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Mechanical characterization of sisal fiber-groundnut shell powder reinforced epoxy composites

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This study focuses on sustainable materials across various engineering fields, specifically investigating natural fibre-reinforced composites. It examines the mechanical properties of epoxy composites reinforced with sisal fibre and groundnut shell powder through a comparative analysis. The innovative aspect of this research lies in the variety of sisal fibre and groundnut shell powder ratios used to create the composites: 100:0, 80:20, 60:40, 40:60, 20:80, and 0:100. The composites were fabricated using the hand-laying technique. To evaluate their durability, the composites underwent a series of tests, including assessments of elasticity, flexibility, impact resistance, and hardness. The samples exhibiting the best tensile, flexural, and impact strengths were subjected to a comprehensive examination using Scanning Electron Microscopy (SEM) to analyse their internal structure, identify cracks, and observe surface characteristics on the broken surfaces. The findings indicate significant variations in mechanical properties based on the different ratios of sisal fibre and groundnut shell powder used for reinforcement. The composite with a cellulose fibre to groundnut powder ratio of 20:80 demonstrated the highest tensile strength, while the composite with a 100:0 ratio exhibited superior flexural strength. Additionally, the laminate with 100% sisal fibre reinforcement exhibited enhanced impact strength, and the 60:40 ratio presented the maximum hardness.

Keywords Composites, Laminates, Hardness, Impact strength, Rigidity

Abbreviations

ASTM	American society for testing and materials
CBF	Fibre glass
S20G80	20% sisal fibre and 80% groundnut shell powder
S40G60	40% sisal fibre and 60% groundnut shell powder
S60G40	60% sisal fibre and 40% groundnut shell powder
S80G20	80% sisal fibre and 20% groundnut shell powder
G100	100% Groundnut shell
CFRP	carbon-fibre-reinforced
CFF	chicken feather fibre
GNS	groundnut kernels
GPa	Gigapascals
HRL	Rockwell L hardness
Kg	kilojoules
Mpa	Megapascals
MMT	Montmorillonite
SEM	Scanning electron microscopy

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S100	100% sisal fibre
TETA	Triethylenetetramine
UTM	Universal testing machine
4D	4 Dimensional
3D	3 Dimensional

In recent years, there has been a growing interest in developing sustainable and environmentally friendly materials, particularly in the realm of composites. Organic composites with fibre reinforcement have attracted significant attention because they provide an eco-friendly alternative to traditional synthetic composites. These materials hold considerable potential across various industries due to their sustainable, biodegradable, and cost-effective properties. Wear strength is a critical factor influencing their performance, as it determines their ability to withstand friction and wear in everyday applications. This study investigates the mechanical properties of composites composed of epoxy reinforced with silk fibre and groundnut shell powder to conduct a comparative analysis of their wear resistance. The addition of groundnut shells in powdered form and sisal fibres to the epoxy matrix enables an investigation into how these biological enhancements affect wear resistance. To appreciate the significance of this research project, it is essential to review existing studies on synthetic composites reinforced with fibres and their damage characteristics. Study[1] focused on hybrid bio-composites, reinforced with coir and groundnut shells as an alternative to gypsum ceiling tiles, highlighting how natural fibres enhance the mechanical properties of composite materials, which is particularly important for wear-resistant applications. Study[2] examined the acoustic properties of composite materials made from bentonite and banana or prickly fibres. While their research focused on acoustic qualities, it is noteworthy that coconut fibres have been used as reinforcement in natural composites, potentially enhancing wear resistance. Study[3] provides a comprehensive analysis of plant-based fibres and their combinations as sustainable alternatives to traditional materials, emphasizing the abrasion resistance of natural composites with fibre reinforcement and their applicability across various fields. Study[4] explored the effects of alkaline treatment on the physical and chemical properties of sisal fibres and their bonding with a cement-based matrix. Although this study focused on cement-based composites, it is recognized that alkali treatment can enhance the mechanical properties of sisal fibres, particularly wear strength, when incorporate into a polymer matrix. Finally, Study[5] highlighted the characteristics of epoxy jute/glass fibre reinforcement hybrid composites, showcasing the reinforcing potential of sisal fibres within epoxy matrices. A study[6] conducted a tribological analysis of alkali-treated MMT nano-clay-reinforced hybrid materials. Composites derived from coconut sheaths demonstrate the wear-resilience of materials made from coconut pulp. Studies[7] explored the potential of using fibre powder as a granular substance in polymeric composites, suggesting that sisal-based polymers could be employed for durability purposes. Another set of studies[8] provided an overview of the physical characteristics of sisal fibreglass mixed polymer composites, highlighting their resistance to wear. Research[9] examined the compressive properties of hybrid composites made from higher-density polyethene, nano-alumina, and groundnut shells, which may contribute to a better understanding of their wear behaviour.

Additionally, the research from[10] analyzed the thermal and mechanical properties of bio-composites made from bagasse fibre and coconut shell powder bonded with cardanol resin, indicating their potential applications in wear-resistant contexts. Eco-friendly and environmentally conscious materials are increasingly being adopted across various engineering sectors, driven by a growing awareness of ecological issues and the need to reduce resource consumption. Some notable applications of these materials include:

- The use of reclaimed concrete, bamboo, also known as hempcrete, and other renewable resources in constructing structures, walkways, and roads.
- The adoption of bio-based insulation materials for energy conservation.
- The development of bio-composites and lightweight materials, such as graphite-studded polymers, enhances combustibility and reduces pollutants.
- The repurposing of recyclable plastics for automotive panels and non-essential components.
- The integration of thin composites to improve mileage and lower carbon emissions.
- Research into biological composites containing fibres for non-structural applications.
- The incorporation of plant-based composites in naval vessels and systems aims to reduce reliance on fossil fuels.

