI," "GenAI," "ChatGPT," "large language model," and "LLM"); (b) Epistemic Engagement (e.g., "epistemic," "trust," "credibility," "validity," "evaluation," "verification," "critical thinking," and "authority"; and (c) Science Education (e.g., "science education," "science learning," "science classroom," and "scientific literacy.") The search criteria included 2022-2026 and only peer-reviewed journals or conference proceedings. The reference lists of the selected papers and systematic reviews are screened for further papers.

2.3 INCLUSION AND EXCLUSION CRITERIA

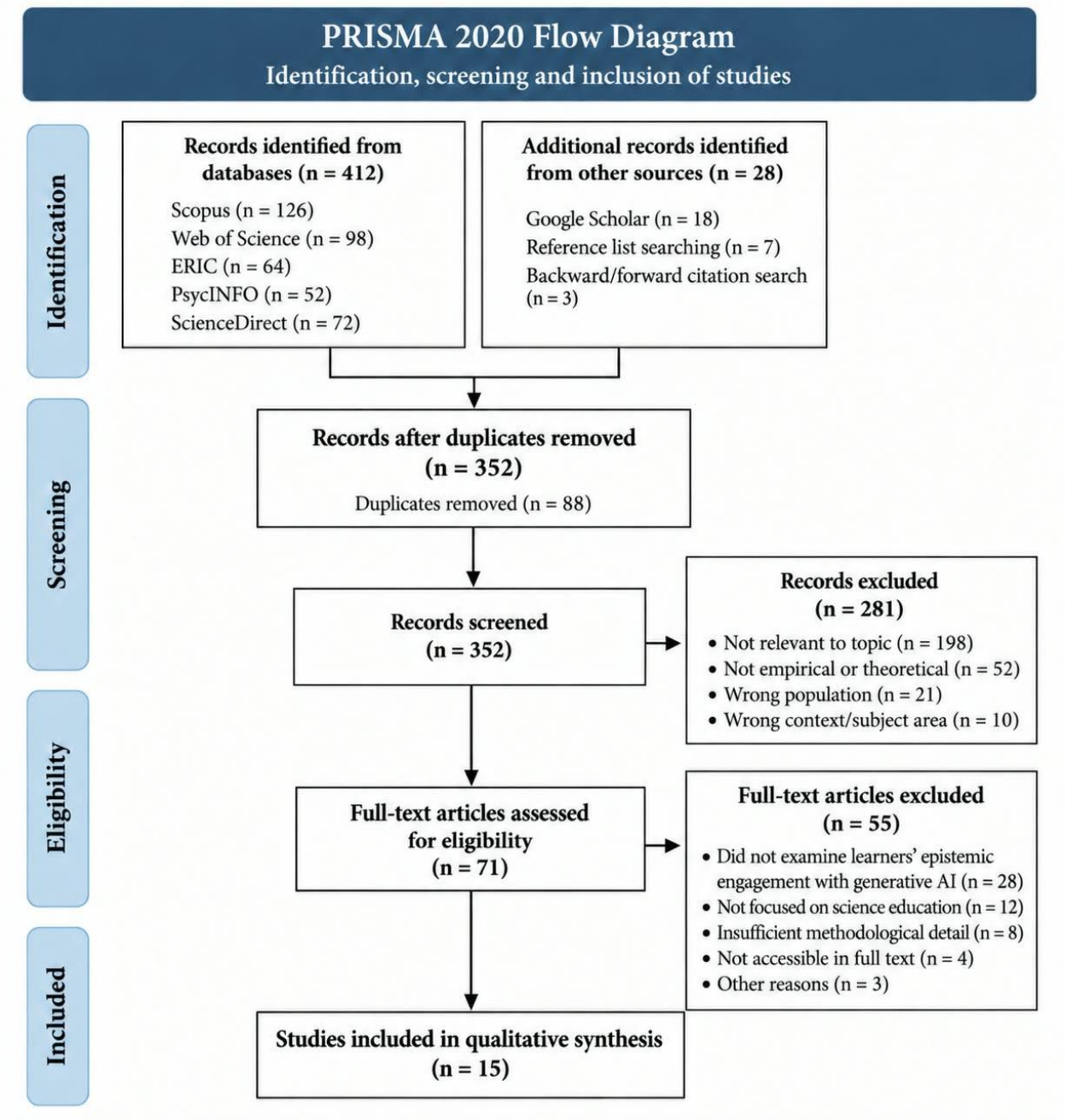
The studies to be considered are those that met the following requirements: (a) they reported empirical data; (b) they concern learners' interaction with AI-generated scientific materials or tools used in science education; (c) they studied at least one form of epistemic engagement such as trust in AI output, questioning and doubting AI-generated content, searching for evidence, evaluating sources, or making conclusions about the scientific validity of information; and (d) they were published in peer-reviewed journals. The studies to be rejected are those that are about theoretical or opinion articles without empirical evidence on the subject; concentrate on teachers or AI rather than on learners; write about AI only as a type of educational technology without adding any scientific materials; and provide no learner's level evidence regarding the study.

2.4 SCREENING AND SELECTION

We conducted the screening of titles and abstracts of all records we got regarding the selection criteria and then analysed the full texts of the studies that potentially matched the criteria. All steps along with the numbers at every stage of screening process are represented in a PRISMA 2020 flow chart.

Figure 1

PRISMA 2020 Flow Diagram for the Identification, Screening, Eligibility, and Inclusion of Studies



2.5 DATA EXTRACTION

From each included study, the following data were extracted: authors and year, country, educational level and sample, AI tool used, task or context, and reported findings relating to learners' epistemic engagement with AI-generated scientific content.

2.7 DATA SYNTHESIS

The included studies were synthesised thematically in three stages, following Thomas and Harden (Thomas, 2008). First, the findings of each study were coded line-by-line. Second, codes were grouped into descriptive themes that remained close to the primary studies. Third, descriptive themes were organised into analytical themes that go beyond the primary studies to generate new interpretive

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constructs. In this review, the analytical themes corresponded to the trajectory of engagement with AI-generated content (acceptance, questioning, verification, evaluation, revision or rejection); the factors shaping that trajectory (prior scientific knowledge, epistemic beliefs and stances, perceptions of AI as an epistemic authority, and understanding of the nature of scientific knowledge); documented risks of uncritical engagement; and pedagogical responses. Throughout the synthesis, recurrent themes (patterns appearing across studies), connections (complementary or mutually reinforcing findings), and conflicts (contradictory findings, such as the contrast between widespread initial trust and documented critical evaluation) were recorded and are reported in the findings.

3. RESULTS AND ANALYSIS

3.1 OVERVIEW OF THE INCLUDED STUDIES

15 empirical studies met the inclusion criteria and were included in the synthesis. The studies varied substantially in design, from large-scale surveys to multi-case classroom studies, grounded theory interviews, and task-based validation experiments, and the synthesis treated this methodological diversity as a strength, since converging findings across designs carry greater weight.

Table 1

Characteristics of the Included Studies

S.No.	Study	Educational Level / Participants	AI Tool / Technology	Year	Geographical Context
1.	Zhou	Upper-secondary students (n = 21)	Generative AI / ChatGPT	2026	China – Southwest China
2.	Ding et al.	Undergraduate physics students (n = 40)	ChatGPT	2023	USA
3.	Cooper	Science education / exploratory analysis; no learner sample	ChatGPT	2023	Australia
4.	Jose et al.	Educational/learning contexts; conceptual analysis	Generative AI / LLMs	2025	India
5.	Urhahne et al.	University students (n = 185)	ChatGPT	2026	Germany
6.	Urban et al.	University students (n = 98)	ChatGPT	2025	Czech Republic
7.	Wu et al.	Higher education / conceptual and illustrative student interactions	Generative AI, Including ChatGPT	2025	Taiwan / broader East Asian context
8.	Cheung et al.	Grade 9 students; two pairs (n = 4)	POE using GPT-3.5	2026	Hong Kong
9.	Dahlkemper et al.	Undergraduate physics students (n = 102)	ChatGPT	2023	Germany
10.	Stadler et al.	University students (n = 91)	ChatGPT 3.5 vs. Google Search	2024	Germany
11.	Fan et al.	University students (n = 117)	ChatGPT vs. human expert/other supports	2025	China / Australia research collaboration

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12.	Liu et al.	Higher-education students	Generative AI	2026	China / Taiwan
13.	Chang et al.	Elementary/Grade 4 students (n = 80)	ChatGPT-4o	2026	South Korea
14.	Chen et al.	10 high-school students — 6 boys and 4 girls	ChatGPT	2023	South America
15.	Deguchi et al.	First-year undergraduates (n = 31)	ChatGPT	2026	Japan

3.2 THEME 1: THE TRAJECTORY OF EPISTEMIC ENGAGEMENT

The central recurrent theme across studies is a trajectory in which learners move from initial acceptance of AI-generated scientific content toward questioning, verification, evaluation, and selective reconstruction or rejection. The trajectory is conditional rather than automatic, and several studies document learners who do not traverse it, so the synthesis treats it as the dominant pattern within a broader field of variation.

3.2.1 INITIAL ACCEPTANCE AND TRUST

Learners commonly begin from a position of provisional trust in AI-generated scientific content. Interview evidence from 21 upper secondary students described an "initial trust under the halo of technical authority," in which fluent, authoritative AI responses were accepted on first encounter, especially when the task was efficiency-driven (Zhou, 2026). This pattern is consistent with survey evidence from higher education, where physics students trusted ChatGPT's answers despite measurable inaccuracy (Ding, 2023), and with conceptual analyses arguing that GenAI's confident, fluent output positions it as an epistemic authority that invites trust without scrutiny (Cooper, 2023) (Jose, 2025). Trust, however, was rarely total: even students who accepted AI output described it as provisional material requiring eventual confirmation (Zhou, 2026).

3.2.2 QUESTIONING AND VERIFICATION

Where learners moved beyond acceptance, verification took layered forms. Students first applied internal consistency checks against their own knowledge and, when uncertainty persisted or task stakes rose, turned to external corroboration in a consistent hierarchy: textbooks and official materials first, then reputable online sources, and finally teachers or high-achieving peers (Zhou, 2026). A classroom study of students judging AI-generated physics solutions found that no student accepted the AI's solution as valid on first reading, with students invoking physics-based criteria such as correct units and signs, procedural logic, and consistency with the problem statement.

The synthesis also surfaced a conflict within this theme. According to the aforementioned analysis utilizing grounded theory, verification turned out to be a laborious process that sometimes did not take place at all in case when students were under time constraints. Therefore, having recognized the importance of verification, students did not follow through and decided to take a shortcut by submitting AI-generated outputs without verification instead (Zhou, 2026). In a remarkable study of 63 middle schoolers, it became clear that many students were perfectly happy with AI and never questioned its output at all, even though vague explanations provided by AI could have triggered further inquiry. Questioning is thus a capacity that some learners exercise, some defer, and some have not yet developed.

3.2.3 EVALUATION, RECONSTRUCTION AND REJECTION

The endpoint of the trajectory is active evaluation. Students who did pursue verification of AI outputs modified their prompts, reconstructed the outputs, or neglected the use of AI for some specific tasks if they found it too costly (Zhou, 2026). Abandonment was task-specific rather than a rejection of GenAI as a whole. Case-study evidence from ninth graders in socio-scientific argumentation shows, however, that movement along this trajectory is not unidirectional: one pair moved toward treating GenAI as the communicator of correct knowledge and asked the chatbot to emulate a professor, while a second pair

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moved toward cooperating with and evaluating the tool as their evaluation competence developed (Cheung, 2026). The trajectory is therefore better described as reversible and competence-dependent than as a fixed progression.

3.3 THEME 2: FACTORS SHAPING EPISTEMIC ENGAGEMENT

Across studies, four factors consistently determined where learners sat on the trajectory and how they moved along it.

3.3.1 PRIOR SCIENTIFIC KNOWLEDGE

Prior knowledge functioned as the internal resource against which AI claims were checked. Students who could not judge an AI answer internally could not verify it and were dependent on external sources (Zhou, 2026). The physics validation study demonstrated the mechanism most directly: students who had solved the problem themselves could evaluate the AI solution using disciplinary criteria, while students who struggled could not follow the AI's reasoning and withheld acceptance for that reason alone, meaning their caution did not reflect successful scrutiny. Validation is thus contingent on the learner's disciplinary knowledge: without it, the learner can judge neither the answer nor the reasoning behind it.

3.3.2 EPISTEMIC BELIEFS AND STANCES

Epistemic beliefs about the source, certainty, and justification of knowledge predicted engagement with AI. University students' epistemic beliefs strongly predicted both adoption and avoidance of ChatGPT (Urhahne, 2026), and epistemic beliefs together with metacognitive accuracy predicted the amount of incorrect ChatGPT-generated content students integrated into their writing (Urban, 2025). Conceptually, the literature positions evaluativist stances, in which claims are justified through evidence and inquiry procedures, as the stance best suited to critical GenAI use, while absolutist stances leave learners vulnerable to accepting authoritative-sounding output without evaluation (Wu, 2025).

3.3.3 PERCEPTIONS OF AI AS AN EPISTEMIC AUTHORITY

How learners positioned AI relative to human and institutional authorities shaped their engagement. The "halo of technical authority" describes the initial trust granted to fluent AI output (Zhou, 2026), and where learners regarded GenAI as a superior knower, critical reflection on its limits tended to be bypassed (Jose, 2025). The ninth-grade pair who asked the chatbot to emulate a professor illustrates how authority attribution can deepen over time rather than erode with use (Cheung, 2026). This factor was entangled with the others: learners who trusted the source were less likely to apply prior knowledge or epistemic criteria to its output.

3.3.4 UNDERSTANDING OF THE NATURE OF SCIENTIFIC KNOWLEDGE

Learners' understanding of how scientific knowledge is produced and justified provided the criteria for judging AI claims. Studies of AI's own epistemic character found that current models represent some aspects of science adequately but struggle to differentiate the nature of science from the nature of GenAI-influenced science, leaving learners to make that distinction themselves (Cheung, 2026). Research with elementary students showed that epistemic understanding of scientific inquiry could be elicited through structured GenAI interactions (Chang, 2026), and a study of 44 eighth and ninth graders found epistemic evaluation to be the most difficult domain of reading AI-generated scientific texts, harder than content interpretation or genre reasoning (Cheung, 2024). Learners' NOS understanding is therefore both a prerequisite for evaluation and a dimension on which school learners are still developing.

3.4 THEME 3: RISKS OF UNCRITICAL ENGAGEMENT

A connected set of findings, drawn largely from higher education, documents what happens when the trajectory stalls at acceptance. Learners using LLMs experienced lower cognitive load than search-engine users yet produced lower-quality reasoning and argumentation, an effect described as "cognitive ease at a cost" (Stadler, 2024). Randomised evidence showed that ChatGPT-supported learners improved on essay scores without corresponding gains in knowledge transfer, consistent with "metacognitive laziness" in which AI dependence weakens self-regulated learning (Fan, 2024). A

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structural model linked greater AI use to cognitive offloading, which in turn predicted epistemic trust transfer toward AI and reduced learning accountability (Liu, 2026). Conceptually, AI systems embedded in practice can perform cognitive operations in ways that substitute for skilled epistemic action rather than sustaining it. The evidence at the school level is less robust but still in line: the overdependence of middle schoolers on ChatGPT, which prevents verification, even when time is not a factor (Zhou, 2026), insinuates that similar processes occur in the school environment

3.5 THEME 4: PEDAGOGICAL RESPONSES THAT SUSTAIN EPISTEMIC AGENCY

The final theme comprises studies and frameworks that design instruction to keep learners on the evaluative end of the trajectory. Frameworks argue for deliberately cultivating adaptive epistemic stances, since learners with more knowledge evaluate credibility critically while learners with less knowledge accept authoritative sources without question (Wu, 2025). A four-stage model of student engagement in scientific argumentation with GenAI provides a structured pathway for designing such epistemic partnerships. Empirically, customized chatbots as dialogic partners enhanced multiple perspectives, reasoning, and argumentation in science education, prompted GenAI supported elementary students' epistemic understanding of scientific inquiry, with AI scoring agreeing strongly with human raters (kappa 0.825) and feedback rated strong on promoting student agency (Chang, 2026), and a high school knowledge-building study found that teacher-designed scaffolding enabled students to use ChatGPT for distinct epistemic purposes and to develop emerging AI literacy (Chen, 2023). The shared instructional target is validation taught as a learned practice within problem solving rather than assumed.

3.6 SYNTHESIS OF THEMES: CONNECTIONS AND CONFLICTS

Three connections across themes deserve emphasis. First, the four factors in Theme 2 are mutually reinforcing: prior knowledge enables verification, verification practice develops evaluation competence, evaluation competence recalibrates perceptions of AI authority, and NOS understanding supplies the criteria for both (Zhou, 2026). Second, the risks in Theme 3 and the pedagogy in Theme 4 are opposite sides of the same mechanism: both operate through whether learners sustain skilled epistemic action in the presence of AI. Third, the trajectory in Theme 1 is the observable expression of the factors in Theme 2, which is why studies that measure beliefs find they predict behaviour (Urhahne, 2026) (Urban, 2025).

Two conflicts mark the evidence base and define its limits. First, the coexistence of widespread initial trust in survey and interview data (Ding, 2023) (Zhou, 2026) with documented critical evaluation in task-based studies indicates that trust measures and actual validation behaviour do not always align. Second, the risk mechanisms (metacognitive laziness, cognitive offloading) are well established in higher education (Fan, 2024) (Stadler, 2024) but rest on a much thinner school-level evidence base, so claims about school learners must be made with corresponding caution.4. Discussion

4.1 THE VALIDITY QUESTION AND THE MAIN FINDINGS

The synthesis addresses three research questions, and its central finding answers all of them at once. Learners' engagement with AI-generated scientific content follows a conditional trajectory from initial acceptance toward questioning, verification, evaluation, and selective revision or rejection, and the position a learner occupies on that trajectory is determined by prior scientific knowledge, epistemic beliefs, perceptions of AI authority, and understanding of the nature of scientific knowledge (Zhou, 2026). Who decides what is scientifically valid, on this evidence, is the learner, but only where the learner possesses the resources to inspect AI-generated claims. Where these resources are missing, the decision is made in favour of the pleasant and assured surface of the AI (Jose, 2025).

This creates another way of posing the validity question. It is natural to see the issue as a struggle between somebody learning and AI or as somebody learning and teaching with the help of an AI. The data indicate that, validity is actually decided when the learners engage with the systems, that is at the point when learners either accept an AI input or put it to the test. At this moment the decision made depends on epistemic resources possessed by a learner. Thus, the process cannot be viewed as a sequential stage of development, it must be seen as a practice defined by the context and influenced by the stakes of the task, prior experience, time pressure, and teacher regulations (Zhou, 2026). That is why the same students can pass a certain task with a thorough evaluation, but then fail to do the same in the

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following task, despite the fact that they have the knowledge that they must check information (Zhou, 2026).

4.2 THEORETICAL CONTRIBUTION

The review connects three bodies of theory to the validity question in ways the existing literature has not fully integrated. First, it extends the literature on epistemic beliefs and stances to the GenAI context. The absolutist-multiplist-evaluativist distinction, developed to describe how learners justify knowledge claims, maps directly onto how learners position AI output: absolutist learners accept authoritative-sounding output without justification, while evaluativist learners weigh evidence and inquiry procedures (Wu, 2025). The synthesis shows that these stances are not only predictors of engagement but are themselves shaped by engagement, since evaluation competence can shift learners toward more critical stances and, in some cases, away from them (Cheung, 2026).

Second, the findings speak to the concept of epistemic agency. AI systems embedded in learning can perform cognitive operations in ways that either sustain or substitute for skilled epistemic action. The reviewed studies show both possibilities realised: learners who verify, reconstruct, and evaluate AI output are exercising epistemic agency, while learners who accept, offload, and delegate are ceding it (Liu, 2026) (Fan, 2024). Epistemic agency, on this account, is not a fixed trait but a practice that pedagogy can either cultivate or erode.

Third, the review brings the nature of science literature into the AI context. If learners must judge whether AI-generated claims are scientifically valid, they must hold criteria for what makes scientific knowledge valid, and those criteria are precisely what NOS understanding supplies. The finding that current models struggle to differentiate the nature of science from the nature of GenAI-influenced science makes this the learner's task by default (Cheung, 2026). The theoretical contribution of the review is to show that these three traditions, epistemic beliefs, epistemic agency, and nature of science, converge on a single question, who decides what is scientifically valid, and that each contributes a distinct part of the answer.

4.3 IMPLICATIONS FOR SCIENCE EDUCATION, SCIENTIFIC LITERACY AND AI LITERACY

For science education, the implications are practical and immediate. If validation depends on prior knowledge, then instruction must build the disciplinary knowledge that makes evaluation possible, and teach validation explicitly as a component of problem solving rather than assume it. If epistemic stances shape engagement, then pedagogy must deliberately cultivate adaptive stances (Wu, 2025). If authority perception governs whether learners even attempt to evaluate, then classrooms must position GenAI explicitly as a fallible source whose output warrants scrutiny (Jose, 2025). The reviewed partnership designs, customized chatbots, prompted GenAI, and scaffolded knowledge building, offer concrete templates for instruction that meets these conditions (Chang, 2026) (Chen, 2023).

For scientific literacy, the review implies that the ability to judge the validity, credibility, and evidentiary basis of AI-generated claims is now part of what it means to be scientifically literate. Scientific literacy has long included the capacity to evaluate sources and evidence; in the age of generative AI it must include the capacity to evaluate sources that generate fluent, authoritative-sounding text on demand. For AI literacy, the implication is that competence cannot be reduced to technical familiarity with tools; it must include the epistemic dimension, the capacity to interrogate AI output as a fallible source, which the reviewed evidence shows is the binding constraint on productive use (Urban, 2025).

4.4 METHODOLOGICAL CONSIDERATIONS

Several features of the synthesis warrant caution in interpretation. The included studies are heterogeneous in design, from large-scale surveys to grounded theory interviews, case studies, and task-based experiments, and each design captures a different facet of epistemic engagement. Survey-based trust measures and task-based validation behaviour did not always align in the reviewed evidence, which suggests that self-reported engagement and enacted engagement are distinct constructs. The school-level evidence base remains thin relative to higher education (Yusuf, 2024), so conclusions about school learners rest on a smaller set of studies and should be read with corresponding caution. Finally, the field

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is evolving rapidly, and the tools learners use are changing faster than the research that studies them, which means that some findings, particularly those tied to specific models, may not generalise to future systems.

4.5 FUTURE RESEARCH

The gaps identified in the results point toward a research agenda. Longitudinal studies are needed to establish how epistemic engagement with AI develops over time and whether it transfers across tasks and tools. Intervention research should test whether explicit validation training changes engagement and learning outcomes. Measurement work should develop and validate instruments for epistemic engagement with AI-generated scientific content, so that future studies can move beyond self-report. And cross-level comparisons should determine whether younger learners differ systematically from older students in trust calibration and evaluation capacity, a question the current evidence base cannot yet answer.

5. CONCLUSION

This review set out to answer a question that generative AI has made unavoidable in science education: who decides what is scientifically valid when learners encounter knowledge produced by AI systems? The synthesis points to a consistent answer. The decisive agent is the learner, but only insofar as the learner possesses the epistemic resources required to inspect AI-generated claims: prior scientific knowledge supplies the criteria for validation, epistemic beliefs and stances determine whether those criteria are applied, perceptions of AI as an epistemic authority determine whether the learner attempts to apply them at all, and understanding of the nature of scientific knowledge frames what counts as evidence and justification (Wu, 2025) (Jose, 2025) (Cheung, 2026). Where these resources are absent, acceptance or abandonment replaces evaluation, and the validity question is resolved by default in favour of the AI's fluent surface (Zhou, 2026).

The paper's central argument follows directly. Employing generative AI productively in science education requires reconceiving learners not as users of AI technologies but as epistemic agents who actively question, evaluate, and validate the knowledge they acquire. This is not a call to reject GenAI, but to recognise that its educational value depends on whether learners sustain the evaluative practices that give scientific claims their warrant, and that educators are responsible for building the conditions under which learners can exercise that agency. As generative AI becomes a permanent feature of science classrooms, the question of who decides what is scientifically valid will not recede; the task for science education research is to ensure that learners, not the tools they use, remain the ones who answer it.

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FROM CHRONIC WOUND EXUDATE TO PRECISION WOUND CARE: CLINICAL POTENTIAL OF MULTI-OMIC BIOMARKERS

KRONİK YARA EKSÜDASINDAN HASSAS YARA BAKIMINA: MULTİ-OMİK BİYOBELİRTEÇLERİN KLİNİK POTANSİYELİ

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ABSTRACT

Chronic wounds are biologically heterogeneous microenvironments in which persistent inflammation, excessive proteolytic activity, impaired angiogenesis, metabolic stress, and a microbial environment comprising diverse microorganisms adversely affect tissue repair. Clinical parameters such as wound area, tissue appearance, and exudate volume form the basis of wound monitoring; however, they may not always reflect molecular changes that occur before visible wound deterioration begins. Wound exudate is in direct contact with the wound bed and contains a rich array of proteins, peptides, metabolites, lipids, extracellular nucleic acids, extracellular vesicles, and microbial products. Its ability to be collected serially using relatively non-invasive methods makes exudate a valuable liquid biopsy candidate for monitoring the biological status of wounds. This narrative review evaluates proteomic, peptidomic, degradomic, metabolomic, lipidomic, transcriptomic, extracellular RNA, and microbiome analyses applied to chronic wound exudate, with a focus on biomarkers related to impaired wound healing and their clinical potential in precision wound care. Current evidence suggests that protease–antiprotease imbalance, increased inflammatory activity, alterations in energy and redox metabolism, anti-angiogenic extracellular vesicle-derived microRNAs, and a wound environment characterized by microbial imbalance are interconnected processes underlying failure to heal in chronic wounds. No single universal biomarker has yet demonstrated sufficient reliability across different wound types. Integrating multiple molecular layers with serial clinical measurements and machine-learning models may contribute to the early prediction of healing trajectories, monitoring of treatment response, differentiation between colonization and harmful microbial activity, and molecular phenotyping of chronic wounds. However, heterogeneity in sampling and storage methods, dilution and normalization problems, small patient cohorts, inconsistent definitions of wound healing, and insufficient external validation limit translation into clinical practice. For exudate-based multi-omic approaches to be implemented in precision wound care, standardized, multicenter, longitudinal studies and feasible panels comprising a limited number of analytically and clinically validated biomarkers are required.

Keywords: chronic wound exudate, multi-omics, biomarker, proteomics, microbiome, wound healing

ÖZET

Kronik yaralar; kalıcı inflamasyon, aşırı proteolitik aktivite, bozulmuş anjiyogenez, metabolik stres ve çeşitli mikroorganizmaların bir arada bulunduğu mikrobiyal ortamın doku onarımını olumsuz etkilediği, biyolojik olarak heterojen mikroortamlardır.Yara alanı, doku görünümü ve eksüda miktarı gibi klinik parametreler yara izleminin temelini oluşturur; ancak bunlar gözle görülür şekilde yarada bozulma başlamadan önce meydana gelen moleküler değişiklikleri her zaman yansıtmayabilir. Yara yatağıyla doğrudan temas eden eksüda; proteinler, peptitler, metabolitler, lipidler, hücre dışı nükleik asitler, ekstraselüler veziküller ve mikrobiyal ürünler bakımından zengin bir içeriğe sahiptir. Görece invaziv olmayan yöntemlerle seri olarak toplanabilmesi, eksüdayı yaranın biyolojik durumunun izlenmesinde kullanılabilecek değerli bir sıvı biyopsi adayı haline getirmektedir. Bu anlatı derlemesinde kronik yara eksüdasına uygulanan proteomik, peptidomik, degradomik, metabolomik, lipidomik, transkriptomik,

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hücre dışı RNA ve mikrobiyom analizleri; bozulmuş yara iyileşmesi ile ilgili biyobelirteçler ve bu biyobelirteçlerin hassas yara bakımındaki klinik potansiyelleri açısından değerlendirilmiştir. Mevcut bulgular; proteaz–antiproteaz dengesindeki bozulma, artmış inflamatuvar aktivite, enerji ve redoks metabolizmasındaki değişiklikler, anjiyogenezi baskılayan ekstraselüler vezikül kaynaklı mikroRNA'lar ve mikrobiyal dengenin bozulduğu yara ortamının, kronik yaralarda iyileşme bozulmasının altında yatan birbiriyle ilişkili süreçler olduğunu düşündürmektedir. Farklı yara türlerinde yeterli güvenilirliğe sahip tek bir evrensel biyobelirteç henüz bulunmamaktadır. Birden fazla moleküler katmanın seri klinik ölçümler ve makine öğrenmesi modelleriyle bütünleştirilmesi; iyileşme seyrinin erken öngörülmesine, tedavi yanıtının izlenmesine, kolonizasyon ile zararlı mikrobiyal aktivitenin ayrımına ve kronik yaraların moleküler fenotiplendirilmesine katkı sağlayabilir. Bununla birlikte örnekleme ve saklama yöntemlerindeki heterojenlik, seyreltme ve normalizasyon sorunları, küçük hasta grupları, yara iyileşmesinin farklı tanımlanması ve dış doğrulama eksikliği klinik uygulamaya geçişi sınırlamaktadır. Eksüda temelli multi-omik yaklaşımların hassas yara bakımında kullanılabilmesi için standartlaştırılmış, çok merkezli ve uzunlamasına çalışmalara; ayrıca analitik ve klinik olarak doğrulanmış, sınırlı sayıda belirteç içeren uygulanabilir panellere gereksinim vardır.

Anahtar Kelimeler: kronik yara eksüdası, multi-omik, biyobelirteç, proteomik, mikrobiyom, yara iyileşmesi

1. GİRİŞ

Yara iyileşmesi; hemostaz, inflamasyon, proliferasyon ve remodelling evrelerinin birbiriyle koordineli ilerlediği bir süreçtir. Diyabet, venöz hipertansiyon, arteriyel yetersizlik, basınç, nöropati, enfeksiyon ve sistemik metabolik bozukluklar bu koordinasyonu bozduğunda yara inflamatuar fazda kalabilir. Kronik yaralarda devam eden nötrofil aktivitesi, proteaz fazlalığı, oksidatif stres, yetersiz anjiyogenez ve hücre dışı matriks yıkımı birbirini güçlendiren bir döngü oluşturur (Frykberg & Banks, 2015).

Klinik izlemde yara alanı, derinlik, eksüda miktarı, granülasyon dokusu, nekroz, enfeksiyon bulguları ve belirli süredeki yüzey alanı değişimi değerlendirilir. Ancak klinik görünümü benzer iki yara farklı biyolojik iyileşme potansiyeline sahip olabilir. Diyabetik ayak ülseri yara sıvısı çalışmalarını inceleyen sistematik derlemede 46 farklı belirteç bildirilmiş, buna karşın örnekleme ve sonlanım ölçütlerindeki değişkenlik nedeniyle rutin kullanıma uygun tek bir biyobelirteç eşiği tanımlanamamıştır (Longfield et al., 2023).

Yara eksüdası, damar geçirgenliğinin artmasıyla yara yatağına ulaşan plazma kökenli bileşenlerin yanı sıra hücrelerden, hücre dışı matriksten ve mikroorganizma kaynaklı molekülleri içeren karmaşık bir biyolojik sıvıdır (Cutting, 2003; Sabino et al., 2018). Eksüda içerisinde proteinler, proteolitik parçalanma ürünleri, sitokinler, büyüme faktörleri, metabolitler, lipit mediyatörleri, serbest nükleik asitler ve ekstraselüler veziküller birlikte bulunabilir (Cutting, 2003; Guda et al., 2023; Junka et al., 2017; Sabino et al., 2018). Yara yatağıyla doğrudan temas etmesi ve farklı zaman noktalarında görece noninvaziv biçimde toplanabilmesi, eksüdanın yaranın moleküler durumunu ve iyileşme sürecindeki değişimleri izlemek için sıvı biyopsi benzeri bir örnek olarak değerlendirilmesini sağlamaktadır (Harvey et al., 2022; Sabino et al., 2018).

Omik teknolojiler, önceden seçilmiş birkaç analitin ölçülmesi yerine belirli bir molekül grubunu geniş ölçekte incelemeyi amaçlar. Proteomik proteinleri, metabolomik küçük molekülleri, lipidomik lipidleri, transkriptomik RNA'ları ve mikrobiyomik mikrobiyal toplulukları değerlendirir. Multi-omik yaklaşım ise bu katmanları klinik verilerle birlikte bütünleştirerek tek belirteçten çok moleküler profiller oluşturmayı hedefler. Bu derlemenin amacı, kronik yara eksüdasında kullanılan omik yöntemleri, iyileşmeme ile ilişkilendirilen aday biyobelirteçleri ve klinik uygulamaya geçişteki temel sorunları bütüncül olarak değerlendirmektir.

2. KRONİK YARA EKSÜDASI VE BİYOBELİRTEÇ POTANSİYELİ

Eksüda, doku hasarına bağlı olarak damar geçirgenliğinin artması sonucunda yara yatağına geçen plazma kökenli sıvının, yerel hücresel bileşenler ve mikroorganizma kaynaklı ürünlerle karışmasıyla oluşur (Cutting, 2003). Akut yara iyileşmesinde uygun miktardaki eksüda; yara yüzeyinin nemli

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kalmasına, onarım hücrelerinin göçüne ve büyüme faktörleri gibi iyileşme için gerekli moleküllerin taşınmasına katkı sağlar (Cutting, 2003). Kronik yaralarda ise uzamış inflamasyon ve devam eden damar geçirgenliği eksüda miktarını artırabilir. Bu ortamda yükselen proteaz aktivitesi, hücresel kalıntılar, mikrobiyal ürünler ve oksidatif stres; hücre dışı matriksin ve büyüme faktörlerinin parçalanmasına katkıda bulunarak iyileşmeyi geciktirebilir (Moore et al., 2007; Trengove et al., 1999; Wlaschek & Scharffetter-Kochanek, 2005).

Yara eksüdasının biyokimyasal bileşimi serumla tamamen aynı değildir. Sekiz kronik bacak ülseri hastasından eş zamanlı olarak alınan yara sıvısı ve serum örneklerinin karşılaştırıldığı bir çalışmada, yara sıvısındaki laktat ve laktat dehidrogenaz düzeylerinin serumdakinden anlamlı biçimde yüksek; glukoz ve bikarbonat düzeylerinin ise daha düşük olduğu belirlenmiştir (Trengove et al., 1996). Bu bulgular, yara yatağındaki yerel hipoksi ve hücresel hasarla ilişkili değişikliklerin eksüdanın bileşimine yansıyabileceğini göstermektedir. Aynı çalışmada iyileşme sürecinde yara eksüdasındaki glukoz ve bikarbonat düzeyleri artarken C-reaktif protein düzeyinin azaldığı, buna karşılık serum değerlerinin değişmeden kaldığı bildirilmiştir (Trengove et al., 1996). Bu sonuçlar, yara eksüdasının yerel iyileşme ve inflamasyon süreçlerindeki değişimleri sistemik örneklere göre daha doğrudan yansıtabilecek bir biyobelirteç kaynağı olabileceğini desteklemektedir (Moore et al., 2007; Trengove et al., 1996).

2.1. ÖRNEKLEME VE PREANALİTİK DEĞİŞKENLER

Yara eksüdası; doğrudan aspirasyonla, filtre kâğıdı, sünger veya swab gibi emici materyallerle, negatif basınçlı yara tedavisi haznesinden ya da kullanılmış yara örtüsünden toplanabilir. Ancak her yöntem yara yatağının farklı bir bölgesinden örnek alabilir ve molekülleri farklı miktarlarda toplayabilir. Bu nedenle ölçülen biyobelirteç düzeyi yalnızca yaranın biyolojik durumuna değil, kullanılan örnekleme yöntemine de bağlıdır.280 proteomik çalışmanın incelendiği bir kapsam derlemesinde, örnekleme yöntemleri arasında belirgin farklılıklar bulunduğu; çalışmaların çoğundaki küçük örneklem büyüklükleri ve kısa toplama sürelerinin biyobelirteçlerin güvenilir biçimde doğrulanmasını güçleştirdiği bildirilmiştir (Harvey et al., 2022).

Örnekleme öncesinde yaranın yıkanması veya temizlenmesi numuneyi seyreltebilir; pansumanın yara üzerinde kalma süresi ise eksüdanın birikme süresini ve ölçülen biyobelirteç düzeylerini değiştirebilir. Farklı toplama sürelerinde elde edilen yara sıvılarında bazı sitokinlerin farklı düzeylerde ölçülebildiği gösterilmiştir (Zillmer et al., 2011). Numunenin kanla karışması, dolaşım kaynaklı moleküllerin örneğe eklenmesine; topikal antiseptik veya antibiyotik kullanılması ise yaranın mikrobiyal ve moleküler bileşiminin değişmesine neden olabilir. Bu nedenle yara temizliği, kanama durumu ve örnekleme öncesinde uygulanan tedaviler standartlaştırılmalı veya ayrıntılı biçimde kaydedilmelidir (Kalan et al., 2017; Rembe et al., 2024).

Toplama sonrasında yara sıvısının işlenmesi ve saklanması, ölçülecek analitlerin güvenilirliği açısından kritik preanalitik aşamalardır. Venöz bacak ülserlerine ilişkin çalışmaların değerlendirildiği bir literatür incelemesinde, toplama, işleme ve saklama yöntemlerinin belirgin ölçüde heterojen olduğu; çalışmaların çoğunda yara sıvısının santrifüj edildikten sonra ultra düşük sıcaklıklarda saklandığı bildirilmiştir (McDaniel et al., 2023). Protein, küçük RNA ve mikrobiyom analizlerini kapsayan güncel bir örnekleme protokolünde ise numunelerin iki saat içinde en az −20 °C'ye, sekiz saat içinde de −80 °C'ye ulaştırılması uygulanmıştır (Rembe et al., 2024).

Sonuçların karşılaştırılabilir ve tekrarlanabilir olması için toplama zamanı, anatomik bölge, yara yüzey alanı, eksüda miktarı, kullanılan örnekleme materyali, pansumanın yara üzerinde kalma süresi, numunenin işlenmesine kadar geçen süre, santrifüj koşulları, proteaz inhibitörü veya RNA stabilizasyon çözeltisi kullanımı, saklama sıcaklığı ve dondurma-çözme sayısı ayrıntılı biçimde kaydedilmelidir (Harvey et al., 2022; Ramsay et al., 2016; Rembe et al., 2024). Farklı örneklerde ölçülen biyobelirteç düzeylerini doğru biçimde karşılaştırabilmek için sonuçlar; alınan örnek miktarı, toplam protein düzeyi, yaranın büyüklüğü veya eksüdanın toplanma süresi dikkate alınarak hesaplanabilir. Ancak bu düzeltmenin nasıl yapılacağı konusunda henüz ortak kabul gören tek bir yöntem bulunmamaktadır (Harvey et al., 2022; Ramsay et al., 2016).

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3. EKSÜDA TEMELLİ OMİK YAKLAŞIMLAR

3.1. PROTEOMİK, PEPTİDOMİK VE DEGRADOMİK

Proteomik analizler çoğunlukla sıvı kromatografisi-tandem kütle spektrometrisiyle yüzlerce veya binlerce proteinin tanımlanmasına dayanır. Akut iyileşen ve kronik yaraların karşılaştırıldığı öncü çalışmada, iyileşen yara eksüdasında doku oluşumu ve onarımla ilişkili proteinler; kronik yara eksüdasında ise kalıcı inflamasyon ve doku yıkımıyla ilişkili proteinler baskın bulunmuştur (Eming et al., 2010). Diyabetik ayak ülseri eksüdasının tedavi sürecindeki farklı zamanlarda incelendiği başka bir çalışmada 1.865 protein tanımlanmış ve erken, orta ve geç dönemler arasında geniş proteom değişiklikleri gösterilmiştir (Tan et al., 2022).

Kullanılmış yara örtülerinin analizi, düşük eksüdalı yaralarda ve seri izlemde önemli bir gelişmedir. Diyabetik ayak ve venöz bacak ülseri bulunan 16 hastada çıkarılan örtülerden çözünür sıvı, canlı hücreler ve ekstraselüler veziküller ayrıştırılmış; çözünür bölümde 489, hücresel ve veziküler bölümlerde binden fazla protein tanımlanmıştır. Keratinosit aktivasyonu, akut faz yanıtı ve vezikül ilişkili stres proteinleri iyileşen ve iyileşmeyen yaralar arasında farklılık göstermiştir (Soto et al., 2025). Bu yaklaşım noninvaziv ve tekrarlanabilir olmakla birlikte örtü materyalinin seçici protein adsorpsiyonu sonuçları değiştirebilir.

Proteomik bolluk, enzim aktivitesiyle aynı değildir. Kronik yaralarda MMP-1, MMP-8, MMP-9, nötrofil elastazı ve katepsinler fizyolojik remodelling sınırını aşarak matriks proteinlerini, büyüme faktörlerini ve reseptörleri parçalayabilir. Diyabetik ayak ülserlerinde başlangıçtaki yüksek MMP-1/TIMP-1 oranı iyi iyileşmeyle; yüksek MMP-9 ve MMP-9/TIMP-1 oranı ise düşük iyileşme hızıyla ilişkilendirilmiştir (Liu et al., 2009; Muller et al., 2008). Bu nedenle yalnızca toplam protein düzeyinin ölçülmesi yeterli değildir; aktif proteazların ve bu enzimlerin oluşturduğu özgül protein parçalarının da incelenmesi gerekir.Peptidomik ve degradomik yaklaşımlar, bu bileşenleri birlikte değerlendirerek iyileşme sürecinin bozulmasına eşlik eden protein parçalanma profilini daha doğru ortaya koyabilir.

3.2. METABOLOMİK, LİPİDOMİK VE REDOKS PROFİLLEME

Metabolomik, ölçüm anındaki hücresel ve mikrobiyal aktiviteye yakın bilgi sağlayan düşük molekül ağırlıklı bileşikleri inceler. Nükleer manyetik rezonansla analiz edilen kronik bacak ülseri eksüdalarında 42 metabolit tanımlanmış; laktat, lizin ve lösin öne çıkmıştır. Metabolik profillerin mikrobiyolojik durum, diyabet tipi, hipoksi ve nötrofil aktivitesiyle ilişkili olabileceği gösterilmiştir (Junka et al., 2017). Diyabetik yara eksüdasının yüksek çözünürlüklü kütle spektrometrisiyle incelendiği güncel bir çalışmada betain, laktat, karnitin, kolin ve kreatin gibi küçük moleküller saptanmıştır (Gould & Mahmoudi, 2024).

Laktat artışı lokal hipoksi, konak hücrelerinin glikolitik aktivitesi veya bakteriyel fermentasyondan kaynaklanabilir. Amino asitler kollajen sentezi ve immün yanıtı yansıtabileceği gibi doku yıkımının sonucu da olabilir. Karnitin ve açilkarnitinler yağ asidi oksidasyonuna, kolin ve fosfolipidler membran bütünlüğüne, seramidler ise inflamasyon ve hücre ölümü sinyallerine ilişkin bilgi sağlayabilir. İyon hareketliliği-kütle spektrometrisiyle yapılan yapısal analizler, diyabetik yara iyileşmesinin tek metabolit yerine birden fazla biyomoleküler özellikten oluşan moleküler profillerle ayırt edilebileceğini göstermiştir (Hines et al., 2013).

Kronik ve akut yara sıvılarının redoks profilleri karşılaştırıldığında kronik eksüdada TNF-alfa, IL-8, VEGF ve laktat dehidrogenazın daha yüksek olduğu; glutatyon ve radikal süpürücü kapasitenin de değiştiği bildirilmiştir (Bodnár et al., 2018). Bu bulgular, oksidatif stresin tek bir belirteç üzerinden ve tek yönlü olarak yorumlanmaması gerektiğini göstermektedir. Antioksidan kapasitedeki artış, oksidatif yükün azaldığını göstermek yerine, yoğun oksidatif strese karşı endojen antioksidan savunma sistemlerinin etkinleşmesiyle gelişen telafi edici bir yanıt olabilir (Hunt et al., 2024; James et al., 2003). Metabolomik ve lipidomik profiller; yara bölgesinin oksijenlenmesi ve pH'sı ile hastanın glisemik durumu, böbrek fonksiyonu, beslenme durumu ve mikrobiyal özellikleri gibi metabolit düzeylerini etkileyebilecek etmenlerle birlikte değerlendirilmelidir (Chen et al., 2022; Grams et al., 2018; Haller et al., 2021; Junka et al., 2017).

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3.3. HÜCRE DIŞI RNA, MİCRORNA VE EKSTRASELÜLER VEZİKÜLLER

Eksüda, serbest RNA'ların yanı sıra RNA'yı enzimatik parçalanmadan koruyan ekstraselüler veziküller içerir. MikroRNA'lar gen ekspresyonunu transkripsiyon sonrası düzeyde düzenleyerek inflamasyonun çözülmesi, keratinosit göçü, fibroblast aktivasyonu ve anjiyogenezi etkileyebilir. Diyabetik ayak ülseri yara sıvısından izole edilen veziküllerde miR-195-5p ve miR-205-5p artışı gösterilmiş; bu mikroRNA'ların VEGFA ekspresyonunu baskılayarak endotel hücrelerinde tüp oluşumunu ve anjiyogenezi azalttığı bildirilmiştir (Liu et al., 2021).

İnsan kronik yara sıvısındaki keratinosit kökenli eksozomların KRT14 üzerinden ayrıştırıldığı çalışmada, diyabetik ve diyabetik olmayan yara örneklerinde vezikül özelliklerinin ve biyolojik etkilerin farklı olduğu gösterilmiştir (Guda et al., 2023). Yara eksüdasındaki hücre dışı veziküllerin sayısının, olası hücresel kökenlerini gösteren yüzey belirteçlerinin ve taşıdıkları protein ile RNA içeriğinin birlikte değerlendirilmesi, çözünür eksüda bileşenlerinin analizini tamamlayarak yara mikroçevresi hakkında ek ve daha kapsamlı bilgiler sağlayabilir (Mari et al., 2024; Welsh et al., 2024).

Veziküllerdeki RNA miktarının düşük olabilmesi, hemoliz ve hücresel kontaminasyon, izolasyon yöntemleri veya ticari kitler arasındaki verim ve saflık farklılıkları ile RNA analizlerinde uygun endojen kontrolün belirlenmesi, sonuçların güvenilirliğini ve çalışmalar arasındaki karşılaştırılabilirliği sınırlayan önemli sorunlardır (Ding et al., 2018; Kirschner et al., 2013; Pinheiro et al., 2024; Welsh et al., 2024).

Hücre dışı RNA alanı mikroRNA ile sınırlı değildir; uzun kodlamayan RNA, dairesel RNA ve tRNA parçaları da potansiyel biyobelirteçlerdir. 2026 tarihli değerlendirmeler, kronik iyileşmeyen yaralarda hücre dışı RNA'ların hasta sınıflandırması ve tedavi yanıtının izlenmesi için umut taşıdığını, ancak örnekleme ve analitik doğrulamanın henüz yetersiz olduğunu vurgulamaktadır (Rowlands et al., 2026). Eksüda RNA profillerinin doku transkriptomiği ve hücre tipi bilgileriyle eşleştirilmesi, belirtecin biyolojik kaynağını açıklamak açısından önemlidir (Theocharidis et al., 2020, 2022).

3.4. MİKROBİYOMİK VE METAGENOMİK

Kronik yaralarda sıklıkla birden fazla mikroorganizmanın oluşturduğu karmaşık mikrobiyal topluluklar bulunmaktadır (Price et al., 2009; Rhoads et al., 2012). Kültür yöntemleri canlı ve klinik açıdan önemli patojenlerin tanımlanmasında yararlı olmakla birlikte, zor üreyen veya kültüre edilemeyen mikroorganizmaları ve mikrobiyal topluluğun bütününü tam olarak ortaya koyamayabilir (Price et al., 2009; Rhoads et al., 2012). 16S rRNA gen dizilemesi, yarada hangi bakteri gruplarının bulunduğu ve bu grupların birbirlerine göre ne kadar yoğun olduğu hakkında bilgi verir. Shotgun metagenomik ise bakterileri tür ve suş düzeyinde ayırt etmeye; hastalık oluşturma, biyofilm geliştirme ve antibiyotiklere direnç gösterme ile ilişkili genleri incelemeye olanak sağlar (Kalan et al., 2019).

Yüz diyabetik ayak ülserinin uzunlamasına değerlendirildiği çalışmada mikrobiyal toplulukların zamanla valığının devam etmesi kötü iyileşmeyle; topluluk değişkenliğinin ise daha hızlı iyileşmeyle ilişkili olduğu gösterilmiştir (Loesche et al., 2017). Daha güncel bir uzunlamasına çalışmada iyileşen yaralarda Alcaligenes ve Corynebacterium, kötüleşen yaralarda Enterococcus ve Serratia daha çok olduğu bildirilmiş. (Sachdeva et al., 2025). Bu bulgular tek bir patojenden çok mikrobiyal ekosistemin dinamiğinin önemli olduğunu düşündürmektedir.

Metagenomik verilerin metabolomik ve konak inflamasyon profilleriyle birlikte değerlendirilmesi, kolonizasyon ile zararlı mikrobiyal aktiviteyi ayırmaya yardımcı olabilir. Belirli bir bakterinin bolluğu klinik enfeksiyon anlamına gelmez; mikrobiyal metabolitler, virülans genleri ve konağın yanıtı birlikte yorumlanmalıdır. Antibiyotik, debridman ve topikal ürünlerin mikrobiyomu hızla değiştirebilmesi nedeniyle seri örnekleme tek zamanlı ölçümden daha değerlidir.

4. EKSÜDA TEMELLİ MULTİ-OMİK BİYOBELİRTEÇLERİN KLİNİK KULLANIM ALANLARI

4.1. İYİLEŞME SEYRİNİN ERKEN ÖNGÖRÜLMESİ

Kronik yaraların klinik takibi çoğunlukla yara alanındaki azalma, granülasyon dokusunun gelişimi, eksüda miktarı ve enfeksiyon bulgularına dayanmaktadır. Ancak bu değişiklikler, yara

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mikroçevresindeki moleküler bozulmalar başladıktan sonra görünür hâle gelebilir. Eksüdanın seri olarak analiz edilmesi, klinik kötüleşme belirginleşmeden önce yaranın iyileşme eğilimi hakkında bilgi sağlayabilir.

Proteaz-antiproteaz dengesi, inflamatuvar mediyatörler, metabolik stres göstergeleri, anjiyogenezle ilişkili moleküller ve mikrobiyal topluluk özelliklerinin birlikte değerlendirilmesi, tek bir biyobelirteçten daha kapsamlı bir prognostik yaklaşım sunabilir. Bununla birlikte omik verilerin yara alanı, yara süresi, iskemi, enfeksiyon, glisemik kontrol ve uygulanan tedavi gibi klinik değişkenlerle birlikte yorumlanması gerekir (Liu et al., 2025; Longfield et al., 2023). Bu yaklaşım hastaların hızlı iyileşme, gecikmiş iyileşme ve yüksek komplikasyon riski gibi klinik açıdan anlamlı gruplara ayrılmasına katkı sağlayabilir.

4.2. TEDAVİ YANITININ İZLENMESİ

Metagenomik verilerin metabolomik bulgular ve konağın inflamatuvar yanıtıyla birlikte değerlendirilmesi, yarada bulunan mikroorganizmaların yalnızca varlığını değil, metabolik etkinliğini ve konak üzerindeki etkilerini de anlamaya yardımcı olabilir. Böylece zararsız kolonizasyon ile dokuya zarar verebilecek mikrobiyal aktivite arasındaki ayrım daha güvenilir biçimde yapılabilir (Ammons et al., 2015; Radzieta et al., 2021). Belirli bir bakterinin yarada yüksek oranda bulunması tek başına klinik enfeksiyon göstergesi değildir. Enfeksiyon değerlendirilirken mikroorganizmaların etkinliği, taşıdıkları virülans genleri ve konağın oluşturduğu inflamatuvar yanıt birlikte yorumlanmalıdır (Radzieta et al., 2021). Antibiyotikler, debridman ve bazı topikal tedaviler yara mikrobiyomunun yapısını ve zaman içindeki kararlılığını değiştirebilir. Bu nedenle mikrobiyomun yalnızca tek bir zamanda değil, belirli aralıklarla alınan örneklerle izlenmesi daha anlamlıdır (Kalan et al., 2019; Loesche et al., 2017; Malone et al., 2021).