Moreover, research[11] has characterized the quantitatively epoxy resin augmented with organic fibres, providing insights into their wear characteristics. Investigation[12] focused on the development and evaluation of composites made from waste groundnut shells and coir cellulose, potentially demonstrating their durable characteristics as environmentally friendly stress-resistant materials. A study[13] examined the essential reinforcing elements in natural composites and sisal fibres. It is crucial to determine the maximum deformations of these elements before manufacturing the product to ensure its integrity. The methods for assessing fractures or failures are predicted using Ansys software, and various element types must be studied prior to conducting the investigation[14–16]. The examined research highlights the significance of natural composites composed of fibres and their potential as wear-resistant materials. This research investigates sisal fibre and groundnut shell powder-reinforced epoxy alloys to enhance the understanding of ecologically sound and economically viable materials, enabling their use in various wear-prone environments[17].

The selection of groundnut shell powder as reinforcement material is because, whenever mixed with polyamide in polyethene materials, charcoal generated from husks of significantly enhanced longitudinal (as high as forty-six MPa), bending (fifty-four MPa), and impacting (thirty-six J/m) toughness has enormous benefits in terms of mechanical characteristics[18].

The scanning microscopy using electrons, absorbed water, and infrared spectroscopy were all employed for analyzing the components. The experimental results demonstrated that the materials have a rupture strength of 40 MPa and an elasticity coefficient of 3 GPa, as well as a bending strength of 90 MPa and a viscosity of 10 GPa each. The decreasing empty space in blends with forty per cent by weight and ten per cent by weight results from the excellent interaction between the scaffolding and the filaments[19]. The combination of Steel and carbon-fibre-reinforced (CFRP) in rectangular tubing provides an attractive biomechanical performance/structural economical trade-off[20]. But beneath transverse effects, traditional hybrid tubing frequently buckles too soon and doesn't dissipate enough force. Filling steel/CFRP hybrid cylinders with a quadrilateral lattice matrix is a revolutionary energy-absorbing architecture that this investigation offers to conquer those drawbacks[21]. This study, from[22], has an overarching goal to develop and evaluate compression-moulded natural composite fibres. A battery of engineering evaluations, including extensible consequences, and Hollingsworth, was implemented to describe these materials. An SEM technique was used to examine the strand network adhesion. The benchmark from[23]. Using epoxy resin as the matrix, five examples of composites with different proportions of groundnut kernels (GNS) to fibreglass (CBF) were created. Tensile durability, resilience to impacts, thermal conduction, and other characteristics were determined using conventional testing at a temperature of deterioration. The findings suggested that adding extra carbon fibre considerably improved toughness, resilience to impact from 30 to 72 J/m^2, as well as elasticity from 125 to 320 MPa. As a result, increased cellulose percentages also enhanced depreciation frequency (264–340 °C) and heat transfer. Groundnut, also known as shell, on the other hand, showed poorer durability but added to resilience. According to the results, carbon fibre-groundnut shell materials can be made for uses where excellent durability and stable temperature are necessary or for environmentally friendly alternatives, wherein functionality is not as important. The present research lays the groundwork for the creation of outstanding durability recyclable polymers in the decades to come. According to[24], an enormous opportunity exists to engage in sustainable manufacturing to fulfil humanity's societal requirements in the decades to come. By developing a novel component by fortifying materials in the polyurethane matrix, the present study meets such criteria by integrating environmentally friendly resources, such as ground nuts, along with fibre. This experiment made use of peanut shell fragments as a binder. While the overall epoxy quantity decreased by 55,50,45, and 40 wt. proportion and the Amount of filler quantity by 5,10, and 20 per cent. The fibre compositional percentages stayed unchanged at forty per cent in each of the tests. The elastic strength is eighteen per cent, and the flexion strength is fourteen per cent at a filler percentage of 20 per cent. Results showed that decreased padding percentages (up to 10 wt%) had superior impact capacity compared to increasing padding percentages. From the study[25], the customized composites are examined for their physical and mechanical features, including microhardness, size, and shear stiffness. In order to determine what went wrong, electromagnetic images (SEM) of objects that have been compressively fractured are also examined. The findings of the investigation show that the compressive and bending strengths increase up to a filler loading of fifteen per cent of weight before slightly decreasing; on the other hand, the tiny hardness measurements rise as the quantity of filler increases. The filler proportions in compounds can vary, which in turn affects how dense they are and their porosity. Due to their inherent weakness, fibres from plants are utilized as support in polymerization. Organic fibres such as kenaf, sisal, the fruit, bamboo, and bananas are being covered here. Additionally, a lot of thought has been given to the origins and characteristics of every single one of these fibres. These organic materials have been investigated for use as augmentation in various materials[26]. From[27], hybridization laminated nanocomposites of duckling feathered fibre, as well as rayon fibre augmented plastics, are fabricated and their behaviours are experimentally investigated. Creating a new material fortified with burlap and leftover waterfowl plume threads in a polymer's matrix is the primary goal. The research[28,29] has talked about plant-based yarns such as abaca trees, rayon, cotton, silk, and burlap. Additionally, a lot of thought has been given to the origins and characteristics of all these fibres. These fibres of nature are currently investigated for use as reinforcements in various kinds of composites. Similarly, these indigenous materials' stiffness and uses are also covered. According to the investigation, silky has the largest stretch at dissolution of jute with the greatest Young's modulus, and abaca.

Furthermore, specimen 4's tribological, flexibility, and shape features demonstrated that its advantageous fibre dispersion resulted in improved qualities.

The research[30,31], The mixtures are made using various mounting algorithm configurations. In comparison to other hybridization and pristine adhesive materials, the jute-agave combination demonstrated superior tensile torque (90 MPa), stretching strength (132 MPa), impact (3.5 J), and roughness, according to the findings. The research[32,33] proves that the use of naturally occurring fibres like bananas and tropical plants in 3D printers to produce greener polymers is examined in 3D printing of customized plastic alloys: strengthening resilience with papaya and pineapple fruit component supplements. The study emphasizes how the structural properties of the final composites are impacted by the Amount of the portion within these fibres. The interesting research is carried out on one good alternative to the imitations is chicken feather fibre (CFF). As an outcome of chicken raising, CFF is challenging to analyze, manage, and treat due to the absence of consistent methods of removal. However, the stuff is an intriguing class of fibres with the opportunity to be employed for a wide range of situations due to its low cost and suitable qualities[34]. Fibres derived from creatures and plants are referred to as natural fibres. Synthetic yarns may eventually be replaced with renewable resources like coconut, cannabis, jute, and rattan to create compact, nontoxic materials with better durability[35]. Several alterations to chemicals can improve these physical traits. Additionally, a variety of scientific therapies that improve the mechanical interlocking can be used to alter the internal structure of the above fibres. The characteristics of organic fibres like hemp, oil palm, the use of bamboo, and burlap are discussed in this overview, besides the most recent possible uses to advance environmental and profitability. An intriguing field is the creation of sustainable compounds utilising natural fibres, and its potential uses in 4D printers and 3D printers[36,37].

The research gaps identified from various kinds of literature from Sisal Fibre-Groundnut Shell Powder, including the possibility of using coatings to improve the bond between polyurethane and sisal strands. Few studies have investigated the possibility of additive effects on tensile and failure strength. At larger load values, groundnut shell powder has a tendency to clump, which impacts the even dispersion of tension. Very little is known about these combinations' ability to absorb moisture, age thermally, or degrade when exposed to ultraviolet light. Little is known about the physical attributes of maintenance in practical problem surroundings over the years. The novelty behind the usage of sisal fibre with groundnut shell powder possesses enormous benefits, followed by the long-term strategy for creating green, durable substances, which is the use of composites. The Performance Improvements in the mechanism domain combining six to twenty-five per cent by weight of ground nuts metallic to epoxy-based polymers with 40 per cent cellulose fibre demonstrated: An eighteen per cent boost in durability is achievable with a twenty per cent filler. Strengthening the flexure by fourteen per cent. The ideal padding proportions above 15 per cent by weight for the impact rating were achieved when there was a more uniform distribution and less coagulation. The crystalline homogeneity interaction was influenced by the filler ingredient attention, according to a scanning electron microscope examination. The formation caused by more than fifteen weight% of filler weakens its structural strength owing to insufficient capillary traction. These compostable materials act as a substitute for polyester interwoven with imitation fibres in a variety of applications in the diversified field of mechanical engineering. The substrate Synthesis for Sustainability is proven for sisal fibre and groundnut shell, an everlasting material exhibiting excellent pulling qualities. Sisal is powerful, environmentally friendly, and everlasting. The additive that improves structural and thermodynamic qualities, groundnut hull powders, is an organic byproduct high in lignin composition. They come combined to create a bio-composite that promotes the concepts of the adaptive economy and reduces ecological harm by making use of crop residues.

The behaviour of hydration consumption is substantial, with carbohydrate emotions, organic yarns, including sisal, that are fluid-loving, meaning they are more likely to accept moisture. Due to the fact that nutshell powder is lignocellulosic, it also aids in the absorption of humidity, particularly when component coefficients are larger. The epoxy substance can nonetheless diffuse via microvoids or poor fibre-matrix connections, even though it is typically moisture-resistant. Sisal rug fibre, groundnut core particle, welded urethane Connectors are appropriate for a variety of real-world uses because they provide an appealing combination of long-term viability, robustness, and economic affordability. It is widely used in the field of automotive, construction and aerospace applications. Because sisal fibres are organically reusable, they will break down in six to twelve months when composted. According to tiny particles and the surroundings, nut shell powder, which breaks down in no more than three months. Nevertheless, the epoxy coating does not biodegrade. However, the total degradation is dramatically enhanced when between forty and sixty per cent of the aggregate is made up of plant-based additives.The reason behind this research is to use an inexpensive additive that lessens its influence on the surroundings, which is nutshell substance, which is derived from crop residue. Utilizing such substances lessens dependency on synthetic yarns and chemicals, therefore advancing the concepts of the regenerative economy.

To find improved mechanical characteristics, because of its advantageous hardness-to-weight ratio, sisal yarns help to achieve enormous tensile and flexibility. Protection from impacts and thermal insulation are enhanced by nut shell powdery substances, particularly when filler contents are tuned. The combination composition, composite hybrids exhibit encouraging outcomes like softness and tensile durability. Customizable component approaches to practical engineering difficulties are made possible by the study's assistance in customizing interconnected recipes for particular practical needs.