Başarılı tedaviyle birlikte aşırı proteolitik ve inflamatuvar aktivitenin azalması, doku onarımı ve anjiyogenezle ilişkili süreçlerin hızlanması ve mikrobiyal topluluğun yeniden düzenlenmesi beklenebilir. Örneğin başlangıçta yüksek olan MMP-9/TIMP-1 oranının seri ölçümlerde azalması proteolitik yükün azaldığını düşündürebilir (Liu et al., 2009; Muller et al., 2008).Tek bir zamanda elde edilen ölçümden çok, aynı hastada biyobelirteçlerin zaman içindeki değişiminin ve bu değişimin klinik iyileşmeyle uyumunun değerlendirilmesi daha anlamlı olabilir (Loesche et al., 2017; Mikosiński et al., 2022).

4.3. KOLONİZASYON İLE ENFEKSİYONUN AYRIMINA KATKISI

Kronik yaralar, klinik olarak enfeksiyon olmasa bile mikroorganizmalar tarafından kolonize edilebilir. Bu nedenle yara örneğinde belirli bir bakterinin saptanması tek başına enfeksiyon kanıtı olarak kabul edilmemeli; konağın lokal veya sistemik yanıtını gösteren klinik bulgular da değerlendirilmelidir (Swanson et al., 2022). Kültür ve dizileme yöntemleri yara ortamındaki mikroorganizmaların belirlenmesine ve yapısının incelenmesine yardımcı olabilir. Ancak özellikle DNA temelli dizileme yöntemleri, mikroorganizmaların canlı ve aktif olup olmadığını veya yara yatağında hangi işlevleri yerine getirdiğini tek başına kesin olarak gösteremez (Heravi et al., 2020; Misic et al., 2014).

Metagenomik verilerin konağa ait inflamatuvar proteinler, proteaz aktivitesi, mikrobiyal metabolitler ve klinik enfeksiyon bulgularıyla birlikte değerlendirilmesi kolonizasyon ile zararlı mikrobiyal aktivitenin ayrılmasına yardımcı olabilir. Virülans faktörleri, biyofilmle ilişkili genler, antibiyotik direnç genleri ve konak yanıtının eş zamanlı incelenmesi, yalnızca mikroorganizmaların yara örneğinde hangi oranlarda bulunduğunun belirlenmesine göre daha kapsamlı ve anlamlı bilgi sağlayabilir (Loesche et al., 2017; Sachdeva et al., 2025).

Bu yaklaşım, standart mikrobiyolojik incelemelerin ve klinik değerlendirmenin yerini alan bağımsız bir tanı yöntemi olarak değil, bu değerlendirmeleri tamamlayan ve klinik karar sürecini destekleyen ek bir bilgi kaynağı olarak kullanılmalıdır (Senneville et al., 2024; Swanson et al., 2022).

4.4. KRONİK YARALARIN MOLEKÜLER FENOTİPLENMESİ

Benzer klinik görünüme sahip kronik yaralar, farklı hücresel ve moleküler bozukluklar nedeniyle iyileşmeyebilir (Falanga et al., 2022; Pastar et al., 2023). Bazı yaralarda sürekli inflamasyon ve aşırı

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proteaz aktivitesi öne çıkarken, diğerlerinde hipoksi, metabolik bozukluklar, yetersiz anjiyogenez veya mikrobiyal biyofilm aktivitesi iyileşmeyi engelleyen temel mekanizma olabilir (Falanga et al., 2022; Pastar et al., 2023). Tek hücreli transkriptomik ve konak-mikroorganizma multi-omik çalışmalarında, klinik açıdan benzer görünen diyabetik ayak ülserlerinin hücre dağılımları, gen ifade profilleri, konak yanıtları ve mikrobiyal işlevleri bakımından farklılık gösterebildiği bildirilmiştir (Radzieta et al., 2021; Theocharidis et al., 2022). Bu bulgulara dayanarak multi-omik analizlerin, yaraları baskın biyolojik mekanizmaya göre inflamatuvar-proteolitik, hipoksik-metabolik, anjiyogenez yetersizliğinin baskın olduğu, mikrobiyal-biyofilm baskın veya karma moleküler fenotiplere ayırmada kullanılabileceği düşünülmektedir. Ancak bu gruplar şimdilik araştırma amacıyla önerilebilecek kuramsal bir sınıflandırma niteliğindedir (Radzieta et al., 2021; Weigelt et al., 2022).

Moleküler fenotiplemenin temel amacı, standart klinik ve etiyolojik değerlendirmeyi tamamlayarak tedavinin yarada baskın olan biyolojik soruna göre kişiselleştirilmesini sağlamaktır (Weigelt et al., 2022). Örneğin, aşırı proteolitik aktivitenin belirgin olduğu yaralarda proteaz düzenleyici yaklaşımlar; klinik enfeksiyonla uyumlu aktif mikrobiyal süreçlerin bulunduğu yaralarda hedefe yönelik antimikrobiyal tedavi; hipoksi ve damar yetersizliğinin ön planda olduğu yaralarda ise damarsal değerlendirme ve uygun hastalarda perfüzyonu iyileştiren girişimler önceliklendirilebilir (Falanga et al., 2022; Mikosiński et al., 2022; Pastar et al., 2023). Ancak bu mekanizmaya dayalı sınıflandırma henüz doğrulanmış bir klinik karar sistemi değildir. Moleküler fenotiplerin tedavi yanıtını öngörüp öngöremediğinin belirlenebilmesi için farklı hasta gruplarında gerçekleştirilecek, standartlaştırılmış ve ileriye yönelik klinik çalışmalara gereksinim vardır (Theocharidis et al., 2022; Weigelt et al., 2022).

4.5. HASSAS YARA BAKIMINA GEÇİŞ

Hassas yara bakımının temel amacı, tüm hastalara aynı biyobelirteç eşiklerini veya standart bir tedavi yaklaşımını uygulamak yerine, hastanın klinik özelliklerini ve yaranın moleküler durumunu birlikte değerlendirerek bireyselleştirilmiş kararlar vermektir (Pastar et al., 2023; Weigelt et al., 2022). Bu yaklaşımda multi-omik teknolojiler, binlerce molekülün rutin olarak ölçülmesinden çok, iyileşme süreci ve tedavi yanıtı hakkında en fazla bilgi sağlayabilecek biyobelirteç adaylarının keşfedilmesi ve önceliklendirilmesi amacıyla kullanılabilir (Radzieta et al., 2021; Weigelt et al., 2022). Keşif çalışmalarında belirlenen adaylar arasından proteolitik aktiviteyi, metabolik stresi, anjiyojenik kapasiteyi ve mikrobiyal etkinliği yansıtan az sayıda belirteç seçilerek bir panel oluşturulması, klinik uygulama açısından daha uygulanabilir bir strateji olarak değerlendirilebilir (Pastar et al., 2023; Radzieta et al., 2021; Weigelt et al., 2022). Ancak böyle bir panelin klinik kullanıma alınabilmesi için seçilen belirteçlerin analitik ve klinik olarak doğrulanması, eşik değerlerinin belirlenmesi ve tedavi yanıtını öngörme gücünün ileriye yönelik klinik çalışmalarda gösterilmesi gerekir (Weigelt et al., 2022).

Giyilebilir sensörler ve mikroakışkan sistemler, seçilen biyobelirteçlerin hasta başında veya ev ortamında ölçülmesini mümkün hale getirebilir. İnsan kronik yaralarında nitrik oksit, hidrojen peroksit, oksijen, pH ve sıcaklığı birlikte değerlendiren mikroakışkan bir sistem, çoklu yara verilerinin makine öğrenmesiyle klinik sınıflandırmaya dönüştürülebileceğini göstermiştir (Wang et al., 2025). Bu tür platformlar, kapsamlı multi-omik analizlerin yerine geçmek üzere değil; bu analizlerle keşfedilen ve doğrulanan biyobelirteçlerin, klinikte hızlı biçimde ölçülebilen sınırlı ve yorumlanabilir test panellerine dönüştürülmesi amacıyla geliştirilmektedir. Dolayısıyla multi-omik yöntemler biyobelirteçlerin keşfedildiği araştırma aşamasında, hedefe yönelik test platformları ise bu bulguların klinik uygulamaya aktarılmasında birbirini tamamlayan yaklaşımlar olarak değerlendirilmelidir (Rifai et al., 2006; Weigelt et al., 2022)

5. VERİ ENTEGRASYONU, MAKİNE ÖĞRENMESİ VE KLİNİK ÖNGÖRÜ

Multi-omik veri kümelerinde hasta sayısı genellikle sınırlı olmasına karşın ölçülen moleküler değişkenlerin sayısı binleri bulabilir. Değişken sayısının örnek sayısından çok daha fazla olduğu bu yapı, modellerin çalışma verisine aşırı uyum göstermesine ancak yeni hasta gruplarındaki performansının düşmesine yol açabilir (Picard et al., 2021). Bu nedenle her omik katmanına uygun ön işleme ve normalizasyon yapılması; eksik değerlerin yönetilmesi, parti etkilerinin düzeltilmesi, özellik seçimi ve doğrulama yönteminin dikkatle belirlenmesi gerekir (Leek et al., 2010; Picard et al., 2021). LASSO, rastgele orman ve destek vektör makineleri gibi yöntemlerin yanı sıra farklı omik katmanlarını

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birlikte inceleyen çok bloklu veri bütünleştirme yöntemleri de kullanılabilir (Picard et al., 2021). Ancak ön işleme ve özellik seçimi yalnızca eğitim verileri kullanılarak yapılmalı ve aynı hastadan alınan tekrarlayan örneklerin tamamı aynı veri bölümünde tutulmalıdır. Aynı kişiye ait örneklerin hem eğitim hem de test kümelerinde yer alması, veri sızıntısına neden olarak model performansının gerçekte olduğundan daha yüksek görünmesine yol açabilir (Rosenblatt et al., 2024).

Fare yara dokusundaki protein profilleri ile yara eksüdasındaki mikroRNA verilerini inceleyen bir çalışmada, farklı hayvanlardan aynı iyileşme evresinde elde edilen protein ve mikroRNA verileri eşleştirilerek sentetik bir birleşik veri kümesi oluşturulmuştur. Bu veri kümesine uygulanan LASSO analizinde MMP-2, HGF, miR-1b ve miR-107-3p, yara iyileşmesinin farklı evreleriyle ilişkili özellikler arasında belirlenmiştir. İnsanlardan seri olarak alınan serum örneklerinde ise fraktalkin erken dönemde, FGF-2 de daha ileri dönemde iyileşen ve iyileşmeyen yaraları ayırmaya katkı sağlayan özellikler olarak öne çıkmıştır (Sumpio et al., 2025). Bununla birlikte çalışma gruplarının küçük olması, fare proteinleri ile mikroRNA verilerinin aynı hayvanlardan elde edilmemesi ve insanlarda lokal yara eksüdası yerine serum kullanılması nedeniyle bu sonuçlar doğrulanmış klinik biyobelirteçlerden çok ön bulgular olarak değerlendirilmelidir. Deneysel fare yaraları, sistemik serum örnekleri ve lokal yara eksüdası farklı biyolojik bilgileri yansıttığından, bu örneklerden elde edilen sonuçlar birbirine doğrudan eşitlenmemelidir (Sumpio et al., 2025).

Güvenilir bir multi-omik model geliştirme süreci; biyobelirteçlerin keşfedilmesi, özelliklerin seçilmesi, modelin iç doğrulamasının yapılması ve ardından bağımsız bir hasta grubunda dış doğrulamaya tabi tutulması aşamalarını içermelidir. Özellik seçimi ve model ayarlarının belirlenmesi de doğrulama sürecinin içinde gerçekleştirilmeli, test verileri bu işlemlerde kullanılmamalıdır (Rosenblatt et al., 2024; Steyerberg & Vergouwe, 2014). Model değerlendirmesinde yalnızca doğruluk veya ayırt etme gücü değil; tahminlerle gözlenen sonuçların uyumunu gösteren kalibrasyon, klinik yorumlanabilirlik ve mevcut klinik değerlendirmeye sağlanan ek yarar da incelenmelidir (Picard et al., 2021; Steyerberg & Vergouwe, 2014). Gelecekte keşif amaçlı omik çalışmalarda belirlenen sınırlı sayıdaki biyobelirtecin analitik ve klinik olarak doğrulandıktan sonra hedefli kütle spektrometrisi, multipleks immünoanalizler veya giyilebilir sensör platformlarına aktarılması, yüksek boyutlu araştırma verilerinin klinikte kullanılabilecek karar araçlarına dönüştürülmesine katkı sağlayabilir (Hüttenhain et al., 2009; Weigelt et al., 2022).

6. KLİNİK KULLANIMA GEÇİŞTE SINIRLILIKLARI

İlk sorun biyolojik ve yöntemsel heterojenitedir. Diyabetik ayak ülseri, venöz bacak ülseri ve basınç yarası kronik yara olarak sınıflandırılsa da oluşum nedenleri ve iyileşmeyi engelleyen mekanizmalar birbirinden farklıdır (Falanga et al., 2022). İskemi ve enfeksiyon durumu, yaranın süresi ve yüzey alanı, uygulanan debridman, antibiyotik kullanımı, glisemik kontrol, böbrek fonksiyonları ve beslenme durumu hem iyileşme sürecini hem de moleküler ölçüm sonuçlarını etkileyebilir. Bu nedenle söz konusu değişkenlerin çalışma başlangıcında kaydedilmesi ve veri analizinde dikkate alınması gerekir (Graw et al., 2021; Jeffcoate et al., 2016). Bu değişkenler kontrol edilmediğinde elde edilen moleküler profil, yaranın etiyolojisinden çok hastaların klinik özellikleri arasındaki farklılıkları yansıtabilir. Örnek toplama, işleme ve saklama yöntemlerindeki çeşitlilik de çalışmalar arasında karşılaştırma yapılmasını zorlaştırabilir (Harvey et al., 2022; Ramsay et al., 2016).

İkinci sorun analitik geçerliliktir. Keşif çalışmalarında belirlenen aday moleküller, hedefli ve nicel ölçüm yöntemleriyle yeniden değerlendirilmelidir. Bir ölçüm yönteminin klinik araştırmalarda kullanılabilmesi için doğruluk, kesinlik, seçicilik, ölçüm aralığı, matriks etkisi, stabilite ve tekrarlanabilirlik gibi performans özelliklerinin gösterilmesi gerekir (ICH, 2022; Rifai et al., 2006). Yara eksüdasının toplanması ve analiz edilmesine ilişkin ortak yöntemlerin sınırlı olması, farklı laboratuvarlardan elde edilen sonuçların karşılaştırılmasını zorlaştırmaktadır. Bu nedenle yara eksüdasına uygun referans materyallerin, kalite kontrol örneklerinin ve laboratuvarlar arası değerlendirme programlarının geliştirilmesi önemli bir gereksinimdir (Harvey et al., 2022; Ramsay et al., 2016). Ayrıca çok sayıda molekülün eş zamanlı incelendiği çalışmalarda yanlış pozitif bulguları azaltmak amacıyla çoklu karşılaştırma düzeltmeleri uygulanmalıdır (Benjamini & Hochberg, 1995). Belirlenen aday biyobelirteç paneli, başlangıçtaki çalışma grubundan bağımsız ve tercihen farklı merkezlerden oluşturulan hasta gruplarında doğrulanmalıdır (Rifai et al., 2006).

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Üçüncü sorun klinik yarardır. Bir biyobelirtecin yara alanı veya iyileşme süresiyle ilişkili bulunması, tek başına klinik kullanıma uygun olduğunu göstermez. Biyobelirtecin mevcut klinik değerlendirmeye ek bilgi sağlaması, hastaların risk sınıflandırmasını iyileştirmesi veya tedavi kararında değişiklik oluşturması gerekir (Day, 2016; Weigelt et al., 2022). Çalışmalarda tam yara kapanması, belirli bir sürede yara alanındaki azalma, enfeksiyon gelişimi, amputasyon veya tedaviye yanıt gibi farklı sonlanımların kullanılması sonuçların karşılaştırılmasını zorlaştırmaktadır(FDA, 2006; Jeffcoate et al., 2016). Bu nedenle biyobelirtecin hangi zamanda ölçüleceği, hangi değerin karar eşiği kabul edileceği, sonucun ne kadar sürede bildirileceği ve sonuca göre hangi müdahalenin uygulanacağı çalışma başlamadan önce tanımlanmalıdır (Day, 2016).

Multi-omik analizlerin maliyeti, yüksek boyutlu veri üretmesi ve gelişmiş bir biyoinformatik altyapı gerektirmesi de klinik kullanımı sınırlandırmaktadır (Graw et al., 2021; Picard et al., 2021). Klinik laboratuvarlarda amaç binlerce molekülü rutin olarak ölçmekten çok, keşif çalışmalarından elde edilen veriler arasından en fazla klinik bilgi sağlayan sınırlı ve güvenilir bir biyobelirteç paneli oluşturmaktır (Liu et al., 2025; Rifai et al., 2006; Weigelt et al., 2022). Örneğin proteaz dengesini, metabolik stresi, anjiyojenik kapasiteyi ve mikrobiyal aktiviteyi temsil eden üç ila altı analitten oluşan bir aday panel geliştirilebilir. Bununla birlikte, üç ila altı analitlik panel yerleşik bir klinik standart değil, uygulanabilirliği artırmaya yönelik örnek bir tasarım önerisidir. Kullanılacak analitlerin sayısı ve içeriği; analitik performans, maliyet, klinik yarar ve bağımsız doğrulama sonuçlarına göre belirlenmelidir. Multi-omik teknolojiler doku onarımında biyobelirteç keşfi, hasta sınıflandırması ve tedavi yanıtının izlenmesi açısından önemli bir potansiyele sahip olsa da klinik uygulamaya geçişte yöntemlerin standartlaştırılması ve aday belirteçlerin bağımsız hasta gruplarında doğrulanması belirleyici olacaktır (Liu et al., 2025).

7. SONUÇ VE GELECEK PERSPEKTİFLER

Kronik yara eksüdası, yara yatağındaki inflamatuvar, proteolitik, metabolik, anjiyojenik ve mikrobiyal süreçlerin tekrarlayan ölçümlerle ve doku biyopsisine göre daha az girişimsel biçimde izlenmesine imkân veren zengin bir biyolojik örnektir. Proteomik çalışmalar, kronik yara eksüdasında kalıcı inflamasyon ve doku yıkımıyla ilişkili proteinlerin arttığını göstermektedir (Eming et al., 2010). Metabolomik analizlerde laktat, karnitin ve kolin gibi enerji metabolizmasıyla ilişkili moleküller saptanırken; hücre dışı RNA ve vezikül çalışmaları, hücreler arasındaki düzenleyici sinyaller ve anjiyogenezin baskılanması hakkında bilgi sağlamaktadır (Gould & Mahmoudi, 2024; Liu et al., 2021). Mikrobiyom çalışmaları ise yara içindeki mikrobiyal ORTAMIN zaman içerisindeki değişimini ve bu değişimin iyileşme süreciyle ilişkisini ortaya koymaktadır (Loesche et al., 2017).

Mevcut bulgular, bütün kronik yara türlerinde iyileşmeme riskini tek başına gösterebilecek evrensel bir biyobelirtecin henüz bulunmadığını göstermektedir (Longfield et al., 2023; Moore et al., 2007). Yara sıvısındaki yüksek MMP-9/TIMP-1 oranı basınç yaralarında yavaş iyileşmeyle ilişkilendirilmiş; CXCL6 düzeylerinin ise iskemi ve enfeksiyon bulunmayan bazı diyabetik ayak ülserlerinde iyileşme hızıyla bağlantılı olabileceği bildirilmiştir (Ladwig et al., 2002; Wang et al., 2019). Laktat, karnitin ve kolin gibi metabolitler, oksidatif dengeyi yansıtan moleküller, anjiyogenezi baskılayan veziküler mikroRNA'lar ve mikrobiyal ORTAMIN zaman içindeki kararlılığı da aday göstergeler arasında yer almaktadır (Gould & Mahmoudi, 2024; Liu et al., 2021; Loesche et al., 2017; Moore et al., 2007). Ancak bu bulgular farklı yara türlerinden, sınırlı hasta gruplarından ve birbirinden farklı örnekleme yöntemlerinden elde edildiği için söz konusu moleküllerin doğrulanmış klinik biyobelirteçler olarak kabul edilmesi henüz mümkün değildir (Harvey et al., 2022; Longfield et al., 2023). Bu nedenle klinik açıdan daha uygulanabilir yaklaşımın, farklı biyolojik süreçleri temsil eden az sayıdaki belirtecin yara alanındaki değişim ve hastanın klinik özellikleriyle birlikte değerlendirilmesi olduğu düşünülmektedir (Day, 2016; Weigelt et al., 2022).

Gelecekteki çalışmaların standart örnekleme ve analiz protokolleri kullanılarak çok merkezli, uzunlamasına ve yeterli sayıda hastayı kapsayacak şekilde tasarlanması gerekmektedir (Harvey et al., 2022; Longfield et al., 2023). Omik araştırmalarla belirlenen aday moleküller, öncelikle hedefli ve nicel testlerle doğrulanmalı; daha sonra bağımsız hasta gruplarında tanısal veya prognostik performansları değerlendirilmelidir (Rifai et al., 2006). Ayrıca geliştirilen biyobelirteç panelinin mevcut klinik değerlendirmeye ek bilgi sağlaması, iyileşmeme riskini erken dönemde gösterebilmesi ve tedavi kararını

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değiştirebilmesi gerekmektedir (Day, 2016; Weigelt et al., 2022). Dolayısıyla başarılı bir eksüda temelli sistem, en fazla sayıda molekülü ölçen değil; klinik açıdan önemli az sayıdaki belirteci güvenilir, hızlı ve hasta başında uygulanabilir biçimde değerlendiren sistem olacaktır.

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CROSS-BORDER CONFLICT MEDIATION DURING THE REPUBLIC OF MOLDOVA'S ACCESSION TO THE EUROPEAN UNION

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ABSTRACT

This paper examines the role of cross-border conflict mediation as a determinant factor in the Republic of Moldova's accession process to the European Union. Given the persistence of the Transnistrian conflict and its implications for regional stability, the study analyzes how mediation mechanisms, both formal and informal, influence Moldova's compliance with EU accession criteria, particularly those concerning territorial integrity, rule of law, and good neighborly relations. Drawing on a qualitative methodology that combines document analysis and comparative case study review, the research explores the interplay between international mediators (OSCE, EU), Moldovan state institutions, and local actors involved in conflict resolution. The findings suggest that effective cross-border mediation not only facilitates conflict de-escalation but also strengthens Moldova's institutional credibility within the accession framework. The paper argues that the EU's conditionality mechanisms function as both an incentive and a constraint on mediation outcomes. This analysis contributes to the broader literature on EU enlargement policy and post-Soviet conflict resolution, offering policy-relevant insights for practitioners engaged in Moldova's ongoing European integration.

Keywords: cross-border mediation; Transnistrian conflict; EU accession; conditionality; Republic of Moldova; OSCE; 5+2 format

1. Introduction

Since the Republic of Moldova declared independence in 1991, the unresolved conflict over the Transnistrian region has remained one of the most persistent structural constraints on the country's political consolidation, territorial integrity and international integration trajectory. Frozen at the level of large-scale violence since the 1992 ceasefire yet never formally settled, the conflict has coexisted uneasily with Chișinău's progressive rapprochement with the European Union (EU). This rapprochement culminated in the granting of EU candidate status in June 2022, the formal opening of accession negotiations on 25 June 2024, the completion of bilateral screening across all thirty-three negotiating chapters in September 2025, and, most recently, the opening of the first negotiating cluster on 15 June 2026 together with the EU–Moldova Summit of 22 June 2026 (European Commission, 2024; Council of the European Union, 2026; EEAS, 2026).

This confluence of events raises a research problem that is at once theoretical and immediately policy-relevant: how do cross-border conflict mediation mechanisms – both the formal architecture inherited from the 1990s, centred on the Organization for Security and Co-operation in Europe (OSCE) and the so-called 5+2 negotiation format, and the informal, technical channels that have substituted for it since the format's suspension in 2019 – shape, and how are they in turn shaped by, Moldova's compliance with EU accession criteria, in particular those concerning territorial integrity, the rule of law and good neighbourly relations (European Council, 1993)? The question is not merely academic. As the EU's revised enlargement methodology makes the negotiating “fundamentals” cluster the first to open and the last to close (European Commission, 2020), the credibility of Moldova's entire accession trajectory becomes tied, directly or indirectly, to its capacity to demonstrate the rule of law, functioning institutions and stability across a territory over which its government does not exercise full effective control.

The paper argues that, in the absence of senior-level mediated settlement, the EU's own accession conditionality has come to perform latent mediating functions, while simultaneously imposing constraints that a divided territory renders more difficult to satisfy. This dual character – conditionality as both incentive and constraint – is examined against the backdrop of the June 2026 juncture, which the paper treats as a critical case for observing how mediation and conditionality logics interact in

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practice. In doing so, the study situates itself within the broader literature on EU enlargement policy and post-Soviet "protracted" or "frozen" conflicts, and seeks to offer policy-relevant insight for practitioners engaged in Moldova's ongoing European integration.

The remainder of the paper is structured as follows. Section 2 develops the theoretical and conceptual framework, combining conflict-mediation theory with the EU studies literature on conditionality and border conflicts. Section 3 sets out the relevant legal and institutional framework, distinguishing EU primary and secondary legislation from Moldovan constitutional and organic law. Section 4 describes the qualitative methodology. Section 5 presents the findings, organised around the erosion of formal mediation, the EU's emergence as a parallel mediation channel, the dual incentive/constraint function of conditionality, the June 2026 juncture, and a scenario analysis grounded in institutional credibility. Section 6 draws out policy implications, and Section 7 concludes.

2. Theoretical and Conceptual Framework

Two bodies of literature inform the analysis. The first is classical conflict-mediation theory, and in particular the concept of "ripeness," according to which third-party mediation is more likely to succeed when the disputing parties perceive themselves to be locked in a "hurting stalemate" that neither can unilaterally escape (Zartman, 2000). Ripeness theory offers an explanation for the dormancy of the senior-level 5+2 negotiation format since October 2019 that does not reduce to institutional failure alone: in the absence of a perceived mutually hurting stalemate at leadership level, incentives to negotiate a comprehensive settlement remain weak even where technical, lower-level cooperation continues.

The second body of literature concerns the European Union's role as an external actor in border and territorial conflicts. Diez, Stetter and Albert (2006) propose a fourfold typology of the EU's potential impact on such conflicts: a "compulsory" impact, through direct conditionality and pressure exercised on conflict parties; an "enabling" impact, through the empowerment of domestic reform-oriented coalitions; a "connective" impact, through functional cooperation across the line of conflict, typically economic; and a "constructive" impact, through the reshaping of identities and discourses surrounding the conflict. This typology is used in Section 5 as an analytical lens for classifying the mechanisms through which EU accession conditionality operates on the Transnistrian case, even in the absence of a formal linkage between accession and conflict resolution.

Complementing this typology, the external incentives model developed by Schimmelfennig and Sedelmeier (2004) explains candidate-country compliance with EU rules as a function of the size and speed of the rewards offered, the credibility of the conditionality applied, and the determinacy – that is, the clarity and specificity – of the conditions themselves. The EU's 2020 revised enlargement methodology reinforces precisely these credibility and determinacy dimensions through the sequencing of clusters and an explicit reversibility clause allowing the suspension or reversal of negotiations in the event of serious backsliding (European Commission, 2020).

Combining these two strands, the paper proposes an integrated analytical framework in which mediation-ripeness and conditionality-incentive logics are treated not as alternative but as potentially complementary explanations. The working hypothesis is that EU accession conditionality can function simultaneously as a substitute mediation channel – principally through the enabling and connective pathways identified by Diez, Stetter and Albert (2006) – and as a constraint, insofar as the rule-of-law and fundamental-rights benchmarks embedded in the "fundamentals" cluster implicitly, if not formally, presuppose a level of territorial and institutional coherence that a divided state finds difficult to demonstrate comprehensively.

3. Legal and Institutional Framework

3.1. European Union legal architecture

The legal gateway to EU membership is Article 49 of the Treaty on European Union, which provides that any European state respecting the values referred to in Article 2 TEU may apply to become a member (European Union, 2016). The substantive accession criteria were elaborated by the Copenhagen European Council of 21–22 June 1993, which requires candidate states to achieve stability of institutions

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guaranteeing democracy, the rule of law, human rights and respect for and protection of minorities; a functioning market economy; and the capacity to take on the obligations of membership, including adherence to the aims of political, economic and monetary union (European Council, 1993). These political, economic and acquis-related criteria remain the normative core against which Moldova's progress, including on territorial and governance matters linked to Transnistria, is assessed.

The procedural architecture through which these criteria are operationalised was substantially revised by the European Commission's 2020 Communication on enhancing the accession process, which introduced a cluster-based negotiation structure, reinforced political steering by member states, and – critically for this paper – established the principle that the "fundamentals" cluster, covering the judiciary, fundamental rights, and functioning democratic institutions, is to be opened first and closed last, with a reversibility mechanism allowing the Council to slow down or suspend negotiations in response to serious or persistent backsliding (European Commission, 2020).

For Moldova specifically, the relevant legal-institutional sequence runs from the 2014 Association Agreement and its Deep and Comprehensive Free Trade Area (DCFTA), which already required extensive regulatory approximation with the EU acquis and, notably, the registration of economic operators – including those based in Transnistria – with Moldovan customs authorities in order to benefit from preferential trade (European Union, 2014), through the granting of candidate status in June 2022, to the formal opening of accession negotiations on 25 June 2024 (European Commission, 2024). Bilateral screening of all thirty-three negotiating chapters was completed in September 2025, and on 15 June 2026 the Council of the European Union opened negotiations on Cluster 1, "Fundamentals," comprising Chapter 23 (judiciary and fundamental rights), Chapter 24 (justice, freedom and security), Chapter 5 (public procurement), Chapter 18 (statistics) and Chapter 32 (financial control), with interim benchmarks set both at the level of the cluster and specifically for the rule-of-law chapters 23 and 24 (Council of the European Union, 2026).

One week later, on 22 June 2026, the EU–Moldova Summit in Brussels produced a Joint Declaration and a non-binding Research Framework Arrangement, reaffirmed EU support for Moldova's sovereignty and territorial integrity in the face of what the declaration terms Russian "hybrid attacks," and reviewed progress under the €1.9 billion EU Growth Plan for Moldova covering the 2025–2027 period (EEAS, 2026). That Growth Plan is legally and financially anchored in the Reform and Growth Facility for Moldova, signed on 9 May 2025 by the European Commissioner for Enlargement and the Moldovan Prime Minister, under which disbursements are made twice yearly and are conditional on the Commission's verification that reforms set out in Moldova's Reform Agenda have been implemented (European Commission, 2025). The Facility thus operates as a financial conditionality instrument that operationalises, in material terms, the political criteria discussed above.

3.2. Moldovan legal framework

At the domestic level, the Constitution of the Republic of Moldova, adopted in 1994, contains in Article 110(2) the constitutional basis on which forms of special autonomous status may be granted to localities on the left bank of the Nistru river and in southern Moldova (Constitution of the Republic of Moldova, 1994). On this basis, Parliament adopted Law No. 173-XVI of 22 July 2005 on the Basic Provisions of the Special Legal Status of Settlements on the Left Bank of the Nistru (Transnistria), which sets out a comprehensive, if never implemented, framework for autonomy conditional on demilitarisation and democratisation of the region; the law has remained without practical effect precisely because Chișinău does not exercise effective authority over the territory it addresses (OSCE, 2005). A structurally similar instrument, Law No. 344-XIII of 1994 on the Special Legal Status of Gagauzia, contains a clause permitting external self-determination "in case of a change in the status of the Republic of Moldova as an independent state," whose applicability to a prospective loss of full sovereign competences upon EU accession remains legally undetermined and politically sensitive (cited in Public International Law and Policy Group [PILPG], 2024).

A further, more recent layer of domestic law is of direct relevance: on 20 October 2024 Moldovan citizens narrowly approved, in a constitutional referendum conducted amid documented instances of external interference, an amendment entrenching the country's accession to the European Union as a

"strategic and irreversible" national objective within the constitutional text itself (ConstitutionNet, 2024). This constitutional entrenchment, discussed further in Section 5.5, raises the domestic audience costs of any future reversal of the European trajectory and is treated in this paper as a significant credibility-enhancing development within the meaning of the external incentives model (Schimmelfennig and Sedelmeier, 2004). Finally, Moldova's Reform Agenda, negotiated with the European Commission under the Reform and Growth Facility, embeds EU-oriented governance benchmarks directly into national medium-term planning instruments, creating an additional domestic legal-administrative layer through which conditionality is transmitted (European Commission, 2025).

4. Methodology

The study adopts a qualitative research design combining two complementary methods. The first is systematic document analysis of primary legal and policy sources, including EU primary law (the Treaty on European Union), secondary and soft-law instruments (Commission communications, Council press releases, EU–Moldova summit declarations), Moldovan constitutional and organic legislation, OSCE mission documents, and the official communiqués surrounding the June 2026 Summit and the opening of Cluster 1. The second method is a comparative case-study review, in which the Republic of Cyprus's 2004 accession to the EU under conditions of unresolved territorial division is used as the principal comparator, with particular attention to the mechanism of Protocol 10 to Cyprus's Act of Accession, which suspended the application of the acquis communautaire in areas not under the effective control of the Republic of Cyprus while preserving the possibility of its later extension (cited in PILPG, 2024).

The temporal scope of the analysis runs from the granting of EU candidate status to Moldova in June 2022 through to September 2026. Source selection was purposive, prioritising primary legal and institutional documents and supplementing them with specialist policy analysis – notably reports by the Swedish Center for Eastern European Studies (SCEEUS), the Public International Law and Policy Group (PILPG), and the Center for Strategic and International Studies (CSIS) – given that the substantive record of 5+2 negotiations is only partially and unevenly disclosed in public sources. The study acknowledges several limitations. First, the rapidly evolving character of EU–Moldova relations means that the analysis reflects the state of affairs as of the time of writing and should be read as a snapshot of an ongoing process. Second, reliance on secondary and policy-oriented literature for the reconstruction of informal mediation dynamics introduces an unavoidable degree of interpretive mediation by the cited authors themselves. Third, the single-country design constrains the generalisability of findings, a limitation partly mitigated through the systematic use of the Cyprus comparison as an external benchmark.

5. Findings and Discussion

5.1. The erosion of formal mediation and the persistence of low-level cooperation

The OSCE Mission to Moldova, established in 1993, was mandated to facilitate a lasting, comprehensive political settlement of the Transnistrian conflict while helping to consolidate Moldova's sovereignty and independence and accommodate an appropriate special status for the region (OSCE Mission to Moldova, 2024). Negotiations initially proceeded in a "3+2" configuration, with Russia, Ukraine and the OSCE Mission mediating between Chișinău and Tiraspol following commitments made at the 1999 Istanbul Summit; from 2005 the format was widened to "5+2" through the addition of the European Union and the United States as observers (SCEEUS, 2024). Since October 2019, however, senior-level 5+2 talks have been inactive, a state of affairs the Center for Strategic and International Studies characterises as a conflict that is "unfrozen but not thawed" – no longer entirely static, given periodic tension, but without any credible prospect of near-term comprehensive settlement (CSIS, 2023).

Importantly, the suspension of the senior political format has not entailed a complete breakdown of cross-border cooperation. Subsidiary and technical mechanisms – including the Joint Control Commission overseeing the demilitarised security zone and periodic "1+1" expert-level contacts – continue to produce incremental, largely depoliticised agreements on matters such as freedom of movement, telecommunications and access to agricultural land (OSCE Mission to Moldova, 2024). Read through the lens of ripeness theory (Zartman, 2000), this pattern suggests the absence, at leadership level, of a mutually hurting stalemate sufficient to compel a comprehensive settlement: Tiraspol's

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growing, if unacknowledged, economic dependence on EU market access secured through DCFTA-related customs registration, and Chișinău's rising political and reputational stakes in each successive accession milestone, together produce an asymmetric structure of incentives in which technical cooperation persists precisely because it does not require either side to resolve the underlying political status question.

5.2. EU accession as a parallel mediation channel

Even as the formal 5+2 format has remained dormant, the accession process itself increasingly performs functions that classical mediation theory would attribute to a third-party intermediary. Applying the fourfold typology proposed by Diez, Stetter and Albert (2006), the EU's connective impact is most clearly illustrated by the DCFTA registration requirement, under which Transnistrian economic operators wishing to access the EU market must register with Moldovan customs authorities, thereby producing a functional, de facto acknowledgment of Moldovan sovereignty over trade governance without requiring any formal political settlement (PILPG, 2024). This represents a striking empirical instance of economic integration proceeding in the absence of, and arguably as a substitute for, political conflict resolution.

The EU's enabling impact operates through the Reform and Growth Facility and associated technical assistance, which strengthen the administrative and institutional capacity of reform-oriented actors within the Moldovan state – capacity that would also be directly relevant to the future governance of any reintegrated territory (European Commission, 2025). Its compulsory impact is exercised through the conditionality attached to Chapters 23 and 24 on the rule of law, which, although not formally addressed to the Transnistrian question, shapes the broader governance environment within which any eventual settlement would have to be implemented and monitored (Council of the European Union, 2026). Finally, a constructive impact can be discerned in the discursive reframing achieved through the constitutional entrenchment of the EU objective in October 2024, which recasts Moldovan statehood in explicitly European terms and, in doing so, potentially reduces the salience of the Transnistrian conflict as an existential threat to statehood, reframing it instead as a bounded governance and reintegration challenge (ConstitutionNet, 2024).

5.3. Conditionality as incentive and constraint

The European Union's declared position – articulated by the Union's High Representative and reiterated in subsequent official communications – that Moldova's accession is independent of the resolution of the Transnistrian situation functions as a deliberate incentive mechanism (cited in PILPG, 2024). By refusing to make accession formally conditional on a settlement, the EU denies Russia, through its residual leverage over Tiraspol, an effective veto over Moldova's European trajectory, a methodological choice explicitly aimed at avoiding the reward of spoiler behaviour (SCEEUS, 2024).

Yet the same conditionality architecture simultaneously functions as a structural constraint. The 2020 methodology's requirement that the fundamentals cluster be opened first and closed last, together with its reversibility clause permitting the Council to suspend or slow negotiations in the event of serious backsliding, means that full closure of the rule-of-law chapters – and hence of the accession process as a whole – presupposes a governance and security environment that a territorially divided state finds inherently difficult to certify in a comprehensive manner (European Commission, 2020). The interim benchmarks established specifically for Chapters 23 and 24 upon the opening of Cluster 1 on 15 June 2026 illustrate the EU's attempt to manage this tension through incremental, monitorable sequencing rather than by awaiting a definitive territorial settlement before proceeding (Council of the European Union, 2026). In practice, this represents only a partial operationalisation of what SCEEUS (2024) frames as “post-settlement accession”: the EU has opted instead for a hybrid, parallel-track logic that departs from each of the pure ideal-typical scenarios discussed below.

5.4. June 2026 as an institutional-credibility juncture

The near-simultaneous opening of Cluster 1 on 15 June 2026 and the holding of the EU–Moldova Summit on 22 June 2026 can be read as a joint credibility-building juncture for both parties. On the Moldovan side, the capacity to open the fundamentals cluster on schedule, following completion of

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screening in September 2025, demonstrates a baseline level of institutional readiness; on the EU side, the biannual, verification-conditioned disbursement mechanism of the Reform and Growth Facility operationalises, in material and recurring form, the "governance by conditionality" logic identified by Schimmelfennig and Sedelmeier (2004) (European Commission, 2025).

Notably, the Joint Declaration issued at the Summit explicitly frames Russian "hybrid attacks" as a threat to be jointly addressed, an implicit securitisation that links Moldova's border and territorial stability to the credibility of its accession process even in the absence of any formal accession clause referring to Transnistria by name (EEAS, 2026). This securitised framing reinforces the argument advanced in Section 5.2: cross-border stability and EU accession credibility are treated by both parties as substantively, if not textually, linked, even as the formal legal architecture of accession studiously avoids making that linkage explicit or justiciable.

5.5. Institutional credibility, local actors and scenario analysis

The narrow but constitutionally entrenching outcome of the October 2024 referendum is of particular analytical interest (ConstitutionNet, 2024). Within the external incentives model (Schimmelfennig and Sedelmeier, 2004), such entrenchment should increase the determinacy, and hence the effectiveness, of EU conditionality, since any future reversal of the European trajectory would require amending the Constitution itself, raising the domestic audience costs of backsliding for any incumbent government. At the same time, the involvement of local and sub-national actors – including the authorities in Tiraspol and the autonomous region of Gagauzia, whose own special-status law contains an unresolved external self-determination clause – complicates the EU's assessment of the "good neighbourly relations" and minority-protection dimensions of the Copenhagen criteria, since the domestic legitimacy and representativeness of these actors remain contested (PILPG, 2024; Constitution of the Republic of Moldova, 1994).

SCEEUS (2024) proposes three ideal-typical scenarios for the relationship between Transnistrian settlement and EU accession, which can now be evaluated against the June 2026 evidence. The first, accession despite an unresolved conflict, carries the risk of importing Russian leverage into EU internal decision-making through Tiraspol's continued dependence on Moscow; Moldovan and EU practice as of mid-2026, however, suggests a deliberate effort to avoid creating any formal veto point of this kind. The second, an international transitional administration modelled on the United Nations Transitional Administration for Eastern Slavonia (1995–1998), remains theoretically available but is politically improbable, given Russia's position as a permanent member of the UN Security Council and its active, rather than merely residual, revisionist posture in the region – a decisive disanalogy with the consensual post-conflict environment of the Eastern Slavonia case. The third, post-settlement accession, is normatively preferred by SCEEUS (2024) but does not correspond to the operative track actually chosen by the EU, which opened Cluster 1 without any settlement precondition.

The evidence assembled in this paper points instead to an emergent fourth pathway, which may be termed parallel-track accession: cluster-based, benchmark-driven negotiation proceeds on its own institutional timetable, without formal linkage to the conflict, while informal cross-border cooperation – customs registration, technical-level agreements, financial conditionality – progressively narrows the practical space for continued division. This pathway functionally approximates a gradual, de facto reintegration without requiring a prior formal political settlement, and it echoes, while adapting, the precedent set by Protocol 10 to Cyprus's Act of Accession, which suspended application of the acquis in areas outside the government's effective control while preserving the possibility of later extension – a mechanism that could plausibly serve as a legally tested fallback should Cluster 1 approach closure before a comprehensive Transnistrian settlement is reached (PILPG, 2024).

6. Policy Implications

Several policy implications follow from the analysis. First, the European Union should consider moving from a largely passive observer role within any reconstituted negotiation architecture towards a more active facilitation function, while continuing to avoid formally conditioning accession on a Transnistrian settlement, so as not to hand Russia an effective veto over Moldova's European trajectory (SCEEUS, 2024). Second, the tangible benefits generated by Reform and Growth Facility-funded infrastructure and

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by preferential market access should, where feasible, be extended in practice to economic actors on the left bank through the existing DCFTA customs-registration channel, deliberately deepening the "connective" impact identified by Diez, Stetter and Albert (2006). Third, Moldovan authorities should continue to pursue technical, depoliticised reintegration measures – of the kind historically advanced through the 1+1 and Joint Control Commission channels – in parallel with, rather than sequentially after, the cluster negotiations. Fourth, should Cluster 1 approach closure without a comprehensive settlement, both parties would be well advised to examine, in advance, a Protocol 10-type acquis-suspension mechanism as a legally tested fallback that would allow accession to proceed while formally preserving Moldova's claim to territorial integrity (PILPG, 2024). Finally, the credibility effects of the October 2024 constitutional entrenchment on future domestic compliance merit closer, sustained academic and policy monitoring as negotiations advance.

7. Conclusion

This paper has argued that cross-border conflict mediation and European Union accession conditionality, in the case of the Republic of Moldova, function not as parallel but as substantially entangled mechanisms. Formal senior-level mediation through the 5+2 format has, since 2019, been largely superseded by a combination of low-level technical cooperation and the EU's own conditionality architecture, which performs latent mediating functions across the compulsory, enabling, connective and constructive pathways identified by Diez, Stetter and Albert (2006). The events of June 2026 – the opening of Cluster 1 on 15 June and the EU–Moldova Summit on 22 June – illustrate conditionality's dual character as both incentive, accelerating reform and anchoring Moldova against Russian leverage, and constraint, embedding rule-of-law and governance benchmarks that a territorially divided state finds inherently difficult to satisfy in full.

The analysis contributes to the literature on EU enlargement policy and post-Soviet conflict resolution by proposing "parallel-track accession" as an emergent, empirically grounded alternative to the accession-sequencing scenarios previously theorised in the literature, and by offering practitioners a framework for anticipating how mediation and conditionality logics will continue to interact as negotiations advance towards Moldova's stated 2028 accession target. Future research should track the eventual closure of Cluster 1's rule-of-law chapters and any resumption of senior-level 5+2 or successor negotiation formats as critical empirical tests of the framework proposed here, and should extend the comparative analysis to other EU candidate and potential candidate states confronting unresolved territorial disputes.

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LEGAL LEVERAGES THAT WILL DEFINE THE ECONOMIC ENVIRONMENT DURING REPUBLIC OF MOLDOVA ACCESSION TO THE EUROPEAN UNION

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ABSTRACT

This paper examines the legal instruments that will shape the economic environment of the Republic of Moldova during its accession process to the European Union. Accession negotiations require substantial legislative approximation with the acquis communautaire, particularly in areas governing competition policy, public procurement, taxation, banking regulation, and free movement of capital. The study analyzes how the transposition of EU directives and regulations into national law functions as a lever for restructuring Moldova's economic institutions, influencing investment climate, trade relations, and market competitiveness. Special attention is given to the interplay between legal harmonization and macroeconomic stability, including the risks of regulatory misalignment and implementation gaps typical of candidate states. The paper further explores the role of conditionality mechanisms embedded in the accession framework and their capacity to accelerate structural reform. Drawing on comparative experience from previous EU enlargement rounds, the analysis argues that consistent legal transposition, coupled with institutional capacity building, constitutes the decisive factor in determining Moldova's economic trajectory during accession. The findings contribute to the broader literature on legal-economic integration in EU candidate countries.

Keywords: EU accession; Republic of Moldova; acquis communautaire; legal complying; conditionality; economic integration.

1. Introduction

The accession of the Republic of Moldova to the European Union has moved, within the space of four years, from a declaratory political aspiration into a structured, chapter-based negotiating process governed by binding legal instruments and measurable benchmarks. Moldova submitted its application for EU membership on 3 March 2022, obtained candidate status in June 2022, and saw accession negotiations formally opened on 25 June 2024 on the basis of a Negotiating Framework adopted by the Council (Council of the European Union, 2024). The operative turning point for the purposes of this paper occurred at the Second Accession Conference of 15 June 2026, when the European Union and the Republic of Moldova opened negotiations on Cluster 1 – 'Fundamentals', comprising the chapters on judiciary and fundamental rights, justice, freedom and security, public procurement, statistics, and financial control (Council of the European Union, 2026a). This event, together with the interim benchmarks attached to it, constitutes in substance the pre-accession framework agreement referred to throughout this paper: it fixes the legal sequencing, the horizontal and chapter-specific conditions, and the pace at which Moldova's domestic legal order must be aligned with the acquis communautaire before membership can be concluded.

Legal complying is not a peripheral technicality of the accession process; it is its principal operative mechanism. Because the acquis communautaire embeds specific economic models – concerning market competition, public spending, taxation, financial intermediation and capital mobility – the act of transposing EU directives and regulations into Moldavian law simultaneously performs an act of economic engineering. Each transposed norm reallocates rights, constrains discretion, and redefines the rules under which domestic and foreign economic actors compete, invest, and contract. The central question addressed in this paper is therefore not whether Moldova will legislate in line with the acquis – this is a binding condition of accession – but how the specific legal levers embedded in the negotiating chapters on competition, public procurement, taxation, banking regulation and free movement of capital will shape the country's economic environment during the transitional period, and what risks and

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enabling conditions determine whether that reshaping produces genuine structural convergence or merely formal compliance.

The paper proceeds as follows. Section 2 sets out the institutional and legal architecture within which Moldova's accession negotiations unfold, situating the June 2026 opening of the Fundamentals cluster within the broader sequence running from the 2014 Association Agreement to the 2025–2029 National Accession Programme. Section 3 analyses, chapter by chapter, how transposition of the relevant EU secondary legislation operates as a lever restructuring competition, procurement, taxation, banking and capital markets. Section 4 examines the tension between rapid legal harmonization and macroeconomic stability, focusing on the risks of regulatory misalignment and implementation gaps. Section 5 discusses the conditionality mechanisms built into the 2020 enlargement methodology and their capacity to accelerate reform. Section 6 draws comparative lessons from the 2004, 2007 and 2013 enlargement rounds and from the Western Balkans experience. Section 7 discusses the combined explanatory weight of legal transposition and institutional capacity, and Section 8 concludes.

2. Institutional and Legal Architecture of Moldova's Accession Process

The legal foundation of EU–Moldova relations was laid by the Association Agreement, including a Deep and Comprehensive Free Trade Area (AA/DCFTA), signed in 2014 and ratified domestically through Law No. 112 of 2 July 2014 (Republic of Moldova, 2014), entering into full force on 1 July 2016. The AA/DCFTA already required partial approximation with EU technical, sanitary, competition and trade-related rules, and it remains the legal substratum on which the accession acquis is now built; by 2025 the European Union accounted for 55.9% of Moldova's goods trade, underlining the depth of pre-existing integration (European Commission, 2025).

Accession negotiations proper are conducted under the revised enlargement methodology endorsed by the Council in 2020, which reorganised the thirty-five negotiating chapters into six thematic clusters and made progress conditional on a 'fundamentals first' principle: the cluster grouping the rule-of-law and public-administration chapters is the first to open and the last to close, and can trigger a suspension or reversal of negotiations on other clusters where backsliding occurs (European Commission, 2020; European Western Balkans, 2020). This reversibility clause is significant for the economic chapters analysed in this paper, because chapters 5 (public procurement), 18 (statistics) and 32 (financial control) were placed inside Cluster 1 precisely so that budgetary and procurement governance would be secured before the negotiation of the internal-market and economic clusters proceeds.

At the Second Accession Conference of 15 June 2026, the Council and Moldova formally opened Cluster 1 'Fundamentals'. The Council attached to this opening a layered system of benchmarks: horizontal benchmarks applicable to the cluster as a whole, specific benchmarks conditioning the closing phase of the rule-of-law chapters (23 and 24), and provisional closure benchmarks applicable to the public procurement, statistics and financial control chapters (5, 18 and 32) (Council of the European Union, 2026a). The Council's own assessment that 'progress under this cluster will determine the overall pace of negotiations' confirms that the fundamentals cluster functions as the master lever of the entire accession timetable. One month later, on 14 July 2026, the Third Accession Conference opened Cluster 6 on external relations (Council of the European Union, 2026b), demonstrating that the pace-setting function of Cluster 1 does not preclude parallel progress on other fronts once the initial benchmarks are accepted.

Domestically, the legislative implementation of these commitments is channelled through the 2025–2029 National Programme for the Accession of the Republic of Moldova to the European Union, which operationalises the negotiating chapters into a sequenced schedule of laws, secondary regulations and institutional measures, including in the areas of competition, public procurement, taxation and financial services examined below (Government of the Republic of Moldova, 2025). It is this triangular structure – the Council's negotiating framework and cluster benchmarks, the European Commission's annual country reports assessing preparation levels chapter by chapter, and the domestic National Accession Programme transposing the corresponding acquis – that constitutes the legal architecture governing Moldova's economic environment for the duration of the accession process.

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3. Legal Complying as an Instrument of Economic Restructuring

The acquis communautaire is not a neutral regulatory checklist; each of its economically relevant chapters encodes a specific institutional model developed within the internal market and transplants it, through the act of transposition, into the domestic legal order of the candidate state. This section examines five such levers – competition policy, public procurement, taxation, banking regulation and free movement of capital – chosen because they correspond directly to the areas identified in the negotiating architecture described above and because, taken together, they define the operating conditions for investment, trade and market competition in Moldova during accession.

3.1. Competition policy (Chapter 8)

EU competition law, anchored in Articles 101–102 TFEU on restrictive agreements and abuse of dominance and Articles 107–109 TFEU on state aid, requires candidate states to establish an independent competition authority, an operational merger-control regime and a transparent state-aid monitoring mechanism. Moldova's domestic framework rests on the Competition Law No. 183 of 11 July 2012 (Republic of Moldova, 2012), subsequently amended to strengthen merger-control thresholds and enforcement powers. The European Commission's 2025 country report credits Moldova with 'some level of preparation' in this chapter, while identifying persistent gaps regarding the procedure for dismissing members of the Competition Council, the adequacy of fine levels, and the transparency of the state-aid framework (European Commission, 2025). From an economic-environment perspective, the transposition of EU competition disciplines operates as a lever against the legacy of market concentration and informal state capture inherited from the post-Soviet transition: a credibly independent authority reduces the risk premium demanded by foreign investors and disciplines incumbent operators, while an EU-consistent state-aid regime constrains ad hoc fiscal favouritism toward politically connected enterprises, a precondition for a level playing field.

3.2. Public procurement (Chapter 5)

Directives 2014/24/EU on public procurement and 2014/25/EU on procurement by entities operating in the utilities sectors codify principles of transparency, non-discrimination, proportionality and electronic tendering that candidate states must transpose in full, given that public procurement was placed inside the fundamentals cluster itself. Moldova's Law No. 131 of 3 July 2015 on public procurement (Republic of Moldova, 2015) constitutes the primary transposition vehicle, complemented by more recent legislation on concessions and amendments to public-private partnership rules; the European Commission notes 'some level of preparation' together with a concrete implementation risk, since the secondary legislation implementing a new procurement law due to enter into force in January 2027 is still being developed (European Commission, 2025). Because public procurement typically represents a substantial share of gross domestic product in transition economies, the economic significance of this chapter is considerable: a rules-based, electronically auditable procurement system (Moldova already operates the MTender e-procurement platform) narrows the space for corruption rents, lowers the effective cost of public contracts, and opens the domestic market to EU economic operators – precisely the outcome the Council's provisional-closure benchmark for Chapter 5 is designed to secure before this chapter can be closed.

3.3. Taxation (Chapter 16)

Fiscal approximation centres on Council Directive 2006/112/EC on the common system of value added tax and, more recently, on anti-avoidance instruments such as Directive (EU) 2016/1164 (ATAD). The Commission's 2025 assessment records 'good progress' in aligning indirect and direct taxation and excise-duty provisions, together with a modernised digital tax administration, while flagging that VAT and excise legislation still requires further alignment 'to minimise competitive distortions and prevent tax evasion schemes' (European Commission, 2025). Fiscal harmonization functions as an economic lever in two complementary ways: it removes indirect subsidies embedded in preferential or excise-differentiated regimes that distort competition between domestic and EU-origin goods, and it increases the predictability of the tax base on which investors price long-term projects – an especially important consideration given Moldova's narrow export base and comparatively modest inflow of foreign direct investment noted in the same report.

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3.4. Banking regulation and financial services (Chapter 9)

The EU prudential framework – the Capital Requirements Directive IV (2013/36/EU) and the Capital Requirements Regulation (EU) No. 575/2013, the Bank Recovery and Resolution Directive 2014/59/EU, the Deposit Guarantee Schemes Directive 2014/49/EU and, for the insurance sector, the Solvency II Directive 2009/138/EC – defines the prudential architecture candidate states must approximate before their financial systems can be considered compatible with the internal market. In Moldova, the Law No. 202 of 6 October 2017 on the activity of banks (Republic of Moldova, 2017) and the Law No. 232 of 3 October 2016 on the recovery and resolution of banks (Republic of Moldova, 2016) transpose significant elements of this framework, complemented by National Bank of Moldova regulations partially aligned with Solvency II. The European Commission rates this chapter at 'some level of preparation', pointing to outstanding work on the bank recovery framework, the deposit guarantee scheme and securities-market alignment (European Commission, 2025). Because prudential convergence is what ultimately allows cross-border banking, correspondent relationships and eventual passporting arrangements with EU financial institutions, this chapter functions as the lever that determines the depth, cost and stability of financial intermediation available to the Moldovan economy during accession.

3.5. Free movement of capital (Chapter 4)

Articles 63–66 TFEU establish the free movement of capital as one of the four fundamental freedoms, while the Fourth and Fifth Anti-Money Laundering Directives (Directive (EU) 2015/849 and Directive (EU) 2018/843) impose the safeguards without which capital-account liberalization would be economically hazardous for a state exposed to significant informal-economy pressure. The Commission's 2025 report describes Moldova as 'moderately prepared' in this chapter, crediting 'good progress' in strengthening the institutional capacity of the anti-money-laundering framework, the completion of upgrades against three Financial Action Task Force recommendations, capacity building within the Financial Intelligence Unit, and the approval of Moldova's application to participate in Single Euro Payments Area schemes (European Commission, 2025). This chapter illustrates a general pattern of the accession process: capital-account opening is legally sequenced behind, not ahead of, the institutional safeguards meant to contain it – a sequencing logic long recognised in the economic literature on financial liberalization in transition economies (McKinnon, 1991) and one that the negotiating framework operationalises through chapter-specific benchmarking rather than leaving to unilateral domestic discretion.

4. Legal Harmonization and Macroeconomic Stability: Misalignment Risks and Implementation Gaps

The transposition of EU secondary legislation is a necessary but not a self-executing condition of economic convergence. A substantial body of Europeanization scholarship distinguishes between formal legal alignment and effective, sustained implementation, describing the risk that transposed rules remain, in practice, a 'world of dead letters' when domestic administrative capacity is insufficient to enforce them (Falkner and Treib, 2008). The European Commission's 2025 country report on Moldova illustrates this risk directly: notwithstanding 'good progress' on several fronts, the report records a widened current account deficit, stalled 2024 growth, a 'substantial informal economy' constraining the business environment, labour shortages at both skill levels, modest foreign direct investment and a narrow export base, alongside 'limited public administration capacity' identified as a systemic constraint affecting the implementation of policy across all economic chapters (European Commission, 2025).

Three specific channels of regulatory misalignment merit attention. First, partial or sequential transposition can generate a dual legal regime in which formally EU-consistent rules coexist with unreformed implementing practice, producing legal uncertainty that is, from an investor's perspective, often more costly than the pre-existing status quo. Second, chapters transposed ahead of the institutional capacity required to enforce them – for instance, competition or state-aid rules enacted without a correspondingly empowered and adequately resourced authority – risk becoming symbolic compliance rather than operative constraint, a pattern well documented in the 2004 enlargement round (Sedelmeier, 2014). Third, and most acutely for the capital and banking chapters, liberalization measures that outpace

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prudential and anti-money-laundering capacity can transmit financial instability rather than absorb it; this is precisely the logic behind the EU's decision to require completed FATF-related upgrades and reinforced Financial Intelligence Unit capacity as preconditions rather than parallel tracks to further capital-account opening (European Commission, 2025).

The practical implication for Moldova's economic trajectory is that the sequencing embedded in the fundamentals-first methodology is not merely a political device for maintaining leverage; it is also a macro-prudential safeguard. By requiring provisional closure benchmarks on public procurement, statistics and financial control before the internal-market and economic clusters can be substantively advanced, the negotiating framework seeks to ensure that the institutional and statistical infrastructure needed to monitor macroeconomic stability is in place before deeper market-opening measures take effect (Council of the European Union, 2026a).

5. Conditionality Mechanisms and the Acceleration of Structural Reform

The theoretical starting point for understanding EU conditionality is the 'external incentives model', under which a candidate government adopts EU-consistent rules when the size and credibility of the reward offered by the Union outweighs the domestic political cost of reform (Schimmelfennig and Sedelmeier, 2005). Applied to Moldova, this model operates through several concrete mechanisms embedded in the current accession framework. The 2020 enlargement methodology introduced the possibility of positive and negative conditionality within each cluster, including accelerated integration benefits – phased access to specific internal-market segments and EU funding instruments – for candidates that meet interim benchmarks, and the reversal of an entire cluster's progress where fundamentals-related backsliding occurs (European Commission, 2020).

For Moldova specifically, this architecture is reinforced by substantial ex ante financial conditionality: the Reform and Growth Facility for the Western Balkans and, in a parallel instrument, Moldova's own Reform and Growth Facility for 2025–2027, combining €385 million in grants with €1.5 billion in loans, described as the largest EU financial-support package since Moldova's independence and explicitly tied to the implementation of a reform agenda (European Commission, 2025). This is conditionality of the classical type identified by Moravcsik and Vachudova (2003): EU leverage is at its most 'active' during the pre-accession phase, when the prospect of membership and of large-scale financial support remains conditional on continued, verifiable reform, and diminishes sharply once accession is achieved and the principal disciplining mechanism disappears. The explicit statement by the Council that progress in the fundamentals cluster 'will determine the overall pace of negotiations' operationalises this leverage directly onto the economic chapters analysed in Section 3, since chapters 5, 18 and 32 cannot be provisionally closed – and negotiations on the internal-market cluster cannot meaningfully advance – without measurable delivery on procurement, statistics and financial-control reform (Council of the European Union, 2026a).

Historical experience across the post-communist enlargements suggests that this form of conditionality is capable of accelerating reforms that domestic political economy alone would not have produced within the same timeframe, particularly in areas – competition enforcement, procurement transparency, prudential regulation – where short-term rents accrue to incumbent economic and political actors resistant to reform (Vachudova, 2005). The credibility of the reward, however, is itself contingent on the EU's own willingness to enforce the reversibility clauses consistently, a point to which the comparative analysis in the following section returns.

6. Comparative Lessons from Previous Enlargement Rounds

The 2004 enlargement to eight Central and Eastern European states remains the primary reference case for legal-economic integration through accession. That round was characterised by extraordinarily rapid formal transposition of the acquis, often achieved through what has been described as a 'fuzzy fit' between EU templates and pre-existing domestic institutions, in which candidate legislatures adopted EU-consistent statutes without always adapting the administrative and judicial capacity needed to enforce them (Grabbe, 2006). The consequence, documented extensively in post-accession compliance studies, was a persistent gap between legal transposition and effective application in exactly the areas most relevant to this paper – competition and state aid enforcement, public procurement oversight and

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financial-sector supervision – which several new member states only closed gradually after accession, under continued informal monitoring by the Commission (Falkner and Treib, 2008; Sedelmeier, 2014).

The 2007 accession of Bulgaria and Romania offers a still sharper illustration of the risk that legal transposition can outpace institutional readiness in the fundamentals area: both states required a dedicated post-accession Cooperation and Verification Mechanism to continue monitoring judicial reform and the fight against corruption precisely because pre-accession benchmarking in these areas had not been sufficiently binding. Croatia's accession in 2013, negotiated under an already more benchmark-intensive methodology, is generally regarded as having achieved a more durable alignment between legal transposition and institutional practice, particularly in competition policy and public administration, lending early support to the logic later generalised in the 2020 'fundamentals first' methodology now applied to Moldova (European Western Balkans, 2020).

The Western Balkan candidates negotiating under the same post-2020 methodology illustrate a further, complementary lesson: where the legal and technical benchmarks are well specified but political will to implement fundamentals-related reforms is weak, the pace-setting function of Cluster 1 can stall the entire process for years, regardless of formal transposition rates in the economic chapters. For Moldova, the comparative record therefore points in a consistent direction: the economic pay-off of legal approximation in competition, procurement, taxation, banking and capital movement is conditional upon two factors that lie substantially outside the text of the transposed norms themselves – the credibility of enforcement institutions built in parallel with the legislation, and the sustained political commitment required to keep the fundamentals cluster moving rather than stalling at the benchmark stage.

7. Discussion: Legal Transposition and Institutional Capacity as the Decisive Variable

The analysis developed in the preceding sections supports a central proposition: the legal levers examined in Section 3 – competition, public procurement, taxation, banking regulation and free movement of capital – possess real capacity to restructure Moldova's economic institutions, but the direction and magnitude of that restructuring is not determined by the text of the transposed acquis alone. It is determined jointly by the quality of transposition and by the institutional capacity available to apply it, a conclusion consistent with both the Europeanization literature on Central and Eastern Europe (Grabbe, 2006; Schimmelfennig and Sedelmeier, 2005) and the European Commission's own 2025 diagnosis of Moldova, which repeatedly pairs an assessment of 'some level of preparation' in legislative terms with an explicit warning about 'limited public administration capacity' undermining implementation (European Commission, 2025).

This has three practical implications for the economic environment during accession. First, investors and market participants should expect a period of formal-substantive divergence in several chapters – legislation that reads as EU-consistent while enforcement practice catches up – and should price the associated legal-uncertainty risk accordingly, rather than treating transposition dates as equivalent to full regulatory convergence. Second, the specific design of the fundamentals-first, benchmark-based methodology gives Moldova an institutional advantage relative to the 2004 cohort, precisely because it forces sequencing of institution-building (chapters 23, 24, 32, 18) ahead of full economic-chapter closure, reducing the risk of a Bulgaria/Romania-style post-accession capacity gap. Third, and most importantly for the thesis of this paper, the empirical trajectory of Moldova's economic integration will be determined less by the pace of legislative drafting – which the National Accession Programme already schedules in considerable detail (Government of the Republic of Moldova, 2025) – than by the sustained allocation of administrative, judicial and regulatory resources needed to make competition authorities, procurement oversight bodies, tax administrations, banking supervisors and financial-intelligence units operationally independent and adequately staffed.

8. Conclusions

This paper has examined the legal instruments that will shape the economic environment of the Republic of Moldova during its accession to the European Union, taking as its operative reference point the opening, at the Accession Conference of 15 June 2026, of negotiations on the fundamentals cluster and the benchmark structure attached to it. The analysis has shown that legal approximation in competition policy, public procurement, taxation, banking regulation and free movement of capital functions as a

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genuine lever of economic restructuring, reshaping the rules governing market competition, public spending, fiscal predictability, financial intermediation and capital mobility. At the same time, the study has shown that this lever operates within clear limits: the risk of regulatory misalignment and implementation gaps, well documented both in the European Commission's own assessment of Moldova and in the comparative record of the 2004, 2007 and 2013 enlargement rounds, means that legal transposition alone cannot guarantee economic convergence.

The paper's central argument is that consistent legal transposition, combined with sustained institutional capacity-building, constitutes the decisive factor determining Moldova's economic trajectory during accession – more decisive than the drafting of compliant legislation in isolation, and more decisive, in the medium term, than the conditionality mechanisms that initially compel that legislation to be drafted. The conditionality embedded in the 2020 enlargement methodology and reinforced through Moldova's Reform and Growth Facility provides a credible external incentive for reform, but its lasting economic effect will depend on whether the institutions created under chapters 5, 8, 9, 4 and 16 acquire genuine operational independence before, rather than after, accession is concluded. Future research should track the provisional closure of chapters 5, 18 and 32 and the subsequent opening of the internal-market cluster as empirical markers against which the propositions advanced in this paper can be tested, contributing further to the broader literature on legal-economic integration in EU candidate states.

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DO BRANCHED-CHAIN AMINO ACIDS AND L-GLUTAMINE ALTER SMALL INTESTINAL HISTOMORPHOLOGY IN BROILER CHICKENS?

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ABSTRACT

Intestinal histomorphology can be influenced by the amino acid profile of broiler chicken diets. In particular, branched-chain amino acids (BCAAs)—consisting of leucine, isoleucine, and valine—play critical roles in regulating muscle protein synthesis and cellular metabolism, whereas L-glutamine is essential for maintaining intestinal epithelial integrity, enterocyte metabolism, and gut development processes. This study aimed to determine the effects of dietary supplementation with different levels of BCAAs and L-glutamine on the small intestinal histomorphology of Anadolu-T broiler chickens. A total of 560 one-day-old Anadolu-T broiler chickens were assigned to eight treatment groups over a 42-day trial period. The treatments consisted of a control group, diets with dietary BCAA levels increased by 20%, 35%, and 50%, a 1% L-glutamine group, and their respective combinations. In the study, villus height, villus width, and villus surface area were significantly affected by the dietary treatments ($P < 0.05$). The 1% L-glutamine and 50% BCAA groups alone yielded the highest villus height, whereas the 1% L-glutamine group and the 20% BCAA + 1% G and 35% BCAA + 1% G combination groups exhibited significantly higher villus width and total surface area compared to the control and 20% BCAA groups ($P < 0.05$). In terms of sex, male broilers had significantly greater villus height, width, and surface area than females ($P < 0.05$). In conclusion, dietary supplementation with 1% L-glutamine alone or combinations of 20% to 35% BCAA with L-glutamine represents the most effective nutritional strategy to enhance intestinal villus development and absorptive surface area in broiler chickens.

Keywords: Anadolu-T, BCAA, L-glutamine, Intestinal histomorphology

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INTRODUCTION

Growth performance and feed efficiency in broiler chickens are directly associated with the anatomical development of the digestive system and particularly the absorptive capacity of the small intestinal mucosa (Öztürk et al., 2026). Histomorphological parameters of the small intestine—such as villus height, villus width, and crypt depth—can undergo substantial modifications driven by advancing age, physiological maturation, and the functional amino acid composition of the diet. L-glutamine, a functional amino acid, plays a critical role in the development and maintenance of gut tissue. Previous studies in broilers have reported that dietary L-glutamine supplementation exerts beneficial effects on villus height and the morphological development of the intestinal mucosa (Bartell & Batal, 2007; Murakami et al., 2007). Conversely, branched-chain amino acids (BCAAs)—leucine, isoleucine, and valine—participate not only in protein synthesis but also in gut tissue development and nutrient

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utilization. Leucine, in particular, stimulates protein synthesis via the mTOR signaling pathway, and adequate dietary BCAA levels contribute to the preservation of intestinal morphology. However, maintaining an optimal balance among BCAAs is critical, as excess dietary leucine may impair the utilization of isoleucine and valine (Zeitz et al., 2019; Ospina-Rojas et al., 2020; Kim et al., 2022). Furthermore, literature regarding how digestive tract physiology and intestinal histomorphological dynamics are modulated by targeted nutritional strategies during the growth phases of the native Anadolu-T broiler genotype remains very limited. Accordingly, this study was designed to elucidate the alterations induced by dietary supplementation with varying levels of BCAAs and L-glutamine in the small intestinal (ileal) histomorphology and absorptive surface area of the native Anadolu-T broiler genotype.

MATERIALS AND METHODS

The experimental trial was conducted at the Poultry Research Unit of the Faculty of Agriculture, Ondokuz Mayıs University. A total of 560 one-day-old male and female Anadolu-T broiler chicks with uniform initial body weights were randomly allocated into 56 floor pens across 8 dietary treatment groups, with 7 replicates of 10 birds per pen. Diets were supplemented with BCAAs, L-glutamine, and their combinations. The experimental groups are presented in Table 1. A four-phase feeding program was implemented throughout the 42-day trial: starter (days 0–10), grower (days 11–28), finisher (days 29–35), and withdrawal (days 35–42).

Table 1. Experimental groups used in the study

L-glutamine	Dietary Treatments
-	Basal Diet (Control)
-	Basal Diet + %20 BCAA supplementation
-	Basal Diet + %35 BCAA supplementation
-	Basal Diet + %50 BCAA supplementation
+	Basal Diet + L-glutamine supplementation
+	Basal Diet + L-glutamine +%20 BCAA supplementation
+	Basal Diet + L-glutamine + %35 BCAA supplementation
+	Basal Diet + L-glutamine+ %50 BCAA supplementation

The study was carried out in the poultry rearing facilities of Ondokuz Mayıs University Agricultural Research and Application Farm, while histological evaluations were conducted at the Laboratory of the Department of Histology and Embryology, Faculty of Veterinary Medicine. The 560 healthy chicks obtained from the farm hatchery were housed in 56 pens measuring 1 m^2 and 50 cm in height, constructed with plastic wire mesh floors bedded with a 5–8 cm layer of coarse wood shavings. Each pen was equipped with one tube feeder (15 kg capacity) and two nipple drinkers. Heating was supplied electrically, and lighting was maintained at 20–25 lux at animal level using 9 W compact fluorescent lamps (24 h for the first 3 days, 20 h from days 4–14, and 18 h from days 15–42). Chicks were weighed individually at placement and randomly assigned to pens. Broilers were slaughtered at 43 days of age at the poultry slaughterhouse of Ondokuz Mayıs University Agricultural Research and Application Farm following standardized slaughter protocols for all treatments. From each treatment, 7 male and 7 female broilers were housed in separate pens and fasted for 8 h prior to slaughter with ad libitum access to water. Preslaughter individual live weights were recorded to determine final slaughter live weight (g). Birds were scalded in water at 55–60°C for 15–20 s and defeathered using a mechanical rotary plucker.

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Tissue samples were collected anatomically and fixed in a 10% formaldehyde solution for 24 h. Following fixation, ileal tissue samples were processed through standard histological dehydration and clearing series and embedded in paraffin blocks at the Department of Histology and Embryology. Sections of 5–7 \mu\text{m} thickness were cut from paraffin blocks and stained with Crossmon's trichrome staining technique for histomorphological assessment (Crossmon, 1937; Güzel et al., 2015). The prepared slides were examined in detail for ileal mucosal architecture, epithelial cell layer, villus intestinalis, and Lieberkühn crypts. Small intestinal (ileal) histomorphological parameters (villus height, villus width, crypt depth, villus surface area, and villus height-to-crypt depth ratio) were evaluated (Figure 1) (Öztürk et al., 2026). Villus surface area was calculated using the formula: \text{Villus Height} \times \text{Villus Width} \times \pi (Bami et al., 2022). Histomorphometric measurements and photomicrographs were captured using a Nikon Eclipse E-80i research microscope equipped with the Nikon Digital Sight DS-Fi1 imaging system.

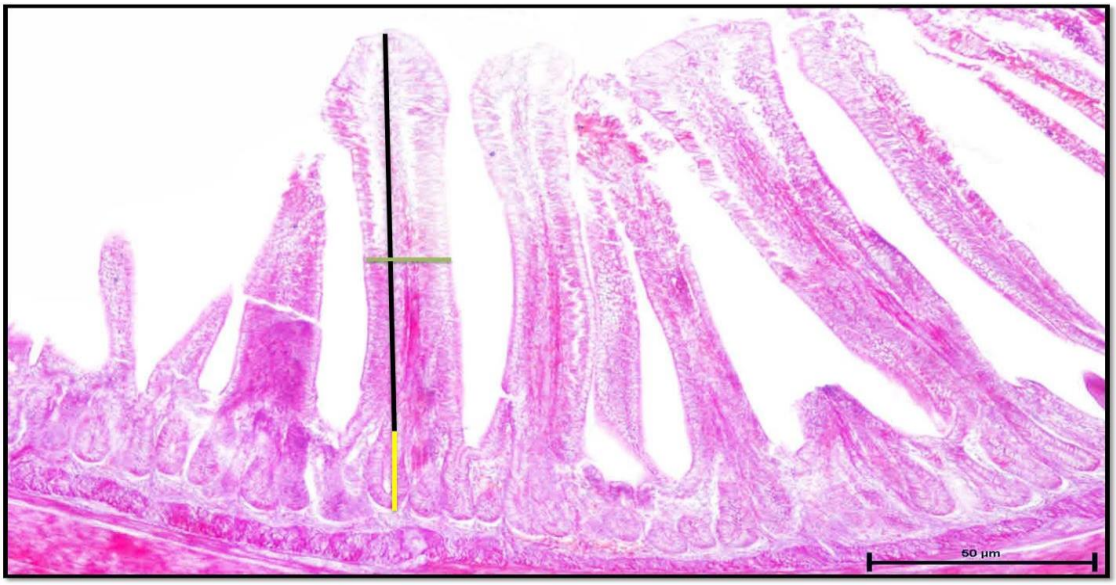


Figure 1. Histomorphological Measurement Reference Scheme. Ileal histomorphometric measurement parameters (Yellow: Crypt depth, Black: Villus height, Green: Villus width), (Ileal section, Crossmon's trichrome stain).

RESULT

Histomorphometric measurements obtained at the end of the experiment were evaluated from 10 distinct intact areas per slide to determine villus height, crypt depth, and villus width, from which total villus absorptive surface areas were calculated (Bami et al., 2022; Öztürk et al., 2026; Table 2). Examination of ileal cross-sections from all experimental groups revealed typical structural organization consisting of three primary layers extending from the lumen. The innermost layer, tunica mucosa, comprised the lamina epithelialis, lamina propria, lamina muscularis mucosae, and submucosa. The lamina epithelialis was composed of a simple columnar epithelium interspersed with goblet cells. Intestinal crypts (crypts of Lieberkühn) embedded in the connective tissue beneath the lamina epithelialis completely occupied the lamina propria in a physiologically normal pattern. Physiological levels of lymphocyte infiltration were observed in the lamina propria across all groups. Comparative microscopic evaluations revealed no pathological lesions, tissue degeneration, or structural differences among the experimental groups (Figures 2–9).

Experimental findings demonstrated that dietary supplementation with BCAAs and L-glutamine significantly influenced small intestinal villus morphology ($P < 0.05$). Statistically significant differences were identified among treatments for villus height, villus width, and absorptive surface area ($P < 0.05$); the highest villus height, width, and total absorptive surface area were recorded in the diet supplemented with 1% L-glutamine alone. While dietary addition of 20% BCAA alone restricted these

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histomorphological indices, combining 20% and 35% BCAA with 1% L-glutamine (20% BCAA + 1% G and 35% BCAA + 1% G) significantly improved villus width and surface area, placing these combinations in the highest statistical tier. Regarding main sex effects, male broilers exhibited significantly greater villus height, villus width, and surface area values than females ($P < 0.05$). Crypt depth and the villus height-to-crypt depth ratio did not differ significantly across dietary treatments or sexes ($P > 0.05$), and no significant treatment X sex interaction was detected for any of the investigated parameters ($P > 0.05$).

Figure 2a. Kontrol Grubu - MALE	Figure 2b. Kontrol Grubu - FEMALE

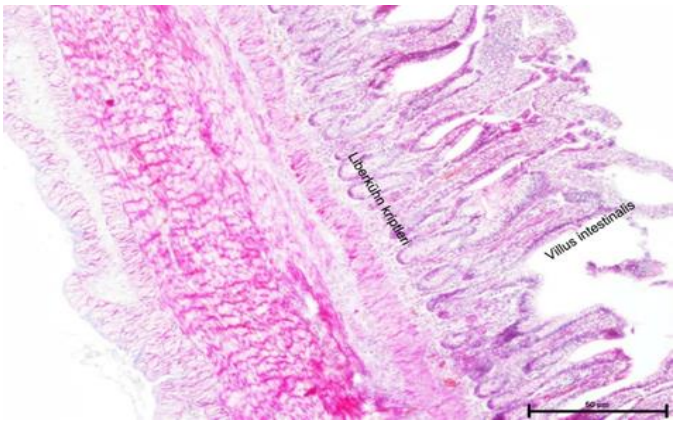


Figure 3a. %20 BCAA- MALE

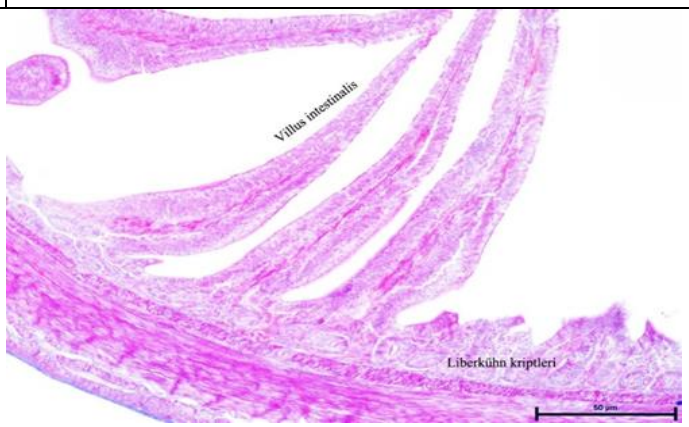


Figure 3b. %20 BCAA- FEMALE

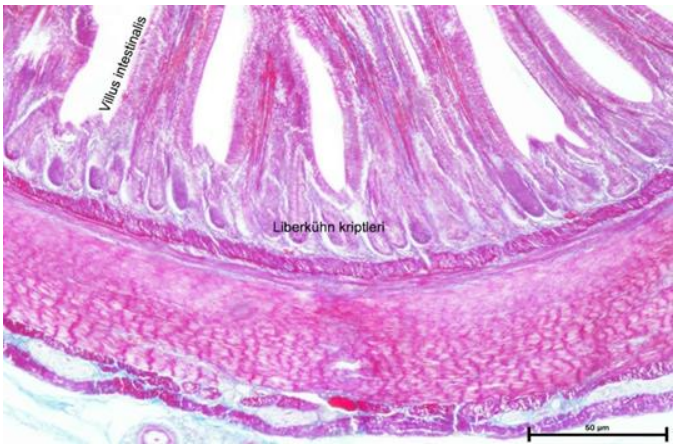


Figure 4a. %35 BCAA- MALE

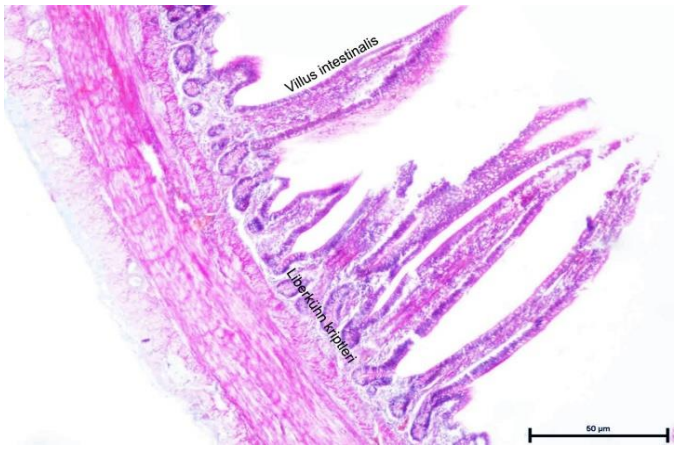


Figure4b. %35 Figure 4b. %35 BCAA- FEMALE

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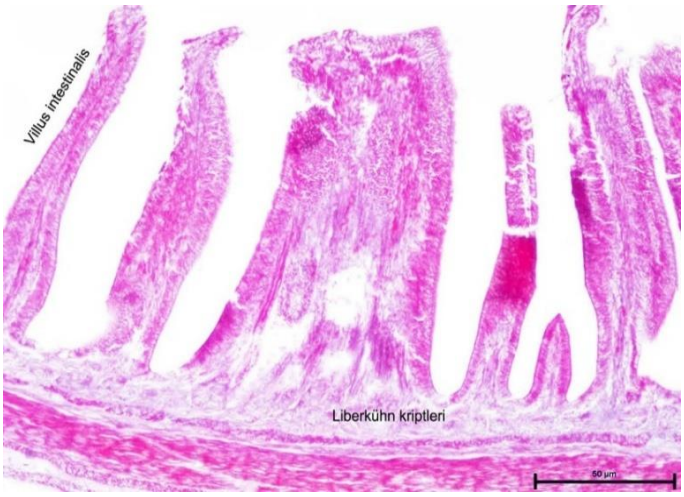


Figure 5a. %50 BCAA – MALE

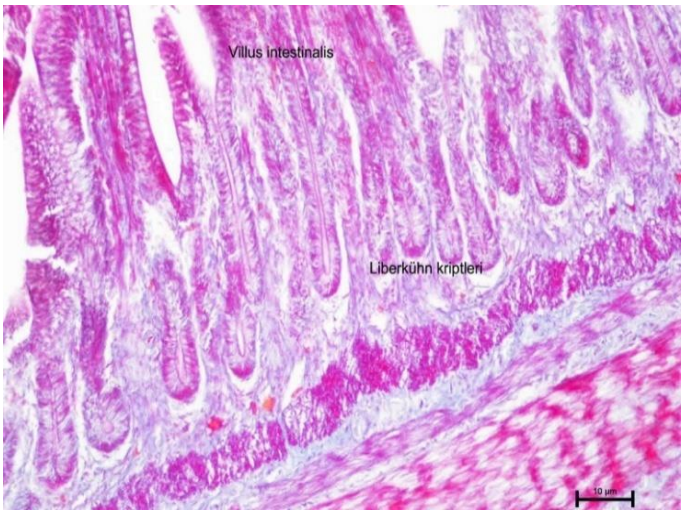


Figure 5b. %50 BCAA - FEMALE

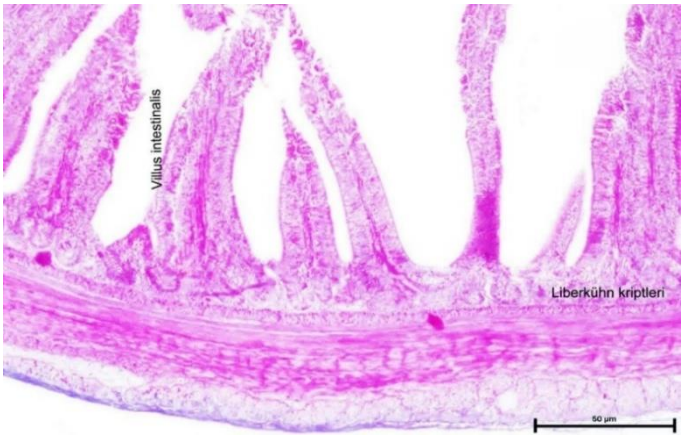


Figure 6a. %50BCAA %1 L-Glutamine - MALE



Figure 6b. %50BCAA %1 L-Glutamine - FEMALE

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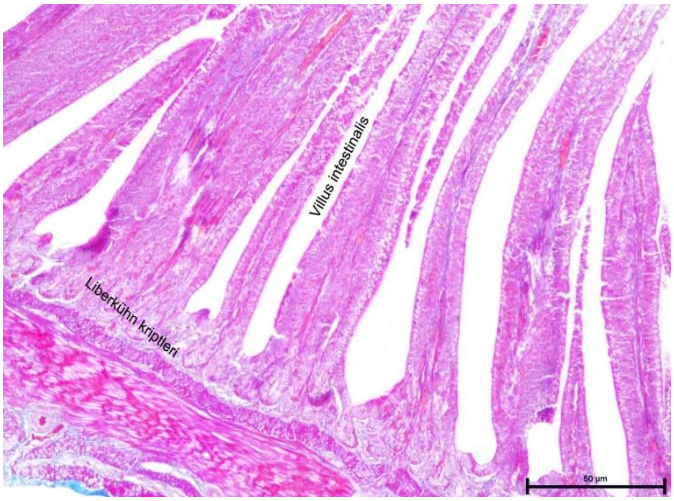


Figure 7a. %35 BCAA + %1 L-Glutamine-MALE

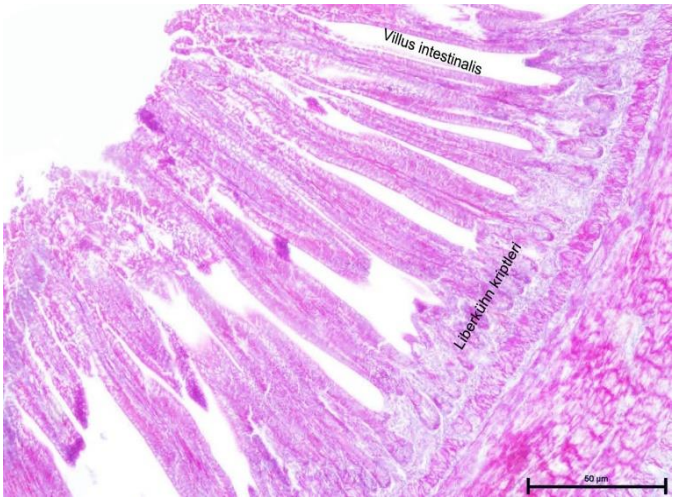


Figure 7b. %35 BCAA + %1 L-Glutamine- FEMALE

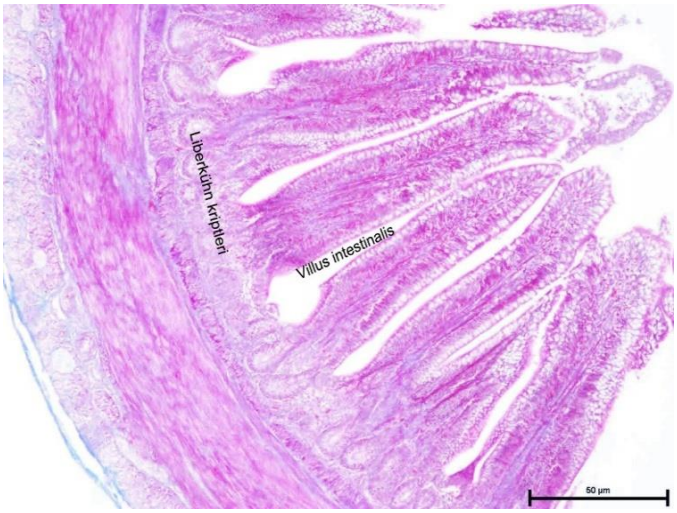


Figure 8a. %20 BCAA + %1 L-Glutamine- MALE

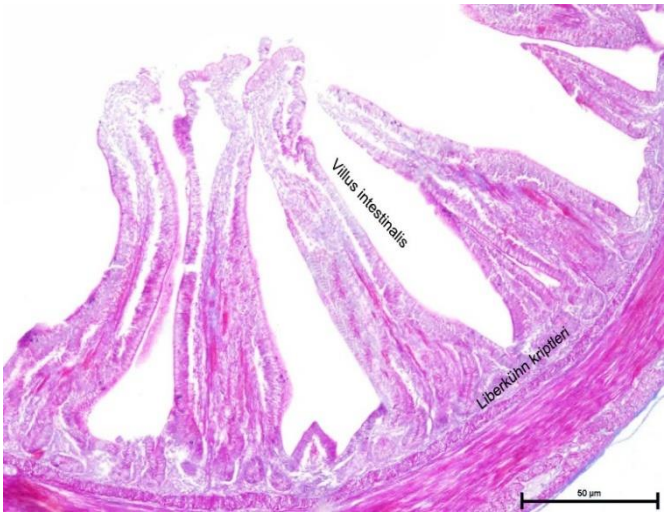


Figure 8b. %20 BCAA + %1 L-Glutamine- FEMALE

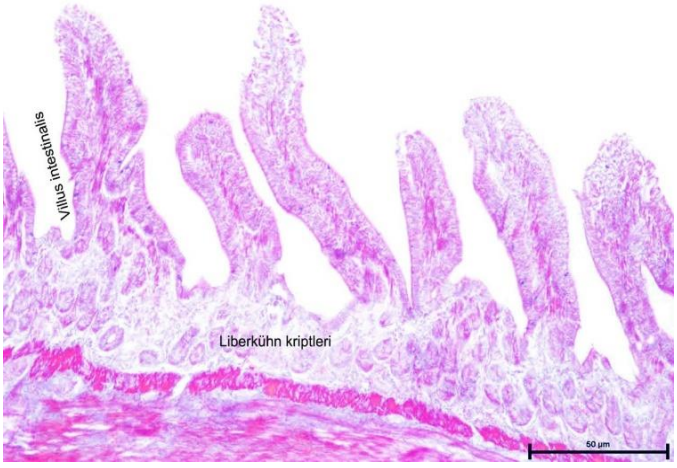


Figure 9a. %1 L-Glutamine - MALE

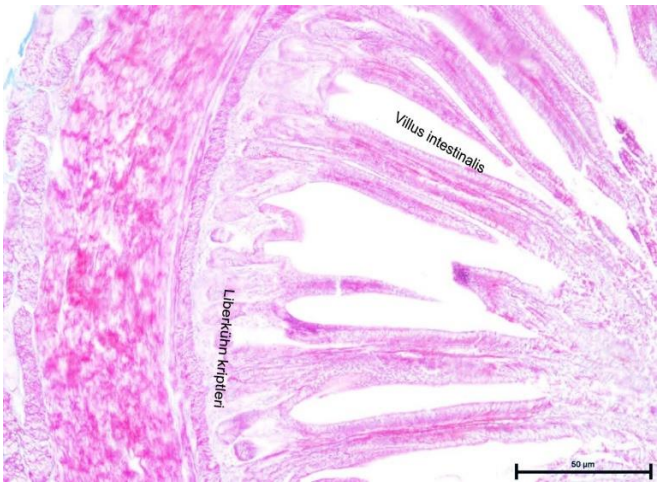


Figure 9b. %1 L-Glutamine- FEMALE

Muamele	Sex	Villus Height (µm)	Villus Width(µm)	Villus Surface Area(µm²)	Crypt Depth(µm)	Villus Height / Crypt Depth
Control	FEMALE	138,0	15,26	6656,5	30,31	4,78
	MALE	140,3	19,05	8421,4	26,89	5,72
%20 BCAA	FEMALE	134,7	16,91	7150,0	23,03	6,05
	MALE	133,9	17,65	7396,0	23,61	5,99
%35 BCAA	FEMALE	144,6	20,53	9709,4	27,07	6,08
	MALE	142,5	19,89	8795,3	31,36	4,70
%50 BCAA	FEMALE	145,0	17,30	7634,2	27,92	5,75
	MALE	153,5	21,11	10571,6	29,51	5,96
%1G	FEMALE	143,7	20,42	9042,8	28,63	5,77
	MALE	153,4	21,23	10408,0	33,95	5,15
%20 BCAA+%1G	FEMALE	141,2	19,80	8865,3	24,54	6,65
	MALE	147,3	22,27	10304,7	28,96	5,49
%35 BCAA+%1G	FEMALE	138,6	19,18	7751,5	31,03	4,55
	MALE	145,9	22,21	10931,3	23,85	7,24
%50 BCAA+%1G	FEMALE	129,4	19,26	7869,6	23,70	5,82
	MALE	142,6	19,59	8936,6	37,80	4,53
SEM		1,309	0,335	203,38	0,845	0,181
Main Effect						
Treatment		**0.048**	**0.028**	**0.024**	**0.352**	**0.835**
Control		139,7^{ab}	18,10^{ab}	7980,2^{bc}	27,75	5,48
%20 BCAA		134,3^{b}	17,28^{b}	7273,0^{c}	23,32	6,02
%35 BCAA		143,5^{ab}	20,21^{a}	9252,4^{ab}	29,22	5,39
%50 BCAA		149,2^{a}	19,21^{ab}	9102,9^{ab}	28,72	5,86
%1G		149,8^{a}	20,93^{a}	9896,1^{a}	31,95	5,39
%20 BCAA+%1G		143,5^{ab}	20,73^{a}	9405,1^{ab}	26,20	6,22
%35 BCAA+%1G		142,2^{ab}	20,69^{a}	9341,4^{ab}	27,44	5,90
%50 BCAA+%1G		136,0^{b}	19,42^{ab}	8403,1^{abc}	30,75	5,18
Sex		**0.040**	**0.010**	**<0.001**	**0.151**	**0.821**
FEMALE		139,4^{b}	18,79^{b}	8174,2^{b}	26,67	5,77
MALE		144,8^{a}	20,27^{a}	9411,9^{a}	29,49	5,60
Treatment×Sex		**0.804**	**0,591**	**0.220**	**0.108**	**0.092**

Table 2. Small intestinal villus histomorphometric parameters at 42 days of age

µm: micrometer. Measurements were taken under a 10\times objective lens. a,b,c: Means within the same column sharing common superscripts do not differ significantly (P > 0.05). SEM: Standard Error of the Mean.

DISCUSSION

In modern broiler production, rapid growth rates and associated elevations in metabolic nutrient demands render the maintenance of intestinal structural integrity and absorptive capacity essential. In small intestinal histomorphology, villus height (VH), crypt depth (CD), and the villus height-to-crypt depth ratio (VH:CD) serve as primary, well-established biomarkers for evaluating intestinal health. Increased villus height and elevated VH:CD ratios are generally associated with enhanced absorptive capacity, whereas crypt depth provides insights into enterocyte turnover and cellular renewal kinetics (Ducatelle et al., 2018). In this context, dietary supplementation with functional amino acids such as L-glutamine and branched-chain amino acids (BCAAs: leucine, isoleucine, valine), along with their combinations, plays a pivotal role in modulating intestinal mucosal development. Indeed, our findings confirmed that dietary supplementation with BCAAs and L-glutamine significantly altered villus morphology (P < 0.05). Statistically significant differences were detected across dietary treatments for villus height, villus width, and absorptive surface area, with the highest values achieved in the 1% L-glutamine supplemented group. This response can be attributed to the indispensable role of glutamine in fuel metabolism, differentiation, and mitotic proliferation of intestinal epithelial cells. Bartell and

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Batal (2007) reported that dietary addition of 10 g/kg L-glutamine from 21 days post-hatch elongated villus height and augmented humoral immune responses in broilers. Similarly, previous research demonstrated that dietary glutamine supplementation can increase villus height and the villus height-to-crypt depth ratio (Murakami et al., 2007). These outcomes indicate that glutamine supplementation directly supports the maintenance of mucosal architecture and preserves epithelial absorptive capacity. Regarding the individual effects of BCAAs, supplementing 20% BCAA alone restricted villus height and absorptive surface area in our study, whereas increasing BCAA supplementation to 50% restored villus height to maximal levels comparable to those observed in the 1% L-glutamine group. BCAAs (Leu, Ile, and Val) participate in intestinal tissue development in addition to their canonical roles as substrates for protein synthesis. In particular, leucine activates protein translation via the mTOR signaling pathway, thereby promoting mucosal development (Chang et al., 2015). Furthermore, modulating dietary BCAA levels in low-crude protein diets has been documented to exert marked impacts on small intestinal morphology (Khalilzadeh et al., 2025; Oliveira et al., 2024). A key finding of this study was that the restricted villus development observed with 20% BCAA alone was completely restored when combined with 1% L-glutamine (20% BCAA + 1% G and 35% BCAA + 1% G). These combination groups achieved significantly higher villus width and total absorptive surface area compared to the control and 20% BCAA alone groups ($P < 0.05$). This indicates that combined supplementation of BCAAs and L-glutamine may act synergistically to preserve and optimize intestinal histomorphology. BCAAs are actively involved in mucosal development and nutrient utilization, with leucine playing a prominent regulatory role in epithelial protein synthesis (Kim et al., 2022). Nonetheless, further research is warranted to fully delineate the underlying molecular mechanisms governing this synergistic interaction between BCAAs and L-glutamine. In the present study, crypt depth and the villus height-to-crypt depth ratio did not differ significantly among dietary treatments or between sexes ($P > 0.05$). The stability of crypt depth confirms that the tested amino acid concentrations maintained physiological homeostasis without inducing mucosal damage or requiring compensatory hyperplasia. Evaluating the main effect of sex revealed that male broilers possessed significantly higher villus height, villus width, and total absorptive surface area than females ($P < 0.05$). This sexual dimorphism can be explained by the higher growth trajectory, greater body weight gain, and elevated feed consumption capacity in male broilers, necessitating an expanded intestinal absorptive surface area. The lack of a significant treatment \times sex interaction ($P > 0.05$) across all evaluated parameters indicates that the stimulatory effects of BCAAs and L-glutamine on mucosal development operate through conserved biological pathways in both sexes.

CONCLUSIONS

Dietary supplementation with 1% L-glutamine alone, or combinations of 20% to 35% BCAA with 1% L-glutamine, represents an effective nutritional strategy to positively modulate intestinal histomorphology by increasing villus height, villus width, and total absorptive surface area in Anadolu-T broiler chickens. This beneficial response can be attributed to the complementary actions of glutamine in enterocyte proliferation and mucosal maintenance, coupled with the anabolic and metabolic regulatory roles of BCAAs in cellular protein synthesis.

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AİLENİN YÜKSEK ÖĞRENİM PROFİLİNİN BİREYİN YÜKSEK ÖĞRENİME KATILIMI ÜZERİNDEKİ ETKİSİ

THE IMPACT OF FAMILY'S HIGHER EDUCATION PROFILE ON AN INDIVIDUAL'S PARTICIPATION IN HIGHER EDUCATION

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ÖZET

Bu çalışma, ebeveynlerin eğitim düzeyinin bireyin akademik başarısı, okula devamlılığı, öğrenme sorumluluğu ve yükseköğretime erişimi üzerinde güçlü bir belirleyici olduğunu ortaya koymaktadır. Bourdieu'nün kültürel sermaye teorisi çerçevesinde, yüksek eğitimli ebeveynlerin çocuklarına aktardığı kültürel bilgi, dil becerileri ve eğitime bakış açısı önemli avantajlar sağlamaktadır. Araştırmalar, ebeveyn eğitim seviyesinin akademik başarıyı yordayan en güçlü değişken olduğunu ve bu etkinin aile gelirinden bile daha belirleyici olduğunu göstermektedir. Bununla birlikte, aşırı müdahaleci "helikopter ebeveynlik" tutumlarının öğrenci özerkliğini olumsuz etkileyebileceği vurgulanmaktadır. Çalışma ayrıca, üniversite deneyimi olan büyük kardeşlerin, özellikle ebeveyn desteğinin düşük olduğu durumlarda tamamlayıcı bir destek kaynağı olarak işlev görebileceğini belirtmektedir. Sonuç bölümünde, eğitimde fırsat eşitliğini artırmak için aile temelli politikaların geliştirilmesine yönelik öneriler sunulmaktadır.

Anahtar kelimeler: Üniversiteye Katılım, Yüksek Öğrenim, Ailenin Eğitim Düzeyi, Ebeveyn Destekleri.

ABSTRACT

This study reveals that parents' educational level is a strong determinant of an individual's academic achievement, school attendance, learning responsibility, and access to higher education. Within the framework of Bourdieu's theory of cultural capital, the cultural knowledge, language skills, and perspective on education that highly educated parents transmit to their children provide significant advantages. Research shows that parental education level is the strongest predictor of academic success, and this effect is even more decisive than family income. However, it is emphasized that excessively intrusive "helicopter parenting" attitudes can negatively affect student autonomy. The article also notes that older siblings with university experience can serve as a complementary source of support, particularly in situations where parental support is low. In the conclusion, recommendations are offered for developing family-based policies to enhance equality of opportunity in education.

Keywords: University Enrollment, Higher Education, Family Education Level, Parental Support.

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GİRİŞ

Aile, toplumun en küçük yapı taşı olarak nitelendirilmekle birlikte, bireyin doğumundan itibaren içinde büyüdüğü veya yaşamının önemli bir kısmını geçirdiği sosyal bir kurumdur. Bu bağlamda, bireyin doğumla başlayan yaşamı boyunca eğitilmesi zorunludur. Eğitim, insanların sosyal, duygusal, bilişsel ve benzeri alanlarda gelişimini desteklerken, hayatın her anında varlığını sürdüren bir süreçtir. Alınan eğitim, bireyin toplumsallaşmasını sağlamakla kalmaz, aynı zamanda toplum içinde bir kimlik edinmesine de katkı sunar. Bireyin ilk kez toplumsallaştığı ortam ise ailedir (Cavkaytar, 2012: 12; Mengi, 2020; 20; Akt. Kartal vd., 2024: 112).

Eğitim, yalnızca okullarda edinilen bilgilerden ibaret olmayıp, aynı zamanda aile ortamında başlayan ve yaşam boyu devam eden bir süreçtir. Bu süreçte ailenin sosyoekonomik ve kültürel özellikleri, özellikle de ebeveynlerin eğitim düzeyi, bireyin eğitim hayatını şekillendiren en önemli faktörlerden biridir.

Bireyin eğitim yaşamı, yalnızca okul içinde edindiği bilgi ve becerilerle sınırlı olmayıp, içinde yetiştiği aile ortamının sağladığı imkânlarla da yakından ilişkilidir. Ailenin eğitim düzeyi, ekonomik durumu, kültürel birikimi ve çocuğun öğrenme sürecine yönelik tutumları, bireyin akademik başarısını ve eğitim kariyerini şekillendiren en temel faktörler arasında yer almaktadır. Özellikle anne ve babanın yüksek öğrenim profili, çocuklara erken yaşlardan itibaren sunulan uyarıcı zenginliği, evdeki eğitim desteği, akademik beklentiler ve rol model olma açısından belirleyici bir rol oynamaktadır.