Methodology

Materials

Groundnut shell powder and organic sisal fabric are supplied by Tokyo Technology Company Pvt. Ltd., located in Coimbatore, India. The epoxy resin and the hardener were purchased from Sakthi Fibre Glass Pvt. Ltd. in Chennai, India.

Methods

Picking out the right components is the first of many steps in making material composites. Here, the bonding substrate is a resin made from epoxy, and reinforcement reagents are nut shells powder and polyamide fibres. Figure 1. represents the methodology part involved in this process. The combination of these parts creates a novel substance with unique characteristics. The mixture of materials is made using an individual lay-up process. To do this, you'll need to combine nut shell powdered form and sisal strands with epoxy glue, then pour the finished product into a mold. The amalgamation is transformed into an immobile laminate after curing. Several mechanical tests are carried out to evaluate the hybrid material's characteristics. The blunting obstructions, flexural durability, and tensile endurance of a substance are all determined by such tests.

Sisal fibre and its extraction

To decorate, one scrapes the cellulose away using a machine or by hand, preserving only the brittle filaments. The next step is to scrub the material to get rid of any remaining dirt or leaves. The level of moisture is usually reduced to less than 10% by baking it in direct sunlight or in the microwave. The filaments are chopped or cut to dimensions ranging from ten to thirty millimetres for use as reinforcing in composites. The pulpy material of the leaf is removed to extract the sisal fibres. The yarns are then sun-dried for two to three days. After that, the recovered fibres are rinsed with water to remove any debris and allowed to dry in the sunshine for an additional two to three days. Each leaf produces approximately 800 to 1,200 fibres, which are used in the production of cables, flooring, and carpets. The hand-laying process used in composite fabrication encompasses the stages, equipment, and methods tailored to various composite ratios[38]. Pulverizing and screening Groundnut shell

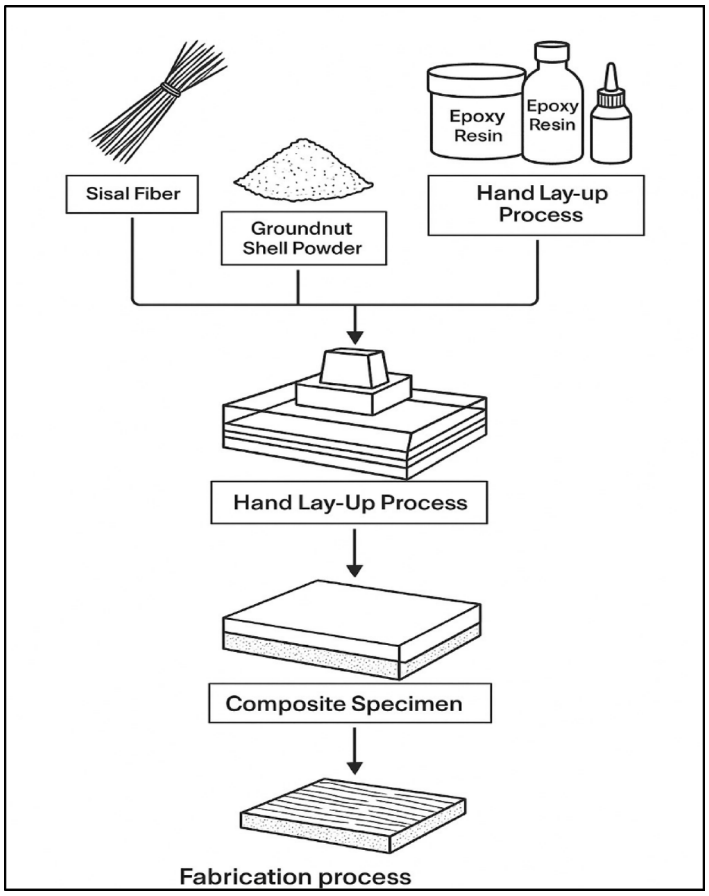

Fig. 1. Methodology.

powder. As a lignin agronomic byproduct, groundnut kernels have the makings of a promising laminate binder. Any remaining seeds, particles, or other debris are removed from the husks during the sterilization process.

For the preservation of the product, it is usually dried outdoors or baked until the water content is below five per cent. Granular breaking by means of a crusher, like a jaw or impact milling, is known as squeezing. Pulverised to a fine powder employing rapid connectivity, abrasives, disc textile mills, or ball mills for precise milling.

Procedures in the hand-laying method

The interior of the mould is sanitized and treated with an agent that inhibits material attachment. For complicated shapes, beeswax or speciality-releasing films may be used to facilitate shaping. A gel polish is applied to the mould to achieve a polished appearance and enhance the visual appeal of the final product. This process is particularly beneficial for applications that require aesthetically pleasing or durable surfaces. Cut layers of reinforcement materials, such as fibreglass, steel, carbon fibre, or natural fibres, are positioned on the mould. The alignment of the fibres is adjusted according to the desired mechanical properties (e.g., strength and stiffness). Resin (such as epoxy resin, polyester, or bio-based resin) is applied to the reinforcement material using rollers or spray guns. Care is taken to ensure complete saturation of the fibres. A hand roller is used to compress the reinforcing layers and eliminate any trapped air bubbles, creating a consistent resin-fibre matrix. Special attention is given to avoiding both over-saturation and under-saturation of the fibres, as this impacts the material's strength and weight. In multilayer composites, additional reinforcement and resin are added, repeating the saturation and compaction processes. The composite can cure at ambient temperature or under controlled heat, depending on the resin system. Vacuum bags or compression moulds may be used to ensure uniform thickness and minimize voids during curing. The cured composite is carefully removed from the mould. Excess material is trimmed, and the surface is either sanded or coated as necessary. Customized mould (tailored to the product's configuration), Application tools for resin, including rolling implements, brushes, or spray guns, and Hand-operated rollers for compaction.

The usual proportion of adhesive to harder substance is 5:4. The Parts of the Mortar Mix include the Amount of groundnut shells powder: around 5 to 40% weight, contingent upon the objective's durability. The fibre transferring can vary between five and twenty weight per cent for sisal fibre, which is commonly laminated in weaving or shredded condition. Get the Fibres and Fillers Ready treated with sodium hydroxide (usually a mixture consisting of sodium hydroxide for four to six hrs) for strengthening the bonds between surfaces. Performed a full drying cycle prior to usage. Powdered peanuts shell, roughly ground to a size of just about 1 mm.

Thoroughly dried and screened to guarantee even distribution. The Techniques for removing rust includes about the disclosure agent followed by laminate surface-applied silicone spraying or a waxy substance. To help with removing the moulds and interface finishing, a plastic sheet is occasionally utilized as a foundation membrane. Setting up the hollow cavity is filled with layers of agave fibres. A comparable proportion of nutshell powder and resin-hardener concoction is dumped and then dispersed. To eliminate airborne particles and guarantee even flooding, manually pressure or stretch the material. Table 1 represents the Parameters for curing time and pressures.

Groundnut shell powder

Groundnut shell (Arachis hypogea) is obtained by removing the nut from the shell. The shells are then ground into a fine powder known as groundnut shell powder. This powder has a light brown colour and is commonly used as a filler to fill gaps and voids in the plywood industry. It can also be combined with glue or adhesives for enhanced bonding[39].

Epoxy resin and hardener

Epoxy (Araldite LY556) is a copolymer formed from two different components: the "resin" and the "hardener." The epoxy resin is produced through a reaction between epichlorohydrin and bisphenol-A. The hardener is made up of polyamine monomers, such as triethylenetetramine (TETA). A specific hardener, known as HY-951, enables the composite laminate to set quickly and easily. There are various types of hardeners available, including HY-951, HT-972, HY-974, and HZ-978. The mixing ratio of resin to hardener is 10:1 by weight.

NaOH treatment

Sisal fibre must be treated by immersing it in a 2% sodium hydroxide (NaOH) solution for 45 min. After soaking, the fibres should be washed with clean water to remove any excess sodium hydroxide. Finally, the washed fibres are dried in sunlight for a few hours.

Preparation of mould

The mould consists of a rectangular glass plate that measures 400 mm in length and 400 mm in width. This plate is covered with a plastic film, and a releasing agent, specifically PVOH, is applied over the plastic film. Surrounding the glass plate on all four sides is a frame that has a thickness of 3 mm. Another rectangular glass plate of the exact dimensions (400 mm long and 400 mm wide) is placed on top of the frame, which is also covered with plastic film. This setup is referred to as the mould.

Preparation of composite specimen

The composite materials are prepared using the hand layup method. First, the mould should be thoroughly cleaned and dried. An epoxy resin and hardener are mixed in a 10:1 ratio. The fibres are initially dried in sunlight for a few hours to remove any moisture. Next, the epoxy mixture is applied uniformly onto the mould using a brush as the first layer. The appropriate proportions of sisal fibre and groundnut shell powder are then placed onto the mould. An additional layer of epoxy resin is applied uniformly over the fibres. Once this is complete, the mould is closed, and a weight of 10–15 kg is applied to the mould containing the composite materials for a curing period of 12–24 h. After curing, the composite material is allowed to dry completely before being separated from the mould[40].

Mechanical testing

Tensile test

The tensile test was performed using a Universal Testing Machine (UTM). The specimens were prepared according to the dimensions specified in ASTM D3039. A test specimen was placed in the tensile machine, and the load was applied until it fractured. The tests were conducted on six different types of specimens, specifically S100, S80G20, S60G40, S40G60, S20G80, and G100. The setup for the tensile test conducted with the UTM is illustrated inFigure 2.

Tests designed to evaluate materials typically involve compressing the substance to examine its ability to adapt without undergoing irreversible deformation. The criteria for measuring the compressive properties of verified polymers and nanomaterials. Adaptability is essential for processes that require metals to conform to various shapes or movements while maintaining their integrity and structural stability. Impact assessments involve applying a sudden force or shock to the material, such as in a Charpy or Izod test, to evaluate its resistance to fracture. Standards like ASTM D256 (which pertains to the Izod impact strength of polymers) and ISO 180 are commonly referenced. In these assessments, a defined force is applied to a specific area of the material using a penetrator or indenter, allowing for the measurement of its surface roughness. Specifications such as ASTM

S.NO	Parameters	Range
1	Conditions at ambient	Dry
2	Pressure	1–3 bar
3	Curing Time	24 to 72 h
4	Post curing	50–100°C

Table 1. Parameters for curing time and pressures.



Fig. 2. Tensile test using a Universal Testing Machine.

Property tested	ASTM	Property	Description
1	D695	Compressive strength	Rigid parts
2	D5379	Shear strength	Beam composites
3	D638	Tensile strength	tensile properties of composites
4	D256 or D6110	Impact strength	Impact test of composites and nut shell
5	D790	Flexural strength	Flexural properties fibres
6	ASTM D2240	Hardness	Durometer hardness Sisal fibre

Table 2. ASTM standards and testing the properties.