Smits ve Hoşgör (2006), Türkiye'de çocukların ilkokul ve ortaokula devam durumları üzerinde aile arka planının etkilerini geniş ve temsili veri setleriyle incelemektedir. Araştırmada, özellikle kız çocuklarının eğitime katılımının hâlâ ciddi bir sorun olduğu, okula kayıtlı olmama oranının ise özellikle kırsal bölgelerde ve ülkenin doğusunda yüksek seyrettiği belirlenmiştir. Ebeveyn eğitimi, kardeş sayısı, hane geliri, babanın mesleği, annenin geleneksel tutumları ve annenin Türkçe konuşabilme becerisi, eğitime katılımı etkileyen temel faktörlerdir. Kız çocuklarının ilkokula devamı açısından en belirleyici etmen, annenin ilkokul mezunu olması ve Türkçe konuşabilmesidir. Annenin geleneksel cinsiyet rolleriyle ilgili tutumları ise kız çocuğunun ortaokula devam etme olasılığını düşürmektedir. Erkek çocuklarının eğitime katılımında ise hane halkının ekonomik durumu öne çıkmaktadır. Bulgular, okul dışında kalan çocukların annelerinin bu süreçte kilit bir role sahip olduğunu ortaya koymaktadır. Çoğunluğu okuma yazma bilmeyen ve geleneksel değerlere sahip kadınlardan oluşan bu kitleye ulaşmak, durumu iyileştirmek isteyen politika yapıcılar için büyük bir engel teşkil etmektedir. (Jeroen Smits ve Ayşe Gündüz Hoşgör, 2006)

Ailenin yüksek öğrenim profili, bireyin eğitim hayatı üzerinde çok yönlü ve güçlü bir etkiye sahiptir. Kültürel sermaye aktarımından akademik desteğe, kariyer rehberliğinden motivasyon ve rol model olmaya kadar birçok mekanizma aracılığıyla, bireyin okul başarısını, eğitim beklentilerini ve yüksek öğrenime devam etme olasılığını artırır.

Bu çalışmada, ailenin yüksek öğrenim profilinin bireyin eğitim sürecine olan etkileri çeşitli boyutlarıyla ele alınmaktadır. Öncelikle ebeveynlerin öğrenim düzeyinin çocukların akademik başarısı, okula devamlılığı, öğrenme sorumluluğu geliştirmesi ve üst öğretim kurumlarına erişimi üzerindeki etkileri incelenmektedir. Ayrıca, yüksek öğrenim görmüş ebeveynlerin çocuklarına sağladığı sosyal, kültürel ve ekonomik avantajlar ile bu avantajların eğitimde fırsat eşitliği bağlamında doğurduğu sonuçlar tartışılmaktadır. Çalışma, alanyazındaki araştırma bulgularından hareketle, ailenin yüksek öğrenim profilinin bireyin eğitim hayatını destekleyici yönlerine odaklanmakta ve bu etkinin sürdürülebilir kılınmasına yönelik öneriler sunmaktadır.

Bu doğrultuda çalışama, öncelikle aile faktörünün eğitim üzerindeki kuramsal temellerini, ardından ebeveyn öğrenim düzeyinin çocuk başarısına yansımalarını ve son olarak eğitim politikalarına yönelik çıkarımları ele alarak konuyu bütünlüklü bir perspektifle değerlendirmeyi amaçlamaktadır.

Bu çalışmada, ailenin yüksek öğrenim profilinin (anne ve babanın üniversite mezunu olması veya yüksek lisans/doktora yapmış olması) bireyin eğitim sürecine, akademik başarısına, kariyer hedeflerine ve eğitimsel beklentilerine olan etkileri, sosyolojik ve psikolojik teoriler ışığında incelenecektir.

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1. TÜRKİYE'DE OKULLAŞMA ORANLARI

Türkiye'de bundan 20 yıl önce okuma yazma bilmeyenlerin oranı, yükseköğretim mezunlarınınkinden daha fazla iken, bugün ise bu tablo tamamen tersine dönmüş durumdadır. Son 15 yılda eğitim düzeyinde dikkat çekici bir dönüşüm yaşanmıştır. 2008'de 25 yaş üstü nüfusun yaklaşık beşte biri herhangi bir okul bitirmemişti ve Yükseköğretim mezunlarının payı ise sadece %10 dolaylarındaydı. 2024'e gelindiğinde, okuma yazma bilmeyenlerin oranı %12,2'den %3'e inerken, yükseköğretim mezunlarının oranı %25,2'ye çıkmıştır. Bununla birlikte, hâlâ nüfusun yarısından fazlası lise altı eğitim seviyesindedir. Bu durum, yıllarca eğitime erişimin kısıtlı oluşunun ve yükseköğretimin yaygınlaşmasında geç kalınmış olmanın toplumsal yapıdaki kalıcı izlerini gözler önüne sermektedir. 1970'ten günümüze uzanan süreçte küresel brüt okullaşma oranları incelendiğinde, Türkiye'nin yükseköğretime katılım düzeyinin 1990'lı yıllara dek dünya ortalamasının gerisinde kaldığı gözlenmektedir. Bu bağlamda, iktisadi kalkınmışlık, ileri teknoloji üretimi ve inovasyon kapasitesi gibi boyutlarda sıklıkla Türkiye ile mukayese edilen Güney Kore örneği önemli bir karşılaştırma noktası sunmaktadır. 1970'lerde yükseköğretimdeki katılım oranları bakımından Türkiye ile hemen hemen aynı düzeyde bulunan Kore, 1980'li yıllarda belirgin bir atılım gerçekleştirmiş; buna karşılık Türkiye'de benzer bir sıçrayış yaklaşık 20-25 yıl sonra ortaya çıkmıştır. Türkiye'deki asıl ivmelenme 2000'li yılların başında başlamış, özellikle 2008 sonrasında yükseköğretimin yaygınlaşarak hızlı bir kitleselleşme sürecine girdiği görülmektedir. Bu kitleselleşme eğilimi nicel verilere açık biçimde yansımaktadır. 2001/02 öğretim yılında %23,4 olan brüt okullaşma oranı, 2024/25 itibarıyla %100,6 düzeyine ulaşmıştır. Bununla birlikte, brüt okullaşma oranının sisteme kayıtlı tüm yaş gruplarındaki öğrencileri kapsaması nedeniyle, ikinci üniversite ve açıköğretim gibi uygulamaların etkisiyle bu oranın %100'ün üzerinde gerçekleşebileceğini belirtmek gerekir. Yalnızca 18-22 yaş aralığını dikkate alan net okullaşma oranı ise %46,3 olup bu değer, küresel eğilimlerle paralellik arz etmektedir. Türkiye'de sıklıkla dile getirilen "aşırı üniversitelileşme" ve "fazla sayıda mezun" tartışmalarının, mevcut veriler ışığında yeniden değerlendirilmesi gerekmektedir. Niceliksel göstergeler, Türkiye'nin küresel ölçütlerle uyumlu bir okullaşma ve mezuniyet düzeyine eriştiğini ortaya koymaktadır. Hâlihazırda genç nüfus içinde yükseköğretim mezunu olanların oranı OECD ortalamasında %47 iken Türkiye'de bu oran %43'tür. Bu noktada asıl tartışılması gereken konu, eğitimin niteliği ile eğitim-istihdam uyumudur. Genel tablo içinde eğitim düzeyindeki artış, toplumsal yapıyı dönüştüren en önemli dinamiklerden biri olarak ele alınmalıdır. 2008 yılında 70 milyonun üzerinde nüfusa sahip bir ülkenin kaydettiği bu hızlı ilerleme; evlilik yaşının yükselmesi, doğurganlık oranlarındaki düşüş, hanehalkı yapısındaki değişim, kadınların işgücüne katılımı, kentleşme süreci ile toplumsal norm, değer ve rollerin dönüşümü gibi olguların zeminini oluşturmaktadır. Bu sebeple, söz konusu toplumsal dönüşümleri anlamlandırırken eğitim düzeyindeki değişimin göz ardı edilmemesi gerekmektedir (Koru, 2026).

Türkiye'de okullaşma oranının ve üniversite mezunu sayılarının artmasında ailelerin önemi yadsınamaz. Dolayısıyla, çalışmamızda öncelikle aile kavramına yer verilmiş, yüksek öğrenime katılımda ailenin rolü ve katkıları aşağıda incelenmeye çalışılmıştır.

2. AİLE VE EBEVEYN KAVRAMLARI

Aile kavramı, birçok disiplin tarafından ele alındığından farklı tanımları bulunmaktadır. Psikolojik açıdan aile, yasal zorunluluk hissetmeksizin, ölmüş bireyler de dâhil olmak üzere birbirine duygusal, zihinsel ve davranışsal olarak bağlanmış gruptur (akt. Güler ve diğ., 2012, s.17). Türk Dil Kurumu'na göre aile, evlilik ve kan bağına dayanan en küçük topluluk, aynı soydan gelenler, birlikte oturan yakınlar, eş ya da ortak amaç için çalışanların bütünüdür. En yaygın tanımıyla aile anne, baba ve en az bir çocuktan oluşur. Yapı, işlev ve ihtiyaçlar bakımından farklılık gösteren ailenin işlevleri, üyelerin ve birimin ihtiyaçlarını karşılamaya yöneliktir. Murdock'a göre ailenin evrensel dört işlevi cinsel, ekonomik, eğitimsel ve çoğalmadır. Parsons'a göre ise temel işlevler çocukların sosyalleşmesi ve yetişkinlerin kişilik dengesini korumasıdır. Aile, üyelerine güven, aidiyet duygusu, güvenli gelişim ortamı ve sosyalleşme imkânı sağlar. Özellikle çocuğun eğitimi ve gelişiminde ailenin görevleri; temel ve duygusal ihtiyaçların karşılanması, koruma, sosyalleştirme ve kültürlemedir (Battal, 2021: 26-27).

"Aile" ve "ebeveyn" kavramları, özellikle çocuğun akademik tutumu ve öğrenme sorumluluğu bağlamında birbirini tamamlayan ancak farklı düzeylerde etkiye sahip iki temel kavramdır. "Aile", çocuğun doğduğu andan itibaren içinde bulunduğu ilk ve en etkili sosyal çevredir. Sadece anne, baba ve

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çocuklardan oluşan bir yapı değil; aynı zamanda çocuğun değerlerini, tutumlarını, alışkanlıklarını ve dünyaya bakış açısını şekillendiren bir kültür aktarım ortamıdır. “Ebeveyn (anne ve baba)”, aile kurumunun en aktif ve uygulayıcı özneleridir. Ailenin soyut etkisini, somut davranışlara, tutumlara ve günlük eylemlere dönüştüren kişilerdir. Ebeveynler, ailenin "nasıl" yapıldığını gösteren aktörlerdir.

Dam (2008: 81)'e göre, çocukluk ve gençlik döneminde kişilik hızla şekillenir ve bu süreçte ailenin tutumu, çocuğun hem akademik hem de gelecekteki yaşam başarısını doğrudan etkiler. Aile, çocuğun sosyal normları, kuralları ve beklentileri öğrendiği ilk yerdir.

Ailenin eğitime ve öğrenmeye bakışı, çocuğun okula karşı geliştireceği tutumun temelini oluşturur. Şeker (2013)'in belirttiği gibi, destekleyici bir aile çocuğu başarıya motive ederken, gerçekçi olmayan beklentilerle baskı kuran aile ise başarısızlık korkusuna neden olur.

Steinberg vd. (1992), Fan ve Chen (2001) ile Zhao ve Hong (2012)'nin çalışmalarında vurgulandığı gibi, ebeveynlerin ödev kontrolü, okul koşullarını tartışma gibi “davranışsal destekleri”, çocuğun iyi çalışma alışkanlıkları kazanmasını ve akademik performansını doğrudan etkiler.

Ebeveynlerin eğitim düzeyi, gençlere yönelik tutumlarını etkilediği için anne-baba-çocuk arasındaki ilişkilerin niteliğini belirleyen önemli bir faktördür. Aydoğdu ve Dilekmen’e (2016) göre eğitim durumu, çocuk yetiştirme anlayışından çocuğa nasıl davranılacağına kadar ebeveyn-çocuk ilişkilerinde belirleyici rol oynamaktadır (Akt. Paslı ve Ziyalar, 2022: 358). Ayrıca ebeveyn ile çocuğun eğitim seviyeleri arasındaki farklılıklar, dünyayı algılama biçimlerini ve karşılıklı konuşma konularının kapsamını şekillendirerek anne-baba ilişkilerinde de belirleyici bir konumda yer almaktadır (Paslı ve Ziyalar, 2022: 358).

Özer ve Suna'nın (2023) yaptığı araştırma, ebeveynlerin eğitim seviyesinin akademik başarıyı öngören en güçlü değişken olduğunu ve bu etkinin aile gelirinden bile daha belirleyici olduğunu göstermiştir.

Özdemir (2018), yükseköğretim kitleselleşse bile, bireyin üniversite mezunu olmasında “cinsiyet, anne eğitimi ve baba eğitimi” değişkenlerinin hâlâ anlamlı etkisi olduğunu göstermektedir. Örneğin, lojistik regresyon analizine göre, kadınların üniversite derecesine erişme şansı erkeklerin yarısı kadardır.

Ulukuz, (2023) tarafından yapılan çalışmada; ebeveynlerin eğitim durumunun, özellikle kız çocuklarının üniversiteyi tamamlama olasılığı üzerindeki etkisini incelenmiştir. Annenin ve babanın eğitim düzeyinin etkisinin benzer olduğunu, ancak zaman içinde annenin lise mezunu olmasının etkisinin azaldığını (üniversiteye erişimin kolaylaşması nedeniyle) ortaya çıkarılmıştır.

Özdemir (2018), yükseköğretimin kitleselleşmesine rağmen bireyin üniversite mezunu olmasında cinsiyet, anne eğitimi ve baba eğitiminin hâlâ anlamlı etkisi olduğunu göstermektedir. Yapılan analizler, üniversite derecesine erişimde cinsiyet (kadınların şansı erkeklerin yarısı kadardır), ebeveyn mesleki statüsü, anne-baba eğitim düzeyi ve kuşak değişkenlerinin önemini koruduğunu göstermektedir (Özdemir, 2018: 545-548).

Aile, çocuğun akademik yolculuğunun “bağlamını” (kültür, ekonomik durum, beklentiler) oluştururken; ebeveynler bu bağlam içinde çocuğa “doğrudan müdahale eden, destekleyen veya engelleyen aktif öznelerdir”. Her ikisi de ayrılmaz bir bütündür, ancak ebeveynlerin eğitim düzeyi, desteği ve tutumu, aile etkisinin en somut ve değiştirilebilir parçasını oluşturur. Bu nedenle araştırmalar, müdahalelerin genellikle ebeveynlere yönelik olmasını önermektedir.

2.1. Ebeveyn Katılımının Tanımı ve Kapsamı

Ebeveyn katılımı, çocuğun eğitim süreci ve gelişim alanlarında (okul, sosyal çevre, ev ortamı gibi) anne ve babanın aktif rol üstlenmesi, çocuğun öğrenme deneyimlerine doğrudan veya dolaylı yolla destek sağlamasıdır. Bu katılım; okul etkinliklerine katılmaktan, evde öğrenme ortamı hazırlamaya; öğretmenle düzenli iletişim kurmaktan, çocuğun ilgi ve ihtiyaçlarına duyarlı olmaya kadar geniş bir yelpazeyi kapsar. Temel amacı, çocuğun akademik başarısını, sosyal-duygusal gelişimini ve okula aidiyet duygusunu olumlu yönde desteklemektir.

Eğitim dendiğinde akla ilk olarak okullar, öğretmenler, ders kitapları ve müfredatlar gelmektedir. Oysa eğitim, okul duvarlarıyla sınırlı olmayan, yaşam boyu devam eden bir süreçtir ve bu sürecin en kritik

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basamağı aile ortamında atılır. Tezel Şahin ve Özbey'in (2007) ifade ettiği gibi, "erken çocukluk dönemi boyunca çocuk en çok aile ortamı içerisindedir" ve "ailede alınan eğitim ileriki yıllara temel teşkil etmektedir". Bu tespit, ailenin eğitimdeki belirleyici rolünü açıkça ortaya koymaktadır.

Literatürde ebeveyn katılımı, genellikle ebeveynlerin çocuklarının eğitim sürecine aktif olarak dahil olma düzeyi olarak tanımlanmaktadır. Bu katılım, yalnızca akademik konularda yardım etmekle sınırlı olmayıp, duygusal destek sağlama, finansal yardım, kariyer rehberliği ve üniversite ile iletişim kurma gibi çok boyutlu faaliyetleri içermektedir. Araştırmalar, ebeveyn katılımının akademik başarının en iyi göstergelerinden biri olduğunu ve hatta "algılanan" ebeveyn katılımının bile akademik performansı olumlu etkilediğini göstermektedir.

Nalule (2024) tarafından yapılan bir çalışmada, öğrenciler üniversiteye geçiş yaptıkça ailenin doğrudan akademik katılımının azaldığı, ancak duygusal ve finansal desteğin öğrencilerin motivasyonunu artırmada ve streslerini azaltmada kritik bir rol oynamaya devam ettiği ifade edilmiştir. Benzer şekilde, Fyfe (2024) tarafından lisans öğrencileriyle yapılan fenomenolojik bir çalışmada, öğrenciler akademik başarılarına en çok katkıda bulunan faktörler olarak ebeveyn katılımı, desteği ve teşvikini doğrudan işaret etmişlerdir.

Aile yapısı, öğrenci başarısını psikolojik faktörler kadar güçlü etkiler. Ebeveynlerin eğitim seviyesi arttıkça, çocukların akademik olarak daha başarılı olduğu ve başarısız çocukların çoğunlukla daha düşük eğitim seviyesine sahip ailelerin çocukları olduğu görülmektedir. Ayrıca ailenin sosyal yapısı, büyüklüğü, kuşaklar arası birlikte yaşama durumu, evde kullanılan dil, ebeveyn-çocuk iletişimi ve aile ortamı gibi faktörler de çocukların eğitimini etkilemektedir. Bununla birlikte çalışan baba, çocuklarını doğrudan denetlemek yerine onlar hakkında bilgiyi anneye dayanarak edinmektedir (Şahin, 2023: 3199).

Belirtmek gerekir ki, ebeveynlerin eğitim fırsatları hakkındaki mevcut bilgileri ve bu fırsatlarla başa çıkma becerileri de belirleyicidir. Çocuklar için daha uzun eğitim süreçleri, aile açısından daha yüksek maliyetler getirir. Bunun yanı sıra, ebeveynler çocuklarının belirli bir eğitim seçeneğinde başarılı olma ihtimalini de değerlendirir. Eğer ebeveynler, çocuklarının en az kendileriyle aynı eğitim seviyesine ulaşamaması durumunda statü kaybı yaşayacaklarını öngörüyorlarsa, daha uzun bir eğitim hayatının getirisi onlara daha büyük görünmektedir (Nauck & Lotter, 2016; Meulemann, 1985; Akt. Kuhnt, 2017: 235).

2.1.1. Üniversite Öğrencileri ve Ebeveyn Katılımının Kritik Rolü

Günümüz yükseköğretim sisteminde, öğrencilerin üniversite başarısını etkileyen faktörlerin başında akademik hazır bulunuşluk gelmekle birlikte, akademik olmayan faktörler de en az bunlar kadar belirleyicidir. Aile geçmişi, ebeveynlerin eğitim düzeyi ve gelir durumu, demografik özellikler ile algılanan akademik ve sosyal destek, öğrencilerin eğitsel çıktılarını şekillendiren önemli değişkenler arasında yer almaktadır. Bu faktörler içerisinde, ebeveyn katılımı, üzerinde çalışılabilecek ve geliştirilebilecek en önemli araçlardan biri olarak öne çıkmaktadır.

Hayattaki zorluklar arasında belki de en önemlisi üniversiteye başlama sürecidir. Bu süreç, hem öğrencilerin içinde bulunduğu gelişimsel dönem (çoğunlukla çocukluktan yetişkinliğe geçiş evresi) hem de üniversite yaşamının kendine has özellikleri nedeniyle ayrı bir önem taşır. Bu döneme özgü sorunların yanı sıra; aileden ayrılma, maddi koşullar ve yeni bir sosyal çevreye uyum sağlama gibi pek çok yenilik ve güçlükle de baş etmek zorunda kalırlar (Sayım, 2022: 34).

Ebeveyn katılımının etkisi, özellikle ailesinde üniversite eğitimi almamış bireyler bulunan "birinci kuşak" öğrenciler söz konusu olduğunda daha da belirginleşmektedir. Ebeveynleri üniversite mezunu olan çocukların üniversiteden mezun olma olasılıkları daha yüksekken, birinci kuşak öğrencilerin üniversiteye gitme olasılıkları daha düşüktür ve eğer giderlerse de terk etme olasılıkları akranlarına kıyasla çok daha fazladır.

Bu durumun temelinde, ebeveynlerin sahip olduğu "eğitsel kültürel sermaye" farkı yatmaktadır. Orta ve üst sosyo-ekonomik düzeydeki ebeveynler, üniversite sistemini tanıma, bürokratik işlemleri takip etme ve akademik zorluklarla başa çıkma stratejileri konusunda birikime sahipken, üniversite deneyimi olmayan ebeveynler bu bilgi ve sermayeden yoksundur. Bu ebeveynler çocuklarının başarılı olmasını

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içtenlikle isteseler de üniversite kültürünü anlamama, maddi yardım olanaklarını bilmeme ve uygun destek mekanizmalarına erişimde zorluk yaşama gibi engellerle karşılaşmaktadırlar.

Wang, Cheatham-Hemphill ve Harrington (2025) tarafından Delaware Eyalet Üniversitesi'nde yürütülen "Parent University" programı bu noktada önemli bir müdahale örneği sunmaktadır. Bu programda, birinci sınıf öğrencilerinin ebeveynlerine yönelik bir yıllık bir iletişim planı geliştirilmiş; ebeveynlerin eğitsel kültürel sermayelerini artırmak ve destekleyici bir çevre oluşturmak hedeflenmiştir. Programın sonuçları, ebeveynlerin edindikleri bilgilerden fayda sağladığını göstermiştir.

Ebeveynlerin çocuklarının eğitimine katılımı, öğrencilerin akademik başarısı üzerinde derin ve geniş kapsamlı etkilere sahiptir. Araştırmalar, aktif ebeveyn katılımının öğrencilerin daha başarılı olması, öğrenmeye karşı olumlu tutum geliştirmesi ve gerekli becerileri kazanmasıyla ilişkili olduğunu göstermektedir. Daha iyi notlar, yüksek motivasyon ve devamlılık gibi olumlu sonuçlar, ebeveyn katılımının eğitim sürecindeki kritik rolünü ortaya koymaktadır. Bu etkiler sınıfla sınırlı kalmayıp uzun vadeli eğitim ve kariyer başarısını da kapsamaktadır. Bu nedenle eğitimcilerin, politika yapıcıların ve toplulukların ebeveyn katılımını teşvik etmesi öncelikli olmalıdır. Ev ile okul arasında köprü kuran bu iş birliği, iletişim ve karşılıklı desteği güçlendirerek öğrencilerin değerli ve motive hissettiği destekleyici bir öğrenme ortamı oluşturur. Ayrıca okulda topluluk bilincini artırarak ortak sorumluluk kültürünü besler. Ebeveynlerin katkılarını tanıyan okullar, öğrencilerin akademik, sosyo-duygusal ve yaşam boyu öğrenme başarısı için sağlam bir temel oluşturabilir. Bu yüzden ebeveyn katılımını artıracak yenilikçi yaklaşımları geliştirmek, eğitimde eşitlik ve mükemmellik için hayati önem taşımaktadır (Sharma, 2024: 46).

Analizler, annenin eğitim düzeyi ile özellikle kız öğrencilerin kişilik yapısı arasında anlamlı bir ilişki olduğunu göstermiştir. Annenin eğitimi yükseldikçe, kız çocuklarının kişilik gelişimi olumlu yönde etkilenmektedir (Yeşilyaprak, 1993: 7).

Ailelerin ekonomik, sosyal ve kültürel özellikleri, bireylerin eğitim sürecindeki maddi kaynaklarını, ek materyallere erişimini ve anne-babanın okula ilgi ve desteğini etkilemektedir. Bu faktörler hem öğrencilerin akademik başarısı hem de üniversite sonrası kazançları açısından belirleyicidir. Denizli'de 2012'de mezun olan öğrencilerle yapılan anket verileriyle, aile özelliklerinin YGS başarısına etkisi sayısal ve eşit ağırlık puan türlerinde ikili lojistik regresyonla analiz edilmiştir. Sonuçlara göre, sayısal puanda evdeki kitap sayısı, cep telefonu sahipliği ve dershane en etkili değişkenlerdir; eşit ağırlıkta ise en büyük etki dershaneye aittir. Sayısal puanda annenin eğitim düzeyindeki artış, babanınkinden daha güçlü bir başarı artışı sağlarken, eşit ağırlıkta yalnızca babanın eğitim düzeyindeki artış anlamlıdır. Aynı değişkenlerle yapılan analizde, sayısal öğrencilerde anlamlı değişken sayısının daha fazla olması, ailenin sosyoekonomik donanımının özellikle sayısal başarıda daha belirleyici olduğunu göstermektedir. Son on yılda Türkiye'de üniversite ve kontenjan sayıları hızla artmış, ancak yeni bölümler çoğunlukla ücretlerin daha düşük olduğu sosyal bilimler alanında açılmıştır. Bu durum, üniversiteli işgücü arasındaki ücret eşitsizliklerinin diğer eğitim düzeylerine göre daha hızlı artmasının nedenleri arasında sayılmaktadır (Tansel ve Bircan Bodur, 2012).

Anne-babasının eğitim ve gelir seviyesi düşük olan, eğitim hayatlarında yeterli ilgi ve desteği göremeyen öğrencilerin, üniversite sonrası kazançları nispeten yüksek ancak kontenjanları dar ve puanları yüksek olan tıp, mühendislik, diş hekimliği ve hukuk gibi bölümleri kazanma ihtimalleri daha düşüktür. Bu durum, Denizli'de bu bölümlere en fazla öğrenci gönderen dört başarılı lisedeki ebeveynlerin eğitim düzeylerinin (yaklaşık %55-70'i üniversite mezunu) ve gelirlerinin belirgin şekilde yüksek olmasıyla da desteklenmektedir. Bu nedenle, devlet sosyoekonomik düzeyi düşük ailelere, onların yaşadığı bölgelerdeki ilköğretim öğrencilerine, öğretmenlere ve okullara yönelik politikalar geliştirmedikçe, eğitim başarısını artırmak ve gelir eşitsizliklerini gidermek için kalıcı çözümler üretmek zorlaşacaktır. Bu bağlamda devlet, düşük gelirli ailelerin yoğun olduğu okullardaki öğretmenlere, öğrenci başarısına katkıları ölçüsünde maddi teşvikler sağlayabilir. Ayrıca öğretmenlerin, bu okullardaki öğrencilerin ders saatleri dışında da okulda vakit geçirebileceği eğitici ve sosyal programlar geliştirmesi desteklenmelidir. Bu tür programlar, düşük gelirli ailelerin çevresel olumsuzluklarının etkisini azaltmada önemli rol oynayabilir. Okul yönetimleri ve öğretmenler, öğrencilerin akademik ve sosyal gelişimlerinin izlenmesi için velilerle etkin koordinasyon kurmaya teşvik edilmelidir (Çiftçi ve Çağlar, 2014: 167-168).

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Öğrencinin başarısında ve üniversiteye girişinde etkili olan diğer bir unsur ise öğrencilerin öğrenme sorumluluğudur. Öğrenme sorumluluğu, öğrencinin kendi görevlerini fark etmesiyle ilgili bir kavramdır. Kolan'a (2020) göre bu sorumluluk; öğrencinin akademik başarısından kendini sorumlu hissetmesi, aktif öğrenme sürecine katılması, derslere hazırlıklı gelmesi, ödevlerini zamanında yapması ve hedeflerine ulaşmak için plan yapıp uygulamasıdır. Yakar ve Saracaloğlu (2017) ise bunu, bireyin eksiklerini tamamlama ve hedefe ulaşma yolunda hissettiği duygu olarak tanımlar. Temel eğitimin işlevlerinden biri, öğrenciye bu bilinci kazandırmaktır. Öğrenme sorumluluğunu geliştiren dış kaynaklar (aile, kültür, öğretmen, akran vb.) ve iç kaynaklar (öz saygı, öz düzenleme, ideal vb.) vardır. Allan'a (2006) göre bu kavramın altı boyutu bulunur: okula ve öğrenmeye yönelim, aktif katılım, özerklik, inisiyatif alma, kaynakları kontrol etme ve sınıf içi iş birliği. Öğüt vermek yeterli olmayıp okullarda eğitim verilmelidir. Öğrenme sorumluluğu akademik başarıyı artırır, istenmeyen davranışları azaltır, eğitim kalitesini yükseltir ve öz denetimle öz düzenlemeyi geliştirir. Bu sorumluluğa sahip öğrenci, öğrenmeye adanmış, engelleri aşmaya çalışan ve elinden gelenin en iyisini yapan kişidir Allan'a (2006) göre böyle bir öğrenci, öğrenmeyi hemen ister, en iyisini dener, okul başarısının gelecekte önemli olduğuna inanır ve zor görevleri tercih eder. Demokratikleşen eğitim ortamlarında öğrenci daha fazla sorumluluk üstlenir. Sosyobilişsel kuramlar, öğrencinin kendi öğrenmesinde etkili olduğunu vurgulamakla birlikte dış kaynakların da etkisini kabul eder. Öz düzenleme becerisine sahip öğrenci, duygu ve düşüncelerini denetleyerek sorumluluklarını yerine getirir (Kolan, 2020:34; Yeşil, 2013: 1217-1215; Yakar ve Saracaloğlu, 2017: 28; Allan, 2006: 92,93; Şekerci, 2020; Bacon, 1993: 202; Cook-Sather ve Luz, 2015: 1100; Corno, 1992; Zimmerman ve Schunk, 1989; Akt. Sontur vd., 2021: 302-303).

2.1.2. "Helikopter Ebeveynlik" ve Aşırı Katılımın Olumsuz Etkileri

Her ne kadar ebeveyn katılımı genellikle faydalı görülse de literatürde son yıllarda artan bir tartışma konusu, katılımın dozajı ile ilgilidir. Aşırı müdahaleci ve kontrolcü ebeveyn tutumu, "helikopter ebeveynlik" olarak tanımlanmakta ve bu durumun öğrencilerin özerkliklerini kısıtlayarak gelişimlerini engelleyebileceği belirtilmektedir. Bu tür bir aşırı katılım, öğrencinin kendi problemlerini çözme becerisini köreltebileceği gibi, üniversitede öğrenim gördüğü fakültesi ve idaresi ile yaşanabilecek çatışmaları da beraberinde getirebilmektedir. Bu olumsuz etkiler nedeniyle, bazı üniversitelerin ebeveynlerin müdahalesini sınırlandırma yoluna gittiği görülmektedir.

Bu bağlamda, ideal olan "destekleyici" ancak "müdahaleci olmayan" bir ebeveyn tutumudur. Nalule (2024) de çalışmasında, aşırı ebeveyn katılımının öğrenci özerkliğini azaltma ve artan baskı gibi potansiyel dezavantajlarını tartışmakta ve ebeveynler ile üniversite yöneticilerine, öğrenci bağımsızlığını en üst düzeye çıkaracak şekilde desteğin optimize edilmesi konusunda öneriler sunmaktadır.

Literatüre göre, eğitim seviyesi yükseldikçe ebeveynlerin çocuklarının akademik ve mesleki geleceğine dair beklentileri artmakta ancak, bu da ebeveynlerin çocuklarının hayatına daha yoğun müdahil olmasına yol açabilmektedir. Doepke ve Zilibotti (2019), özellikle yüksek eğitimli ebeveynlerin çocuklarının başarısını garanti altına almak için daha fazla zaman, kaynak ve duygusal yatırım yaptığını, bunun zamanla aşırı yönlendirme ve kontrole dönüşebildiğini belirtmektedir (Doepke ve Zilibotti, 2019; Akt. Kaygusuz, 2026: 68). Bu bağlamda, lisansüstü eğitimli annelerin çocuklarının akademik ve sosyal performansını yakından izleme, riskleri azaltma ve kararlara daha fazla karışma eğiliminde olabileceği; bunun da çocuk tarafından daha yoğun bir helikopter ebeveynlik olarak algılanabileceği söylenebilir. Buna karşın, baba eğitim düzeyinin algılanan baba helikopter ebeveynliğinde anlamlı bir fark yaratmaması, babalık rollerinin toplumsal ve kültürel olarak annelik rollerinden farklı biçimde yapılandırılmasıyla açıklanabilir. Literatürde babaların, çocukların günlük bakımı, akademik takibi ve duygusal düzenlemesine annelere göre daha az katıldığı ve daha çok ekonomik destek rolüyle tanımlandığı belirtilmektedir (Lamb, 2010; Akt. Kaygusuz, 2026: 69). Bu durum, babanın eğitim düzeyi ne olursa olsun, çocukla etkileşiminin benzer kalmasına yol açabilir (Kaygusuz, 2026: 68-69).

Avcı ve Akıncı (2023) tarafından yapılan araştırma sonuçlarına göre, algılanan anne ve baba stilleri öz düzenleyici öğrenme stratejilerini ve motivasyonel inançları kısmen etkilemektedir. Ortak bir ebeveyn etkisi bulunmazken, anne ve babanın ayrı ayrı etkileri vardır. Anne stilinin etkisi babadan daha yüksektir. Demokrat ve izin verici anne stiline sahip bireyler, otoriter ve ihmalkâr stile sahip olanlara

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göre daha fazla bilişsel strateji kullanırken, baba stilinde izin verici stil ihmalkârdan daha avantajlıdır. Anne demokrat stili, öz düzenleme becerilerinde ihmalkâr stile göre daha başarılıdır. Otoriter ve demokrat ebeveyne sahip bireylerde sınav kaygısı daha yüksektir. İçsel değerde anne için izin verici stil, otoriter stile göre daha olumludur. Öz yeterlik üzerinde ise ebeveyn stillerinin etkisi yoktur. En çok tercih edilen stiller otoriter ve izin verici, en az tercih edilen ise demokratiktir (özellikle babalarda daha fazla). Otoriter stil annelerde daha yaygındır. Ebeveynler arasında en fazla uzlaşma otoriter ve izin verici stillerde, en az uzlaşma ise ihmalkâr ve demokrat stillerde görülmektedir. Sosyo-ekonomik ve kültürel statünün ise ne ebeveyn stili ne de öğrenme stratejileri üzerinde etkisi bulunmamıştır.

2.1.3. Aile Desteğinin Tamamlayıcı Unsuru: Kardeşlerin Rolü

Üniversiteye giriş süreci, yalnızca akademik bir sınav değil, aynı zamanda yoğun stres, belirsizlik ve duygusal dalgalanmaların yaşandığı bir dönemdir. Bu süreçte ebeveyn desteği elbette temeldir; ancak kardeşler, bu desteğin tamamlayıcı ve çoğu zaman daha samimi bir unsuru olarak devreye girer. Özellikle aynı evde yaşayan bir kardeş, sınav hazırlığındaki gencin günlük rutinini gözlemleyen, moral ihtiyacını fark eden ve ebeveyne söylemekten çekinilen kaygıları paylaşabileceği en yakın kişidir. Abla veya ağabey, kendi sınav deneyimlerinden yola çıkarak çalışma taktiği önerebilir, ders çalışma ortamının düzenlenmesine yardım edebilir veya sadece sessiz bir anlayış sunarak baskıyı hafifletebilir. Küçük kardeş ise masum bir oyun çağrısı ya da beklenmedik bir kahkaha ile aşırı ciddi atmosferi dağıtarak adeta doğal bir stres azaltıcı işlevi görebilir.

Ayrıca, üniversite sınavına hazırlık sürecinde kardeşler, ebeveynlerin zaman zaman kaçınılmaz olarak sergilediği aşırı beklenti veya kaygılı tutumları dengeleyici bir rol üstlenir. Ebeveynler "Nasıl gidiyor, şu netleri artırmalısın" derken, kardeş "Hadi biraz mola ver, birlikte film izleyelim" diyerek duygusal yükü hafifletebilir. Bu destek, özellikle sınav senesinde evde yalnız hissetmemeyi sağlar. Kardeş aynı zamanda, dershaneye gidip gelme, ödev kontrolü ya da hatırlatıcı notlar bırakma gibi pratik konularda da yardımcı olabilir. Bununla birlikte, sağlıklı bir kardeş desteğinden söz edebilmek için ebeveynlerin kıyaslamadan kaçınması ve kardeşleri birbirine rakip değil, doğal müttefik olarak görmesi gerekir. Sonuç olarak, üniversiteye giriş yolculuğunda kardeşler, ebeveynlerin verdiği koşulsuz desteği, daha yatay, yaşıt ve günlük hayatın içinden bir samimiyetle tamamlar; bu da sınav maratonunu daha katlanılır ve hatta anlamlı kılar.

Aile başarısında rol oynayan tek faktör ebeveynler değildir. Özellikle birinci kuşak üniversite öğrencileri için, üniversite deneyimi olan abi veya ablalar, kritik bir tamamlayıcı destek kaynağı olarak işlev görebilir. Hagler (2024) tarafından yapılan boylamsal bir çalışmada, ebeveyn desteğinin akademik ve sosyal uyumla olumlu ilişkisi doğrulanırken, aynı zamanda ilginç bir etkileşim bulgusu elde edilmiştir: Ebeveyn desteğinin düşük olduğu durumlarda, üniversite deneyimi olan büyük kardeş(lere) sahip olmak, öğrencilerin sosyal uyumu ile pozitif ilişkili bulunmuştur. Bu bulgu, aile desteğinin sadece dikey (ebeveyn-çocuk) bir ilişki olmadığını, aynı zamanda yatay (kardeşler arası) ilişkilerin de özellikle dezavantajlı durumlarda boşluğu doldurabileceğini göstermektedir (Hagler (2024).

2.2. Ailenin Akademik Tutumunun Öğrenme Sorumluluğuna Etkisi

Ailenin, çocuğun akademik tutum ve öğrenme sorumluluğu üzerinde belirleyici bir rolü vardır. Çocuğun ilk sosyal çevresi olan aile; ona yönelik tutumları, eğitime bakışı ve desteğiyle onun hem okul hem de yaşam başarısını etkiler. Aile çocuğun eğitimini desteklediğinde çocuk okula istekli olur ve başarmaya çalışır. Oysa gerçekçi olmayan beklentilerle çocuğu baskılayan aileler, başarısızlık korkusuna yol açar. Bu nedenle pek çok ülkede aileler eğitim sürecine dâhil edilmeye çalışılmaktadır. Ailenin eğitim düzeyi, ekonomik durumu, kültürü ve çocuğa sunduğu fırsatlar da akademik başarıyı doğrudan etkiler (Dam, 2008: 81; Şeker, 2013: 64; Kayısılı, 2008: 69-83; Bayoğlu vd., 2009: 125; Sontur vd., 2021: 308).

Ebeveynlerin çocuklarına yönelik eğitim beklentisi ve davranışsal desteği, sosyoekonomik durum, kaynaklar ve aile yeteneklerinden kısmen etkilenir. Farklı imkânlara sahip ailelerin sağlayabileceği eğitim desteği önemli ölçüde değişir. Ödev kontrolü, okul koşullarını tartışma gibi davranışsal destekler, çocuğun çalışma alışkanlıklarını geliştirip akademik performansını etkileyebilir (Steinberg vd., 1992; Fan ve Chen, 2001; Zhao ve Hong, 2012).

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Ailenin kendi geçmişi, ekonomik durumu, sosyal statüsü ve yaşadığı çevre de eğitime bakışını şekillendirir. Aile, çocuğu bir yük veya gelir kapısı olarak gördüğünde eğitiminin önünde engel oluşturabilir; bu durum çocukta eğitime karşı olumsuz tutum geliştirir. Oysa öğrenme sorumluluğunun oluşması için ailenin eğitime önem vermesi, çocuğu teşvik etmesi ve okul ile iş birliği yapması gerekir (Sontur vd., 2021: 304).

Araştırmalar, annesinin eğitim seviyesi yüksek olan çocukların kendi sağlık algılarının daha olumlu olduğunu göstermektedir. Örneğin, annesi üniversite mezunu olan çocukların yalnızca %11,2'si sağlık durumunu "orta veya kötü" olarak değerlendirirken, annesinin mesleki yeterliliği bulunmayan çocuklarda bu oran yaklaşık %20'dir. Ayrıca gelir ve ebeveyn eğitiminin yanı sıra yaş, cinsiyet, göçmenlik geçmişi ve yaşanılan yer gibi sosyoekonomik etmenler de çocukların gelişimini etkiler. Farklı federal eyaletlerdeki eğitim sistemlerinin çeşitliliği de okul hayatını farklı şekillerde etkileyebilir (Seyda ve Lampert, 2009: 3-4).

Ebeveynlerin çocuklarının akademik yeteneklerine güvenmesi, onları desteklemesi, çalışmalarına katkı sağlaması, uygun çalışma ortamları hazırlaması ve başarıyı maddi-manevi ödüllerle teşvik etmesi, çocukların öğrenme sorumluluğunu üstlenerek başarılı olmalarını sağlar. Buna karşın, ebeveynlerin kendi başarı algıları doğrultusunda çocuklarına baskı yapması, başarısını küçümsemesi, akranlarıyla kıyaslaması, daha yüksek not beklemesi veya başarısızlık durumunda aşağılaması gibi yanlış tutumlar, çocukta öğrenme sorumluluğu gelişimini engellemektedir. Sontur ve ark. (2021) tarafından yapılan araştırmada kullanılan Regresyon analizi sonuçlarına göre ailenin akademik tutum puanı 1 birim arttığında öğrenme sorumluluğunun 0,685 birim arttığını; baskı 1 birim arttığında sorumluluğun 0,684 birim azaldığını; destek 1 birim arttığında ise 0,718 birim arttığını göstermektedir. Sonuçlar, aile akademik tutumunun öğrenme sorumluluğunu anlamlı şekilde etkilediğini ortaya koymaktadır. Bu nedenle okullarda, ebeveynlere yönelik olumlu tutum ve bilinç geliştirmeyi hedefleyen eğitimler düzenlenmeli; öğrencilerin olumsuz duygularla baş edebilmesi için rehberlik hizmetlerinden yararlanmaları sağlanmalıdır. Ayrıca, okul rehber öğretmenleriyle iş birliği yapılarak başarı ve başarısızlık durumları detaylı incelenebilir (Sontur vd., 2021: 308).

3. AİLENİN KÜLTÜREL BİRİKİMİ VE YARATTIĞI ETKİLEŞİMLER

3.1. Kültürel Sermayenin Etkileri

Ebeveynlerin mesleki statüsünün çocuğun üniversite eğitimi alma şansı üzerinde anlamlı bir etkisi bulunmaktadır; mesleki statü yükseldikçe çocuğun yükseköğrenim görme olasılığı da artmaktadır. Anne ve babanın eğitim düzeyine ilişkin analizlerde ilköğretim ya da daha alt bir eğitim seviyesi referans kategori olarak alınmıştır. Lojistik regresyon bulgularına göre, annenin lise mezunu olması, ilköğretim veya altı bir dereceye sahip olmasına kıyasla çocuğun üniversite mezunu olma ihtimalini yaklaşık üç katına çıkarmaktadır. Annenin üniversite veya daha yüksek bir dereceye sahip olması durumunda ise bu fark beş katın üzerine çıkmaktadır. Baba eğitim düzeyi için de benzer bir ilişki gözlenmektedir: Babanın lise eğitimi çocuğun üniversite bitirme olasılığını 3,3 kat, üniversite eğitimi ise 5,9 kat artırmaktadır. 1950 öncesi doğumlular referans grup olarak alındığında, daha genç kuşaklara ilerledikçe üniversite derecesi elde etme olasılığının yükseldiği görülmektedir. Örneğin, diğer tüm değişkenler sabitken 1980 veya sonrasında doğan bir bireyin, 1950 öncesinde doğan birine göre üniversite diplomasına sahip olma olasılığı on kattan fazladır (Özdemir, 2018: 547-548).

Pierre Bourdieu'nün kültürel sermaye teorisine göre, ebeveynlerin eğitim düzeyi yükseldikçe, çocuklarına aktardıkları kültürel bilgi, dil becerileri, alışkanlıklar ve eğitime bakış açısı da olumlu yönde şekillenir (Bourdieu & Passeron, 1990). Yüksek öğrenim görmüş aileler, evde kitap okuma alışkanlığını teşvik eder, müzelerden ve kütüphanelerden daha sık yararlanır ve çocuklarının eğitim sürecine daha bilinçli bir şekilde rehberlik eder. Bu durum, çocuğun akademik başarısını doğrudan artırır.

Araştırmalar, ailesinde en az bir üniversite mezunu bulunan öğrencilerin, ebeveynleri ilkokul mezunu olan akranlarına kıyasla üniversiteye devam etme olasılığının 3 kat daha fazla olduğunu göstermektedir (Coleman, 1988). Bunun temel nedeni, yüksek eğitimli ailelerin çocuklarının eğitimine yönelik yüksek beklentiler geliştirmesi ve bu beklentilerini çocuklarına başarıyla içselleştirmesidir.

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Hisarcıklılar'a (2002) göre, çocukların eğitimine yapılan yatırımı etkileyebilecek bir diğer faktör de anne babaların eğitim seviyesidir. Bu durum, çocuğun eğitim başarısını farklı yollarla etkileyebilir: Ebeveynlerin eğitime ilişkin tercihlerini şekillendirerek; çocukla birlikte geçirilen zamanın niteliğini ve niceliğini belirleyerek; ebeveynlerin rol model olmasıyla ve dolaylı olarak hane halkı geliri ile oluşmaktadır. Ayrıca, eğitim düzeyi yüksek ebeveynlerin geleneklerden daha az etkilendiği ve çocukları arasında ayrım yapma ihtimallerinin daha düşük olduğu ifade edilebilir (Hisarcıklılar, 2002: 7).

3.2. Ailenin Statü Aktarımı

Ailedeki yüksek öğrenim profili, ebeveynlere çocuklarının derslerine yardımcı olma konusunda daha fazla bilgi ve beceri kazandırır. Özellikle matematik, fen bilimleri ve dil gibi temel alanlarda, üniversite mezunu ebeveynler çocuklarının ödevlerine, projelerine ve sınav hazırlıklarına daha etkin katkı sağlayabilirler (Eccles, 2007).

Bunun yanı sıra, bu aileler çocuklarının kariyer planlaması ve yüksek öğrenime geçiş süreçlerinde daha bilinçli bir rehberlik sunar. Üniversite sınavı sistemleri, bölüm seçenekleri, yurt dışı eğitim fırsatları veya burs olanakları hakkında daha fazla bilgiye sahiptirler. Bu durum, çocukların eğitim kariyerlerinde daha isabetli ve ileriye dönük kararlar almalarını sağlar.

Statü aktarımı, bireyin toplumsal konumunun (meslek, gelir, eğitim düzeyi, saygınlık gibi özelliklerinin) ailesi tarafından belirlenmesi veya güçlü biçimde etkilenmesi sürecidir. Özellikle eğitim alanında bu aktarım, üç ana kanaldan gerçekleşir:

- Kültürel sermaye aktarımı: Eğitimli ebeveynler evde kitap, sanat, entelektüel tartışma ortamı sağlar. Çocuk bu donanımla okula gelir; öğretmenlerin beklentilerini karşılaması kolaylaşır.

- Ekonomik sermaye: Yüksek öğrenim görmüş aileler genellikle daha yüksek gelire sahiptir. Bu sayede özel ders, etüt, yurt dışı dil okulu, iyi okullar gibi olanaklara yatırım yapabilirler.

- Sosyal ağlar: Eğitimli ailelerin tanıdıkları arasında akademisyenler, öğretmenler, staj imkânı sunacak profesyoneller bulunur. Bu "torpil" veya "referans" olarak değil, bilgi ve fırsat akışı şeklinde işler.

Statü aktarımı, genellikle "ailedeki yüksek öğrenim görme oranı" ile "bireyin eğitim başarısı" arasında pozitif bir ilişki olarak gösterilir.

Ebeveynler, sahip oldukları yüksek eğitim düzeyi ve gelir gibi toplumsal statü koşullarını çocuklarına aktararak onların deneyimlerini, tutumlarını ve davranışlarını şekillendirirler. Sosyoekonomik statünün nesiller arası aktarımı, çocukların ilerleyen yaşamlarında gönüllü faaliyetlere katılma eğilimleri üzerinde hem doğrudan hem de dolaylı etkiler yaratmaktadır. Doğrudan etki bağlamında, ebeveynlerin statüsü, çocuğun kendi eğitim düzeyinden bağımsız olarak, yetişkin çocuğun sivil toplum kuruluşlarında aktif gönüllülük yapma olasılığını artırmaktadır. Dolaylı etki ise şu şekilde işlemektedir: Yüksek statülü ebeveynlerin çocukları genellikle daha yüksek eğitim seviyesine ulaşmakta; ebeveynlerin çocuklarının beşeri sermayesine yaptığı bu yatırım, onların hem işgücü piyasasındaki konumlarına hem de gönüllü olma potansiyellerine katkı sağlamaktadır (Nesbit, 2013: 1135; Janoski ve Wilson, 1995; Martin, 2012: 34; Akt. Sadıkoğlua, 2024: 415).

İlave olarak, ebeveynleri yüksek öğrenim görmüş bireyler için akademik başarı "olağan" ve "ulaşılabilir" bir hedef haline gelebilmektedir. Ebeveynlerin kendi eğitim hikayeleri, mesleki başarıları ve entelektüel birikimleri çocukları için somut birer rol model oluşturur. Bu durum, Bandura'nın sosyal öğrenme teorisi çerçevesinde, çocuğun akademik öz-yeterlik algısını güçlendirir (Bandura, 1997). Yani birey, "Ben de başarabilirim, ailem bunu yaptı" düşüncesiyle eğitim hayatına daha motive bir şekilde devam eder.

3.3. Sosyoekonomik Faktörlerle Etkileşim

Nihal Lindberg (2021) tarafından yapılan bir araştırmada, literatüre uygun şekilde ebeveynlerin eğitim düzeyi ile akademik başarı arasında pozitif ve anlamlı bir ilişki bulunmuştur. Şirin'e (2005) göre ebeveyn eğitimi akademik başarı üzerinde sosyoekonomik durumdan daha etkiliyken, Lindberg'in çalışmasında ailenin sosyoekonomik durumu ile akademik başarı arasında da anlamlı pozitif bir ilişki saptanmıştır. Bu durum, Türkiye'de kaynaklara erişimde gelir düzeyinin belirleyici olduğu ve yüksek

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aile gelirinin çocuğun akademik başarısını olumlu etkilediği şeklinde yorumlanmıştır (Şirin, 2005; Akt. Lindberg, 2021: 827-831).

Ailenin yüksek öğrenim profili çoğu zaman daha yüksek gelir düzeyiyle ilişkilidir. Bu da bireyin eğitimine ek kaynaklar (özel ders, etüt merkezleri, kaliteli okullar, teknolojik araçlar) aktarılmasını mümkün kılar. Ancak bu etkinin sadece ekonomik boyuttan ibaret olmadığı unutulmamalıdır. Çünkü eğitim seviyesi yüksek ancak geliri düşük ailelerde bile, çocukların eğitim başarısı diğer düşük gelirli ailelere kıyasla daha yüksek olabilmektedir (Chevalier, 2004). Bu durum, kültürel sermayenin ekonomik sermayeden bağımsız bir etkiye sahip olduğunu göstermektedir.

Ekinci, (2011) tarafından yapılan ve hane geliri, ebeveyn eğitimi ve ebeveynlerin ikamet durumu (kentsel/kırsal) gibi faktörlerin yükseköğretime katılım üzerindeki etkisini araştıran çalışma sonuçlarına göre; ebeveynlerin eğitim durumunun belirleyici bir faktör olduğunu gösterirken, hane gelirinin doğrudan bir faktör olmadığını ortaya koymaktadır.