E10 (Brinell hardness test) and the protocols established by the American Society for Testing and Materials E18 are used in this context. When studying the physical features of composites of epoxy strengthened with nut shell powder and sisal cellulose, investigators usually refer to the guidelines set by the This is particularly true while testing softness, flexural toughness, resilience to impacts, and breaking strength. Table 2 represents ASTM standards and testing properties.

Flexural test

During the test, a specimen is placed between two supports and a load is applied until it fractures. The setup for the flexural test using the UTM is illustrated in Figure. 3.

Impact test

A universal testing machine (UTM) is utilized to perform the flexural test. An impact test was conducted on samples manufactured according to ASTM D 258 standards. Impact resistance refers to a material's ability to withstand sudden loads. During the test, the sample is struck by a swinging pendulum until it fractures, and the force experienced by the material is recorded. The setup for the Izod impact test is shown in Figure. 4.

Result and discussion

Microstructure analysis

The microstructure analysis, conducted using a Scanning Electron Microscope (SEM), is an essential part of the research paper, which explores the internal structure and interfacial properties of epoxy composites reinforced with sisal fibre and groundnut shell powder. Three SEM images from different composite samples provide valuable insights into their mechanical behaviour and fracture morphology[41].

Scanning electron microscopy (SEM) analysis of the mixture uncovered multiple important characteristics that have a major role in its improved functionality. A striking finding was the low Amount of strand pull-out, which points to excellent interfacial adhesion between the backing material and the individual fibres. For the matrix of fibres to convey loads effectively, which improves toughness, flexibility and durability, this intense adhesion is crucial. Optimal mechanical strength is achieved when strands are firmly attached to the



Fig. 3. Flexural test using a Universal Testing Machine.



Fig. 4. Izod impact test equipment setup.

framework, allowing for the effective transfer of tension and stress. On the other side, fibre pull-out and poor mechanical integrity might result from insufficient hydrophilic adhesion. Optimal physical properties are also achieved when there are few vacancies at the fibre-matrix contact, as shown in the SEM photos. The genuine load-supporting ability of the threads can be diminished, and cracks might spread more easily through gaps. The scanning electron micrographs revealed important details about the hybrid material's growth of crack characteristics. The substrate showed signs of deterioration, with cracks frequently redirected around fibres. By raising the Amount of strength needed for crack propagation, this crack deflection phenomenon is famous for making composites tougher. Furthermore, the scanning electron microscopy (SEM) pictures showed that fibres had bridged the break, which had held the component whole and provided an extra channel for energy loss. Likewise, with the enhanced strength noted in the investigation, images from SEM revealed modest fibre pull-out, negligible voids, and fracture deflecting activity. These results highlight the significance of efficient load transmission as well as robust bonds between interfaces for composites to achieve their mechanical efficiency objectives. Thanks to the tight weave of the yarns and framework, its mechanical characteristics are enhanced, making it more suited to resist tensions and pressures.In sum, the scanning electron microscopy (SEM) images shed light on the hybrid material's architecture and mechanics, demonstrating how crucial powerful cross-facial

and efficient load transfer are for reaching dynamic objectives. Investigators can create polymers with enhanced strength and use them for more things if they can figure out those procedures.

In Figure 5a, the SEM image of S20G80 after the tensile test shows a well-dispersed distribution of groundnut shell powder and sisal fibres within the epoxy matrix. The sisal fibres are uniformly distributed, and their