Araştırmalar, ailelerin çocuklarının eğitimine aktif katılımının akademik başarıyı doğrudan ve olumlu yönde etkilediğini göstermektedir. Tezel Şahin ve Özbey (2007), “ailenin çocuklarının eğitimine katılmaları, eğitimin devamlılığını sağlamakta, çocukların kendine güven duygusu, akademik başarısı ve ailesi ile ilişkilerinde olumlu etkileri olmaktadır” tespitinde bulunmuşlardır. Bu bağlamda evde ders çalışma ortamının hazırlanması, ödevlere ilgi gösterilmesi, kitap okuma alışkanlığının teşvik edilmesi gibi basit görünen davranışlar bile çocuğun okul başarısına önemli katkılar sunar.

Aile, aynı zamanda bir “değerler okulu”dur. Saygı, dürüstlük, sorumluluk, yardımseverlik gibi temel değerlerin içselleştirildiği ilk yer ailedir. Çocuğun karakterinin şekillenmesinde aile tutumları belirleyicidir. Demokratik, saygılı ve iletişime açık bir aile ortamı, sağlıklı kişilik gelişimini desteklerken; otoriter veya ilgisiz aile tutumları çocukta çeşitli davranış sorunlarına yol açabilmektedir.

Değişen sosyal ve kültürel koşullar, ailelerin çocuk yetiştirme konusunda bilgi ve beceriye olan ihtiyacını artırmaktadır. Tezel Şahin ve Özbey (2007), “değişen sosyal ve kültürel şartlarda ailelerin çocuk gelişimi ve eğitimi konusunda aile eğitim programları ile desteklenmesine ihtiyaç duyulmaktadır” görüşünü savunmaktadır. Türkiye’de bu ihtiyaca yönelik olarak Aile ve Sosyal Hizmetler Bakanlığı bünyesinde çeşitli aile eğitim programları geliştirilmiştir.

SONUÇ VE ÖNERİLER

Bu çalışmada, ailenin yüksek öğrenim profilinin bireyin eğitim sürecine olan etkileri çok boyutlu bir perspektifle ele alınmıştır. Araştırma bulguları, ebeveynlerin eğitim düzeyinin bireyin akademik başarısı, eğitim beklentileri, kariyer hedefleri ve üst öğretim kurumlarına erişimi üzerinde güçlü ve çok yönlü bir etkiye sahip olduğunu ortaya koymaktadır.

Bourdieu'nün kültürel sermaye teorisi çerçevesinde değerlendirildiğinde, yüksek öğrenim görmüş ebeveynlerin çocuklarına aktardığı kültürel bilgi, dil becerileri, alışkanlıklar ve eğitime bakış açısı, çocuğun akademik yaşamında önemli bir avantaj yaratmaktadır. Bu aileler, evde kitap okuma alışkanlığını teşvik etmekte, müzelerden ve kütüphanelerden daha sık yararlanmakta ve çocuklarının eğitim sürecine daha bilinçli bir şekilde rehberlik etmektedir. Özer ve Suna'nın (2023) gerçekleştirdiği araştırma, "ebeveyn eğitim seviyesinin" akademik başarıyı yordayan en güçlü değişken olduğunu ve bu etkinin aile gelir düzeyinden bile daha belirleyici olduğunu ortaya koymuştur. Bu bulgu, kültürel sermayenin ekonomik sermayeden bağımsız ve en az onun kadar etkili bir mekanizma olduğunu göstermektedir.

Ebeveynlerin çocuklarının eğitimine katılımı, yalnızca akademik konularda yardım etmekle sınırlı olmayıp, duygusal destek sağlama, finansal yardım, kariyer rehberliği ve okulla iletişim kurma gibi çok boyutlu faaliyetleri içermektedir. Araştırmalar, aktif ebeveyn katılımının öğrencilerin daha başarılı olması, öğrenmeye karşı olumlu tutum geliştirmesi ve gerekli becerileri kazanmasıyla ilişkili olduğunu göstermektedir. Tezel Şahin ve Özbey'in (2007) belirttiği gibi, "ailenin çocuklarının eğitimine katılmaları, eğitimin devamlılığını sağlamakta, çocukların kendine güven duygusu, akademik başarısı ve ailesi ile ilişkilerinde olumlu etkileri olmaktadır."

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Ancak katılımın dozajı kritik önem taşımaktadır. Literatürde son yıllarda artan bir tartışma konusu, aşırı müdahaleci ve kontrolcü ebeveyn tutumunun "helikopter ebeveynlik" öğrencilerin özerkliklerini kısıtlayarak gelişimlerini engelleyebileceğidir. Bu olumsuz etkiler nedeniyle, ideal olan "destekleyici" ancak "müdahaleci olmayan" bir ebeveyn tutumudur. Nalule'nin (2024) çalışmasında vurguladığı gibi, ebeveynler ile üniversite yöneticilerinin, öğrenci bağımsızlığını en üst düzeye çıkaracak şekilde desteğin optimize edilmesi konusunda duyarlı olmaları gerekmektedir.

Sontur ve arkadaşlarının (2021) regresyon analizi sonuçları, ailenin akademik tutumunun öğrenme sorumluluğunu anlamlı şekilde etkilediğini ortaya koymaktadır. Analiz bulgularına göre, ailenin akademik tutum puanı 1 birim arttığında öğrenme sorumluluğu 0,685 birim artmakta; baskı 1 birim arttığında sorumluluk 0,684 birim azalmakta; destek 1 birim arttığında ise 0,718 birim artmaktadır. Bu sonuçlar, ebeveynlerin çocuklarına karşı destekleyici tutumunun, çocukların öğrenme sorumluluğunu geliştirmelerinin en güçlü belirleyicisi olduğunu göstermektedir.

Öğrenme sorumluluğu kazanmış bireyler; öğrenmeye adanmış, engelleri aşmaya çalışan, elinden gelenin en iyisini yapan, öğrenmeyi hemen isteyen, okul başarısının gelecekte önemli olduğuna inanan ve zor görevleri tercih eden kişiler olarak tanımlanmaktadır (Allan, 2006). Bu özelliklerin kazandırılmasında ailenin rolü yadsınamaz.

Araştırmalar, ebeveynleri üniversite mezunu olan çocukların, üniversiteden mezun olma olasılıklarının daha yüksek olduğunu, birinci kuşak öğrencilerin ise üniversiteye gitme olasılıklarının daha düşük olduğunu ve eğer giderlerse de terk etme olasılıklarının akranlarına kıyasla çok daha fazla olduğunu göstermektedir. Bu durumun temelinde, ebeveynlerin sahip olduğu "eğitsel kültürel sermaye" farkı yatmaktadır. Üniversite deneyimi olmayan ebeveynler, çocuklarının başarılı olmasını içtenlikle isteseler de üniversite kültürünü anlamama, maddi yardım olanaklarını bilmeme ve uygun destek mekanizmalarına erişimde zorluk yaşama gibi engellerle karşılaşmaktadırlar.

Bu noktada, üniversite deneyimi olan büyük kardeşlerin varlığı kritik bir tamamlayıcı destek kaynağı olarak işlev görebilmektedir. Hagler'ın (2024) boylamsal çalışmasında, ebeveyn desteğinin düşük olduğu durumlarda, üniversite deneyimi olan büyük kardeşlere sahip olmanın, öğrencilerin sosyal uyumu ile pozitif ilişkili olduğu bulunmuştur. Bu bulgu, aile desteğinin sadece dikey (ebeveyn-çocuk) bir ilişki olmadığını, aynı zamanda yatay (kardeşler arası) ilişkilerin de özellikle dezavantajlı durumlarda boşluğu doldurabileceğini göstermektedir.

Avcı ve Akıncı'nın (2023) araştırması, algılanan anne ve baba stillerinin öz düzenleyici öğrenme stratejilerini ve motivasyonel inançları kısmen etkilediğini göstermektedir. Ortak bir ebeveyn etkisi bulunmazken, anne ve babanın ayrı ayrı etkileri vardır ve anne stilinin etkisi babadan daha yüksektir.

Orta öğretim ve Yükseköğretim kurumları ile politika yapıcılara şu öneriler getirilebilir:

1. Ebeveynlerin eğitsel kültürel sermayesini artırmaya yönelik "Parent University" benzeri müdahale programları geliştirilmeli ve yaygınlaştırılmalıdır.

2. Üniversiteler, veli oryantasyon günlerinde ebeveynleri "destekleyici ancak aşırı müdahaleci olmama" konusunda bilinçlendirmelidir.

3. Öğrencilerin danışmanlık süreçlerinde, üniversite deneyimi olan abla/abinin varlığı bir varlık olarak görülmeli ve bu kardeşlerin sürece dahil edilmesi için mekanizmalar oluşturulmalıdır.

4. Bulgular, eğitim politikalarının yalnızca okulları değil, aileleri de hedef alması gerektiğini göstermektedir. Özellikle ebeveyn eğitim düzeyinin düşük olduğu toplum kesimlerinde:

- Ebeveynlere yönelik yetişkin eğitimi programları (aile okulları, ebeveyn akademileri),

- Okul-aile iş birliğini güçlendiren rehberlik faaliyetleri,

- Mentörlük ve rol model programları (üniversite öğrencilerinin ortaöğretim çağındaki çocuklara destek olması), gibi müdahaleler, eğitimde fırsat eşitliğini artırabilir. Unutulmamalıdır ki, ailenin eğitim profili bir kader değil, toplumsal müdahalelerle dengelenebilecek bir değişkendir.

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5. Okul dışında kalan çocukların annelerine ulaşmak ve onların eğitim düzeyini yükseltmek için hedefe yönelik politikalar uygulanmalıdır.

6. Ev ile okul arasında köprü kuran iş birliği, iletişim ve karşılıklı desteği güçlendirerek öğrencilerin değerli ve motive hissettiği destekleyici bir öğrenme ortamı oluşturulmalıdır.

7. Okul rehber öğretmenleriyle iş birliği yapılarak başarı ve başarısızlık durumları detaylı incelenmeli, ailelere geri bildirim sağlanmalıdır.

8. Düşük gelirli ailelerin yoğun olduğu okullardaki öğretmenlere, öğrenci başarısına katkıları ölçüsünde maddi teşvikler sağlanmalıdır. Öğretmenlerin, bu okullardaki öğrencilerin ders saatleri dışında da okulda vakit geçirebileceği eğitici ve sosyal programlar geliştirmesi desteklenmelidir. Okul yönetimleri ve öğretmenler, öğrencilerin akademik ve sosyal gelişimlerinin izlenmesi için velilerle etkin koordinasyon kurmaya teşvik edilmelidir.

9. Farklı illerde ve farklı öğrenci gruplarında analizler yapılarak, bölgesel farklılıklar ve kültürel özellikler dikkate alınmalıdır.

10. Ailenin akademik tutumu ve öğrenme sorumluluğuna yönelik yeni ölçme araçları geliştirilmelidir.

11. Nitel araştırma yöntemleriyle, yüksek öğrenim görmüş ailelerin çocuklarının eğitim sürecindeki deneyimlerinin derinlemesine incelenmesi, nicel bulguları tamamlayıcı zengin veriler sağlayabilecektir.

12. Ebeveynlere yönelik bilinçlendirme çalışmalarında, aşırı müdahaleci "helikopter ebeveynlik" tutumların çocuğun özerklik gelişimini engellediği ve olumsuz sonuçlar doğurabileceği vurgulanmalıdır.

13. Demokratik, saygılı ve iletişime açık bir aile ortamının sağlıklı kişilik gelişimini desteklediği; otoriter veya ilgisiz aile tutumlarının ise çocukta çeşitli davranış sorunlarına yol açabileceği anlatılmalıdır.

14. Ebeveynler, Çocuklarının ödevlerini takip ederken ve akademik süreçlerine destek verirken, onların kendi problem çözme becerilerini geliştirmelerine izin vermelidir. Başarıyı baskı değil, güven ve teşvik yoluyla desteklemelidirler.

15. Üniversiteler ve rehberlik araştırma merkezleri, “Kardeş Mentorluk Programları” geliştirmelidir. Bu programlarla üniversite öğrencisi abla/abiler, alt kademedeki kardeşlerine akademik rehberlik sağlayabilirler.

Aileler öğrencilerinin, üniversite hayatında sadece maddi bir kaynak değil, aynı zamanda psikolojik dayanıklılığın ve motivasyonun da temelini oluştururken, bu katkıyı yaparken özerkliğe saygılı bir denge kurmaları gerekmektedir.

Sonuç olarak, ailenin yüksek öğrenim profili, bireyin eğitim hayatı üzerinde çok yönlü ve güçlü bir etkiye sahiptir. Kültürel sermaye aktarımından akademik desteğe, kariyer rehberliğinden motivasyon ve rol model olmaya kadar birçok mekanizma aracılığıyla, bireyin okul başarısını, eğitim beklentilerini ve yüksek öğrenime devam etme olasılığını artırmaktadır. Ancak bu etkinin yarattığı fırsat eşitsizliklerinin giderilmesi ve dezavantajlı grupların desteklenmesi için, eğitim politikalarının aile temelli ve bütüncül bir yaklaşımla yeniden yapılandırılması gerekmektedir.

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THE PERSISTENT RISKS OF VIRAL SOCIAL MEDIA TRENDS ON BIOMETRIC SECURITY: DEEPFAKE ATTACKS, LAZY BIOMETRICS VULNERABILITIES, AND REGULATORY ASYMMETRIES

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ABSTRACT

This study examines the systemic biometric security and data privacy vulnerabilities created by viral visual social media trends, particularly those utilizing generative artificial intelligence (GenAI) models for facial manipulation, identity transformation, and age progression processes. Adopting a conceptual framework and qualitative case study methodology, the research models how digital portraits, voluntarily generated by users on open network platforms, are collected by malicious actors (data harvesting) and integrated into algorithmic processes. The scope of the study critically evaluates the threat vector posed by deepfake content derived from single images on primitive authentication architectures, termed "lazy biometrics," and Knowledge-Based Authentication (KBA) protocols. Furthermore, the study addresses the regulatory asymmetry between biometric identity providers subject to strict compliance obligations (GDPR, KVKK/LPPD, etc.) and AI developers who process open data through unconsented scraping methods. The literature review synthesizes current research on biometric Presentation Attack Detection (PAD), Injection Attack Detection (IAD), ISO/IEC compliance standards, and the political economy of the artificial intelligence ecosystem. This synthesis reveals that contemporary deep learning models are sufficient to transform static facial data into dynamic and high-fidelity synthetic identities, thereby rendering traditional template-matching authentication paradigms dysfunctional. The findings indicate that participation in viral visual trends leads to the formation of unencrypted biometric data pools that are continuously open to exploitation, without the users' awareness. While generative AI training infrastructures operate in ambiguous legal gray areas, authentication protocols lacking multi-factor liveness detection remain highly vulnerable to synthetic injection attacks. The study concludes that individual digital restriction is solely inadequate in mitigating these threats; a structural synchronization between advanced Presentation Attack Detection (PAD), encrypted transmission channels, AI training ethics, and international biometric data protection regulations is imperative.

Keywords: Biometric Security, Generative AI, Deepfake Attacks, Presentation Attack Detection (PAD), Lazy Biometrics, Regulatory Asymmetry, Data Privacy.

INTRODUCTION

The evolution of digital communication technologies and social media platforms has radically transformed the ways and frequencies with which individuals share their images on online networks. In particular, the integration of generative artificial intelligence (GenAI) models into mobile applications and social networks via user-friendly interfaces has triggered viral trends that allow users to stylize their photos, age them, or interact with their childhood appearances.

Although these facial manipulation-based trends are perceived by the masses as harmless digital entertainment and a means of self-expression, in the background, they lead to the formation of massive, unencrypted, and ready-to-process visual data pools (data harvesting) (Jasserand, 2018).

In traditional information security approaches, biometric data (facial recognition, fingerprints, iris, etc.) were considered "immutable and unforgeable" security layers compared to passwords. However, recent advancements in deep learning algorithms have made it possible to produce high-fidelity, animated, and voice-synchronized synthetic media content (deepfakes) from a single static image. This situation strips

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the "immutable" nature of biometric data of its advantage, transforming it into a permanent and irreplaceable security vulnerability once compromised (Liu et al., 2025).

The primary factor escalating the magnitude of the threat is that many authentication systems in the market continue to employ primitive authentication protocols, referred to as "lazy biometrics." These systems, which merely audit the superficial match between a registered template and the presented image without incorporating liveness detection or in-channel injection protection, remain defenseless against AI-generated deepfake inputs. On the other hand, the supplementary data that users share regarding their past, families, or personal preferences through these trends paves the way for Knowledge-Based Authentication (KBA) mechanisms to be bypassed via social engineering attacks (Tolosana et al., 2020).

Another critical dimension constituting the original value of this study is regulatory asymmetry. Licensed biometric identity providers operating under legal frameworks such as the European General Data Protection Regulation (GDPR) or the Personal Data Protection Law (KVKK/LPPD) are subject to the obligations of obtaining explicit and informed consent and deleting data in the processing of personal data. Conversely, generative AI actors, who train large language and visual models (LLM/LMM) via unconsented data scraping methods from the open internet, operate in legal and ethical gray areas, freely processing facial data in the public domain (Al-Busaidi et al., 2024).

This study aims to examine the biometric security risks, lazy biometric vulnerabilities, and regulatory legal loopholes created by viral social media trends through a holistic approach. Accordingly, the research seeks answers to the following questions:

1. How do single portraits, transferred to the public domain through viral visual trends, threaten lazy biometric systems via next-generation deepfake algorithms?

2. What kind of security vulnerabilities does the regulatory asymmetry between biometric providers subject to strict legal obligations and generative AI developers processing open internet data cause?

3. What kind of multi-layered technical and legal framework should be developed to protect visual data privacy and biometric authentication infrastructures?

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

Generative AI and Visual Data Harvesting

The development of Generative Artificial Intelligence (GenAI) architectures, particularly Multimodal Large Language/Vision Models, has radically shifted the paradigms in digital content creation. Deep Learning-based Generative Adversarial Networks (GANs) and Diffusion Models have gained the ability to produce high-fidelity synthetic images and videos from highly limited input data (Rombach et al., 2022). The most prominent reflection of this technological transformation on the societal level is the visual manipulation trends rapidly spreading across social media platforms. These viral trends, which transform users' facial features, age them, or synthetically merge them with their childhood portraits, feed a large-scale visual data harvesting ecosystem in the background.

When the political economy of the data shared on social networks is examined, it becomes evident that the digital portraits and selfies voluntarily transferred to the public domain by individuals offer an unencrypted raw biometric data reserve for AI developers and third-party actors. In this phenomenon, conceptualized in the literature as the "public domain paradox," users perceive their images as objects of instantaneous interaction and self-expression, whereas automated web scraping bots and LLM/LMM data collection pipelines index, process, and incorporate these images into datasets (Zuboff, 2019; Hill, 2020).

A static passport-style photo or social media picture can be transformed into dynamic facial maps, 3D mesh models, and latent space representation coordinates via contemporary generative models (Korshunov & Marcel, 2018). Consequently, the process of participating in viral trends leaves individuals' biometric subjectivities defenselessly exposed to digital surveillance and data mining processes (Peirce, 2026).

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Traditional Biometrics vs. "Lazy Biometrics"

Biometric authentication infrastructures were developed to overcome the vulnerabilities created by traditional object-based (key, card) or knowledge-based (password, PIN) authentication methods in information security (Jain et al., 2004). Because biometric data is inherently unique to the individual, immutable, and continuously measurable, it has been accepted as the fundamental authentication standard in high-security domains. However, current security literature emphasizes that existing systems are not homogeneous in terms of their architectural maturity levels and that a significant portion carries the vulnerability of "lazy biometrics" (Node Magazine, 2025).

Lazy Biometrics: Refers to superficial authentication architectures that lack liveness detection, environment verification, and data channel encryption; and that merely audit the mathematical similarity score (vector distance/Euclidean distance) between the facial image presented as input and the biometric template stored in the database (Peirce, 2026).

The fundamental differences between traditional biometrics and lazy biometrics are summarized in the literature as follows (Jain et al., 2015; Peirce, 2026):

- *Template Matching Focus:* Lazy biometric systems do not question whether the incoming data is derived from a physical biological source or a synthetic digital input. They focus solely on template matching.
- *Lack of Dynamic Validation:* While advanced biometric systems analyze dynamic liveness indicators such as micro-expressions, depth maps, and blood flow color variations (rPPG - remote photoplethysmography) (Yalçın, 2015); lazy biometric systems accept static or superficial 2D visuals.
- *Irreplaceability Vulnerability*: While a user whose password is stolen can change it, it is impossible for an individual whose facial biometrics are compromised or whose deepfake model is derived to renew their biometric data (Jain et al., 2004). This situation turns the vulnerability of lazy biometrics into a critical security crisis.

Presentation and Injection Attacks (PAD and IAD Standards)

The development of AI-supported synthetic media has diversified the attack vectors targeting biometric systems into two main categories: Presentation Attacks and Injection Attacks. These attack types, defined within the framework of the International Organization for Standardization (ISO/IEC 30107) standards, play a critical role in testing biometric defense mechanisms.

1. *Presentation Attacks (PA) and PAD Standards*: A presentation attack occurs when a malicious actor deceives the system by holding a physical object (a high-resolution screen display, a 3D silicone mask, or an artificial video broadcast) in front of the biometric sensor (camera, etc.) (ISO/IEC 30107-1, 2016). Presentation Attack Detection (PAD) algorithms, developed to prevent these attacks, apply passive liveness (tactile texture detection, depth analysis) and active liveness (prompting the user for specific eye/head movements) tests in accordance with the ISO/IEC 30107-3 (2017) standard (Yalçın, 2015).

2. *Injection Attacks (IA) and IAD Standards*: An injection attack entirely bypasses the sensor hardware, directly injecting a pre-processed deepfake signal into the software layer, camera drivers, or data transmission channel (ISO/IEC 30107-1, 2016). Injection Attack Detection (IAD) aims to prevent infiltrations carried out via virtual camera software by auditing the cryptographic signatures (hardware attestation) of the transmitted digital data stream, hardware-level encryption, and the authenticity of data packets (Peirce, 2026).

Legal and Ethical Asymmetry (GDPR/KVKK vs. Unconsented AI Training)

Regarding the protection and processing of biometric data, a strict normative regulatory regime exists on a global scale. The European Union General Data Protection Regulation (GDPR Article 9) and the Republic of Turkey Personal Data Protection Law (KVKK/LPPD Article 6) evaluate biometric data under the status of "special category personal data"; binding the processing of this data to extremely strict conditions, explicit consent, data minimization principles, and "right to be forgotten" mechanisms

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(European Union, 2016; T.C. Resmî Gazete, 2016). Legitimate biometric authentication providers undergo rigorous audits to comply with these legal frameworks and to avoid severe administrative/financial sanctions.

However, there is a profound legal loophole conceptualized as "regulatory asymmetry" in current legal and ethical literature (Peirce, 2026):

- *Data Scraping and Legitimate Interest Abuse:* Generative AI developers and technology companies building large language/vision models collect public photos available on the open internet by bypassing copyright and consent mechanisms under the pretext of "fair use" or "publicly available data" (Hill, 2020; Zuboff, 2019).
- *The Illusion of Anonymization and Biometric Persistence in Models:* Once public photos are incorporated into LLM/LMM parameters or embedded into deep learning weights, it becomes technically almost impossible for the data subject to request the deletion or tracking of this data (Carlini et al., 2021).
- *Asymmetric Threat Space:* While legal biometric authentication companies are restricted by user consent, encryption, and deletion standards, malicious actors or unethical AI developers can freely synthesize facial data scraped from open networks (Peirce, 2026).

This situation creates an asymmetric cybersecurity and data ethics vulnerability where legal regulations cover only traditional data processing institutions, remaining inadequate in auditing the AI ecosystem that scrapes data and produces synthetic content on an internet scale.

3. METHODOLOGY

Research Design and Conceptual Approach

This study relies on a hybrid combination of qualitative case study and conceptual framework analysis among qualitative research designs (Yin, 2018). In the research, the vulnerability dimensions created by viral social media trends—emerging as a socio-technical phenomenon—on AI-based visual synthesis algorithms and biometric security architectures have been modeled through a multi-layered approach.

The methodological flow of the study consists of three main stages:

1. *Data Collection and Case Selection:* Trends that become viral on platforms like TikTok and Instagram, where users provide single facial photos as input to generative AI models (e.g., Google Gemini 2.5 Flash / Nano Banana infrastructure images, aging, and retroactive stylization filters), were selected as the object of examination (Peirce, 2026).

2. *Threat Vector Mapping:* The points of technical interaction and vulnerability between the outputs of the selected visual generation models and authentication systems utilizing "lazy biometrics" were mapped (ISO/IEC 30107-1, 2016).

3. *Legislative and Normative Comparison:* Biometric data protection standards (GDPR, KVKK/LPPD) and unconsented data scraping processes were compared via the qualitative document analysis method (Bowen, 2009).

Data Sources and Document Analysis

During the document analysis process (Bowen, 2009), the discrepancies between the provisions regarding the "processing of public data and its use in model training" in the platforms' Terms of Service and the legal frameworks that biometric identity providers are obligated to follow were systematically coded.

4. THREAT ANALYSIS AND FINDINGS

The Threat of Synthetic Identity (Deepfake) Generation from a Single Image

The first fundamental finding of the research is that current deep learning models can produce highly convincing, dynamic, and high-fidelity synthetic identities from a static and single facial image (Korshunov & Marcel, 2018; Rombach et al., 2022). In traditional approaches, for an individual to be

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the subject of deepfake content, dozens of photographs taken from different angles or high-quality video recordings were required. However, Diffusion Models and zero-shot face-swapping algorithms can reconstruct 3D facial anatomy and texture from a single low-resolution selfie shared on social media.

This confirms that viral trends (such as "hug your childhood self" or "see your future self" filters), which users perceive as innocent entertainment or identity performance, constitute a massive, ready-to-process biometric data mine for attackers (Zuboff, 2019; Peirce, 2026).

Knowledge-Based Authentication (KBA) and "Lazy Biometrics" Vulnerabilities

The second finding reveals that social media trends not only weaken biometric data but also Knowledge-Based Authentication (KBA) mechanisms.

1. *Social Engineering and KBA Breach:* The participation of individuals in viral trends involving their past school photos, childhood cities, family members, or first pets transforms the "security questions" used in banking and public services into open-source intelligence (OSINT) for attackers.

2. *Lazy Biometrics Exploitation*: Biometric systems that do not perform liveness detection or only offer 2D template matching ("lazy biometrics") can be easily deceived by synthetic media broadcasts derived from a single photo (Atoum et al., 2018; Peirce, 2026). An artificial video held up to the screen or a deepfake stream injected directly into the camera channel via injection software is perceived as a "valid user" by lazy biometric authentication layers.

The Asymmetric Gap Between Biometric Providers and AI Developers

The third and most critical qualitative finding of the study is the regulatory asymmetry in the biometric data ecosystem.

Evaluation Criteria	Licensed Biometric Identity Providers	Generative AI Developers & Scrapers
Legal Framework	Strict legislation such as GDPR (Art. 9), KVKK (Art. 6)	Legal gray areas, ambiguous Terms of Service (ToS)
Consent Mechanism	Explicit and informed consent required	Tendency to consider open internet data as "implied consent"
Data Deletion Rights	Right to be forgotten and permanent data deletion obligation	Inability to delete data embedded into model parameters
Security Standard	ISO/IEC 30107 PAD/IAD testing obligation	Free data collection without security auditing

This table demonstrates that while the legal system strictly regulates biometric identity providers, it creates a systemic security vulnerability by allowing AI data scrapers to process facial data in the public domain boundlessly (Carlini et al., 2021; Peirce, 2026).

CONCLUSION AND POLICY/FUTURE STUDY RECOMMENDATIONS

This study has comprehensively demonstrated the lasting vulnerabilities created by viral visual trends, which have become widespread as a digital performance and entertainment practice on social media platforms, over individual biometric security and data privacy. The findings confirm that, thanks to

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advancements in generative AI and diffusion models, even a static and single social media photo shared in the public domain can be transformed into high-fidelity synthetic identities (deepfakes).

The main conclusions reached by the study can be summarized along three main axes:

- *Vulnerability of "Lazy Biometrics" Systems:* Primitive biometric authentication infrastructures that only perform 2D template matching and lack liveness detection are rendered entirely dysfunctional against generative AI-output deepfake streams and injection attacks.
- *Social Engineering and KBA Vulnerability*: Users exposing their retrospective data (childhood, school, family, etc.) through viral trends transforms Knowledge-Based Authentication (KBA) questions used in finance and public infrastructures into open-source intelligence (OSINT).
- *Systemic Regulatory Asymmetry:* While licensed biometric identity providers are bound to strict personal data protection legislation (GDPR, KVKK/LPPD), unconsented data scraping of facial data on the open internet by AI developers creates a severe legal and ethical gap.

In conclusion, individual digital literacy and restrictive measures alone are insufficient to prevent these threats. It is imperative to renew cybersecurity infrastructures and synchronize the legal framework with technological reality.

Policy and Regulation Recommendations

The fundamental policy steps that must be implemented to address the risks and legal asymmetry created by viral visual trends are as follows:

1. *Tightening Explicit Consent and Data Scraping Norms:* The evaluation of images published in the public domain under "automatic consent" must be terminated; the principles of explicit and informed consent must be made mandatory for AI data scrapers in accordance with GDPR Article 9 and KVKK/LPPD Article 6.

2. *Algorithmic Right to be Forgotten (Machine Unlearning*): Legal and technical standards must be developed to ensure that biometric data used in the training processes of AI models is permanently deleted from model parameters upon the user's request.

3. *Standardized Liveness and Channel Security (PAD/IAD*): Liveness Detection (PAD) conforming to ISO/IEC 30107-3 standards and encrypted data transmission (IAD) must be made a legal requirement in biometric systems used in finance, e-government, and critical infrastructures.

4. *Biometric Data Watermarking and Labeling:* At the publisher platform and device manufacturer level, the integration of protective digital watermarking and data poisoning technologies, which prevent scraping by AI models, should be encouraged as a standard data protection layer.

Recommendations for Future Studies

In light of the findings presented in this research, it is recommended that the following topics be examined in depth in future academic and technical studies:

- *Empirical Attack Tests (FAR/FRR Analysis):* The impact of different generative AI architectures (Latent Diffusion, multimodal models, etc.) on the False Acceptance Rate (FAR) and False Rejection Rate (FRR) values of current biometric facial recognition systems should be measured through empirical experiments.
- *Algorithmic Deletion Technologies*: Algorithmic solutions for machine unlearning and data protection optimizations regarding how biometric data embedded into AI models can be technically cleansed should be investigated.
- *Remote Photoplethysmography (rPPG) Performance*: The resistance capacity of rPPG technologies, which perform liveness verification by analyzing subcutaneous capillary blood flow, against high-resolution synthetic video streams can be tested under various environmental variables.

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ÇOCUKLARDA DİJİTAL EKRAN MARUZİYETİ: UYKU VE GELİŞİMSEL SONUÇLARIN ÇOCUK SAĞLIĞI VE HASTALIKLARI HEMŞİRELİĞİ PERSPEKTİFİNDEN DEĞERLENDİRİLMESİ

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ÖZET

Dijitalleşen dünyada çocukların dijital medya araçlarına erişimi giderek yaygınlaşmakta, dijital medya kullanımına başlama yaşı ise giderek düşmektedir. Bu durum, dijital ekran maruziyetinin çocuk sağlığı üzerindeki etkilerini önemli bir halk sağlığı konusu hâline getirmiştir. Araştırmalar, dijital medyanın aşırı ve uygunsuz kullanımının çocuklarda uyku düzeni, bilişsel gelişim, dil gelişimi ve psikososyal sağlık üzerinde olumsuz etkiler oluşturabileceğini göstermektedir. Bu derlemenin amacı, dijital ekran maruziyetinin çocuk sağlığı üzerindeki etkilerini güncel bilimsel kanıtlar doğrultusunda değerlendirmek ve çocuk sağlığı ve hastalıkları hemşirelerinin koruyucu, eğitici ve danışmanlık rollerini ortaya koymaktır. İncelenen çalışmalar, ekran süresindeki artışın çocuklarda daha kısa uyku süresi, düşük uyku kalitesi ve uykuya dalma süresinin uzaması ile ilişkili olabileceğini göstermektedir. Bununla birlikte, dijital medya kullanımının çocuk sağlığı üzerindeki etkilerinin yalnızca ekran süresine bağlı olmadığı; dijital içeriğin niteliği, kullanım amacı ve ebeveyn rehberliğinin de önemli belirleyiciler olduğu vurgulanmaktadır. Bu doğrultuda çocuk sağlığı ve hastalıkları hemşirelerinin rutin çocuk izlemlerinde ekran kullanım alışkanlıklarını değerlendirmesi, ailelere yaşa uygun ve bilinçli medya kullanımı konusunda danışmanlık vermesi, sağlıklı uyku alışkanlıklarını desteklemesi ve kanıta dayalı hemşirelik girişimlerini uygulaması önerilmektedir. Bu girişimlerin, dijital medya kullanımına bağlı olumsuz sağlık sonuçlarının azaltılmasına ve çocukların sağlıklı büyüme ve gelişmelerinin desteklenmesine katkı sağlayacağı düşünülmektedir.

Anahtar Kelimeler: Çocuk, Dijital Medya, Ekran Süresi, Uyku, Gelişim, Çocuk Sağlığı Hemşireliği

ABSTRACT

In the digitalizing world, children's access to digital media tools is becoming increasingly widespread, and the age of initiation into digital media use is progressively declining. This situation has made the effects of digital screen exposure on child health a significant public health issue. Research shows that excessive and inappropriate use of digital media can have negative effects on children's sleep patterns, cognitive development, language development, and psychosocial health. The aim of this review is to evaluate the effects of digital screen exposure on child health in line with current scientific evidence and to highlight the preventive, educational, and consultative roles of pediatric nurses. Reviewed studies indicate that an increase in screen time may be associated with shorter sleep duration, poor sleep quality, and prolonged sleep latency in children. However, it is emphasized that the effects of digital media use on child health are not solely dependent on screen time; the quality of digital content, purpose of use,

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and parental guidance are also critical determinants. Accordingly, it is recommended that pediatric nurses assess screen-use habits during routine child evaluations, provide counseling to families on age-appropriate and mindful media use, promote healthy sleep habits, and implement evidence-based nursing interventions. These interventions are thought to contribute to reducing the adverse health outcomes associated with digital media use and supporting children's healthy growth and development.

Keywords: Child, Digital Media, Screen Time, Sleep, Development, Pediatric Nursing

1.GİRİŞ

Dijitalleşen dünyada ekran temelli teknolojik cihazların kullanımı çocukların günlük yaşamının ayrılmaz bir parçası hâline gelmiştir. Akıllı telefon, tablet, bilgisayar, televizyon ve diğer dijital medya araçlarına erişimin yaygınlaşmasıyla birlikte ekran maruziyeti çok erken yaşlara kadar inmiştir. Bu teknolojiler eğitim, iletişim ve eğlence açısından önemli fırsatlar sunmakla birlikte, erken yaşlarda kontrolsüz ve uzun süreli kullanımının çocuk sağlığı üzerindeki etkileri giderek daha fazla araştırılmaktadır (Reid Chassiakos et al., 2016; World Health Organization [WHO], 2019).

Çocukluk dönemi; fiziksel büyüme, nörolojik olgunlaşma ile bilişsel, dil, sosyal ve duygusal gelişimin en hızlı gerçekleştiği yaşam evresidir. Bu nedenle çocukların yeterli uyku uyuması, akranları ve aileleriyle etkileşim kurması, oyun oynaması ve yaşlarına uygun çevresel uyaranlarla karşılaşması sağlıklı büyüme ve gelişmenin temel bileşenleri arasında yer almaktadır. Dijital medya kullanımının bu gelişimsel gereksinimlerin yerini alması veya bu gereksinimleri olumsuz etkilemesi durumunda çocuk sağlığı açısından çeşitli riskler ortaya çıkabilmektedir (WHO, 2019; Madigan et al., 2019).

Literatürde ekran maruziyetinin en sık ilişkilendirildiği sağlık sonuçlarından biri uyku bozukluklarıdır. Özellikle yatmadan önce ekran kullanımının uykuya dalma süresini uzattığı, toplam uyku süresini azalttığı ve uyku kalitesini olumsuz etkilediği bildirilmektedir. Ayrıca dijital içeriklerin oluşturduğu bilişsel ve duygusal uyarılmışlık ile dijital cihazlardan yayılan kısa dalga boylu mavi ışığın melatonin salınımını baskılaması, çocuklarda görülen uyku problemleriyle ilişkilendirilmektedir (Hale & Guan, 2015; Carter et al., 2016; LeBourgeois et al., 2017).

Erken çocukluk dönemindeki ekran maruziyetinin yalnızca uyku üzerinde değil, dil gelişimi, dikkat, yürütücü işlevler ve öğrenme süreçleri üzerinde de etkili olabileceği bildirilmektedir. Güncel çalışmalar, bu ilişkinin yalnızca ekran süresiyle açıklanamayacağını; içeriğin niteliği, çocuğun gelişimsel özellikleri, ebeveyn rehberliği ve ortak medya kullanımının da önemli belirleyiciler olduğunu göstermektedir (Madigan et al., 2020; Bal et al., 2024; Massaroni et al., 2024).

Ekran kullanımının psikososyal gelişim üzerindeki etkileri de son yıllarda önem kazanan araştırma konularından biridir. Yaşa uygun olmayan içeriklere maruz kalma, arka planda sürekli açık televizyon bulunması ve ebeveynlerin yoğun dijital medya kullanımı; çocuklarda davranış sorunları, duygu düzenleme güçlükleri ve sosyal etkileşimde azalma ile ilişkilendirilmektedir. Buna karşın, ebeveyn rehberliğinde gerçekleştirilen ve gelişim düzeyine uygun eğitsel içeriklerin çocukların gelişimine olumlu katkı sağlayabileceği de bildirilmektedir (Mallawaarachchi et al., 2024).

Amerikan Pediatri Akademisi (AAP), önceki önerilerinde ekran süresinin sınırlandırılmasına odaklanırken, güncel yaklaşımında çocukların dijital deneyimlerinin bir "dijital ekosistem" içerisinde değerlendirilmesi gerektiğini vurgulamaktadır. Bu yaklaşım; ekran süresinin yanı sıra dijital içeriklerin niteliği, kullanılan platformların özellikleri, aile ortamı, ebeveyn rehberliği ve çocuğun gelişimsel gereksinimlerinin birlikte değerlendirilmesini önermektedir (Munzer et al., 2026).

Çocuk sağlığı ve hastalıkları hemşireleri, koruyucu sağlık hizmetleri kapsamında çocukların dijital medya kullanım alışkanlıklarının değerlendirilmesi, ailelere yaşa uygun medya kullanımı konusunda eğitim ve danışmanlık verilmesi, sağlıklı uyku alışkanlıklarının desteklenmesi ve riskli ekran kullanım davranışlarının erken dönemde belirlenmesinde önemli sorumluluklar üstlenmektedir. Kanıta dayalı hemşirelik girişimleri ile çocukların sağlıklı büyüme ve gelişmeleri desteklenebilir ve dijital medya kullanımına bağlı olumsuz sağlık sonuçlarının azaltılmasına katkı sağlanabilir (Reid Chassiakos et al., 2016; WHO, 2019; Munzer et al., 2026).

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2. ÇOCUKLARDA DİJİTAL EKRAN MARUZİYETİNİN UYKU VE GELİŞİMSEL SÜREÇLER ÜZERİNE ETKİLERİ

2.1. DİJİTAL EKRAN MARUZİYETİNİN UYKU ÜZERİNE ETKİLERİ

Uyku, çocukluk döneminde büyüme ve gelişmenin desteklenmesi, bağışıklık sisteminin güçlenmesi ve duygusal iyilik hâlinin sürdürülmesi açısından temel bir fizyolojik gereksinimdir. Dijital teknolojilerin günlük yaşamda yaygınlaşmasıyla birlikte ekran kullanımının uyku alışkanlıkları üzerindeki etkileri çocuk sağlığı alanında önem kazanan araştırma konularından biri hâline gelmiştir. Özellikle yatmadan önce ekran kullanımı, uzun süreli ekran maruziyeti ve uyku ortamında elektronik cihazların bulunması; daha geç uykuya dalma, toplam uyku süresinin azalması ve uyku kalitesinin bozulması ile ilişkilendirilmektedir (Carter et al., 2016; Hale & Guan, 2015).

Ekran kullanımının uyku üzerindeki etkileri çeşitli mekanizmalarla açıklanmaktadır. Dijital cihazlardan yayılan kısa dalga boylu mavi ışığın melatonin salınımını baskılayarak sirkadiyen ritmi etkileyebileceği düşünülmektedir. Özellikle akşam saatlerinde dijital medya kullanımının artması, çocukların biyolojik uyku düzenini bozmakta ve uykuya dalma süresinin uzamasıyla ilişkilendirilmektedir. Ayrıca duygusal açıdan uyarıcı dijital içerikler, çocuklarda uyku öncesi zihinsel uyarılmışlığı artırarak uyku kalitesini olumsuz etkileyebilmektedir (Chang et al., 2015; Stiglic ve Viner, 2019).

Okul öncesi ve okul çağı çocuklarında gerçekleştirilen çalışmalar, uzun ekran kullanım süresinin daha kısa uyku süresi ve düzensiz uyku alışkanlıkları ile ilişkili olduğunu göstermektedir. Yaşa göre önerilen sürelerin üzerinde ekran kullanan çocuklarda gece uyanmalarının daha sık görüldüğü, uyku düzeninin bozulduğu ve gündüz yorgunluğunun arttığı bildirilmektedir. Bu olumsuzlukların dikkat, öğrenme süreçleri ve davranışsal beceriler üzerinde de olumsuz sonuçlara yol açabileceği belirtilmektedir (Janssen et al., 2020; Lund et al., 2021).

Amerikan Pediatri Akademisi, çocuklarda sağlıklı uyku alışkanlıklarının desteklenmesi amacıyla özellikle uyku öncesi dönemde ekran kullanımının sınırlandırılmasını, elektronik cihazların uyku ortamında bulundurulmamasını ve ailelerin düzenli medya kullanım rutinleri oluşturmasını önermektedir (American Academy of Pediatrics, 2016; Radesky et al., 2020). Bebeklik ve erken çocukluk döneminde sinir sisteminin hızlı gelişimi nedeniyle ekran maruziyetinin uyku üzerindeki etkileri daha belirgin olabilmektedir. Bu dönemde çevresel uyaranların niteliği ve zamanlaması büyük önem taşımaktadır. Dünya Sağlık Örgütü de beş yaş altındaki çocuklarda ekran süresinin sınırlandırılmasını, fiziksel aktivitenin artırılmasını ve bakım veren ile etkileşimin desteklenmesini önermektedir (World Health Organization, 2019).

Ebeveynlerin yoğun ekran kullanımı, ev içinde elektronik cihazların sürekli açık olması ve düzenli uyku rutinlerinin oluşturulmaması, çocukların medya kullanım alışkanlıklarını etkileyen önemli çevresel faktörler arasındadır. Bu nedenle ekran kullanımının uyku üzerindeki etkileri değerlendirilirken aile ortamı ve ebeveynlerin dijital medya kullanım davranışları da göz önünde bulundurulmalıdır. Dijital medyanın ebeveyn rehberliğinde kullanılması ve ebeveynlerin sağlıklı dijital medya alışkanlıkları konusunda çocuklarına rol model olması, çocuklarda sağlıklı medya kullanım davranışlarının geliştirilmesine katkı sağlayacaktır (Lauricella et al., 2015; Radesky et al., 2020).

2.2. DİJİTAL EKRAN MARUZİYETİNİN DİL GELİŞİMİ ÜZERİNE ETKİLERİ

Çocukların iletişim kurma, düşüncelerini ifade etme, sosyal ilişkiler geliştirme ve öğrenme süreçlerine katılma becerilerinin temelini dil gelişimi oluşturmaktadır. Özellikle yaşamın ilk yıllarında beynin hızlı gelişim göstermesi, dil becerilerinin yetişkinlerle kurulan karşılıklı iletişime ve sunulan sözel uyaranların niteliğine doğrudan bağlı olmasına neden olmaktadır. Günümüzde dijital ekranların erken çocukluk döneminde yaygınlaşması, ekran maruziyetinin dil gelişimi üzerindeki olası etkilerini araştırmaların odak noktalarından biri hâline getirmiştir. Güncel bulgular, erken yaşta başlayan ve uzun süreli ekran kullanımının ifade edici dil becerilerinde gecikmeye ve sözel etkileşimin azalmasına yol açabileceğini göstermektedir (Madigan et al., 2019; van den Heuvel et al., 2019; Kebir & Özkaya, 2023).

Çocuk ile bakım veren arasında kurulan karşılıklı iletişim, erken çocukluk dönemindeki dil gelişiminin en önemli belirleyicilerinden biridir. Konuşma, soru-cevap etkileşimleri ve ortak dikkat gibi iletişim süreçleri çocukların kelime dağarcığının gelişmesine katkı sağlamaktadır. Buna karşılık, ekran başında

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uzun süre pasif olarak zaman geçirilmesi bu gelişimsel fırsatları azaltmaktadır. Özellikle yaşamın ilk üç yılında yüz yüze iletişimin yetersiz olması, çocukların sözcük dağarcığının gelişimini sınırlandırmakta ve iletişim girişimlerini azaltabilmektedir (Brushe et al., 2024)

Araştırmalar, ekran kullanımının dil gelişimi üzerindeki etkisinin yalnızca ekran süresiyle açıklanamayacağını; ekran kullanımına başlama yaşı, içerik özellikleri ve ebeveyn katılımının da önemli belirleyiciler olduğunu ortaya koymaktadır. Yaşa uygun, etkileşimli ve eğitsel içeriklerin yetişkin rehberliğinde kullanılması bazı dil becerilerinin gelişimini destekleyebilmektedir. Bununla birlikte, dijital araçların çocuk ile ebeveyn arasındaki doğal iletişimin yerini alması, dil gelişimi açısından önemli bir risk oluşturmaktadır (Hutton et al., 2020; Madigan et al., 2020).

Küçük çocukların dijital içeriklerden bilgi edinme kapasiteleri, gerçek yaşam deneyimlerine kıyasla daha sınırlıdır. Özellikle üç yaş altındaki çocuklar, ekranda gördükleri sembolik içerikleri gerçek nesne ve olaylarla ilişkilendirmekte güçlük yaşayabilmektedir. Bu nedenle erken çocukluk döneminde kitap okuma, oyun oynama ve ebeveynle kurulan sözel etkileşimler, dil gelişimini desteklemede ekran temelli etkinliklerden daha etkili kabul edilmektedir (Anderson & Pempek, 2005; DeLoache et al., 2010).

Ekran içeriklerinin niteliği de çocukların dil gelişimini etkileyen önemli unsurlardan biridir. Yaşa uygun, sakin ritimli ve etkileşimli içeriklerin ebeveyn eşliğinde izlenmesi kelime dağarcığının gelişimine katkı sağlayabilirken, yoğun görsel ve işitsel uyaran içeren, çocuğu pasif izleyici konumunda bırakan içerikler bilişsel süreçleri ve dil gelişimini olumsuz etkileyebilmektedir (Radesky et al., 2015; Christakis, 2019).

Çocukların dil gelişimini belirleyen tek faktör ekran kullanımı değildir. Asıl önemli olan; ekran kullanımına erken yaşta başlanması, ekran karşısında uzun süre geçirilmesi ve ekranın çocuk ile bakım veren arasındaki iletişimin yerini almasıdır. Çocukların dil gelişimini destekleyen en güçlü unsur, ebeveynleri ve bakım verenleriyle kurdukları nitelikli ve karşılıklı iletişimdir. Bu nedenle çocuk sağlığı ve hastalıkları hemşirelerinin ailelere medya kullanımı konusunda rehberlik etmesi, sağlıklı iletişim ortamlarının oluşturulmasını desteklemesi ve gelişimsel riskler konusunda farkındalık kazandırması büyük önem taşımaktadır.

2.3. DİJİTAL EKRAN MARUZİYETİNİN BİLİŞSEL GELİŞİM ÜZERİNE ETKİLERİ

Bilişsel gelişim; çocuğun dünyayı anlamlandırma, bilgiyi işleme, problem çözme ve dikkatini yönetme becerilerinin temelini oluşturmaktadır. Özellikle sinir sisteminin hızla geliştiği erken çocukluk dönemi, çevresel deneyimlerin bilişsel süreçleri doğrudan şekillendirdiği kritik bir gelişim evresidir. Bu nedenle çocukların dijital ekranlarla kurduğu etkileşim, bilişsel gelişimin yönünü etkileyebilecek önemli çevresel faktörlerden biri olarak değerlendirilmektedir (Kostyrka-Allchorne et al., 2017; Radesky & Christakis, 2016).

Çocuklar bilişsel becerilerini; aktif oyun oynayarak, keşfederek, fiziksel deneyimler yaşayarak ve sosyal etkileşimlerde bulunarak geliştirmektedir. Buna karşın, ekran karşısında uzun süre pasif olarak zaman geçirilmesi; çocukların problem çözme, keşfetme ve çevreleriyle doğrudan etkileşim kurma fırsatlarını azaltabilmektedir. Özellikle erken çocukluk döneminde ekran kullanımının oyun, kitap okuma ve ebeveynle kurulan etkileşimin yerini alması; dikkat gelişimi, sembolik düşünme ve öğrenme süreçlerini olumsuz yönde etkileyebilmektedir (Madigan et al., 2019; Zubrick et al., 2010).

Ekran maruziyeti ile bilişsel gelişim arasındaki ilişkinin önemli bileşenlerinden biri dikkat süreçleridir. Yoğun görsel ve işitsel uyaran içeren hızlı tempolu dijital içeriklerin çocukların dikkat süreçlerini etkileyebileceği bildirilmektedir. Bununla birlikte, mevcut çalışmalar ekran kullanımı ile dikkat sorunları arasında doğrudan bir neden-sonuç ilişkisini kesin olarak ortaya koymamaktadır. Çocuğun mizacı, aile ortamı ve kullanılan dijital içeriğin niteliği gibi birçok faktörün bu ilişki üzerinde etkili olduğu belirtilmektedir (Christakis et al., 2018; Tamana et al., 2019).

Dijital ekran kullanımının bilişsel gelişim üzerindeki etkileri değerlendirilirken yalnızca ekran süresi değil, ekranın kullanım biçimi ve içeriği de dikkate alınmalıdır. Yaşa uygun, etkileşimli ve eğitsel dijital içerikler yetişkin rehberliğinde kullanıldığında çocukların kavram öğrenmesini, erken akademik becerilerini ve problem çözme yeteneklerini destekleyebilmektedir. Ancak bu olumlu etkilerin ortaya

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çıkabilmesi için çocuğun pasif izleyici konumunda kalmaması, aktif katılımının sağlanması ve sosyal etkileşimle desteklenmesi gerekmektedir (Hirsh-Pasek et al., 2015).

Son yıllarda gerçekleştirilen nörogörüntüleme çalışmaları da erken çocukluk dönemindeki yoğun ekran maruziyetinin beyin gelişimi üzerindeki olası etkilerini incelemektedir. Okul öncesi çocuklarda yapılan bazı araştırmalar, yüksek ekran kullanımının dil, bilişsel kontrol ve yürütücü işlevlerle ilişkili beyin bölgelerindeki yapısal farklılıklarla ilişkili olabileceğini bildirmektedir. Bununla birlikte, bu bulgular ekran kullanımının beyin yapısını doğrudan değiştirdiğini göstermemekte; genetik özellikler ve çevresel faktörlerin birlikte değerlendirilmesi gerektiğine işaret etmektedir (Hutton et al., 2020).

Dijital ekran kullanımının bilişsel gelişim üzerindeki etkileri çok boyutlu bir yaklaşımla ele alınmalıdır. Ekran kullanım süresi kadar içerik niteliği, fiziksel aktivite düzeyi, uyku kalitesi, aile içi etkileşim ve çocuğun gelişimsel özellikleri de bilişsel gelişimi etkileyen önemli faktörlerdir. Bu nedenle çocukların bilişsel gelişiminin desteklenmesinde dengeli medya kullanımı ile birlikte oyun, fiziksel aktivite ve sosyal etkileşimlerin teşvik edilmesi önem taşımaktadır (Hale & Guan, 2015; Janssen et al., 2020).