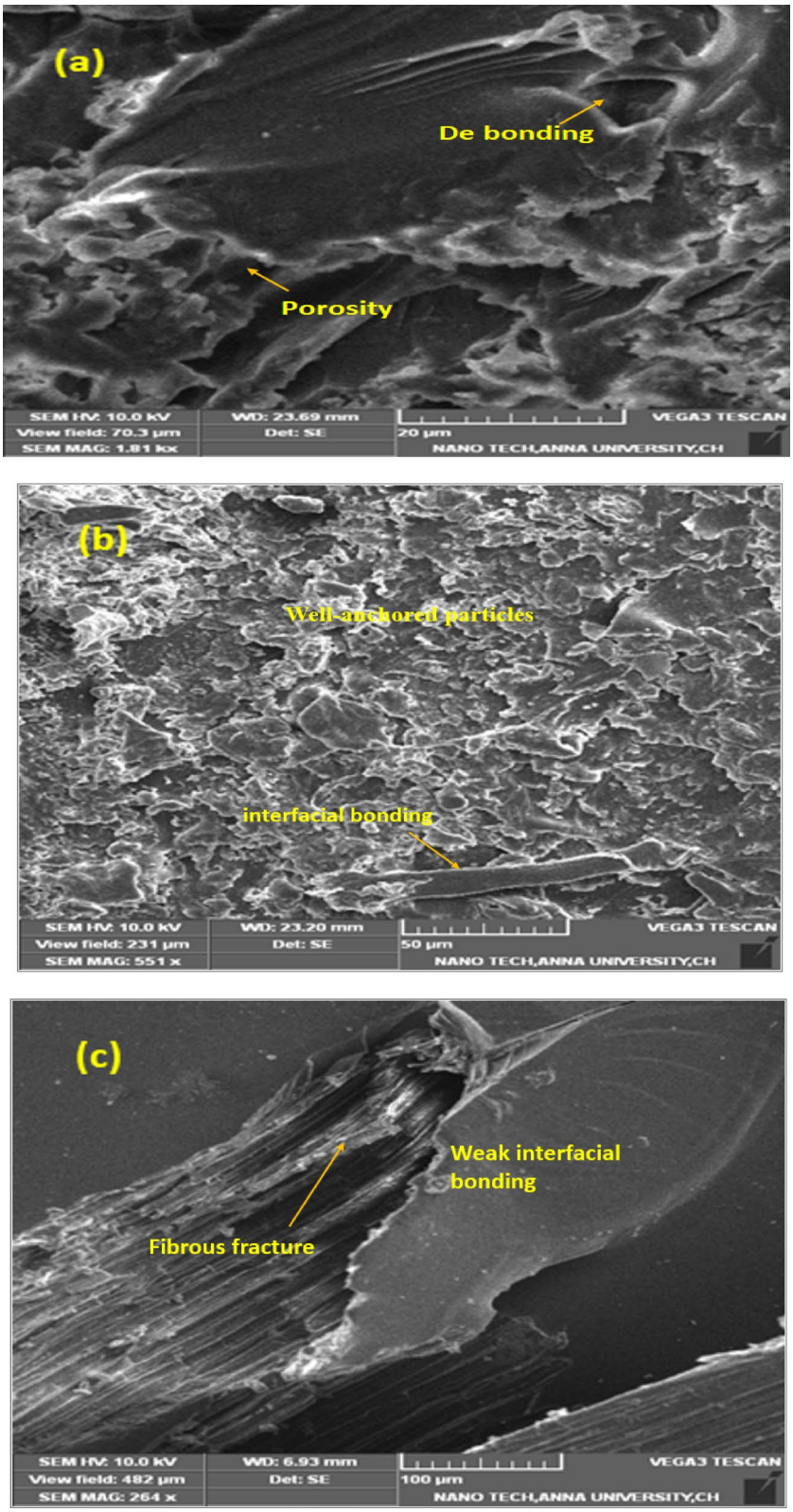

Fig. 5. SEM analysis of (**a**) Tensile specimen, (**b**) Flexural specimen, (**c**) Impact specimen.

noticeable alignment facilitates efficient load transfer along the fibre direction. Additionally, the groundnut shell powder enhances interfacial adhesion between the fibres and the epoxy matrix, thereby improving tensile strength. The phases of groundnut shell powder can be identified as distinct particles dispersed throughout the epoxy matrix. In Figure 5b, the SEM image of G100 after the flexural test reveals a compact and dense microstructure with a uniform distribution of groundnut shell powder. The groundnut shell particles are well-bonded to the epoxy matrix, forming a continuous phase, which contributes to the observed high flexural strength. The microstructure also exhibits minimal porosity or voids, indicating a well-consolidated composite material. Figure 5c presents the SEM image of S100 after the impact test, which shows a fibrous fracture surface. The absence of groundnut shell powder in this composite may lead to reduced energy dissipation during the impact test, resulting in lower impact strength. The sisal fibres are visible on the fracture surface, and their rupture suggests that the composite underwent considerable deformation and absorbed considerable energy[42]. Overall, the SEM microstructure analysis provides valuable visual evidence of the reinforcement dispersion, interfacial properties, and fracture mechanisms of the sisal fibre-groundnut shell powder-reinforced epoxy composites. These microstructural observations are crucial for understanding the mechanical behavior of the composites and optimizing their composition and processing parameters for specific engineering applications. The microstructure analysis complements the mechanical test results, aiding in the interpretation of the overall performance of the composites for potential industrial applications[43,44]. Table 3 represents Quantitative IMAGE J analysis of SEM micrographs.

The SEM micrograph Figure 5a shows the fracture surface after tensile compression, where both filamentous and granular features are well integrated into the matrix. The observed fibers and particles range in size from 2.5 to 5.8 µm, with a median size of 3.9 µm, and are distributed relatively uniformly. Withdrawal lengths of 15–28 µm indicate partial debonding of strands from the substrate, contributing to energy retention after failure. An area fraction of 12% indicates notable permeability; this may reduce durability but can enhance toughness. As in composites made from groundnut powder and sisal fibers, the particles here assist in pressure distribution, promote surface bonding, and help restrict crack propagation. Nonetheless, fiber pull-out is more prevalent than fiber breakage, pointing to limited interaction between the reinforcing fibers and the matrix.

Figure 5b presents a SEM micrograph of a structure primarily made up of particles measuring 1.5 to 10.0 µm, with an average size of 5.3 µm. The area fraction is 18.7%, much higher than in (a), indicating a denser distribution of reinforcement within the matrix. The absence of pronounced pull-out features suggests that the particles are strongly bonded, which improves load transfer and increases flexural strength. The structure is dense and compact with limited porosity, closely resembling G100-type composites that use groundnut shell powder as reinforcement in an epoxy matrix. This configuration promotes efficient load transfer and limits stress concentration, thereby increasing both the rigidity and durability of the nanocomposite under bending loads.

The SEM micrograph Figure 5c reveals a fibrous fracture surface with fibers 6.8–12.4 µm in diameter and an average width of 9.6 µm. The long separation distances, ranging from 90 to 120 µm, indicate weak interfacial bonding but also effective energy absorption through fiber withdrawal after fracture. The deviation in extent, at 10.2%, means there are fewer voids than in (a) and (b), though more gaps result from fiber breakage. Like S100-type synthetic composites, this fiber network shows improved impact resistance by absorbing energy through fiber rupture and pull-out. Although the matrix-fiber adhesion appears suboptimal, the extended pull-out paths help prevent crack growth, thereby enhancing resistance to catastrophic failure from fiber fracture.