2.4. DİJİTAL EKRAN MARUZİYETİNİN YÜRÜTÜCÜ İŞLEVLER VE PSİKOSOSYAL GELİŞİM ÜZERİNE ETKİLERİ

Yürütücü işlevler; dikkatin sürdürülmesi ve kontrolü, çalışma belleği, bilişsel esneklik, planlama, problem çözme ve davranışların düzenlenmesini sağlayan üst düzey nörobilişsel süreçlerdir. Bu beceriler özellikle okul öncesi ve ilkokul döneminde hızla gelişmekte olup çocukların akademik başarıları, sosyal uyumları ve günlük yaşam becerileri açısından büyük önem taşımaktadır (Diamond, 2013; Zelazo & Carlson, 2012).

Yürütücü işlevler, çocukların çevreleriyle aktif etkileşim kurmaları, oyun oynamaları ve sosyal deneyimler yaşamalarıyla gelişmektedir. Buna karşın, ekran karşısında uzun süre pasif olarak zaman geçirilmesi; problem çözme, yaratıcı oyun, planlama ve sosyal öğrenme gibi gelişimsel deneyimlere ayrılan zamanı azaltarak yürütücü işlevleri dolaylı olarak olumsuz etkileyebilmektedir (Diamond ve Ling, 2019; Tandon et al., 2017).

Erken çocukluk döneminde yoğun ve kontrolsüz ekran kullanımının, çocukların uzun süre dikkat gerektiren etkinliklere uyum sağlamalarını güçleştirebildiği bildirilmektedir (Lillard & Peterson, 2011; Radesky et al., 2015). Çalışma belleği, bilişsel kontrol ve öz düzenleme becerileri; oyun, kitap okuma, fiziksel aktivite ve yüz yüze iletişim gibi gelişimsel deneyimlerle desteklenmektedir. Ekran kullanımının bu etkinliklerin yerini alması, öğrenme ve bilişsel kontrol süreçlerini olumsuz etkileyebilmektedir. Ayrıca dijital platformların sunduğu hızlı geri bildirim ve anlık ödül mekanizmalarının çocuklarda sabretme, bekleme ve dürtü kontrolü becerilerinin gelişimini olumsuz etkileyebileceği belirtilmektedir (Lillard et al., 2015; Madigan et al., 2019; Radesky ve Christakis, 2016; Hutton et al., 2020).

Çocukların psikososyal gelişimi; duygusal farkındalık, sosyal ilişkiler, iletişim becerileri ve çevreye uyum süreçlerini kapsamaktadır. Erken çocukluk döneminde bu beceriler büyük ölçüde aile içi etkileşim, oyun ve akran ilişkileri yoluyla gelişmektedir. Dijital araçların günlük yaşamda yaygın olarak kullanılması ise psikososyal gelişim üzerindeki olası etkilerin daha fazla araştırılmasına neden olmuştur. Araştırmalar, uzun süreli ekran kullanımının sosyal etkileşimi azaltabileceğini, duygu düzenleme güçlükleri ve çeşitli davranış sorunlarıyla ilişkili olabileceğini göstermektedir (Domingues-Montanari, 2017; Stiglic & Viner, 2019).

Çocuklar empati, sosyal kurallar ve iletişim becerilerini büyük ölçüde yüz yüze etkileşim yoluyla kazanmaktadır. Ekran kullanımının oyun zamanının ve aile içi etkileşimin yerini alması, özellikle küçük çocuklarda ortak dikkat becerileri ile sosyal katılımı olumsuz etkileyebilmektedir (Kardefelt-Winther, 2017; Radesky et al., 2020). Bunun yanında ekranların çocukları sakinleştirmek veya davranışlarını kontrol etmek amacıyla sık kullanılması, çocukların duygularını yönetme becerilerinin gelişimini sınırlandırabilmektedir (Radesky et al., 2014; Coyne et al., 2021).

Yüksek ekran kullanımının dikkat eksikliği, dürtüsellik ve öz denetim güçlükleriyle ilişkili olabileceği bildirilmekle birlikte, bu ilişkinin tek yönlü olmadığı da vurgulanmaktadır. Davranışsal sorunlar yaşayan çocukların ebeveynlerinin ekran kullanımına daha fazla başvurabilmesi, ilişkinin karşılıklı olabileceğini düşündürmektedir (Tamana et al., 2019; McHarg et al., 2020; Özgür et al., 2024). Okul çağı ve ergenlik

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döneminde ise dijital medya, akran ilişkilerini destekleyebilmekle birlikte, aşırı kullanım sosyal karşılaştırma, yalnızlık ve olumsuz beden algısıyla da ilişkilendirilmektedir. Bu durum, dijital medyanın etkisinin yalnızca kullanım süresine değil, kullanım amacına ve niteliğine de bağlı olduğunu göstermektedir (Odgers & Jensen, 2020; Orben & Przybylski, 2019).

Aile ortamı çocukların dijital medya kullanımının yönetilmesinde belirleyici bir role sahiptir. Ebeveyn rehberliği, ortak medya kullanımı ve sağlıklı dijital alışkanlıkların modellenmesi çocukların psikososyal gelişimini destekleyebilirken, ekran kullanımının aile içi etkileşimin yerini alması çocuk-ebeveyn ilişkisini olumsuz etkileyebilmektedir (American Academy of Pediatrics, 2016; Radesky et al., 2020).

2.5. ÇOCUK SAĞLIĞI VE HASTALIKLARI HEMŞİRESİNİN ROLÜ

Dijital teknolojilerin çocukların günlük yaşamına giderek daha fazla entegre olması, çocuk sağlığı ve hastalıkları hemşirelerinin ekran kullanımını büyüme ve gelişmeyi etkileyen önemli çevresel faktörlerden biri olarak değerlendirmesini gerekli kılmaktadır. Çocuk sağlığı ve hastalıkları hemşireleri, gelişimsel izlem süreçlerinde çocuk ve aile ile sürekli iletişim hâlinde olmaları nedeniyle dijital medya kullanım alışkanlıklarının değerlendirilmesi, risklerin erken belirlenmesi ve sağlıklı medya kullanım davranışlarının kazandırılmasında önemli sorumluluklar üstlenmektedir (American Academy of Pediatrics, 2016; Radesky et al., 2020).

Hemşirelik değerlendirmelerinde ekran maruziyeti; kullanılan cihaz türü, ilk kullanım yaşı, kullanım süresi, içerik niteliği, ebeveyn tutumları ve ekran kullanımının uyku, oyun ile fiziksel aktivite üzerindeki etkileri birlikte ele alınmalıdır. Bu bütüncül yaklaşım, riskli medya kullanım davranışlarının erken dönemde belirlenmesine ve gerekli girişimlerin zamanında planlanmasına katkı sağlayacaktır (Council on Communications and Media, 2016; World Health Organization, 2019).

Çocuk sağlığı ve hastalıkları hemşireleri, rutin büyüme ve gelişme izlemlerinde dijital medya kullanımını standart değerlendirme basamaklarından biri olarak ele almalıdır. Özellikle dil gelişiminde gecikme, dikkat sorunları, sosyal etkileşimde azalma veya davranışsal güçlükler saptandığında çocuğun ekran kullanım alışkanlıkları ayrıntılı olarak değerlendirilmelidir. Gerektiğinde uygun multidisipliner ekip üyelerine yönlendirme yapılması, erken müdahalenin etkinliğini artıracaktır (Lipnowski et al., 2012; Hutton et al., 2020).

Sağlık eğitimi ve danışmanlık, çocuk sağlığı ve hastalıkları hemşiresinin temel rollerinden biridir. Bu kapsamda ailelere yalnızca ekran süresinin değil, içerik kalitesinin, kullanım amacının ve ebeveyn rehberliğinin de çocuk gelişimi açısından önemli olduğu açıklanmalıdır. Ayrıca uyku öncesinde ekran kullanımının sınırlandırılması, yemek sırasında ekran kullanımından kaçınılması, ekran yerine kitap okuma, oyun ve aile içi etkileşimi destekleyen etkinliklerin teşvik edilmesi gibi uygulanabilir öneriler sunulmalıdır (Radesky ve Christakis, 2016; AAP Council on Communications and Media, 2020).

Ebeveyn danışmanlığında aile merkezli bir yaklaşım benimsenmelidir. Ailelerin sosyoekonomik koşulları, günlük yaşam düzenleri ve bakım olanakları dikkate alınarak gerçekçi ve sürdürülebilir öneriler geliştirilmelidir. Bu süreçte hemşirelerin suçlayıcı bir yaklaşım yerine destekleyici ve iş birliğine dayalı bir iletişim kurması önem taşımaktadır. Amaç teknolojiyi tamamen ortadan kaldırmak değil, çocuğun gelişimsel gereksinimlerine uygun, dengeli ve güvenli medya kullanımını desteklemektir (Kardefelt-Winther, 2017; Radesky et al., 2020).

Hemşireler aynı zamanda ailelerin dijital sağlık okuryazarlığının geliştirilmesinde de önemli bir role sahiptir. Ailelere güvenilir bilgi kaynaklarına erişim, doğru dijital içerik seçimi, çevrim içi güvenlik ve dijital risklerin yönetimi konularında rehberlik edilmelidir (Norman ve Skinner, 2006).

Çocuk sağlığı ve hastalıkları hemşireleri; değerlendirme, eğitim, danışmanlık ve savunuculuk rolleriyle çocukların sağlıklı dijital medya kullanımının desteklenmesinde önemli bir konuma sahiptir. Çocukların uyku, oyun, fiziksel aktivite ve sosyal etkileşim gereksinimlerini gözeten bütüncül hemşirelik yaklaşımları, dijital medya kullanımına bağlı olumsuz sağlık sonuçlarının önlenmesine ve sağlıklı büyüme ve gelişmenin desteklenmesine katkı sağlayacaktır (World Health Organization, 2019; American Academy of Pediatrics, 2020).

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3. SONUÇ VE ÖNERİLER

Dijital teknolojilerin çocukların günlük yaşamındaki yerinin giderek artması, ekran maruziyetinin çocuk sağlığı üzerindeki etkilerinin kapsamlı biçimde değerlendirilmesini gerekli kılmaktadır. Bu derlemede incelenen çalışmalar, özellikle erken yaşlarda başlayan ve kontrolsüz dijital ekran kullanımının çocukların uyku düzeni, dil gelişimi, bilişsel gelişimi, yürütücü işlevleri ve psikososyal gelişimleri üzerinde olumsuz etkiler oluşturabileceğini göstermektedir. Bununla birlikte, mevcut literatür ekran kullanımının etkilerinin yalnızca maruz kalınan süre ile açıklanamayacağını; dijital içeriğin niteliği, kullanım amacı, çocuğun gelişimsel özellikleri ve ebeveyn rehberliğinin de belirleyici olduğunu ortaya koymaktadır.

Çocuk sağlığı ve hastalıkları hemşireleri, çocukların dijital medya kullanım alışkanlıklarının değerlendirilmesi, ailelere yaşa uygun medya kullanımı konusunda eğitim ve danışmanlık verilmesi, sağlıklı uyku alışkanlıklarının desteklenmesi ve riskli ekran kullanım davranışlarının erken dönemde belirlenmesinde önemli sorumluluklara sahiptir. Bu nedenle rutin çocuk izlemlerinde ekran kullanım alışkanlıklarının sorgulanması, aile merkezli danışmanlık hizmetlerinin sunulması ve sağlıklı medya kullanımına yönelik kanıta dayalı hemşirelik girişimlerinin uygulanması büyük önem taşımaktadır.

Gelecekte yapılacak araştırmalarda, farklı yaş gruplarında ekran kullanımının uzun dönem etkilerini inceleyen prospektif çalışmaların artırılması, ekran süresinin yanı sıra dijital içerik türü, ebeveyn rehberliği ve aile ortamı gibi değişkenlerin birlikte değerlendirilmesi önerilmektedir. Ayrıca çocuk sağlığı ve hastalıkları hemşireleri tarafından yürütülecek eğitim ve danışmanlık programlarının etkinliğini değerlendiren girişimsel çalışmaların planlanması, çocuklarda sağlıklı dijital medya kullanımının desteklenmesine yönelik kanıtların güçlendirilmesine katkı sağlayacaktır.

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DISPERSION OF TORSIONAL WAVES IN INITIALLY-STRESSED TRANSVERSELY ISOTROPIC HOLLOW COMPOSITE POROELASTIC CYLINDERS

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ABSTRACT

The present study investigates the torsional wave propagation in composite hollow poroelastic cylinder of transversely isotropic nature under initial-stress, within the framework of Biot's poroelastic theory. The composite structure is modeled as two coaxial layers: an inner core and a substrate, with each layer having independent material constants. The governing dynamical equations are derived from the fundamental equilibrium relations for a saturated porous solid. Applying traction-free conditions at the inner and outer surfaces leads to the derivation of the dispersion relation. For numerical computations, three composite cylinders of different materials are considered and then discussed. The influence of wave number, degree of material anisotropy, thickness ratio, and initial stress on the phase velocity is evaluated numerically. It is observed from the numerical results that the presence of initial stress affects the phase velocity values for all materials considered.

Keywords: Poroelasticity, Torsional vibration, Initial stress, Transverse isotropy, Composite cylinder, Phase velocity.

1. Introduction

In recent years, the dynamic behavior of fluid-saturated porous media has been attracting considerable attention due to its importance in various Engineering fields such as Soil Mechanics, Biomechanics, Geophysics and Earth quake Engineering. Composites are one of the most widely used materials because of their adaptability to different situations in everyday life. A composite material consists of two or more constituent materials with different physical properties, that could be joined and produce a material with different characteristics from that of each of the material. From the real time experiences, one may find that buildings, bridges, and some manmade structures consist of two or more materials that could be combined to take advantage of the good characteristics of each of the materials, particularly in making smart materials. The problems related to pre-stressed elastic solids has been a subject of continued interest due to its importance in the said structures. A detailed discussion about the theory of elastic medium under initial stress is given in Biot's incremental theory (Biot 1956). Torsional wave propagation in an initially stressed elastic cylinder is studied by Dey and Dutta (1992). Plane strain deformation of an initially stressed orthotropic elastic medium is studied using eigen value approach (Selim and Ahmed 2006). Surface wave propagation in an initially stressed transversely isotropic thermoelastic solid is studied by Baljeet Singh and Renu (2012). Biot (1956) formulated the constitutive equations and equations of motion for fluid-saturated poroelastic solids. In the frame work of Biot's theory (1956), the effect of boundaries on torsional vibrations in a poroelastic cylinder is reported in several papers (Tajuddin and Sarma 1977, Tajuddin 1982, Ahmed and Tajuddin 2010, Tajuddin and Sarma 1980, Tajuddin and Shah 2007). Torsional vibrations in composite transversely isotropic poroelastic cylinders are investigated by Sandhya and Reddy (2015). In the said paper, the governing equations of transversely isotropic poroelastic dissipative solids are formulated for the case of radial vibrations. Radial vibrations in thick-walled transversely isotropic poroelastic cylindrical bone in presence of dissipation are studied by Reddy and Sandhya (2016). Torsional vibrations in composite transversely isotropic poroelastic cylinders are investigated by Sandhya et.al (2015). In the paper Sandhya et.al (2015), the limiting cases of a poroelastic thick-walled hollow cylinder, thin poroelastic shell and plate are discussed by using appropriate approximations. An analytical and numerical study for the torsional vibrations of viscous fluid-filled three-layer transversely isotropic cylinder is presented

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in the paper (Wafik et. al 2016). The effect of gravity and initial stress on the propagation of torsional surface waves in heterogeneous medium is investigated by Mukhopadhyay et. al (2017). In the said paper, it is observed that the phase velocity of torsional surface waves increases with the growth of rigidity in presence of initial stress and gravity for both rigid and traction free boundary. The behavior of the torsional surface wave in a heterogeneous initially stressed vertical fluid-saturated anisotropic layer sandwiched between inhomogeneous and homogeneous porous half-space is studied by Rajneesh and Shikha (2018). In the paper (Rajneesh and Shikha 2018), it is observed that heterogeneity, porosity, initial stress of the layer and inhomogeneity of the upper and porosity of lower half-spaces affect the torsional wave speed much. Balu et. al (2019) studies torsional vibrations of a poroelastic dissipative thick-walled hollow cylinder in the presence of an initial stress. In the paper (Balu et. al 2019), frequency equations are obtained in the case of dissipation under stress free boundary conditions. Also, the limiting cases of a solid cylinder and thin shell are discussed. The torsional wave in an irregular self-reinforced composite layer bonded between dry sandy media and an isotropic elastic half-space is investigated by Gupta and Das (2020). In the paper (Gupta and Das 2020), the effects of different affecting parameters such as reinforcement, sandiness, initial stress and irregularity parameters are explored. Selene Solorza-Calderon (2021) studied the torsional vibrations of infinite fully saturated, axial-symmetric, poroelastic cylinders based on Biot viscosity-extended theory. In the paper (Selene Solorza-Calderon 2021), the results with both theoretical frameworks, as expected, the torsional waves were attenuated more in the Biot viscosity-extended theory framework. Selim (2021) discussed the torsional vibration of irregular single-walled carbon nanotube incorporating compressive initial stress effects is investigated. In the paper (Selim 2021), the natural frequencies are obtained analytically, and the influences of surface irregularity and compressive initial stresses on the torsional vibration are studied. In the present paper, torsional vibrations in an initially stressed composite transversely isotropic poroelastic cylinder of infinite extent are investigated. This composite poroelastic cylinder consists of an inner solid circular cylinder of one material enveloped by another thick-walled hollow cylinder made of another poroelastic material. The phase velocity is computed as a function of wavenumber, ratio of radii, and anisotropic ratios at different initial stresses.

The rest of the paper is organized as follows. In section 2, governing equations and solution of the problem are discussed. Boundary conditions and frequency equation are presented in section 3. Numerical results are discussed in Sect. 4. Finally, conclusion is given in Sec. 5.

2. Governing Equations and solution of the problem

Let (r, θ, z) be the cylindrical polar coordinates. Consider a composite concentric transversely isotropic poroelastic cylinder with inner and outer radii r_1 and r_2, respectively, coincides with the axis of the cylinder. The core is a circular solid cylinder with radius r_1 and the substrate is a thick-walled hollow cylinder having thickness $h\ (= r_2 - r_1)$. Let the cylinder is in the direction of z-axis as shown in Fig. 1. The z-axis coincides with the axis of the cylinder.

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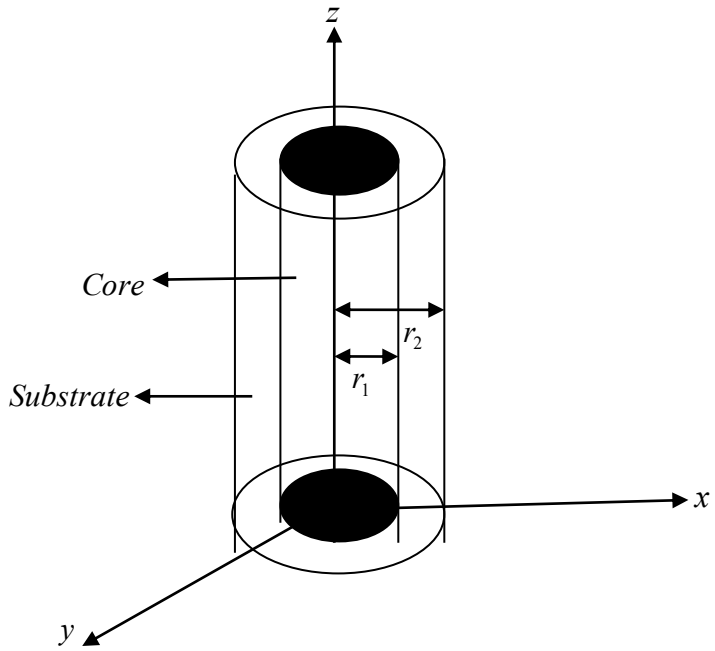


Fig. 1. Composite poroelastic solid cylinder

The equations of motion for initial compression stress σ_{zz} = -p, along the axis of the cylinder are (Biot 1965):

$$\frac{\partial \sigma_{rr}}{\partial r}+\frac{1}{r}\frac{\partial \sigma_{r\theta}}{\partial \theta}+\frac{\partial \sigma_{rz}}{\partial z}+\frac{\sigma_{rr}-\sigma_{\theta\theta}}{r}-p\frac{\partial \omega_{\theta}}{\partial z}=\frac{\partial^2}{\partial t^2}(\rho_{11}u_1+\rho_{12}U_1)+b\frac{\partial}{\partial t}(u_1-U_1),$$

$$\frac{\partial \sigma_{r\theta}}{\partial r}+\frac{1}{r}\frac{\partial \sigma_{\theta\theta}}{\partial \theta}+\frac{\partial \sigma_{\theta z}}{\partial z}+\frac{2\sigma_{r\theta}}{\partial z}+p\frac{\partial \omega_{r}}{\partial z}=\frac{\partial^2}{\partial t^2}(\rho_{11}u_2+\rho_{12}U_2)+b\frac{\partial}{\partial t}(u_2-U_2),$$

$$\frac{\partial \sigma_{rz}}{\partial r}+\frac{1}{r}\frac{\partial \sigma_{\theta z}}{\partial \theta}+\frac{\partial \sigma_{zz}}{\partial z}+\frac{\sigma_{rz}}{r}-p\left(\frac{\partial \omega_{\theta}}{\partial r}-\frac{\partial \omega_{r}}{\partial \theta}\right)=\frac{\partial^2}{\partial t^2}(\rho_{11}u_3+\rho_{12}U_3)+b\frac{\partial}{\partial t}(u_3-U_3),$$

$$Q\frac{\partial e}{\partial r}+R\frac{\partial \varepsilon}{\partial r}=\frac{\partial^2}{\partial t^2}(\rho_{12}u_1+\rho_{22}U_1)-b\frac{\partial}{\partial t}(u_1-U_1),$$

$$\frac{Q}{r}\frac{\partial e}{\partial \theta}+\frac{R}{r}\frac{\partial \varepsilon}{\partial \theta}=\frac{\partial^2}{\partial t^2}(\rho_{12}u_2+\rho_{22}u_2)-b\frac{\partial}{\partial t}(u_2-U_2),$$

$$Q\frac{\partial e}{\partial z}+R\frac{\partial \varepsilon}{\partial z}=\frac{\partial^2}{\partial t^2}(\rho_{12}u_3+\rho_{22}U_3)-b\frac{\partial}{\partial t}(u_3-U_3),$$

(1)

where (u_1,u_2,u_3) and (U_1,U_2,U_3) are the displacement components of solid and fluid respectively, $\sigma_{rr},\sigma_{\theta\theta},\sigma_{zz},\sigma_{rz},\sigma_{r\theta}$ and $\sigma_{\theta z}$ are the stress components, ρ_{ij} are mass coefficients, b is the dissipative coefficient and ω_r, ω_θ are rotational components given by,

$$\omega_r=\frac{1}{2}\left(\frac{\partial u_3}{\partial \theta}-\frac{\partial u_2}{\partial z}\right),$$

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$$\omega_\theta = \frac{1}{2}\left(\frac{\partial u_1}{\partial z} - \frac{\partial u_3}{\partial r}\right). \qquad (2)$$

The constitutive stress-strain relations for transversely isotropic poroelastic solid (Abousleiman Y. and Cui L. 1998) are given under.

$$\begin{bmatrix}\sigma_{rr}\\ \sigma_{\theta\theta}\\ \sigma_{zz}\\ \tau_{r\theta}\\ \tau_{\theta z}\\ \tau_{rz}\end{bmatrix} = \begin{bmatrix}M_{11} & M_{12} & M_{13} & 0 & 0 & 0\\ M_{12} & M_{11} & M_{13} & 0 & 0 & 0\\ M_{13} & M_{13} & M_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & M_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & M_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & M_{55}\end{bmatrix}\begin{bmatrix}e_{rr}\\ e_{\theta\theta}\\ e_{zz}\\ \gamma_{r\theta}\\ \gamma_{\theta z}\\ \gamma_{rz}\end{bmatrix} - \begin{bmatrix}\alpha\\ \alpha\\ \alpha'\\ 0\\ 0\\ 0\end{bmatrix} s,$$

$$s = M[\varepsilon - \alpha(e_{rr} + e_{\theta\theta}) - \alpha' e_{zz}]. \qquad (3)$$

In the Eq. (3), e_{jj} and γ_{jk} are strain components; σ_{jj} and τ_{jk} are stress components in the cylindrical coordinate system, respectively; s is the pore pressure, α and α' are Biot's effective stress coefficients in the isotropic plane (r-θ plane) and in the z - direction, respectively; M is Biot's modulus, ε is the variation of fluid content per unit reference volume, and M_{jk} are components of the drained elastic modulus which depend on $E, E', \nu\ \nu', G$ and G' which are given below:

$$M_{11} = \frac{E(E' - E\nu'^2)}{(1+\nu)(E' - E'\nu - 2E\nu'^2)},$$

$$M_{12} = \frac{E(E'\nu + E\nu'^2)}{(1+\nu)(E' - E'\nu - 2E\nu'^2)},$$

$$M_{13} = \frac{EE'\nu'}{E' - E'\nu - 2E\nu'^2},$$

$$M_{33} = \frac{E'^2(1-\nu)}{E' - E'\nu - 2E\nu'^2},$$

$$M_{44} = G = \frac{M_{11} - M_{12}}{2} = \frac{E}{2(1+\nu)},$$

$$M_{55} = G',$$

where E and ν are drained Young's modulus and Poisson ratio in the isotropic plane, E' and ν' are similar quantities as that of E and ν pertaining to the direction of the axis of symmetry. Non - zero displacement components of solid and fluid for torsional vibrations are $\vec{u}(0,u_2,0)$ and $\vec{U}(0,U_2,0)$, respectively. In the case of torsional vibrations, the equations of motion of transversely isotropic poroelastic solids under initial stress (p) are

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$$2M_{44}\frac{\partial^2 u_2}{\partial r^2}+2M_{55}\frac{\partial^2 u_2}{\partial z^2}+\frac{M_{44}}{r}\frac{\partial u_2}{\partial r}-\frac{2M_{44}u_2}{r^2}-\frac{p}{2}\frac{\partial^2 u_2}{\partial z^2}=\frac{\partial^2}{\partial t^2}(\rho_{11}u_2+\rho_{12}U_2)+b\frac{\partial}{\partial t}(u_2-U_2),$$

$$0=\frac{\partial^2}{\partial t^2}(\rho_{12}u_2+\rho_{22}U_2)-b\frac{\partial}{\partial t}(u_2-U_2).$$

(4)

In the case of harmonic waves, the solutions for circumferential displacements are assumed as follows:

$${}_j u_2(r,z,t)={}_j f(r)\,e^{i(kz+\omega t)},\quad {}_j U_2(r,z,t)={}_j F(r)\,e^{i(kz+\omega t)},\quad j=1,2.$$

(5)

In Eq. (5), the quantities with prefix 1 refer to the core while 2 refers to the substrate. ω is the frequency of wave, k is the wavenumber, i is complex unity, and t is time. Substituting Eq. (5) in Eq. (4), one obtains

$$2M_{44}\frac{d^2\,{}_j f}{dr^2}+\frac{2M_{44}}{r}\frac{d\,{}_j f}{dr}-(2k^2M_{55}+\frac{2M_{44}}{r^2}-\frac{p}{2}k^2)\,{}_j f=-\omega^2[(\rho_{11}-\frac{ib}{\omega})\,{}_j f+(\rho_{12}+\frac{ib}{\omega})\,{}_j F],$$

$$0=-\omega^2[(\rho_{12}+\frac{ib}{\omega})\,{}_j f+(\rho_{22}-\frac{ib}{\omega})\,{}_j F].$$

(6)

Solutions of Eq. (6) are

$${}_2 f(r)=C_1J_1({}_2qr)+C_2Y_1({}_2qr),\ {}_1 f(r)=C_3J_1({}_1qr).$$

(7)

In Eq. (7), ${}_j q=k(\frac{-{}_j M_{55}}{{}_j M_{44}}+\frac{p}{2\,{}_j M_{44}}+c^2(\frac{{}_j\rho_{11}\,{}_j\rho_{22}-{}_j\rho_{12}^2}{2\,{}_j M_{44}\,{}_j\rho_{22}}))^{\frac{1}{2}},\quad j=1,\ 2,$

where, c is the torsional wave velocity. The non-zero stresses both for the core and the substrate are

$${}_2\sigma_{r\theta}=-\,{}_2M_{44}\,{}_2q\left(C_1J_2\left({}_2qr\right)+C_2Y_2\left({}_2qr\right)\right)e^{ik(z+ct)},$$

$${}_1\sigma_{r\theta}=-\,{}_1M_{44}\,{}_1q\left(C_3J_2\left({}_1qr\right)\right)e^{ik(z+ct)}.$$

(8)

3. Boundary Conditions and Frequency Equations

The boundary condition for stress free outer surface $r=r_2$ is

$${}_2\sigma_{r\theta}=0 \text{ at } \quad r=r_2, \tag{9}$$

The conditions for the core and the substrate at the interface $r=r_1$ are

$${}_2\sigma_{r\theta}={}_1\sigma_{r\theta} \text{ at } \quad r=r_1,$$

$${}_2u_2={}_1u_2 \text{ at } \quad r=r_1. \tag{10}$$

Substitution of Eqs. (5), (7) and (8) in Eqs. (9) and (10) gives three homogeneous equations in three unknowns $C_1, C_2,$ and C_3. A non-trivial solution can be obtained if the determinant of the coefficient matrix vanishes. Accordingly, one obtains the following frequency equation:

$$\left|A_{ij}\right| = 0, \qquad (i, j = 1, 2, 3) \tag{11}$$

where,

$$A_{11} = \frac{-2_2 M_{44}}{r_2} J_1(_2 qr_2) + {}_2N_2 q\, J_0(_2 qr_2),\ A_{12} = \frac{-2_2 M_{44}}{r_2} Y_1(_2 qr_2) + {}_2M_{44\ 2} q\, Y_0(_2 qr_2),$$

$$A_{13} = 0,\quad A_{23} = \frac{-2_1 M_{44}}{r_1} J_1(_1 qr_1) - {}_1M_{44\ 1} q\, J_0(_1 qr_1),\ A_{31} = J_1(_2 qr_1),\quad A_{32} = Y_1(_2 qr_1),\quad A_{33} = -J_1(_1 qr_1),$$

A_{21}, A_{22} are similar expressions as A_{11}, A_{12} with r_2 replaced by r_1.

Particular Case:

The traction free boundary conditions in the case of thick-walled hollow cylinder are

$$\sigma_{r\theta} = 0 \text{ at } r = r_1 \text{ and } r = r_2. \tag{12}$$

A non-trivial solution can be obtained if the determinant of the coefficient matrix vanishes. Accordingly, one obtains the following frequency equation:

$$J_2(qr_2)\,Y_2(qr_1) - J_2(qr_1)\,Y_2(qr_2) = 0 \tag{13}$$

4. Numerical Results

The frequency equation (Eq. (11)) is investigated numerically in absence of dissipation. If the dissipation coefficient is non-zero, the wavenumber, densities are complex. Consequently velocities of dilatational waves and shear waves are complex valued. Finally, frequency equations will be complex valued and implicit. Therefore, b is made to be zero so that frequency equation will be real valued and the roots will be obtained easily that explicitly give phase velocity. For numerical process, three composite poroelastic solids are considered, namely, composite cylinder-I and composite cylinder-II using the numerical process performed on MATLAB. Composite cylinder-I consists of the core made of Berea sandstone and the coating with shale rock; while in composite cylinder-II, the materials are reversed and third one is resulted when a cylindrical bone is implanted with Titanium. The material constants M_{44}, M_{55} involves E, E', ν and ν'. Young's modulus (E) and Poisson's ratio (ν) for Berea sandstone saturated with water and shale rock saturated with water are taken to be 14.4 Gpa, 0.20 and 1.854 Gpa, 0.22, respectively (Hart 2000, Cui et. al 1997). Fractured bone is, in general, implanted with Titanium and results in composite cylinder consist of two materials, one is bone and other is Titanium. The density, Young's modulus, and Poisson ratio of Titanium are $4.5\times10^3\, kg/m^3$, 105 Gpa, and 0.32, respectively. In the case of bone, the values of Young's modulus (E) and Poisson's ratio (ν) are respectively taken to be 14.58 Gpa, and 0.32 as suggested in the paper (Nowinski and Davis 1971). Employing these values in the frequency equation, one obtains implicit relation between phase velocity (c), anisotropic ratios ($N_E = E'/E$, $N_\nu = \nu'/\nu$), wavenumber (k), the ratio $(g = r_2 r_1^{-1})$ and initial stress (p). The phase velocity against wavenumber is computed for fixed ratio $g = 2$ and anisotropic ratios $N_E = N_\nu = 0.8$ in the cases initial stress $p = 1$ and 2. The values are computed using the numerical process bisection method implemented in MATLAB and the results are presented in Figs. 2-6. Fig.2 depicts the variation of phase velocity against wavenumber in the case of composite cylinder-I when ratio of radii $g = 2$ in the cases initial stress $p = 1$ and 2. From Figure 2, it is seen that the phase velocity values for $p = 2$ are, in

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general, greater than that of values for $p=1$. Fig.3 depicts the variation of phase velocity against wavenumber in the case of composite cylinder-II when ratio of radii $g=2$ in the cases initial stress $p=1$ and 2. From Figure 3, it is observed that the phase velocity values for $p=2$ are, in general, greater than that of values for $p=1$. Fig. 4 depicts variation of phase velocity against wavenumber at initial stress $p=1$ and 2 in the case of cylindrical bone implanted with Titanium. From Figure 4, it is seen that the phase velocity values for $p=2$ are, in general, greater than that of values for $p=1$. From Figures 2,3 and 4, it is clear that the phase velocity values for $p=2$ are, in general, greater than that of values for $p=1$ in all the cases of composite cylinder-I, composite cylinder-II and bone implanted with Titanium. Fig. 5 depicts variation of phase velocity against wavenumber in the cases of composite cylinder-I and composite cylinder-II when initial stress $p=1$. From Figure 5, it is seen that the phase velocity values for composite cylinder-I are, in general, greater than that of values for composite cylinder-II. Fig. 6 depicts variation of phase velocity against wavenumber in the cases of composite cylinder-I and composite cylinder-II when initial stress $p=2$. From Figure 6, it is seen that the phase velocity values for composite cylinder-I are, in general, greater than that of values for composite cylinder-II. Also, it is observed that the initial stress affects the phase velocity for all the cases. Fig. 7 depicts variation of phase velocity against wavenumber in the cases of thick walled hollow bone. From Figure 7, it is observed that the phase velocity values in case of p=2 are, in general, greater than that of p=1.

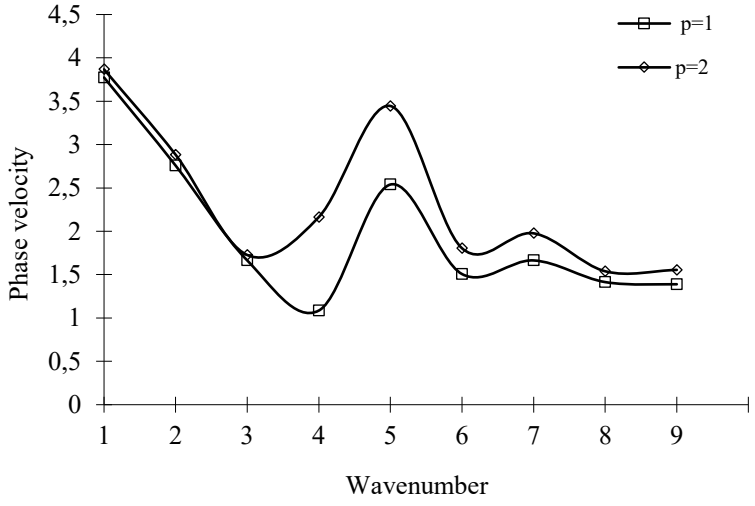


Fig.2. Variation of phase velocity against wavenumber in the case of composite cylinder-I when ratio of radii $g=2$.

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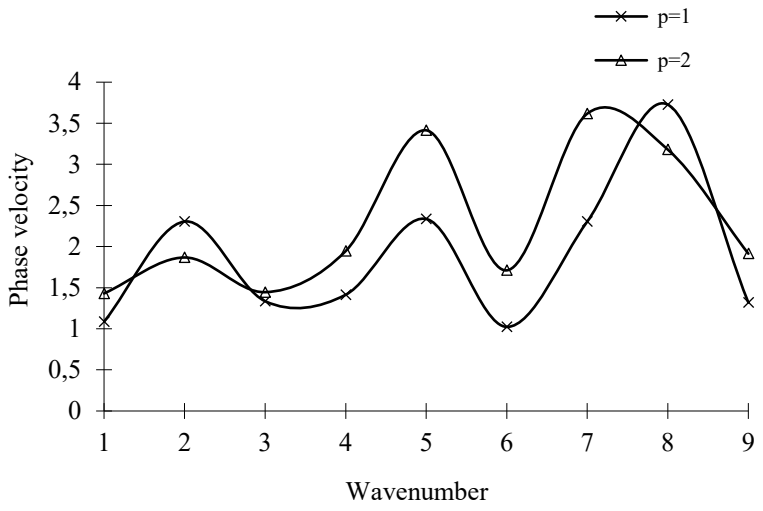


Fig.3. Variation of phase velocity against wavenumber in the case of composite cylinder-II when ratio of radii $g = 2$.

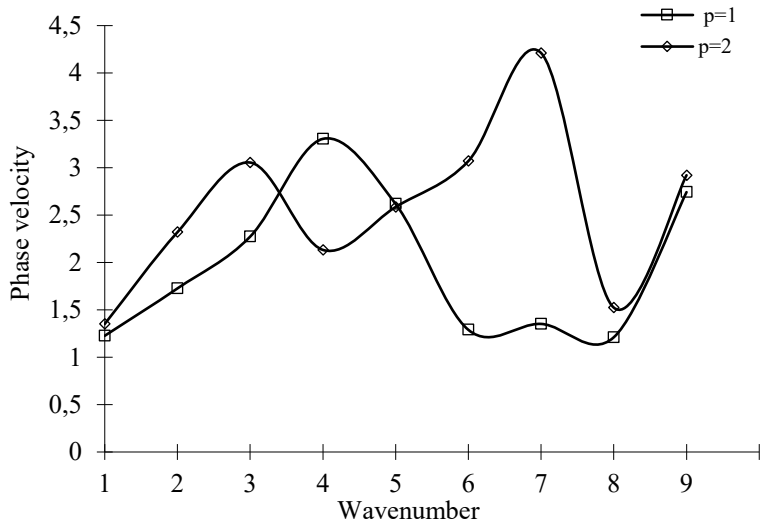


Fig.4. Variation of phase velocity against wavenumber in the case of bone implanted with Titanium when ratio of radii $g = 2$.

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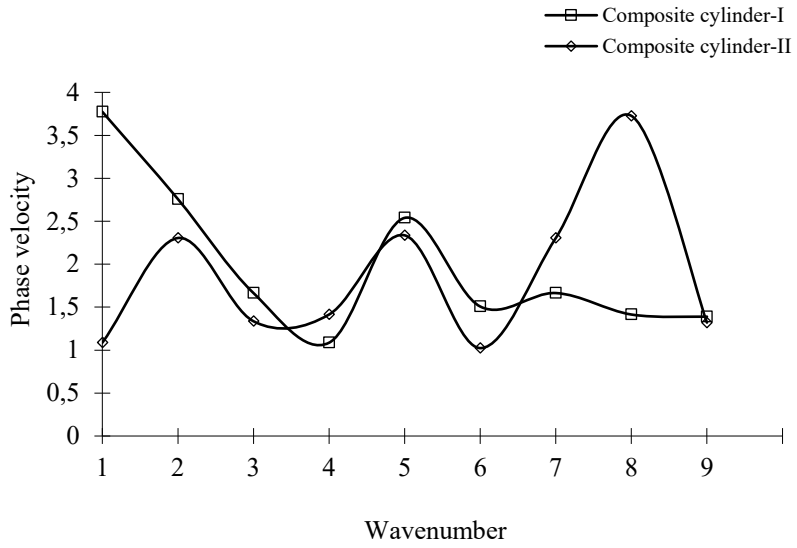


Fig.5. Variation of phase velocity against wavenumber when initial stress p=1.

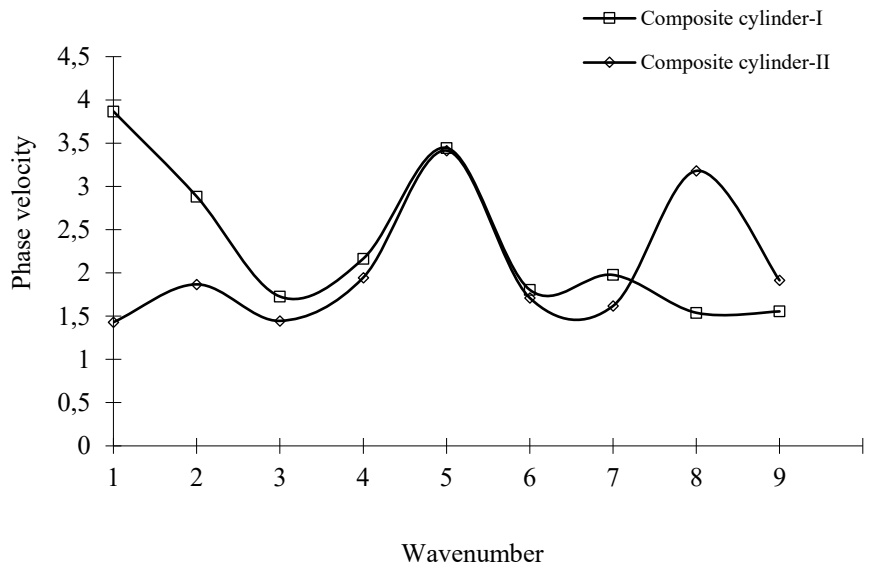


Fig.6. Variation of phase velocity against wavenumber when initial stress p=2.

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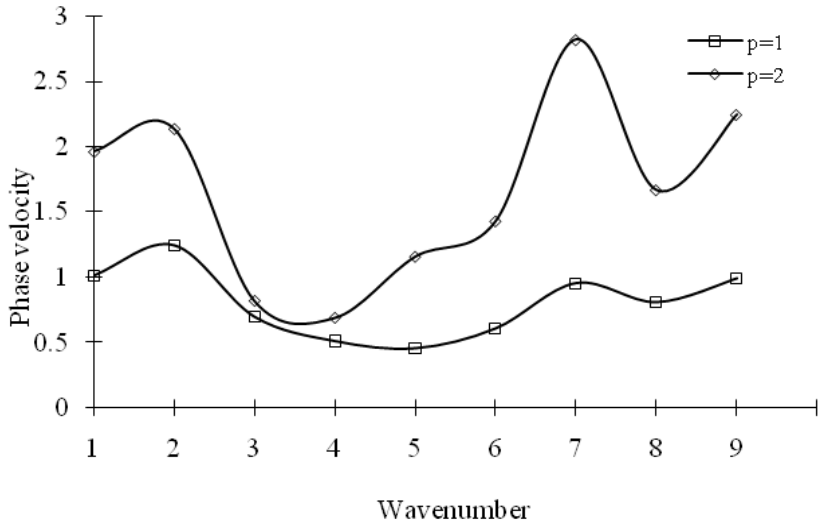


Fig.7. Variation of phase velocity against wavenumber in the case of thick walled hollow bone

5. Conclusion

This paper deals with the torsional vibrations in an initially stressed composite transversely isotropic poroelastic cylinder. The composite cylinder consists of two concentric cylindrical layers namely, core (inner one) and substrate (outer one), each of which retains its own distinctive properties. The phase velocity is computed as a function of wavenumber, ratio of radii and anisotropic ratios at different initial stresses for two different composite cylinders and illustrated the cases under which phase velocity values are greater. Similar analysis is made for a cylindrical bone when it is implanted with Titanium. It is clear from the analysis that the initial stress affects the phase velocity values for all the cases.

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YENİDOĞAN YOĞUN BAKIM HEMŞİRELİĞİNDE GÜNCEL ETİK İKİLEMLER VE KANITA DAYALI YAKLAŞIMLAR

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ÖZET

Yenidoğan yoğun bakım üniteleri, prematüre ve yaşam sınırında bulunan yenidoğanların ileri düzey bakım aldığı, etik açıdan karmaşık kararların sıklıkla gündeme geldiği klinik ortamlardır. Tıbbi teknoloji ve yenidoğan bakımındaki gelişmeler yaşam oranlarını artırırken, yaşam desteğinin başlatılması veya sonlandırılması, tedavinin yararsız (futile) olarak değerlendirilmesi, yaşam sonu bakım kararları, ebeveynlerin karar verme sürecine katılımı, sağlık kaynaklarının adil dağılımı ve bebeğin üstün yararının gözetilmesi gibi etik ikilemleri de beraberinde getirmektedir. Bu süreçlerde yenidoğan yoğun bakım hemşireleri, hasta savunuculuğu, aileye rehberlik etme, etik ilkelere uygun bakım sunma ve disiplinler arası etik karar süreçlerine katılım açısından kritik bir sorumluluk üstlenmektedir. Bu derleme, yenidoğan yoğun bakım hemşirelerinin karşılaştığı güncel etik ikilemleri ve bu ikilemlerin yönetiminde kanıta dayalı yaklaşımları güncel literatür doğrultusunda değerlendirmek amacıyla hazırlanmıştır. Bu kapsamda PubMed, Web of Science, Scopus ve CINAHL veri tabanlarında yayımlanan sistematik derlemeler, klinik uygulama rehberleri ve özgün araştırmalar incelenmiş; literatür taramasında *neonatal intensive care*, *ethics*, *neonatal nursing*, *moral distress*, *family-centered care* ve *end-of-life decision making* anahtar sözcükleri kullanılmıştır. Literatür, hemşirelerin en sık yaşam desteğine ilişkin kararlar, ebeveynlerle ortak karar verme süreci, palyatif bakım uygulamaları, bebeğin üstün yararının korunması ve ahlaki sıkıntı ile ilişkili etik sorunlarla karşılaştığını göstermektedir. Ayrıca etik danışmanlık hizmetlerinin yaygınlaştırılması, disiplinler arası ekip iş birliğinin güçlendirilmesi ve aile merkezli bakım yaklaşımının benimsenmesinin etik çatışmaların azaltılmasına ve karar verme süreçlerinin iyileştirilmesine katkı sağladığı bildirilmektedir (Morillo Palomo ve ark., 2024). Sonuç olarak, yenidoğan yoğun bakım hemşireleri etik karar verme sürecinin temel paydaşlarından biri olup, etik ilkelere dayalı bakım kültürünün güçlendirilmesi, kanıta dayalı etik rehberlerin klinik uygulamalara entegrasyonu, hemşirelere yönelik etik eğitim programlarının yaygınlaştırılması ve etik danışmanlık hizmetlerinin erişilebilirliğinin artırılması; etik ikilemlerin daha etkin yönetilmesine, hemşirelerde ahlaki sıkıntının azaltılmasına ve yenidoğan bakımının kalitesinin geliştirilmesine önemli katkılar sağlayacaktır.

Anahtar Kelimeler: Yenidoğan yoğun bakım, etik, hemşirelik, moral distress, yaşam sonu bakım, aile merkezli bakım.

ABSTRACT

Neonatal intensive care units are clinical settings where premature infants and those at the limits of viability receive advanced care, and where ethically complex decisions frequently arise. While

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advancements in medical technology and neonatal care have improved survival rates, they have also introduced ethical dilemmas—such as the initiation or withdrawal of life support, the assessment of treatment as futile, end-of-life care decisions, parental involvement in decision-making, the equitable allocation of healthcare resources, and the consideration of the infant's best interests. In these processes, neonatal intensive care nurses bear critical responsibilities regarding patient advocacy, family guidance, the provision of care aligned with ethical principles, and participation in interdisciplinary ethical decision-making. This review aims to evaluate current ethical dilemmas faced by neonatal intensive care nurses and evidence-based approaches to managing them, in light of the latest literature. To this end, systematic reviews, clinical practice guidelines, and original research published in the PubMed, Web of Science, Scopus, and CINAHL databases were examined; the keywords used in the literature search included "neonatal intensive care," "ethics," "neonatal nursing," "moral distress," "family-centered care," and "end-of-life decision making."The literature indicates that nurses frequently encounter ethical issues related to life-support decisions, shared decision-making with parents, palliative care practices, safeguarding the infant's best interests, and moral distress. Furthermore, it is reported that expanding ethical consultation services, strengthening interdisciplinary team collaboration, and adopting a family-centered care approach contribute to mitigating ethical conflicts and improving decision-making processes (Morillo Palomo et al., 2024). In conclusion, neonatal intensive care nurses are key stakeholders in the ethical decision-making process; thus, strengthening a care culture grounded in ethical principles, integrating evidence-based ethical guidelines into clinical practice, expanding ethical training programs for nurses, and increasing the accessibility of ethical consultation services will significantly contribute to the more effective management of ethical dilemmas, the reduction of moral distress among nurses, and the enhancement of the quality of neonatal care.

Keywords: Neonatal intensive care, ethics, nursing, moral distress, end-of-life care, family-centered care.

1. GİRİŞ

Yenidoğan yoğun bakım üniteleri (YYBÜ), prematüre, düşük doğum ağırlıklı veya yaşamı tehdit eden hastalıkları bulunan yenidoğanların ileri teknoloji destekli bakım ve tedavi aldığı, etik açıdan karmaşık kararların sıklıkla gündeme geldiği klinik ortamlardır (Önder ve ark., 2024). Neonatoloji alanında son yıllarda yaşanan bilimsel ve teknolojik gelişmeler, özellikle ileri derecede prematüre ve çok düşük doğum ağırlıklı bebeklerde sağkalım oranlarını önemli ölçüde artırmıştır. Bununla birlikte yaşamı sürdürücü tedavilerin yaygınlaşması; tedavinin sınırlandırılması veya sonlandırılması, uzun dönem nörogelişimsel prognozun belirsizliği, palyatif bakımın zamanlaması ve yaşam sonu kararları gibi etik ikilemlerin daha görünür hale gelmesine neden olmuştur (Mills ve Cortezzo, 2020; Arimitsu ve ark., 2025).

YYBÜ'de etik karar verme süreci yalnızca klinik bulguların değerlendirilmesini değil; yararlılık, zarar vermeme, özerkliğe saygı ve adalet ilkelerinin birlikte ele alınmasını gerektiren çok boyutlu bir yaklaşımı ifade etmektedir. Yenidoğanların karar verme kapasitesine sahip olmaması nedeniyle ebeveynler yasal karar vericiler olarak sürece katılmakta; sağlık profesyonellerinin temel sorumluluğu ise her koşulda bebeğin üstün yararını korumaktır. Özellikle yaşam desteğinin başlatılması veya sonlandırılması, tıbben yararsız tedavilerin sürdürülmesi, palyatif bakımın planlanması ve kaynakların adil kullanımı gibi konularda aile ile sağlık ekibi arasında etik görüş ayrılıkları ortaya çıkabilmektedir (Fortney, 2021; Gkiougki ve ark., 2021).

Yenidoğan yoğun bakım hemşireleri, bakım sürecinin her aşamasında aktif rol alan ve aile ile en yoğun iletişim kuran sağlık profesyonelleridir. Bu nedenle hemşirelerin sorumlulukları yalnızca klinik bakım uygulamalarıyla sınırlı olmayıp; aileyi bilgilendirme, hasta savunuculuğu, etik karar süreçlerine katkı sağlama, ağrı ve konfor yönetimini yürütme, gelişimsel bakımı destekleme ve yenidoğanın haklarını koruma gibi önemli etik sorumlulukları da kapsamaktadır. Aile merkezli bakım anlayışının yaygınlaşmasıyla birlikte hemşirelerin etik karar mekanizmalarındaki rolleri daha görünür hale gelmiştir (Ramezani ve ark., 2014; Morillo Palomo ve ark., 2024).

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Bununla birlikte hemşireler, yaşam sonu bakım kararları, tıbbi yararsızlık, kaynak yetersizliği ve aile beklentileri ile klinik gereklilikler arasında yaşanan çatışmalar nedeniyle sıklıkla ahlaki sıkıntı yaşamaktadır. Ahlaki sıkıntı, sağlık profesyonelinin etik açıdan doğru olduğuna inandığı uygulamayı kurumsal, hukuki veya klinik engeller nedeniyle gerçekleştirememesi sonucu ortaya çıkan psikolojik yük olarak tanımlanmakta olup tükenmişlik, iş doyumunda azalma ve bakım kalitesinde düşüş ile ilişkilendirilmektedir (Musto & Rodney, 2018; Mills & Cortezzo, 2020).

Son yıllarda yayımlanan uluslararası rehberler, etik sorunların yönetiminde disiplinler arası ekip yaklaşımının güçlendirilmesini, paylaşılan karar verme modelinin benimsenmesini, etik danışmanlık hizmetlerinin yaygınlaştırılmasını ve sağlık profesyonellerinin etik yeterliliklerinin geliştirilmesini önermektedir. Bu yaklaşımların hem yenidoğanın üstün yararının korunmasına hem de sağlık çalışanlarının etik yükünün azaltılmasına katkı sağladığı bildirilmektedir (Špoljar ve ark., 2025).

Bu derlemede, yenidoğan yoğun bakım hemşirelerinin karşılaştığı güncel etik ikilemlerin güncel literatür doğrultusunda değerlendirilmesi, hemşirelerin etik karar verme süreçlerindeki rollerinin ortaya konulması ve kanıta dayalı uygulamalara yönelik önerilerin sunulması amaçlanmıştır.

2. YENİDOĞAN YOĞUN BAKIM HEMŞİRELİĞİNDE ETİK İLKELER

Yenidoğan yoğun bakım ünitelerinde etik ilkeler, klinik kararların ve bakım uygulamalarının temelini oluşturmaktadır. Yenidoğanların karar verme yeterliliğine sahip olmamaları nedeniyle etik değerlendirmeler yalnızca ebeveynlerin karar verme hakkı üzerinden değil, aynı zamanda bebeğin üstün yararının korunması ilkesi doğrultusunda yürütülmektedir. Bu süreçte hemşireler, etik ilkelerin günlük bakım uygulamalarına yansıtılmasında ve aile ile sağlık ekibi arasında güvene dayalı iletişimin sürdürülmesinde önemli sorumluluk üstlenmektedir (Beauchamp ve Childress, 2019).

Klinik etikte en yaygın kabul gören yaklaşım; yararlılık, zarar vermeme, özerkliğe saygı ve adalet ilkelerinden oluşmaktadır. Ancak YYBÜ'de bu ilkeler birbirinden bağımsız değil, çoğu zaman aynı klinik olay içerisinde birlikte değerlendirilmektedir (Min, 2018; Špoljar ve ark., 2025).

Yararlılık ilkesi, yenidoğanın yaşamını koruyacak ve sağlık sonuçlarını iyileştirecek girişimlerin uygulanmasını ifade etmektedir. Solunum desteğinin sağlanması, enfeksiyonların önlenmesi, anne sütü ile beslenmenin desteklenmesi, gelişimsel bakım uygulamaları ve bireyselleştirilmiş bakım planlarının oluşturulması bu ilke kapsamında değerlendirilmektedir (WHO, 2022).

Zarar vermeme ilkesi, uygulanan tanı ve tedavi girişimlerinin yenidoğana gereksiz ağrı, stres veya ek zarar vermemesini amaçlamaktadır. Bu doğrultuda invaziv işlemlerin azaltılması, kanıta dayalı ağrı yönetimi uygulamalarının kullanılması, çevresel stres faktörlerinin azaltılması ve gelişimsel bakımın sürdürülmesi etik sorumluluğun temel bileşenleri arasında yer almaktadır (Daboval & Shidler, 2014).

Özerkliğe saygı ilkesi, yenidoğanlarda ebeveynlerin bilgilendirilmiş karar verme hakkı üzerinden değerlendirilmektedir. Bununla birlikte ebeveyn tercihleri her zaman bebeğin üstün yararı ile dengelenmeli; ciddi görüş ayrılıklarında multidisipliner değerlendirme ve etik kurul desteği alınmalıdır. Günümüzde bu süreçte paylaşılan karar verme modeli etik açıdan en uygun yaklaşım olarak kabul edilmektedir (Guimarães ve ark., 2012).

Adalet ilkesi ise tüm yenidoğanların sağlık hizmetlerine eşit erişimini, mevcut kaynakların hakkaniyetli kullanımını ve bakım hizmetlerinde ayrımcılığın önlenmesini ifade etmektedir. Özellikle yoğun bakım yataklarının yetersiz olduğu dönemlerde, ileri yaşam desteği uygulamalarında ve afet ya da salgın gibi olağanüstü koşullarda bu ilke daha belirgin hale gelmektedir (Špoljar ve ark., 2025).

Etik ilkelerin klinik uygulamaya aktarılmasında hemşireler kritik rol üstlenmektedir. Etik duyarlılığı yüksek hemşirelerin etik sorunları daha erken fark edebildiği, aile ile etkili iletişim kurabildiği, etik karar süreçlerine aktif katkı sağlayabildiği ve bunun bakım kalitesine olumlu yansıdığı bildirilmektedir (Morillo Palomo ve ark., 2024).

YYBÜ'de etik ilkeler yalnızca teorik bir çerçeve sunmamakta; yaşam desteği kararlarından gelişimsel bakıma, aile katılımından palyatif bakım uygulamalarına kadar tüm klinik süreçlere yön vermektedir. Bu nedenle hemşirelerin etik bilgi, etik duyarlılık ve etik karar verme becerilerinin güçlendirilmesi, hem

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yenidoğanın üstün yararının korunması hem de kaliteli ve güvenli bakımın sürdürülebilmesi açısından temel öneme sahiptir.

3. YENİDOĞAN YOĞUN BAKIM ÜNİTELERİNDE KARŞILAŞILAN GÜNCEL ETİK İKİLEMLER

Neonatal bakım alanında son yıllarda yaşanan bilimsel ve teknolojik gelişmeler, yaşam sınırındaki birçok yenidoğanın sağkalımını mümkün kılmıştır. Bununla birlikte ileri yaşam desteği uygulamalarının yaygınlaşması, etik karar verme süreçlerini daha karmaşık hale getirmiştir. Özellikle aşırı prematüre, çok düşük doğum ağırlıklı veya ciddi konjenital anomalilere sahip yenidoğanlarda tedavinin yarar-zarar dengesi, uzun dönem nörogelişimsel prognozun belirsizliği, yaşam kalitesi beklentisi ve ebeveynlerin farklı değer yargıları sağlık profesyonellerini güç etik ikilemlerle karşı karşıya bırakmaktadır. Güncel etik yaklaşımlar, bu kararların yalnızca tıbbi göstergelere değil, bebeğin üstün yararı, aile tercihleri ve disiplinler arası ekip değerlendirmesine dayandırılması gerektiğini vurgulamaktadır (Morillo Palomo ve ark., 2024).

3.1. YAŞAM DESTEĞİNİN BAŞLATILMASI, SÜRDÜRÜLMESİ VE SONLANDIRILMASI

YYBÜ'de en sık karşılaşılan etik ikilemlerden biri yaşam desteğinin hangi koşullarda başlatılacağı, sürdürülüp sürdürülmeyeceği veya sonlandırılacağına ilişkin kararlardır. Özellikle gebelik haftasının yaşam sınırında olduğu olgularda veya prognozu son derece kötü olan yenidoğanlarda yaşamın korunması ile ağır nörogelişimsel sekel riski arasında denge kurulması önemli etik tartışmalara yol açmaktadır. Günümüzde uluslararası rehberler, bu kararların yalnızca hekim tarafından değil; hemşire, diğer sağlık profesyonelleri ve ebeveynlerin katıldığı paylaşılan karar verme modeli doğrultusunda alınmasını önermektedir. Bu süreçte etik danışmanlık hizmetleri ve klinik etik kurullarının desteği kararların şeffaflığını ve etik kabul edilebilirliğini artırmaktadır (Morillo Palomo ve ark., 2024).

3.2. TIBBEN YARARSIZ TEDAVİ

YYBÜ'de karşılaşılan bir diğer önemli etik sorun, uygulanan tedavinin yaşam süresini uzatmasına rağmen yenidoğanın iyileşme olasılığına veya kabul edilebilir bir yaşam kalitesine anlamlı katkı sağlamayacağının düşünüldüğü durumlardır. Tıbben yararsız tedavi kavramı, klinik uygulamalarda en fazla görüş ayrılığına neden olan konular arasında yer almaktadır. Aileler çoğu zaman yaşamı sürdüren tüm girişimlerin devamını isterken, sağlık profesyonelleri tedavinin yalnızca biyolojik yaşamı uzattığını ve bebeğin üstün yararına hizmet etmediğini düşünebilmektedir. Bu süreçlerde hemşireler yalnızca bakım sunan değil, aynı zamanda yenidoğanın haklarını savunan, aileye psikososyal destek sağlayan ve ekip içi iletişimi güçlendiren önemli etik paydaşlar olarak görev almaktadır (Albersheim, 2004).

3.3. AİLE MERKEZLİ VE PAYLAŞILAN KARAR VERME

Aile merkezli bakım yaklaşımı günümüzde neonatal bakımın temel bileşenlerinden biri olarak kabul edilmektedir. Ebeveynlerin tedavi ve bakım sürecine aktif katılımı hem etik hem de psikososyal açıdan önemli yararlar sağlamaktadır. Bununla birlikte ebeveynlerin dini, kültürel veya bireysel değerleri ile sağlık ekibinin klinik değerlendirmeleri her zaman örtüşmeyebilir. Böyle durumlarda açık iletişim, dürüst bilgi paylaşımı, empatik yaklaşım ve ortak karar verme sürecinin benimsenmesi etik çatışmaların azaltılmasında temel stratejiler arasında yer almaktadır. Hemşireler, aile ile sağlık ekibi arasındaki iletişimin sürekliliğini sağlayarak bu sürecin en önemli kolaylaştırıcılarından biri olarak kabul edilmektedir (Gooding ve ark., 2011; Morillo Palomo ve ark., 2024).

3.4. YAPAY ZEKÂ VE DİJİTAL TEKNOLOJİLERİN ETİK BOYUTU

Yapay zekâ destekli karar destek sistemleri, makine öğrenmesi algoritmaları ve büyük veri analizleri YYBÜ'de erken tanı, klinik risk öngörüsü ve hasta izlemi gibi alanlarda giderek daha yaygın kullanılmaktadır. Bu teknolojiler klinik karar vermeyi destekleme potansiyeline sahip olmakla birlikte algoritmik önyargı, açıklanabilirlik, veri güvenliği, hasta mahremiyeti ve hukuki sorumluluk gibi yeni etik sorunları da gündeme getirmektedir. Güncel yaklaşımlar, yapay zekânın klinik kararların yerine geçen bir araç değil, sağlık profesyonellerinin karar verme süreçlerini destekleyen yardımcı bir teknoloji olarak kullanılması gerektiğini vurgulamaktadır. Bu nedenle yapay zekâ uygulamalarının etik ilkeler,

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klinik deneyim ve insan merkezli bakım anlayışı ile birlikte değerlendirilmesi önerilmektedir (Fortunov ve ark., 2024; Rallis ve ark., 2024; Arora ve ark., 2025).

4. YENİDOĞAN YOĞUN BAKIM HEMŞİRELERİNDE AHLAKİ SIKINTI

Yenidoğan yoğun bakım hemşireleri, yaşamı tehdit eden klinik durumlarla sürekli karşılaşmaları ve etik açıdan karmaşık karar süreçlerine doğrudan tanıklık etmeleri nedeniyle ahlaki sıkıntıyı en yoğun yaşayan sağlık profesyonelleri arasında yer almaktadır. Özellikle yaşam sonu bakım kararları, yaşam desteğinin sınırlandırılması, tıbben yararsız tedavilerin sürdürülmesi ve aile ile sağlık ekibi arasında yaşanan görüş ayrılıkları hemşirelerde önemli düzeyde etik yük oluşturmaktadır (Mills ve Cortezzo, 2020; Morillo Palomo ve ark., 2024).

Ahlaki sıkıntı, sağlık profesyonelinin etik açıdan doğru olduğuna inandığı uygulamayı kurumsal, hukuki veya ekip kaynaklı engeller nedeniyle gerçekleştirememesi sonucu ortaya çıkan psikolojik ve mesleki yük olarak tanımlanmaktadır. Uzun süre devam eden ahlaki sıkıntının yalnızca bireysel iyi oluşu değil, ekip iş birliğini, hasta güvenliğini ve bakım kalitesini de olumsuz etkilediği bildirilmektedir (Mills ve Cortezzo, 2020).

Literatürde ahlaki sıkıntının başlıca nedenleri arasında tıbben yararsız olduğu düşünülen tedavilerin sürdürülmesi, yaşam sonu kararlarına yeterince katılamama, etik karar mekanizmalarında hemşirelerin sınırlı temsil edilmesi, yoğun iş yükü, personel yetersizliği, iletişim sorunları ve kurum kültürüne bağlı etik engeller yer almaktadır. Bu durum zamanla tükenmişlik sendromu, mesleki doyumun azalması, işten ayrılma eğiliminin artması ve hasta bakımının niteliğinde azalma ile ilişkilendirilmektedir (Mills ve Cortezzo, 2020).

Son yıllarda etik dayanıklılık kavramı, ahlaki sıkıntının yönetiminde öne çıkan yaklaşımlardan biri olarak kabul edilmektedir. Etik danışmanlık hizmetlerinin erişilebilir olması, düzenli etik vaka toplantılarının gerçekleştirilmesi, disiplinler arası ekip iletişiminin güçlendirilmesi, palyatif bakım ekiplerinin erken dönemde sürece dâhil edilmesi ve hemşirelere yönelik etik karar verme eğitimlerinin uygulanması ahlaki sıkıntının azaltılmasına katkı sağlayan kanıta dayalı stratejiler arasında gösterilmektedir. Ayrıca hemşirelerin etik karar süreçlerine aktif katılımının desteklenmesi, etik iklimin güçlendirilmesi ve kurumsal liderliğin etik uygulamaları teşvik etmesi, etik dayanıklılığın geliştirilmesinde önemli rol oynamaktadır (Špoljar ve ark., 2025).

5. YENİDOĞAN YOĞUN BAKIM HEMŞİRESİNİN ETİK KARAR VERME SÜRECİNDEKİ PROFESYONEL ROLÜ

Yenidoğan yoğun bakım hemşireleri, etik karar verme sürecinde yalnızca bakım uygulamalarını yerine getiren sağlık profesyonelleri değil; aynı zamanda yenidoğanın haklarını savunan, aileyi destekleyen, disiplinler arası ekip iletişimini güçlendiren ve etik karar mekanizmalarına aktif katkı sağlayan önemli paydaşlardır. Hastayla en uzun süre temas eden ekip üyesi olmaları nedeniyle klinik durumdaki değişiklikleri, bakım gereksinimlerini ve olası etik sorunları erken fark edebilmekte; bu gözlemler etik karar sürecinin şekillenmesinde önemli bir bilgi kaynağı oluşturmaktadır (Morillo Palomo ve ark., 2024).

Hemşirelerin temel etik sorumluluğu, bakımın her aşamasında yenidoğanın üstün yararını gözetmek ve etik ilkeleri klinik uygulamalara yansıtmaktır. Bu kapsamda gereksiz ağrı ve stresin önlenmesi, etkili ağrı yönetiminin sağlanması, gelişimsel bakım uygulamalarının sürdürülmesi ve aile merkezli bakım anlayışının desteklenmesi hemşirelik bakımının temel bileşenleri arasında yer almaktadır. Bunun yanında ebeveynlerin hastalık süreci, tedavi seçenekleri ve olası sonuçlar hakkında doğru, açık ve anlaşılır biçimde bilgilendirilmesine katkı sağlamak, ailelerin ortak karar verme sürecine katılımını kolaylaştırmak ve onların psikososyal gereksinimlerini desteklemek hemşirelerin önemli sorumlulukları arasındadır (Morillo Palomo ve ark., 2024).

Etik açıdan karmaşık olgularda hemşirelerin klinik gözlem ve değerlendirmeleri, multidisipliner ekip tarafından alınacak kararların bütüncül biçimde oluşturulmasına katkı sağlamaktadır. Güncel literatür, hemşirelerin etik kurul toplantılarına ve tedavi hedeflerinin belirlendiği klinik görüşmelere aktif katılımının ekip içi iletişimi güçlendirdiğini, farklı bakış açılarının değerlendirilmesini kolaylaştırdığını ve etik çatışmaların daha etkin yönetilmesine katkı sağladığını göstermektedir (Špoljar ve ark., 2025).

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Bununla birlikte etik liderlik, günümüzde yenidoğan yoğun bakım hemşireliğinin giderek önem kazanan rollerinden biri olarak kabul edilmektedir. Etik duyarlılığı yüksek hemşireler, hasta savunuculuğu rolünü daha etkin yerine getirebilmekte, ekip içinde etik farkındalığın gelişmesine katkı sağlamakta ve etik iklimin güçlenmesini desteklemektedir. Bu nedenle hemşirelerin etik ilkeler, yaşam sonu bakım, perinatal palyatif bakım, aile merkezli bakım ve etkili iletişim konularında sürekli mesleki eğitimlerle desteklenmesi; etik karar verme becerilerinin geliştirilmesi ve etik liderlik rollerinin güçlendirilmesi açısından önem taşımaktadır (Mills ve Cortezzo, 2020).

6. KANITA DAYALI YAKLAŞIMLAR VE HEMŞİRELİK UYGULAMALARINA YÖNELİK ÖNERİLER

Yenidoğan yoğun bakım ünitelerinde etik sorunların tamamen ortadan kaldırılması mümkün olmamakla birlikte, kanıta dayalı uygulamaların sistematik biçimde hayata geçirilmesi etik çatışmaların azaltılmasına ve etik karar süreçlerinin güçlendirilmesine önemli katkı sağlamaktadır. Güncel literatür, etik sorunların yönetiminde yalnızca bireysel etik duyarlılığın değil, aynı zamanda kurumsal etik kültürünün, disiplinler arası iş birliğinin ve yapılandırılmış etik destek mekanizmalarının belirleyici olduğunu göstermektedir (Mills ve Cortezzo, 2020).

Kanıta dayalı yaklaşımlar arasında öncelikle etik danışmanlık hizmetlerinin yaygınlaştırılması ve düzenli etik vaka toplantılarının gerçekleştirilmesi önerilmektedir. Bu uygulamalar, karmaşık klinik olgularda farklı disiplinlerin ortak değerlendirme yapmasına olanak sağlayarak etik kararların daha şeffaf, tutarlı ve hasta merkezli biçimde alınmasını desteklemektedir. Aynı zamanda hemşirelerin etik karar süreçlerine aktif katılımı teşvik edilmekte, hasta savunuculuğu rollerini daha etkin yerine getirmeleri ve bakım sürecine ilişkin gözlem ile değerlendirmelerini ekip üyeleriyle paylaşmaları kolaylaşmaktadır (Fortney, 2021; Albersheim, 2004).

Ahlaki sıkıntının azaltılmasına yönelik kanıta dayalı uygulamalar arasında düzenli etik eğitimlerinin planlanması, iletişim becerilerini geliştirmeye yönelik programların uygulanması, yeterli hemşire istihdamının sağlanması, çalışanlara psikososyal destek sunulması ve ekip içi iş birliğinin güçlendirilmesi yer almaktadır. Son yıllarda etik dayanıklılık yaklaşımı da ahlaki sıkıntının yönetiminde öne çıkan stratejilerden biri olarak kabul edilmektedir. Etik dayanıklılığı geliştirmeye yönelik eğitimler, destek programları ve yansıtıcı uygulamalar, hemşirelerin etik çatışmalar karşısında mesleki bütünlüklerini koruyabilmelerine ve zor karar süreçlerini daha etkin yönetebilmelerine katkı sağlamaktadır (Alipour ve ark., 2024).

Aile merkezli bakım yaklaşımının etik karar süreçlerine sistematik biçimde entegre edilmesi de güncel kanıtlarla desteklenen uygulamalar arasındadır. Ailelerin bakım planlamasına aktif katılımının sağlanması, tedavi seçenekleri hakkında açık ve anlaşılır şekilde bilgilendirilmeleri, soru sormalarının teşvik edilmesi ve kültürel değerlerine saygı gösterilmesi hem etik ilkelere uygun bakımın sürdürülmesine hem de aile memnuniyeti ve sağlık ekibine duyulan güvenin artırılmasına katkı sağlamaktadır (Hodgson ve ark., 2025).

Bunun yanında yapay zekâ destekli klinik karar sistemlerinin yenidoğan yoğun bakım uygulamalarında yaygınlaşması, etik uygulamalara ilişkin yeni sorumluluk alanlarını da beraberinde getirmektedir. Yapay zekâdan elde edilen önerilerin klinik kararların yerine geçen mekanizmalar olarak değil, sağlık profesyonellerinin kararlarını destekleyen araçlar olarak kullanılması; hasta mahremiyetinin korunması, algoritmik önyargıların dikkate alınması, sistemlerin açıklanabilirliğinin sağlanması ve nihai klinik sorumluluğun sağlık profesyonellerinde olduğunun gözetilmesi etik açıdan temel gereklilikler arasında yer almaktadır (Fortunov ve ark., 2024; Arora ve ark., 2025).

Sonuç olarak, yenidoğan yoğun bakım ünitelerinde etik bakımın güçlendirilmesi; etik danışmanlık hizmetleri, sürekli mesleki eğitim, aile merkezli bakım, etik dayanıklılığı destekleyen kurumsal uygulamalar ve disiplinler arası iş birliğini temel alan bütüncül bir yaklaşımla mümkündür. Bu yaklaşımlar yalnızca etik karar verme süreçlerini geliştirmekle kalmamakta; aynı zamanda hasta güvenliği, bakım kalitesi, aile memnuniyeti ve hemşirelerin mesleki iyilik hâli üzerinde de olumlu etkiler oluşturmaktadır (Špoljar ve ark., 2025; Boutillier ve ark., 2025).

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7. YENİDOĞAN YOĞUN BAKIM HEMŞİRELİĞİNDE GÜNCEL ETİK YAKLAŞIMLAR VE GELECEK PERSPEKTİFİ

Yenidoğan yoğun bakım alanında yaşanan bilimsel ve teknolojik gelişmeler, tanı ve tedavi olanaklarını önemli ölçüde genişletirken etik karar verme süreçlerini de yeniden şekillendirmektedir. Günümüzde yapay zekâ destekli karar sistemleri, büyük veri analitiği, genomik uygulamalar, dijital sağlık teknolojileri ve tele-sağlık hizmetleri yenidoğan bakımının giderek daha fazla parçası hâline gelmektedir. Bu yenilikler erken tanı, risk öngörüsü ve bireyselleştirilmiş bakım planlarının oluşturulmasına önemli katkılar sağlamakla birlikte; kişisel sağlık verilerinin korunması, algoritmaların güvenilirliği, karar süreçlerinin şeffaflığı, dijital eşitsizlikler ve klinik sorumluluğun paylaşımı gibi yeni etik tartışmaları da beraberinde getirmektedir (World Health Organization [WHO], 2021; Fortunov ve ark., 2024).

Özellikle yapay zekâ uygulamalarının prematüre retinopatisinin taranması, neonatal sepsis riskinin öngörülmesi, solunum desteği gereksiniminin belirlenmesi ve klinik kötüleşmenin erken fark edilmesi gibi alanlarda önemli avantajlar sağladığı bildirilmektedir. Bununla birlikte güncel etik yaklaşımlar, yapay zekâ sistemlerinin klinik kararların yerini alan bağımsız mekanizmalar değil, sağlık profesyonellerinin değerlendirmelerini destekleyen yardımcı araçlar olarak kullanılmasını önermektedir. Algoritmik önyargıların azaltılması, sistemlerin açıklanabilirliğinin sağlanması, hasta mahremiyetinin korunması ve etik-hukuki sorumluluğun sağlık profesyonellerinde olduğunun kabul edilmesi güvenli kullanımın temel koşulları arasında yer almaktadır (WHO, 2021; Rallis ve ark., 2024).

Genetik tanı yöntemleri ve prenatal tarama teknolojilerindeki gelişmeler de yenidoğan yoğun bakım uygulamalarına yeni etik boyutlar kazandırmıştır. Tüm genom dizilemesi ve ileri genetik testler sayesinde birçok hastalık erken dönemde tanımlanabilmekte ve bireyselleştirilmiş bakım planları oluşturulabilmektedir. Bununla birlikte genetik bilgilerin gizliliği, verilerin paylaşımı, gelecekte ortaya çıkabilecek sağlık risklerinin yönetimi ve ailelerin yaşayabileceği psikososyal yük, dikkatle ele alınması gereken etik konular arasında yer almaktadır (American Academy of Pediatrics [AAP], 2023; Arora ve ark., 2025).

COVID-19 pandemisi sonrasında tele-sağlık uygulamalarının yaygınlaşmasıyla birlikte ailelerle uzaktan iletişim kurulması, çevrim içi görüşmelerin gerçekleştirilmesi ve dijital platformlar aracılığıyla bilgilendirme yapılması yenidoğan yoğun bakım hizmetlerinin önemli bileşenlerinden biri hâline gelmiştir. Tele-sağlık uygulamaları aile katılımını destekleyebilmekte ve bakım sürekliliğini artırabilmektedir. Ancak kişisel verilerin korunması, bilgi güvenliği, dijital okuryazarlık ve sağlık hizmetlerine erişimde yaşanan eşitsizlikler gibi etik konuların göz önünde bulundurulması gerekmektedir (Giuseppe ve ark., 2022).

Gelecekte yenidoğan yoğun bakım hemşireliğinde etik yaklaşımın yalnızca klasik biyomedikal etik ilkeleriyle sınırlı kalmayacağı öngörülmektedir. Dijital etik, yapay zekâ etiği, veri yönetimi, genetik danışmanlık, sürdürülebilir sağlık hizmetleri ve teknoloji destekli klinik karar verme süreçlerinin hemşirelik uygulamalarında giderek daha fazla önem kazanacağı düşünülmektedir. Bu nedenle hemşirelerin değişen teknolojilere uyum sağlayabilecek etik bilgi, dijital yetkinlik ve teknoloji okuryazarlığı becerileriyle desteklenmesi, geleceğin yenidoğan bakımında öncelikli gereksinimler arasında yer almaktadır (Arora ve ark., 2025).

8. SONUÇ VE ÖNERİLER

Neonatal bakım alanındaki bilimsel gelişmeler sağkalım oranlarını artırmış olsa da, yaşam desteğinin sınırları, tedavinin yararı, ailelerin karar süreçlerine katılımı ve sınırlı kaynakların adil kullanımı gibi konular sağlık profesyonellerini karmaşık etik ikilemlerle karşı karşıya bırakmaktadır.

Bu süreçte yenidoğan yoğun bakım hemşireleri yalnızca bakım uygulamalarından sorumlu değildir; aynı zamanda yenidoğanın haklarını savunan, aile ile sağlık ekibi arasında iletişimi sağlayan, etik sorunların erken fark edilmesine katkıda bulunan ve multidisipliner karar süreçlerine aktif katılım gösteren ekibin önemli bir üyesidir. Bu nedenle hemşirelerin etik karar mekanizmalarındaki rollerinin güçlendirilmesi, etik liderlik becerilerinin desteklenmesi ve etik karar süreçlerine aktif katılımlarının teşvik edilmesi bakımın güvenliği ve niteliği açısından temel öneme sahiptir.

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Literatürde etik çatışmaların ve ahlaki sıkıntının azaltılmasında etik danışmanlık hizmetlerinin yaygınlaştırılması, düzenli etik eğitimlerinin verilmesi, disiplinler arası ekip toplantılarının desteklenmesi, etik dayanıklılığı güçlendiren uygulamaların geliştirilmesi ve aile merkezli bakım anlayışının yaygınlaştırılması etkili yaklaşımlar olarak bildirilmektedir. Bunun yanında yeterli hemşire istihdamının sağlanması, çalışanlara yönelik psikososyal destek programlarının uygulanması ve etik karar süreçlerini destekleyen kurumsal politikaların oluşturulması hem çalışanların mesleki iyilik hâline hem de bakım kalitesine olumlu katkı sağlayacaktır.

Gelecekte yapay zekâ, dijital sağlık teknolojileri, genomik uygulamalar ve büyük veri analizlerinin yenidoğan bakımında daha yaygın kullanılacağı öngörülmektedir. Bu değişim, hemşirelerin yalnızca klinik bilgi ve becerilerini değil; aynı zamanda dijital etik, veri güvenliği, teknoloji okuryazarlığı ve teknoloji destekli karar verme konularındaki yetkinliklerini de geliştirmelerini gerekli kılmaktadır. Bu nedenle etik eğitimlerinin güncel teknolojik gelişmeleri kapsayacak biçimde yeniden yapılandırılması ve hemşirelerin sürekli mesleki gelişimlerinin desteklenmesi önem taşımaktadır.

Sonuç olarak, yenidoğan yoğun bakım hemşireliğinde etik bakım; bilimsel kanıt, mesleki deneyim, etkili iletişim, teknolojik gelişmeler ve insan haklarına dayalı yaklaşımın birlikte değerlendirilmesini gerektirmektedir. Etik ilkelerin günlük bakım uygulamalarına yansıtılması, disiplinler arası iş birliğinin güçlendirilmesi, aile merkezli bakım anlayışının benimsenmesi ve geleceğin dijital sağlık ortamına uygun etik yaklaşımların geliştirilmesi hem yenidoğanın üstün yararının korunmasına hem de güvenli, kaliteli ve sürdürülebilir bakımın sağlanmasına önemli katkılar sunacaktır.

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BOUNDARY-AWARE ATTENTION U-NET WITH CONTROLLED MULTI-SCALE GUIDANCE FOR SMALL SURFACE DEFECT SEGMENTATION

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ABSTRACT

Pixel-level detection of industrial surface defects is challenging due to the low visibility of defects, the fact that defective areas occupy a very small portion of the image, and their low contrast with surface texture. This study proposes a Boundary-Aware Attention U-Net using controlled multi-scale boundary guidance for segmentation of small surface defects. The model generates an auxiliary boundary representation by combining features of the Attention U-Net decoder at four resolution levels. This representation is passed to the final decoder feature via a zero-gamma initialized residual path. Thus, the basic Attention U-Net behavior is preserved at the start of training, and the contribution of boundary information is learned only to the extent that it is useful. The loss function combines binary cross-entropy and Dice loss for segmentation, and capped weighted binary cross-entropy and Dice loss for boundary output. In experiments conducted on KolektorSDD2 with three independent runs, the proposed method achieved 0.7550±0.0074 Dice, 0.6065±0.0096 IoU, 0.7544±0.0055 Average Precision, and 0.4909±0.0083 Boundary F1 at a fixed threshold of 0.50. While the number of parameters increased by only approximately 1.25% according to U-Net, the averages of Dice, IoU, Average Precision, and Boundary F1 increased. Qualitative samples show strong overlap in large defects and persistent failure in very small or low-contrast defects.

Keywords: Industrial visual inspection, surface defect segmentation, Attention U-Net, boundary guidance, multi-scale feature fusion, class imbalance

INTRODUCTION

Reliably identifying surface defects in industrial quality control is a fundamental requirement for product safety and production efficiency. Traditional visual inspection systems often rely on manually derived color, texture, or edge features. While such features may be successful in a given surface and lighting configuration, their generalizability can be limited when product type, camera, surface texture, and defect appearance change. Deep learning-based methods have become a powerful option in industrial visual inspection because they learn feature extraction directly from data (Czimmermann et al., 2020; Tabernik et al., 2020). Surface defect segmentation is a more nuanced problem than simply determining whether an image is defective. The goal is to extract all pixels associated with the defect and their boundaries as accurately as possible. In practice, this task is challenging for three reasons. First, defect-free samples make up the vast majority of production data. Second, defect pixels occupy a very small portion of the image. Third, defects such as scratches, blemishes, or material degradation can have similar brightness and color to the surface texture. KolektorSDD2 represents these challenges with real industrial images, a low defect sample rate, and detailed pixel masks (Božič et al., 2021).

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Fully convolutional networks and U-Net type encoder-decoder architectures have provided powerful foundational approaches for dense pixel estimation (Long et al., 2015; Ronneberger et al., 2015). U-Net's skip connections carry high-resolution spatial details to the decoder, while Attention U-Net aims to highlight task-relevant regions by adding attention gates to these connections (Oktay et al., 2018). However, since the boundaries of very small defects are sparse, optimizing only region overlap may not be sufficient for consistent boundary learning. On the other hand, directly multiplying the boundary probability map with segmentation features can lead to erroneous or noisy boundary estimations that corrupt the main output. This study, instead of directly applying boundary information as a mask, transfers a boundary representation learned from multi-scale decoder features to the segmentation path via controlled residual feature injection. Zero-gamma initialization keeps the effect of the additional path close to zero at the start of training. Thus, the model starts with the Attention U-Net behavior first, and then learns the contribution of boundary guidance from the data. The main contributions of the study are:

- A lightweight multi-scale fusion module that converts four decoder resolutions into a common boundary representation has been proposed.
- A controlled guidance mechanism that carries the auxiliary boundary information via a residual path initialized with zero-gamma has been developed. This design offers a more stable alternative to direct boundary modulation in Boundary-Aware V1.
- Top-bounded weighted boundary loss against excessive pixel imbalance has been used, and the method has been compared against U-Net and Attention U-Net in three independent runs under a constant evaluation protocol.

LITERATURE REVIEW

Fully convolutional networks have formed the basis of modern semantic segmentation by transforming classification backbones into structures that produce pixel-level output (Long et al., 2015). U-Net has offered an effective architecture, especially in limited data conditions, by combining shrinking encoder and expanding decoder paths with symmetric hopping connections (Ronneberger et al., 2015). UNet++ aims to reduce semantic gaps at different resolutions with nested and dense hopping paths (Zhou et al., 2018). DeepLabv3+, on the other hand, collects broad context using atrous spatial pyramid pooling while using the decoder path for boundary optimization (Chen et al., 2018). Attention U-Net filters by using attention coefficients generated within the decoder context, rather than directly integrating encoder features (Oktay et al., 2018). This mechanism can reduce background activation. However, attention gates do not explicitly monitor boundary accuracy, and class imbalance persists in learning sparse defect pixels. Therefore, in this study, Attention U-Net was retained as the backbone, and boundary-focused learning was added as a separate but linked auxiliary task via the main segmentation pathway.

In industrial defect inspection, the imaging pattern, surface texture, and defect type vary considerably depending on the application. Czimmermann et al. (2020), in their study encompassing classical image processing, machine learning, and deep learning approaches, demonstrated that this diversity makes it difficult for a single method to prevail across all production conditions. Tabernik et al. (2020) evaluated a deep learning approach that addresses surface defects with decision-making at both the segmentation and image levels in real production data. Božič et al. (2021) presented KolektorSDD2 and compared weak, mixed, and fully supervised learning forms. This dataset reflects the real production imbalance with a large number of defect-free images versus a small number of defective samples. While region-based losses provide good coverage of the object interior, they may not adequately highlight small positional errors near the boundary. Dice-based objective functions directly optimize region overlap (Milletari et al., 2016), while focal loss addresses class imbalance in dense estimation by reducing the contribution of easy samples (Lin et al., 2018). Kervadec et al. (2019) demonstrated that boundary-based loss can be used in conjunction with regional losses in high class imbalance. Gated-SCNN directly models boundary quality by processing shape information in a separate stream and routing it through gates from the main stream (Takikawa et al., 2019). Generalized Dice loss also uses class volume-based reweighting to reduce the suppression of small classes (Sudre et al., 2017). This work combines existing decoder features with lightweight projections instead of a separate and heavy shape backbone. With

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auxiliary boundary supervision, the learned representation is passed to the main path as a controlled residual feature, not directly as a probability mask.

Current studies on industrial surface defect segmentation increasingly focus on the combined modeling of multi-scale context, fine boundary details, and adaptive feature fusion. Othman et al. (2026) proposed the EGONet model, which combines Sobel-guided edge attention and auxiliary edge supervision with dense atrous spatial pyramid pooling (DASPP) and bilateral feature integration to more accurately determine defect boundaries on metal surfaces. DAMF-Net, developed by Liu et al. (2026), uses dynamic receptive-field selection and semantic-guided adaptive fusion to balance shallow-layer boundary details with deep-layer semantic information, especially for segmenting small and low-contrast defects. Similarly, Zheng et al. (2026) developed the MDRNet model, which integrates multi-scale channel attention with CNN–Transformer architecture and region-aware feature refinement. Recently proposed frequency-aware approaches have also highlighted the importance of high-frequency structural information in defect boundary preservation. Yu et al. (2026) adapted the SAM2 model to industrial defect segmentation using Laplacian-enhanced auxiliary branch and cross-branch multi-scale fusion. Liu et al. (2026), on the other hand, combined spatial- and DCT-domain representations with multi-scale segmentation heads to preserve defect boundaries and improve the positioning of small defects. Under limited data conditions, Xia et al. (2025) proposed TMCNet, a few-shot defect segmentation framework based on triplet-based feature enhancement and multi-scale cascaded decoding. Xie et al. (2025) developed a real-time segmentation network using adaptive kernel selection and dual-attention feature fusion for lithium-battery surface defect detection. Rolih et al. (2026) demonstrated that surface defect models can utilize unsupervised, weakly supervised, mixed-supervision, and fully supervised data. Despite these advances, current methods mostly rely on fixed gradient priors, frequency-domain branches, computationally expensive foundation models, or direct feature modulation. In contrast, there has been relatively less focus on controlling the extent and manner in which a learned multi-scale boundary representation is transferred to the main segmentation flow. This deficiency constitutes the fundamental motivation behind the zero-initialized residual guidance mechanism proposed in this study.

MATERIALS AND METHODS

Distinction between dataset and experimental data

KolektorSDD2 includes surface images and pixel-level defect masks obtained from a real production line (Božič et al., 2021). After excluding two duplicate records without masks in the local data integrity check, 3335 usable images remained. Of these, 356 were defective and 2979 were perfect. Defect pixels constitute only 0.2987% of the pixels in the entire data. This rate indicates a significant imbalance at both the image and pixel levels. The official 1004-image test section of the dataset was not modified at any stage. The remaining 2331 images were divided into 1865 training and 466 validation images, maintaining the defective sample rate. There are 197 defective images in the training section, 49 in the validation section, and 110 in the test section. File-level verification confirmed that there was no image overlap between the training, validation, and test records. The test set was not used for threshold selection or model selection.

Preprocessing and data augmentation

The images were resized to 672×256×3 with center zero-padding without altering the original aspect ratio. Since no resizing was applied, the thickness of the fine defects was not changed by scale transformation. The masks were converted to binary form, and the image values were scaled to the range [0,1]. During training, the image and mask were simultaneously subjected to horizontal and vertical flipping. Gaussian noise with a brightness of ±0.08, a contrast of 0.90–1.10, and a standard deviation of 0.01 with 25% probability was applied to the image alone. In the training sample, defective images were replicated at the image-level oversampling until the number of perfect images was reached. This balanced the two image classes in each training period while preserving the natural distribution of the validation and test sets. The boundary target b was derived from the difference between the morphological dilation and erosion of the binary mask with a 3×3 kernel. With y being the segmentation mask, δ_3 being the broadening, and ε_3 being the erosion, the boundary target b is defined as follows:

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$$b = \mathbb{1}[\delta_3(y) - \varepsilon_3(y) > 0] \quad (1)$$

In this formula, y represents the ground-truth segmentation mask, and $\delta_3(y)$ and $\varepsilon_3(y)$ represent the dilation and erosion operations performed using 3×3 structuring element, respectively. Subtracting the eroded mask from the dilated mask yields the morphological gradient encompassing the inner and outer boundaries of the object. The indicator function $\mathbb{1}$ generates the binary boundary mask b by assigning a value of 1 to boundary pixels where the difference is greater than zero, and 0 to other pixels.

Baseline models

Two basic models were used in the comparison. U-Net has four sample reduction levels, 32 initial filters, convolution-batch normalization-ReLU blocks, and a 0.30 dropout at the bottleneck. Attention U-Net maintains the same backbone and adds an attention gate that works with the decoder context to each skip connection. Batch normalization facilitates optimization via mini-batch statistics (Ioffe & Szegedy, 2015). Encoder and decoder depth, initial number of filters, preprocessing, data boosting, sampling, optimizer, and training stop conditions were kept equal for all models.

Proposed Boundary-Aware Attention U-Net

The proposed architecture is shown in Figure 1. D4–D1 respectively show decoder features from coarse resolution to full resolution. The auxiliary boundary output provides training control. The main inference output is the segmentation map. The outputs D4, D3, D2, and D1 of the Attention U-Net decoder are four feature levels, ranging from the coarsest resolution to full resolution, respectively. Each level is projected onto eight channels using 1×1 convolution, batch normalization, and ReLU. D4 is brought to the spatial resolution of D1 by eightfold, D3 by fourfold, and D2 by twofold bilinear upsampling. D1 is already at full resolution. The four tensors are coupled along the channel axis, and the common boundary feature Z is generated by 16-channel 3×3 convolution.

$$Z = \phi_{3\times3}\left(U_8\left(P_4(D_4)\right) \,\|\, U_4\left(P_3(D_3)\right) \,\|\, U_2\left(P_2(D_2)\right) \,\|\, P_1(D_1)\right) \quad (2)$$

Here, P_k represents the 1×1 projection applied to the relevant level, U_r denotes upsampling by a factor of r, $\|$ represents the channel merging, and $\phi_{3\times3}$ represents the convolution–batch normalization–ReLU transformation. Two branches diverge from the common feature. The first branch generates the auxiliary boundary probability q. The second branch generates a 32-channel guidance tensor g. The batch normalization scale parameter γ in this second branch is initialized to zero. The guidance tensor is added to the final decoder feature D_1 by residual addition, and the segmentation probability p is generated:

$$q = \sigma(W_b * Z + c_b), \qquad g = BN_{\gamma=0}\left(W_g * Z\right) \quad (3)$$

$$p = \sigma(W_s * ReLU(D_1 + g) + c_s) \quad (4)$$

Due to zero-gamma initialization, g is approximately zero in the initial steps of training, and the model behaves close to Attention U-Net. Training only learns to transfer boundary features that reduce loss to the main path. This approach differs from the direct modulation used in Boundary-Aware V1. In V1, the sigmoid boundary probability D1 directly affects the noisy boundary prediction segmentation representation because it could suppress it. In the proposed method, the probability map is not used as a multiplier. The learned feature tensor is added via a controlled residual path.

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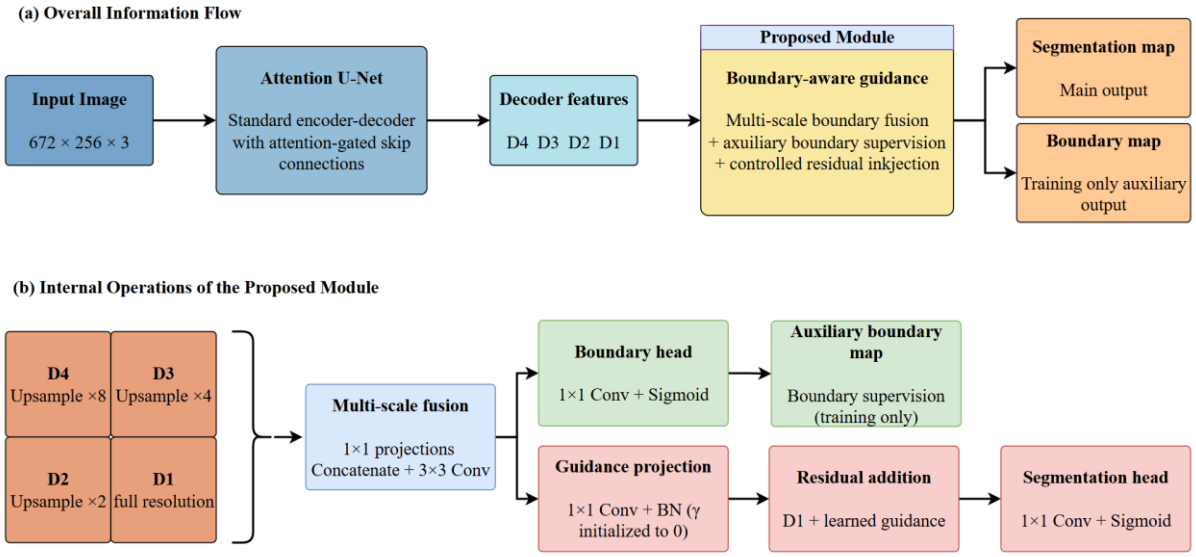


Figure 1. The proposed Boundary-Aware Attention U-Net module provides general information flow and multi-scale boundary guidance.

Loss functions

The principal segmentation loss is the equally weighted sum of binary cross-entropy (BCE) and soft Dice loss. To prevent the abundance of null masks from artificially dominating the Dice term, the Dice loss is centered only on images containing actual defects. False positive pixels in null masks continue to be penalized by BCE. For N pixels, y_i being the actual label, p_i being the prediction, and $\varepsilon = 10^{-6}$:

$$\mathcal{L}_{BCE} = -\frac{1}{N}\sum_{i=1}^{N}[y_i ln p_i + (1-y_i) ln(1-p_i)] \tag{5}$$

$$\mathcal{L}_{Dice} = 1 - \frac{2\sum_i y_i\, p_i + \epsilon}{\sum_i y_i + \sum_i p_i + \epsilon}, \qquad \mathcal{L}_{seg} = 0.5\mathcal{L}_{BCE} + 0.5\mathcal{L}_{Dice} \tag{6}$$

Boundary pixels are extremely sparse. Therefore, in the boundary BCE term, positive pixels are given a weight of 20, background pixels a weight of 1, and the result is normalized by dividing it by the total weight. Limiting the weight to 20 prevents the opposite frequency weight from producing very large gradients. For the boundary label b_i and boundary probability q_i, $w_i = 1 + 19b_i$:

$$\mathcal{L}_{WBCE} = \frac{\sum_i w_i\,[-b_i ln q_i - (1-b_i) ln(1-q_i)]}{\sum_i w_i}, \qquad w_i = 1 + 19b_i \tag{7}$$

$$\mathcal{L}_{boundary} = 0.5\mathcal{L}_{WBCE} + 0.5\mathcal{L}_{Dice,b}, \qquad \mathcal{L}_{total} = \mathcal{L}_{seg} + 0.10\mathcal{L}_{boundary} \tag{8}$$

The boundary loss weight of 0.10 ensures that the auxiliary task supports the segmentation objective but does not hijack the main optimization. This choice was fixed during exploratory development and remained unchanged in three independent final runs.

EXPERIMENTAL SETUP

Training protocol

The models were trained using TensorFlow 2.4.0 on an NVIDIA GeForce RTX 3080. The mini-batch size was 8, the initial learning rate was 10^{-4}, and the optimizer was Adam (Kingma & Ba, 2015). A maximum of 100 epochs were applied, and early stopping was used if no improvement in validation loss was observed after 15 epochs. The learning rate was multiplied by 0.5 if validation loss did not improve after five epochs, and the lower limit was set at 10^{-7}. For U-Net and Attention U-Net, the checkpoint with the lowest total validation loss was selected, and for the proposed model, the checkpoint with the lowest validation segmentation loss was chosen. Each model was independently trained three times with

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different random initializations. Data separation, preprocessing, amplification, sampling, and evaluation thresholds were the same across all models. The reported dispersion is the sample standard deviation (ddof=1). Test results are reported as the mean and variability of three runs, not a single successful run. Since this number is small, no claim of statistical significance is made.

Performance Metrics

The main evaluation threshold was pre-set to 0.50 for all models. TP, FP, and FN represent the number of true positive, false positive, and false negative pixels, respectively. Dice, intersection over union (IoU), precision, and recall were calculated as follows:

$$Dice = \frac{2TP}{2TP + FP + FN}, \qquad IoU = \frac{TP}{TP + FP + FN} \tag{9}$$

$$Precision = \frac{TP}{TP + FP}, \qquad Recall = \frac{TP}{TP + FN} \tag{10}$$

The F2 metric gives four times more weight to recall than to precision and is calculated as 5PR/(4P+R). Average Precision (AP) is not tied to a fixed threshold because it summarizes the area of the precision–recall curve obtained from the probability ranking. In unbalanced datasets, precision–recall analysis is particularly informative because it limits the effect of a large number of true negative pixels (Saito & Rehmsmeier, 2015). Boundary F1 (Perazzi et al., 2016) is the harmonic mean of the boundary precision and boundary recall values calculated by matching the predicted and actual boundary pixels within a two-pixel tolerance:

$$F_1^{boundary} = \frac{2P_bR_b}{P_b + R_b} \tag{11}$$

RESULTS AND DISCUSSION

Table 1 and Figure 2 show the test averages of three independent runs. The proposed method outperformed both baseline models with 0.7550 Dice and 0.6065 IoU. The absolute increase relative to U-Net is 0.0159 for Dice, 0.0202 for IoU, 0.0253 for Average Precision, and 0.0114 for Boundary F1. Recall increased from 0.6721 to 0.7096, while precision decreased from 0.8211 to 0.8067. This result suggests that the proposed model produces a limited amount of additional false positives while capturing more defect pixels. However, the precision value is also higher than the average of the Attention U-Net. The Dice standard deviation of the method is 0.0074 and the AP standard deviation is 0.0055. These are the lowest values among the compared models. Boundary F1 variability is higher than U-Net but lower than Attention U-Net. Therefore, the results support the proposed model not only in terms of mean success but also in terms of inter-run consistency in terms of region overlap and probability ranking.

Table 1. Test performance in three independent runs with a fixed threshold of 0.50.

Model	Parameters (M)	Dice	IoU	Precision	Recall	Average Precision	Boundary F1
U-Net	7.769	0.7391 ± 0.0106	0.5862 ± 0.0134	0.8211 ± 0.0154	0.6721 ± 0.0158	0.7291 ± 0.0175	0.4795 ± 0.0036
Attention U-Net	7.857	0.7339 ± 0.0177	0.5799 ± 0.0220	0.7963 ± 0.0282	0.6830 ± 0.0493	0.7315 ± 0.0169	0.4717 ± 0.0180
Boundary-Aware Attention U-Net (Proposed)	**7.866**	**0.7550 ± 0.0074**	**0.6065 ± 0.0096**	**0.8067 ± 0.0015**	**0.7096 ± 0.0138**	**0.7544 ± 0.0055**	**0.4909 ± 0.0083**

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Values are mean ± sample standard deviation. Average precision is threshold-independent. Other metrics were calculated with a threshold of 0.50. A tolerance of 2 pixels was used for Boundary F1. The highest precision is in U-Net, while the highest of the other reported averages is in the proposed method.

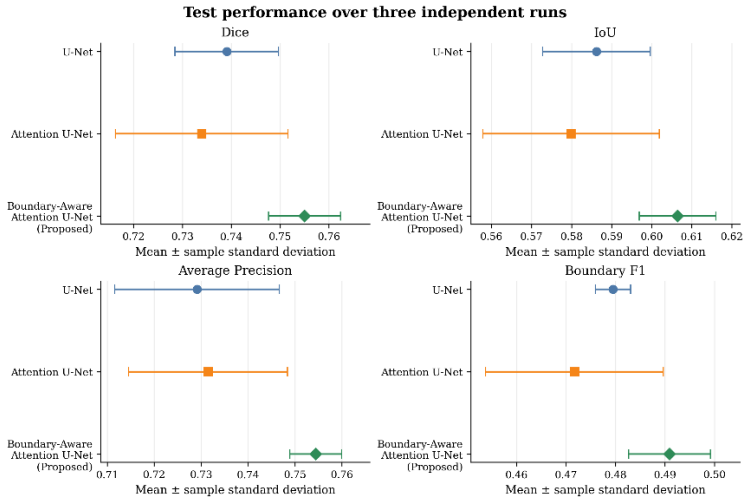


Figure 2. Comparison of test performance in three independent runs using mean and sample standard deviation.

In Figure 2, the points represent the mean, and the horizontal error bars represent the sample standard deviation. Dice, IoU, and Boundary F1 were calculated with a fixed threshold of 0.50; Average Precision was calculated independently of the threshold.

Figure 3 and Table 2 highlight the individual runs behind the averages. The proposed method outperformed the respective baseline models in all three runs across the Dice, IoU, Average Precision, and Boundary F1 metrics. The lowest proposed Dice value was 0.7494, and the highest was 0.7634. The Attention U-Net Dice value varied more widely, ranging from 0.7155 to 0.7508. While the U-Net Average Precision value dropped to 0.7131 in the third run, the proposed method reached 0.7604. In terms of Boundary F1, the proposed method showed notably higher in the first two runs, producing almost the same value as the U-Net in the third run. This observation demonstrates that boundary success is not solely dependent on the average, but that very fine boundaries can still be sensitive to different initializations. Run labels are not performance rankings and are used to present a repeatability pattern rather than revealing the identity of random initializations.

When Figure 3 and Table 2 are considered together, it is seen that the proposed Boundary-Aware Attention U-Net model provides a more balanced and generally higher segmentation performance compared to the basic U-Net and Attention U-Net models across independent studies. The Dice, IoU, Average Precision, and Boundary F1 values presented in the figure show that the proposed model is superior to the models compared in all three independent studies. In particular, the fact that the green curve is in the upper position in all studies in the Dice and IoU metrics shows that the proposed boundary-aware routing mechanism does not provide a coincidental improvement specific to a particular study, but contributes to more accurate segmentation of object regions under different initial conditions. However, it should be noted that the differences between the models are limited in some studies. For example, in the first study, the Dice difference between the proposed model and the U-Net is 0.0014, and the IoU difference is 0.0017. In contrast, the superiority of the proposed model becomes more pronounced in the second and third studies.

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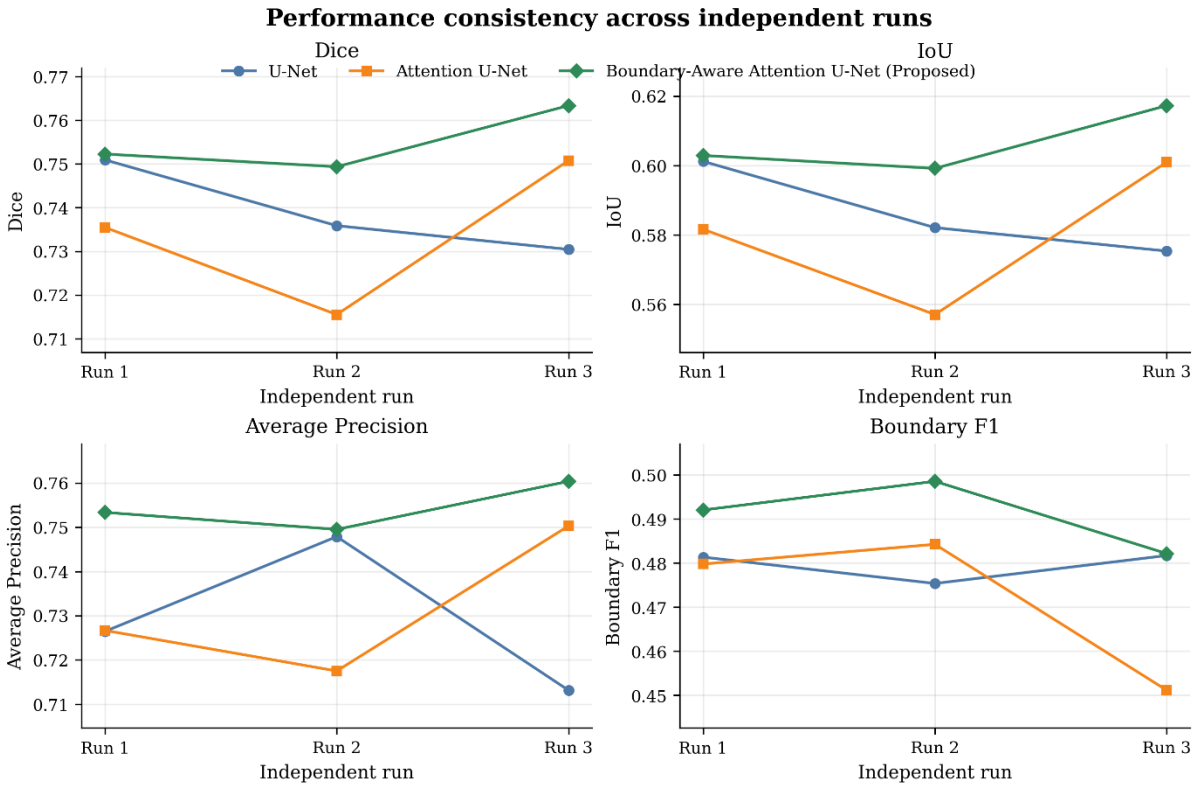


Figure 3. Changes in Dice, IoU, Average Precision, and Boundary F1 metrics across three independent runs.

When the averages of three independent studies are calculated, the proposed model yields a Dice value of 0.7550±0.0074 and an IoU value of 0.6065±0.0096. For U-Net, these values are 0.7391±0.0106 and 0.5862±0.0134, respectively, and for Attention U-Net, they are 0.7339±0.0177 and 0.5799±0.0220. Accordingly, the proposed model provides an absolute increase of 0.0159 in the average Dice value and 0.0202 in the IoU value compared to U-Net. The increases obtained compared to Attention U-Net are 0.0211 for Dice and 0.0266 for IoU. When evaluated relatively, it is seen that the proposed approach increases Dice performance by approximately 2.16% and IoU performance by 3.45% compared to U-Net. Compared to Attention U-Net, the relative gains are approximately 2.87% and 4.58%, respectively. The lower standard deviations of Dice and IoU in the proposed model indicate that the method not only has higher average performance but also produces more stable results in terms of region-based segmentation measures.

Table 2. Test results for individual runs

Run	Model	Parameters	Dice	IoU	Precision	Recall	F2	Average Precision	Boundary F1
Run 1	U-Net	7 768 929	0.7509	0.6012	0.8328	0.6838	0.7091	0.7264	0.4813
Run 1	Attention U-Net	7 856 693	0.7355	0.5816	0.8170	0.6688	0.6939	0.7267	0.4798
Run 1	**Boundary-Aware Attention U-Net (Proposed)**	**7 865 990**	**0.7523**	**0.6029**	**0.8056**	**0.7056**	**0.7235**	**0.7534**	**0.4920**
Run 2	U-Net	7 768 929	0.7359	0.5821	0.8037	0.6786	0.7004	0.7479	0.4754
Run 2	Attention U-Net	7 856 693	0.7155	0.5571	0.8076	0.6423	0.6697	0.7175	0.4843

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Run	Model	Parameters	Dice	IoU	Precision	Recall	F2	Average Precision	Boundary F1
Run 2	**Boundary-Aware Attention U-Net (Proposed)**	**7 865 990**	**0.7494**	**0.5992**	**0.8085**	**0.6983**	**0.7179**	**0.7495**	**0.4985**
Run 3	U-Net	7 768 929	0.7304	0.5754	0.8269	0.6541	0.6827	0.7131	0.4817
Run 3	Attention U-Net	7 856 693	0.7508	0.6010	0.7642	0.7378	0.7430	0.7503	0.4511
Run 3	**Boundary-Aware Attention U-Net (Proposed)**	**7 865 990**	**0.7634**	**0.6173**	**0.8061**	**0.7249**	**0.7398**	**0.7604**	**0.4821**

The results from the studies reveal this general trend in more detail. In the first study, the proposed model achieved 0.7523 Dice and 0.6029 IoU, narrowly surpassing U-Net's results of 0.7509 Dice and 0.6012 IoU. In the second study, the proposed model's values of 0.7494 Dice and 0.5992 IoU were significantly higher than both U-Net's values of 0.7359 and 0.5821, and Attention U-Net's values of 0.7155 and 0.5571. In the third study, the proposed model achieved the highest region-based segmentation performance among all experiments with 0.7634 Dice and 0.6173 IoU. In this study, the fact that U-Net remained at 0.7304 Dice and 0.5754 IoU, while Attention U-Net produced 0.7508 Dice and 0.6010 IoU, suggests that the proposed module can provide a stronger improvement, especially in conditions where the base network exhibits lower or variable performance. When the precision and recall values presented in the table are examined together, a significant performance balance emerges. The average precision value of the proposed model across the three studies is 0.8067. This value is higher than the average Attention U-Net of 0.7963, but lower than the average U-Net of 0.8211. In contrast, the proposed model achieved an average recall value of 0.7096, exceeding the U-Net of 0.6722 and the Attention U-Net of 0.6830. Therefore, the boundary awareness mechanism caused a limited decrease in precision compared to U-Net, while enabling the identification of a larger proportion of the actual defect pixels. This increase in recall value is practically valuable, especially since reducing false negatives is important in the segmentation of small and irregular surface defects. In other words, the proposed model is geared towards capturing defect regions with higher sensitivity, rather than simply producing more selective predictions.

The F2 metric, which gives more weight to the recall value than the precision value, also supports this evaluation. While the average F2 value of the proposed model is 0.7271, these values are 0.6974 and 0.7022 for U-Net and Attention U-Net, respectively. Thus, the proposed model provided an absolute increase of 0.0297 compared to U-Net and 0.0249 compared to Attention U-Net. In the first and second studies, the highest F2 values were obtained by the proposed model. In the third study, Attention U-Net, with 0.7430, slightly surpassed the proposed model's value of 0.7398. However, the overall average of the three studies shows that the proposed method is more balanced in terms of capturing defect pixels and reducing false negatives. The Average Precision results show that the proposed model offers a more reliable precision-recall balance across different decision thresholds. The proposed approach achieved Average Precision values of 0.7534, 0.7495, and 0.7604 in three studies, respectively, yielding the highest result in each study. The average of the three studies was calculated as 0.7544±0.0055, while the U-Net was 0.7291±0.0176 and the Attention U-Net was 0.7315±0.0169. The fact that the proposed model has both a higher mean and a lower standard deviation is an important finding in terms of reducing threshold dependence and ensuring performance consistency between different studies. In addition, the low variability in the Average Precision value of the proposed model indicates that the model's prediction confidence remains more stable across studies.

The Boundary F1 results, directly related to the study's core motivation, also demonstrate the positive impact of boundary supervision. The proposed model achieved Boundary F1 values of 0.4920, 0.4985, and 0.4821 in the first, second, and third studies, respectively. All of these values are higher than the U-Net and Attention U-Net results from the respective studies. The average Boundary F1 value calculated

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from the three studies is 0.4909±0.0083 for the proposed model, 0.4795±0.0035 for U-Net, and 0.4717±0.0180 for Attention U-Net. The average Boundary F1 increase of the proposed model compared to U-Net is 0.0114, and the increase compared to Attention U-Net is 0.0191. This result supports the idea that auxiliary boundary supervision and learnable orientation features improve not only the detection of general object areas but also the determination of the geometric boundaries of defects. However, variability in terms of Boundary F1 should be interpreted cautiously. While the U-Net produced lower but more stable results around 0.48, the proposed model showed a clear improvement in the first two studies and came very close to the U-Net in the third study. In the third study, the Boundary F1 value of the proposed model was 0.4821, while the U-Net value was 0.4817. The difference is only 0.0004. Therefore, although the proposed model produced the highest Boundary F1 value in all studies, the superiority in the third study is quite limited in practical terms. In contrast, the decrease of the Attention U-Net to 0.4511 in the third study reveals that the standard attention mechanism can show higher variability in terms of boundary quality. The proposed boundary-controlled structure reduced this variability, providing higher overall boundary accuracy.

Overall, the findings indicate that the most significant advantage of the proposed model is not simply producing the highest result in a single metric, but rather offering a more balanced performance across region overlap, defect sensitivity, threshold-independent classification success, and boundary accuracy. In particular, the low variability in the Dice, IoU, and Average Precision metrics supports the method's consistency across independent studies. However, results obtained from only three independent studies should not be considered proof of statistical significance. Specifically, the differences in Dice and IoU in the first study and the Boundary F1 difference in the third study are quite small. Therefore, unless supported by appropriate statistical tests or confidence intervals, the results should be expressed as consistent descriptive superiority rather than statistically significant superiority.

The proposed boundary module added only 97,061 trainable parameters to the U-Net. This increase is approximately 1.25%. The difference between the Attention U-Net and the proposed model is 9,297 parameters. In Figure 4, the proposed method remains in almost the same region as the basic models on the horizontal axis, while yielding the highest average Dice value on the vertical axis. Therefore, the gain stems more from boundary-oriented reuse of existing decoder features than from significantly expanding the backbone. Since this study does not directly measure inference time, FLOPs, or memory consumption, the claim of computational efficiency is limited by the number of parameters.

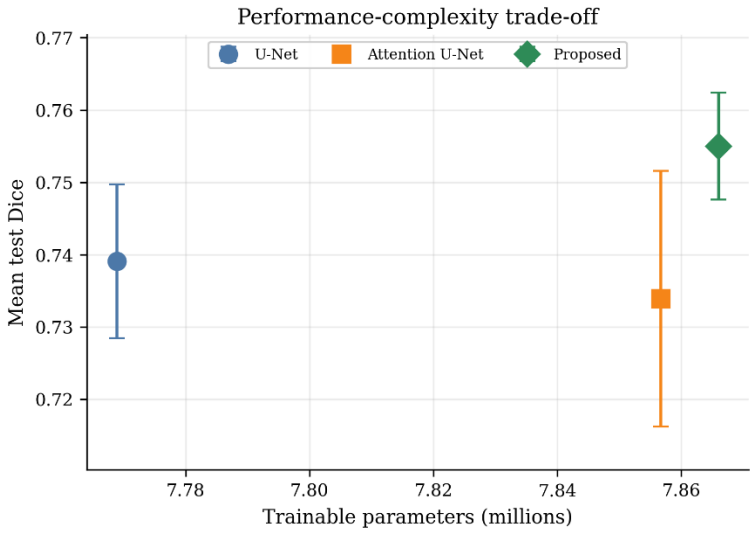


Figure 4. The relationship between the mean test dice and the number of trainable parameters.

Table 3 examines why controlled guidance is necessary through a single representative run. Boundary-Aware V1 used the boundary probability to directly modulate the final decoder feature and applied a higher boundary loss weight. This structure reduced the Attention U-Net Dice from 0.7355 to 0.6833. The proposed controlled residual path produced a Dice of 0.7523 and a Boundary F1 of 0.4920. The

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results show that simply adding an auxiliary boundary output is not sufficient; how the boundary information is passed to the main segmentation path is crucial. However, since V1 was not re-evaluated in three independent runs, this table should be interpreted as exploratory evidence.

Table 3. Exploratory single-run comparison of direct boundary modulation and controlled residual boundary guidance.

Method	Parameters (M)	Dice	IoU	Average Precision	Boundary F1
Attention U-Net	7.8567	0.7355	0.5816	0.7267	0.4798
Boundary-Aware V1	7.8654	0.6833	0.5189	0.6554	0.4327
Boundary-Aware Attention U-Net (Proposed)	**7.8660**	**0.7523**	**0.6029**	**0.7534**	**0.4920**

Boundary-Aware V1 was evaluated in only one representative run. All segmentation measures were calculated with a fixed threshold of 0.50.

Figure 5 compares four highly overlapping samples under the same 0.50 threshold. All outputs were generated with a fixed threshold of 0.50. Cyan represents true mask overlay, red represents prediction overlay; on the error map, green represents true positive (TP), red represents false positive (FP), and blue represents false negative (FN). The examples are not proof of mean superiority, but a visual illustration of typical successful behavior. In large and visually prominent defects, all models closely follow the true mask. The highest Dice at the sample level does not always correspond to the proposed method. However, the proposed model is able to extract defects of different locations and shapes as continuous regions, producing dominant green true positive areas in the defect maps. Red false positive and blue false negative bands are mostly concentrated around the defect. This suggests that the remaining defects are more dependent on boundary location than internal region.

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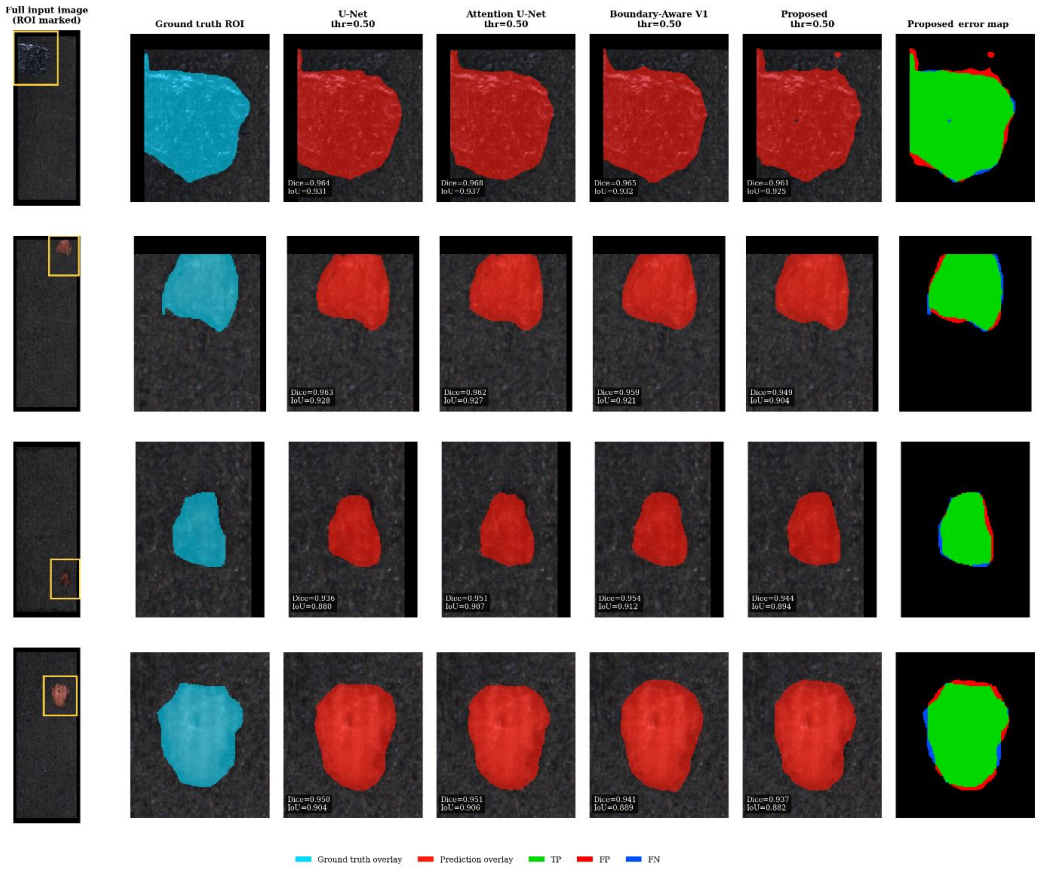


Figure 5. Qualitative comparison of four models in highly overlapping test samples.

This study compares the qualitative segmentation results of models on four different defect samples. The first column shows the full-size input image and the region of interest (ROI) marked with a yellow frame, while the second column shows the ground truth mask for this region. Subsequent columns present segmentation predictions generated by U-Net, Attention U-Net, Boundary-Aware V1, and the proposed model, using a decision threshold of 0.50. The Dice and IoU values at the bottom of each prediction numerically indicate the level of overlap between the predicted defect area and the ground truth mask. In the error maps in the last column, green regions represent true positive pixels (TP), red regions represent false positive pixels (FP) that were incorrectly classified as defects, and blue regions represent false negative pixels (FN) that were overlooked by the model. Examination of the error maps reveals that the majority of correctly classified areas are clustered in the center of the defect, while false positive and false negative pixels mostly occur at irregular defect boundaries. This situation demonstrates that the models successfully determine the overall location and area of the defect, with the fundamental difference emerging in how precisely the boundaries are tracked. While all models generally produce high overlap values, there are small performance differences on a sample basis. In some samples, U-Net or Attention U-Net provide higher Dice and IoU values, while in others, the boundary-aware approach yields more successful results. The proposed model largely accurately identifies defect regions in all samples and produces predictions that preserve the main geometry of the object. However, the fact that it does not yield the highest result in every image indicates that a general superiority should not be drawn from individual qualitative samples. Therefore, visual results should be evaluated together with average performance metrics calculated from independent studies. Overall, the figure clearly shows that the differences between the models mostly emerge in the fine and irregular boundary regions rather than in the inner region of the defect.

Figure 6 includes examples of the method's limitations. In the first example, all models have a Dice value of zero because the predicted regions are spatially separated from the actual defect. In the second example, only Boundary-Aware V1 captures a portion of the fine defect, while the proposed method misses the defect. In the third example, all models find the defect, but Attention U-Net produces the

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highest sample Dice value. These results clearly show that although the proposed method improves average performance, it does not resolve very fine, low-contrast, or near-edge defects in all cases.

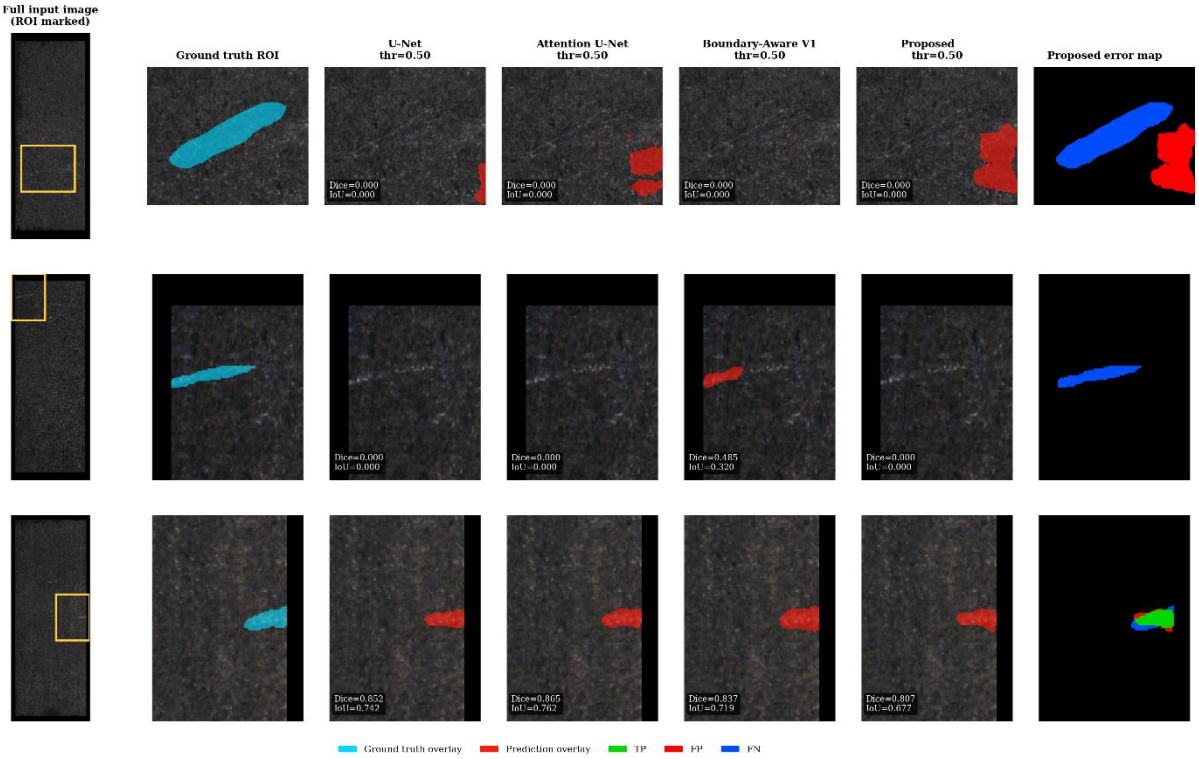


Figure 6. Patterns of failure in small, low-contrast, or spatially indeterminate test samples.

Experiments show that simply generating a separate boundary head is insufficient for boundary information to be useful in small defect segmentation. Direct boundary modulation led to a sparse and initially noisy signal suppressing the main decoder features. The proposed zero-gamma residual path gradually enables guidance while preserving the network's initial functionality. This behavior is consistent with the principle that residual learning facilitates optimization (He et al., 2016). Multiscale merging combines contextual information in D4 with fine spatial detail in D1 in the same representation. Thus, the boundary head accesses not only local gradients but also the broader context of the defect. The most significant aspect of the main results is the increase in recall and average precision. The proposed method captured more true defect pixels and performed better than the two basic models in probability ranking. The fact that the precision is 1.44 percentage points lower than U-Net indicates that the increase in sensitivity comes with additional false positives. Since the cost of a missed defect in industrial inspection is often higher than that of a false alarm, this trade-off is acceptable depending on the application. However, the decision threshold was not adjusted according to the test data. The fixed 0.50 threshold keeps the inter-method comparison clear and reproducible. The Boundary F1 increase is smaller than the increase in region measures. One reason for this is that the boundaries derived with the 3×3 morphological gradient are very fine and the number of positive pixels is very low. Also, while a two-pixel tolerance is more flexible than exact matching, it is sensitive to small positional errors. Therefore, the actual contribution of the auxiliary boundary head should be evaluated not only as the success of the separate boundary map but also in conjunction with the improvement of the main segmentation representation. The higher Dice, IoU, and AP in Table 1 support this combined effect. Qualitative samples present two complementary results. First, in apparent defects, all U-Net derivatives achieve high overlap, and the difference between methods mostly appears in a few boundary pixels. Second, very small and low-contrast defects remain challenging for all models. It is important to show both successful and unsuccessful examples together, as average results can mask these extreme cases. In this study, visuals were used not as a substitute for quantitative comparison, but to illustrate the types of errors that cause the criteria.

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LIMITATIONS

The study has four main limitations. First, the experiments were performed on a single industrial dataset. Cross-domain generalization under different material, camera, and lighting conditions has not yet been demonstrated. Second, while three independent runs provide a useful indication of variability, they are insufficient for reliable hypothesis testing. Therefore, statistical significance has not been asserted. Third, boundary labels are derived from segmentation masks via morphological processing, not from separate human annotations. Mask ambiguities can be directly transferred to boundary targets. Fourth, the number of parameters is reported, but latency, FLOPs, energy, and peak GPU memory are not measured. The Boundary-Aware V1 comparison is based on a single representative run and is an exploratory analysis describing only the method development process. In the future, it is necessary to evaluate all component variants, including V1, with the same number of independent runs, to examine boundary thickness and tolerance together, and to test patch-based or multi-resolution training strategies for very small defects. Probability calibration and cost-sensitive selection of the operating point in the validation data are also important for manufacturing applications.

CONCLUSION

In this study, a Boundary-Aware Attention U-Net with controlled multiscale boundary guidance is developed for the pixel-level identification of small and irregular industrial surface defects. The proposed method combines the D1, D2, D3, and D4 features obtained from different decoder stages of the Attention U-Net into a lightweight multiscale boundary representation by bringing them to a common spatial resolution. The auxiliary boundary map created from this common representation provides boundary supervision only during training, while the learned boundary features are transferred to the main segmentation path via controlled residual injection. Starting the Batch Normalization scale parameter on the residual path with $\gamma = 0$ ensures that the model maintains the basic Attention U-Net behavior at the beginning of training and that boundary guidance is learned incrementally only to the extent that it is useful. Thus, the aim is to prevent noisy or erroneous boundary probabilities from directly distorting the main segmentation features while utilizing multiscale geometric information. In three independent runs performed on the KolektorSDD2 dataset, the proposed method achieved mean Dice values of 0.7550±0.0074, IoU values of 0.6065±0.0096, Average Precision values of 0.7544±0.0055, and Boundary F1 values of 0.4909±0.0083. The proposed model outperformed both the baseline U-Net and the Attention U-Net in terms of average performance across all four metrics. Compared to the U-Net, absolute increases of 0.0159 in Dice, 0.0202 in IoU, 0.0253 in Average Precision, and 0.0114 in Boundary F1 were achieved. The absolute increases achieved compared to the Attention U-Net were 0.0211, 0.0266, 0.0229, and 0.0191, respectively. The low variability, particularly in the Dice, IoU, and Average Precision metrics, demonstrates that the method not only produces higher average results but also exhibits more consistent performance across independent runs.

The increase in the obtained values indicates that the method has developed a more balanced behavior towards reducing false negatives. Considering that overlooking small defects can have significant consequences in quality control processes, this development is valuable from an application perspective. Qualitative results also showed that errors were predominantly clustered at the irregular boundaries of defects, and that the proposed method largely preserved the overall geometry of the object. However, it was observed that the proposed model did not produce the highest result in every individual image; the superiority of the method was more evident in the overall averages obtained from independent runs. This performance gain was achieved with a limited increase in computational and model complexity. The proposed model has 7,865,990 parameters, while U-Net has 7,768,929 and Attention U-Net has 7,856,693 parameters. Accordingly, the proposed boundary guidance module added only 9,297 additional parameters to Attention U-Net. This corresponds to an increase of approximately 0.12%. The total parameter increase compared to U-Net is approximately 1.25%. Therefore, it is considered that the improvement obtained stems not only from the increase in network capacity, but also from the more effective combination of multi-scale features and the controlled use of boundary information. Exploratory component comparisons showed that directly applying boundary probabilities to the main segmentation features does not always yield positive results and can sometimes reduce performance. In contrast, transferring boundary representation via a learnable and zero-initialized residual path produced

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more balanced results. This finding reveals that in small defect segmentation, the mechanism by which boundary information is transmitted to the main network is as important as the presence of this information itself. The auxiliary boundary function alone is insufficient; the interaction between boundary features and region-based segmentation features needs to be regulated in a controlled manner.

The study has some limitations. Experiments were limited to a single industrial dataset and three independent runs. Furthermore, fixed-thickness boundary targets generated by morphological processes may not always provide optimal control for defects with different sizes and geometries. False negatives persist, particularly for very thin, low-contrast defects that show strong similarity to the background texture. Future studies could include validating the method on different industrial defect datasets, investigating adaptive boundary thicknesses, developing uncertainty-aware boundary control, and comparing different boundary loss functions. Overall, the findings indicate that boundary information is useful in segmenting small surface defects, but transferring this information to the main segmentation network via a controlled, learnable, and low-cost mechanism is critical.

DATA AVAILABILITY

KolektorSDD2 is made available for research access through the original study introducing the dataset (Božič et al., 2021). The data separation, training configurations, and assessment outcomes reported in this article are archived by the authors.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

FUNDING

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INVESTIGATING THE INTERACTION BETWEEN DROPOUT AND SPARSE TRAINING IN DEEP NEURAL NETWORKS

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ABSTRACT

Model sparsity aims to enable densely connected deep neural networks to learn using a reduced number of active connections. In this context, the performance of static and dynamic sparse connection patterns across different network architectures, as well as the effect of dropout regularization on sparse networks, remain active research areas. In this study, the image classification performance of deep neural networks with static and dynamic sparse connectivity is investigated under different sparsity levels and dropout settings. To this end, the densely connected versions of the deep neural networks utilized in this study are compared with three sparse training approaches: Static Sparse Training, Sparse Evolutionary Training (SET), and Rigging the Lottery (RigL). Uniform layer-wise sparsity is applied to the layers eligible for sparsification, and sparsity levels of 80% and 90% are examined. To evaluate the effect of dropout, each model configuration is trained both without dropout and with a dropout rate of 20%. All experiments are repeated using three random seeds, and classification performance is evaluated in terms of mean Accuracy and F1 scores. Experiments are conducted on the CIFAR-100 dataset using VGG-16-BN and ResNet-18. The experimental results show that the dynamic sparsity methods SET and RigL achieve higher classification performance than static sparse connectivity in both networks. For VGG-16-BN, the best sparse model performance is obtained with SET at 80% sparsity and a 20% dropout rate, achieving an F1 score of 71.39%. The dense VGG-16-BN model achieves an F1 score of 72.39%. For ResNet-18, the best-performing sparse configuration is obtained with RigL at 80% sparsity without dropout, achieving an F1 score of 75.29%, whereas the best-performing dense ResNet-18 model reaches an F1 score of 76.51%. The effect of dropout is observed to vary depending on the sparsity method, sparsity level, and network architecture. In particular, at 90% sparsity, using a 20% dropout rate improves the average classification performance of Static Sparse Training, SET, and RigL across both CNN architectures. In contrast, at 80% sparsity, the effect of dropout varies according to the sparse training method and network architecture. Overall, the results demonstrate that dynamic connectivity reconfiguration is more effective than static sparse connectivity, particularly at high sparsity levels, and that the interaction between dropout and model sparsity depends on both the sparsity level and the underlying network architecture.

Keywords: Deep neural networks, Sparsity, Regularization.

INTRODUCTION

In recent years, deep neural networks (DNNs) have demonstrated outstanding performance in the field of computer vision. Deep neural network models are often over-parameterized. Therefore, the number of trainable parameters in these networks can exceed the capacity required to represent the target problem. While over-parameterization can facilitate optimization, a subset of network connections may be sufficient to achieve competitive forecasting performance Frankle and Carbin (2019). Consequently,

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there is increasing interest in sparse neural networks or methods that allow sparse connectivity to be directly incorporated into the model training.

Sparse neural networks can broadly be considered from two categories according to whether the connectivity pattern remains fixed or changes during training. In static sparse training, a sparse connectivity pattern is established before training and the same topology is retained throughout the training. Although static sparse training reduces the number of active connections, its performance can depend on the quality of the initially selected sparse structure. In contrast, Dynamic Sparse Training (DST) allows the model's connectivity structure to change during training by periodically removing existing connections and enabling new ones. DST allows the model to explore alternative sparse connections during training, instead of remaining fixed connection Nowak et al. (2024). Mostafa ve Wang (2019), showed that continuously exploring the sparse network structure during training can be crucial for obtaining high-performing sparse models. Mocanu et al. (2018) introduced Sparse Evolutionary Training (SET) that starts with a sparse network and dynamically evolves its connectivity during learning by removing less important connections and introducing new connections. Evci et al. (2020) proposed Rigging the Lottery (RigL) that combines magnitude-based removal of existing weights with gradient-based growth of new connections. RigL uses gradient information to identify inactive connections, rather than randomly introducing new connections. More generally, recent research has continued to highlight the importance of topology exploration in DST. Liu et al. (2021) investigated how overparameterization compensates for the lack of dense connection in sparse networks by exploring different connections throughout the training. Ji et al. (2024) considered DST as a joint optimization problem in which network weights and sparse topology interact during learning. Dropout provides a different form of regularization by temporarily disabling neurons and their associated connections during training. Dropout prevents excessive co-adaptation among learned features by randomly removing a subset of features during training Srivastava et al. (2014). Sparsity and dropout operate in different ways. Sparsity determines which trainable connections exist in the network, whereas dropout introduces stochastic and temporary feature suppression during training. Therefore, combining a dropout with a sparse network introduces an additional stochastic adjustment on top of a permanently constrained connectivity structure.

In this study, we investigate a question regarding whether dropout and structural sparsity complement or interfere with each other. A sparse network already operates with a restricted set of active connections. Applying dropout to such a network may improve generalization by introducing additional regularization, but it may also temporarily suppress information carried by an already limited set of active features. Moreover, the outcome may depend on whether the sparse connectivity is fixed or allowed to evolve during training. Static sparse networks cannot recover from an unfavorable connectivity pattern during optimization, whereas dynamic methods such as SET and RigL can continually reorganize active connections. Consequently, the effect of dropout may vary not only with the overall sparsity level but also with the sparse training strategy and underlying network architecture. To understand the underlying answer to these questions, this study investigates the classification performance of dense, static sparse, and dynamically sparse convolutional neural networks under different sparsity and dropout configurations. Static Sparse Training, SET, and RigL are compared using two representative CNN architectures, VGG-16-BN and ResNet-18, on the CIFAR-100 image classification dataset. The main contributions of this study can be summarized as follows:

- A comparison of static and dynamic sparse training strategies is conducted by evaluating Static Sparse Training, SET, and RigL using two different CNN architectures.
- The interaction between structural sparsity and dropout regularization is investigated at 80% and 90% sparsity levels.
- The results demonstrate that dynamic sparse training outperforms fixed sparse connectivity. Furthermore, dropout provides consistent performance improvement across all evaluated sparse methods and architectures at 90% sparsity.

METHODOLOGY

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This study investigates the classification behavior of dense, static sparse, and dynamically sparse convolutional neural networks under different sparsity and dropout settings. Four training configurations are considered: conventional dense training, Static Sparse Training, Sparse Evolutionary Training (SET) Mocanu et al. (2018), and Rigging the Lottery (RigL) Evci et al. (2020).

Static Sparse Training. At the beginning of training, a random sparse connectivity mask is generated according to the specified sparsity level. This mask remains unchanged throughout the entire training. Only the weights corresponding to active connections are allowed to learn, while gradients of inactive weights are suppressed during optimization. Consequently, the network must learn using the same sparse connectivity structure from the beginning to the end of training.

Sparse Evolutionary Training (SET). The aim of SET is to periodically remove weak connections and replace them with newly generated connections throughout training. At each network structure update, the active connections with the smallest absolute weight values are identified and removed. The same number of new connections is then randomly selected from the set of inactive connections. In this way, the total number of active connections remains constant while the positions of these connections change over time. Newly activated connections are initialized with zero-valued weights and are subsequently optimized during the remaining training iterations.

Rigging the Lottery (RigL). Similar to SET, RigL removes existing connections and activates new connections. However, SET and RigL differ in how newly activated connections are selected. In RigL, active connections with the smallest absolute weight magnitudes are first selected for removal. Instead of selecting replacement connections randomly, RigL evaluates the gradient information associated with currently inactive connections. Inactive connections with the largest absolute gradient values are then activated. Thus, RigL attempts to introduce new connections at positions that are expected to have a stronger immediate influence on reducing the training loss.

Dropout. Dropout temporarily suppresses a subset of learned features during training and is used to reduce feature co-adaptation Srivastava et al. (2014). Dropout and sparsity have different roles in training. Sparsity permanently determines which network weights are active, whereas dropout temporarily suppresses features during training. In this study it is aimed to determine whether combining these two forms of connectivity restriction improves or reduces classification performance under different sparse training strategies and sparsity levels.

Network Architectures. Two CNN models with different structures are used to examine the behavior of sparse training and dropout. The first model is based on VGG-16 Simonyan and Zisserman (2015) and uses batch normalization following the convolutional layers Ioffe and Szegedy (2015). The second model is ResNet-18, which employs residual connections to more effectively utilize gradient flow in deep neural networks He et al. (2016).

Dataset and Implementation Details. All experiments are conducted on CIFAR-100 Krizhevsky (2009), which contains 32x32 RGB 50,000 training and 10,000 test images with 100 classes. The training dataset set is divided into training and validation subsets using stratified sampling. For each random seed, 90% of the original training images are used for model optimization and the remaining 10% are used for validation. During training, data augmentation is applied using random cropping with four-pixel padding and random horizontal flipping. All configurations are trained for 100 epochs using stochastic gradient descent with Nesterov momentum. The initial learning rate is 0.1, momentum is 0.9, weight decay is 0,0005, and the batch size is 128. The learning rate is gradually reduced throughout training using cosine annealing Loshchilov ve Hutter (2017). Cross-entropy loss is used as the objective. To account for stochastic variations arising from weight initialization, sparse mask generation, mini-batch ordering, and dropout, every experimental configuration is independently repeated using the random seeds 42, 123, and 2026. The final classification results are reported as the mean and standard deviation of Accuracy and F1 score. The sparse models are trained at 80% and 90% sparsity, while each configuration is evaluated both without dropout and with a dropout rate of 20%. The same general dropout is used in both models. When dropout is enabled, channel-wise dropout is applied to the final convolutional feature representation immediately before global average pooling.

RESULTS

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The classification performances of Static Sparse Training, SET, and RigL under different sparsity and dropout settings are summarized in Figure. 1. The results reveal two main observations for the VGG-16-BN and ResNet18 models. First, increasing the sparsity level from 80% to 90% decreases classification performance for all sparse training methods. Second, the dynamic sparse training methods, SET and RigL, consistently outperform Static Sparse Training for all sparsity and dropout settings. These findings demonstrate that dynamically changing the sparsity structure during training improves model performance over static sparsity.

For VGG-16-BN Static Sparse Training achieves a F1 score of 69.62%, whereas SET and RigL improve this value to 71.15% and 70.95%, respectively, at 80% sparsity without dropout. For a 20% dropout rate, SET achieves the highest F1 score of 71.39%, compared with 70.06% for Static Sparse Training and 70.67% for RigL. At a 90% sparse data level, the performance difference between static and dynamic sparse training increases. Without dropout, Static Sparse Training achieved 67.44% F1, while SET and RigL achieved scores of 69.71% and 69.95% respectively, corresponding to improvements of 2.27% and 2.51%. With 20% dropout, SET and RigL reached 70.14% and 70.21% F1 score compared with 67.89% for Static Sparse Training.

Similar results are observed for ResNet-18. At 80% sparsity without dropout, Static Sparse Training obtains 73.86% F1, whereas SET and RigL achieve 75.09% and 75.29%, respectively. When sparsity increases to 90%, the advantage of dynamic sparsity becomes larger. Without dropout, Static Sparse Training decreases to 71.22%, while SET and RigL maintain F1 scores of 73.29% and 73.49%, respectively. With dropout, the corresponding values are 71.61%, 73.78%, and 73.85%. Therefore, for both architectures, dynamic sparse training appears to recover a considerable portion of the performance loss by using a fixed sparse structure.

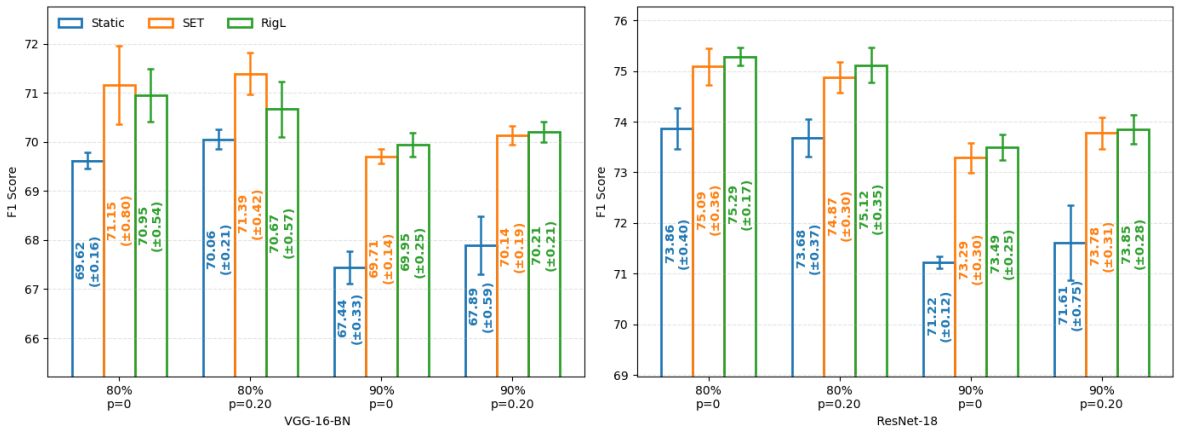


Figure 7. F1 score of Static Sparse Training, SET, and RigL under 80% and 90% sparsity with and without 20% dropout: VGG-16-BN and ResNet-18. Values inside the bars represent the mean F1 and standard deviation over three runs.

The results in Figure 1 reveal that the performance of SET and RigL depends on the model architecture and sparsity level. For VGG-16-BN, SET performs better than RigL at 80% sparsity, especially when dropout is used, whereas RigL surpasses SET at 90% sparsity. In contrast, RigL achieves higher mean F1 scores than SET for ResNet-18 model training. The results show that dynamic sparsity, based on gradient information, depends on both the network architecture and the sparsity level.

Figure 2 examines the effect of dropout by showing the change in F1 score after a 20% dropout was used. The results demonstrate that dropout does not affect sparse networks in the same way. At 80% sparsity, its effect largely depends on the architecture and sparsity method. For VGG-16-BN, dropout improves Static Sparse Training and SET by 0.43 and 0.24 points, respectively, whereas the performance of RigL decreases by 0.28 points. For ResNet-18, dropout reduces the performance of all three sparse training approaches at 80% sparsity.

Under this more aggressive sparsity setting (90% sparsity), dropout improves the mean F1 score for every sparse training method and for both network architectures. For VGG-16-BN, the improvements

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are 0.45, 0.43, and 0.26 points for Static Sparse Training, SET, and RigL, respectively. Similarly, ResNet-18 obtains improvements of 0.40, 0.49, and 0.35 points. The largest dropout improvement is observed for SET on ResNet-18 at 90% sparsity, where F1 increases by 0.49 points.

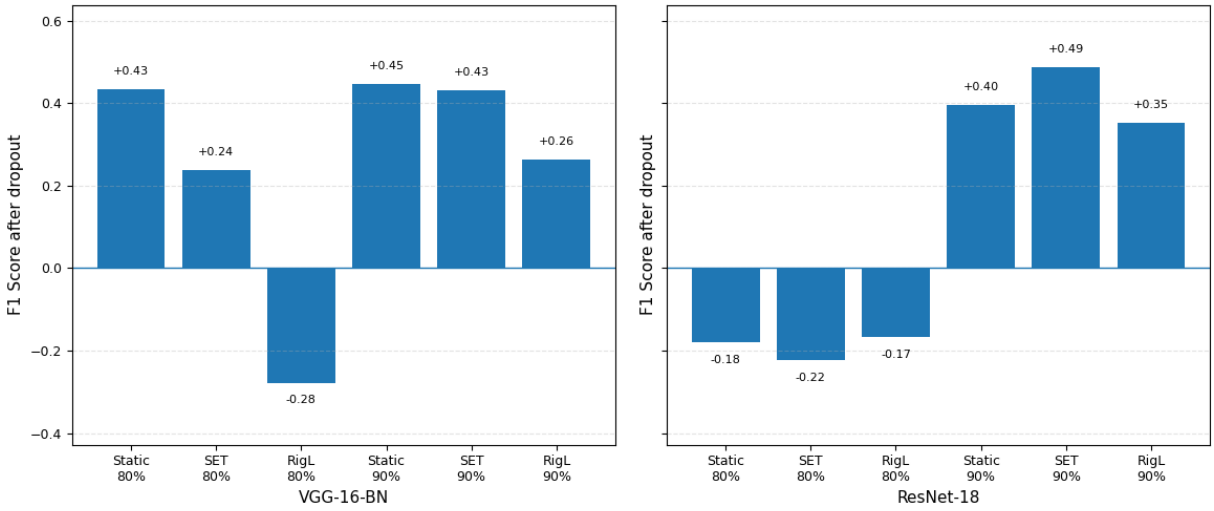


Figure 8. Effect of 20% dropout on the F1 performance of Static Sparse Training, SET, and RigL at 80% and 90% sparsity: VGG-16-BN and ResNet-18. Each bar shows the change in F1 relative to the corresponding model trained without dropout.

These findings indicate that dropout and structural sparsity are not independent design choices. At moderate sparsity, additional stochastic regularization does not consistently improve classification performance. In contrast, when sparsity reaches 90%, the effect of dropout becomes positive across all training configurations. This might be related that the regularization effect introduced by dropout becomes more beneficial when the network operates under a highly sparse structure.

Overall, the experimental results support two main conclusions. First, dynamic network structure provides a clear and consistent classification performance over fixed sparse structure. Second, the effectiveness of dropout depends on the sparsity rate, sparse method, and model architecture. The consistent improvement obtained with dropout at 90% sparsity suggests that the interaction between structural sparsity and stochastic regularization becomes particularly relevant under highly sparse connectivity.

CONCLUSION AND DISCUSSION

This study investigated the interaction between structural sparsity and dropout regularization by comparing dense networks with Static Sparse Training, SET, and RigL using VGG-16-BN and ResNet-18 on CIFAR-100. The experiments are conducted using 80% and 90% sparsity levels and without dropout and with a dropout rate of 20%. The results demonstrate that the behavior of sparse neural networks is influenced not only by the number of active connections but also by whether the sparse topology remains fixed or is dynamically changed during training.

Dynamic sparse training methods, SET and RigL, outperform Static Sparse Training across all training. A fixed sparse mask forces the model to rely on the initially sampled connectivity throughout optimization, whereas dynamic methods can progressively replace less useful connections and explore alternative network structures. Another outcome of the study concerns the interaction between dropout and structural sparsity. Dropout does not provide a uniform improvement across all sparse networks. At 80% sparsity, its effect varies according to the architecture and sparse training method. In contrast, at 90% sparsity, applying 20% dropout improves the F1 score for every sparse training method in both architectures. Structural sparsity permanently limits the available connectivity of the network, whereas dropout temporarily suppresses learned features during training. At moderate sparsity, the additional stochastic suppression introduced by dropout may be unnecessary or may interfere with already effective representations. At more sparsity levels, dropout may provide a complementary regularization effect that reduces excessive dependence on the smaller set of available representations.

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Future work can extend this study by evaluating a wider range of sparsity and dropout levels and by investigating adaptive regularization strategies in which the dropout rate is adjusted according to the current sparsity level or sparse training dynamics. It would also be valuable to examine whether the same interaction occurs in deeper CNNs, vision transformers, and other datasets with different levels of complexity.

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14. INTERNATIONAL EUROPEAN CONGRESS ON ADVANCED SCIENTIFIC RESEARCH

September 3-6, 2026

Zurich, Switzerland

14. ULUSLARARASI AVRUPA TEMEL BİLİMLERDE İLERİ ARAŞTIRMALAR KONGRESİ 3-6 Eylül 2026 tarihleri arasında Zürih - İsviçre'de 26 farklı ülkenin akademisyen/araştırmacılarının katılımıyla gerçekleşmiştir. Kongre kapsamında sunumu yapılan 231 bildirinin 108 adeti Türkiye'den katılımcılar tarafından; 123 bildiri ise 26 ülkeden katılımcılar tarafından sunulmuştur. Kongre 16 Ocak 2020 Akademik Teşvik Ödeneği Yönetmeliğine getirilen "*Tebliğlerin sunulduğu yurt içinde veya yurt dışındaki etkinliğin uluslararası olarak nitelendirilebilmesi için Türkiye dışında en az beş farklı ülkeden sözlü tebliğ sunan konuşmacının katılım sağlaması ve tebliğlerin yarıdan fazlasının Türkiye dışından katılımcılar tarafından sunulması esastır.*" değişikliğine uygun düzenlenmiştir.

Bilgilerinize arz edilir,

Saygılarımla,

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HEAD OF THE CONGRESS

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This Official Protocol Declaration is hereby issued by London Sovereign School (hereinafter referred to as "the Institution"), a duly constituted academic and research entity operating within the United Kingdom and possessing full legal personality under applicable UK law.

Pursuant to the Institutional Charter, Academic Regulations, and Internal Statutes, the Senate of the Institution, at its duly convened session held on **14 January 2026**, did hereby adopt and enact Resolution **No. 2026/7**, whereby it is formally decreed that the scientific event specified hereunder shall be organized under the official auspices and academic supervision of the Institution. The said event shall be deemed an official academic undertaking of London Sovereign School and shall be conducted in strict conformity with principles of academic integrity and all applicable legal and regulatory provisions in force.

By virtue of the aforesaid Resolution, the academicians and designated officials serving within the Organizing Committee, Scientific Committee, Advisory Board, and related academic bodies have been duly nominated and ratified by the Senate. The list of appointed members constitutes an integral and legally operative part of this Declaration.

This Declaration shall enter into force upon issuance and remain in full force and effect unless otherwise amended by Senate resolution.

Dr. Mariam S. OLSSON
Deputy President

LONDON SOVEREIGN SCHOOL
Unit 501 Leroy House, 434-436 Essex Road
London N1 3FY - United Kingdom
Institution No: 16871908

Official Professor Roster of the Organizing Committee Members Appointed Pursuant
Prof. Dr. Arzu AL-Marmara University
Prof. Dr. Mykola VAS'KIV-Borys Grinchenko Kyiv University
Prof. Dr. Petra PELLETIER-Paris University
Assoc. Prof. Dr. Ethem İlhan ŞAHİN-Adana Alparslan Türkeş University of Science and Technology

Title and Venue of the Scientific Event: 14. INTERNATIONAL EUROPEAN CONGRESS ON ADVANCED SCIENTIFIC RESEARCH

Official Date(s) of the Event: September 3-6, 2026
Zurich, Switzerland

Official Web Adresse: https://www.iksadeurope.org/