Tensile properties

Tensile strength is a crucial mechanical property that determines a material's ability to withstand deformation and failure when subjected to tensile forces. In the study titled "Mechanical Characterisation of Sisal fibre-groundnut shell powder Reinforced Epoxy Composites[45,46], A Comparative Study,the tensile strength of various composite samples is examined to assess how different ratios of sisal fibre and groundnut shell powder affect the overall mechanical performance of the composites[47]. The results from tensile strength testing of the composite samples are presented in Table 4.

Figure 6. indicate that the tensile strength of the composites varies significantly with changes in the ratio of sisal fibre to groundnut shell powder. As the percentage of groundnut shell powder increases in the composites, the tensile strength generally shows a rising trend. This behaviour can be attributed to the reinforcing effects of groundnut shell powder, which enhances the load-carrying capacity and stiffness of the composites. For instance, Sample 1, which consists entirely of sisal fibre, demonstrates a tensile strength of 7.24 MPa. As groundnut shell powder is added to the composites (Samples 2 to 5), there is a steady increase in tensile strength. Sample 5, with a composition of 20% sisal fibre and 80% groundnut shell powder (S20G80), exhibits the highest tensile strength of 16.78 MPa among all the tested composites[48,49]. Conversely, when the composites are reinforced with 100% groundnut shell powder (Sample 6), the tensile strength remains relatively high at 14.97 MPa.

The groundnut shell powder, even when used as the sole reinforcing material, significantly contributes to the tensile strength of the composites. The observed trend in tensile strength highlights the significance of the

Image	Feature Type	Size Range (µm)	Average Diameter (µm)	Pull-out Length (µm)	Measured Area Fraction (%)
(a)	Fiber Particle	2.5–5.8	3.9	15–28	12.4
(b)	Particles	1.5–10.0	5.3	–	18.7
(c)	Fibers	6.8–12.4	9.6	90–120	10.2

Table 3. Quantitative IMAGE J analysis of SEM micrographs.

Samples	Composites	Tensile Strength (MPa)
Sample 1	S100	7.24
Sample 2	S80G20	7.85
Sample 3	S60G40	8.82
Sample 4	S40G60	10.99
Sample 5	S20G80	16.78
Sample 6	G100	14.97

Table 4. Tensile strength.

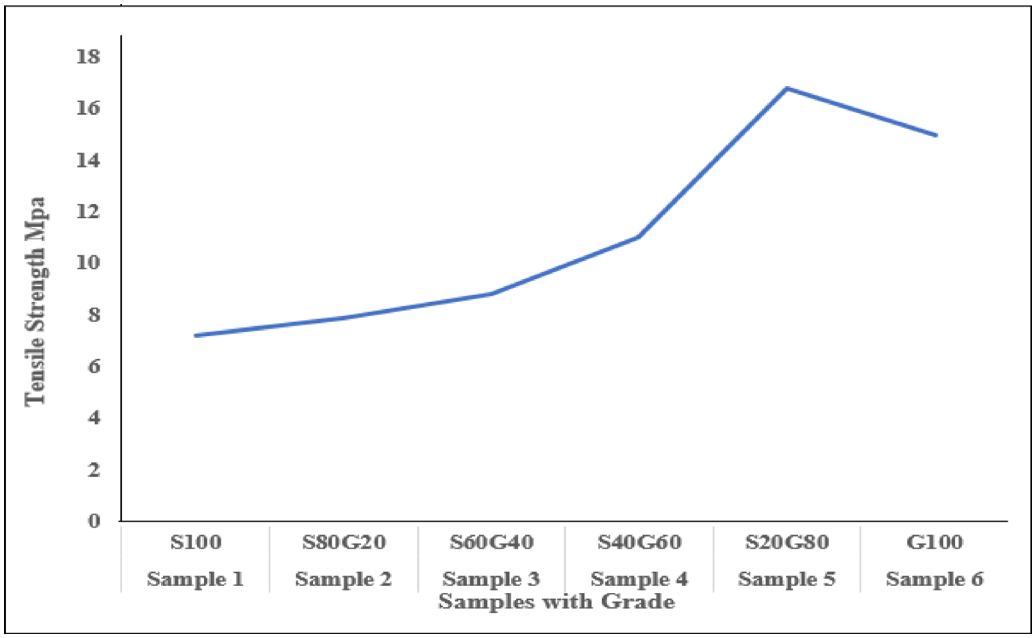

Fig. 6. Tensile strength.

ratio of sisal fibre to groundnut shell powder in determining the mechanical performance of these composite materials[50]. Composites with a higher proportion of groundnut shell powder demonstrate enhanced tensile strength, making them potentially suitable for applications that require a high tensile load-carrying capacity. This valuable insight from the tensile strength analysis will aid in optimizing the composition of sisal fibre-groundnut shell powder-reinforced epoxy composites for specific engineering applications[51].

Flexural properties

The analysis of the flexural properties of sisal fibre and groundnut shell powder-reinforced epoxy composites provides valuable insights into their mechanical performance. The research data reveal that the flexural strength of the composites varies significantly based on their composition[52]. For instance, Sample 6, which consists of 100% groundnut shell powder, exhibits the highest flexural strength of 12.44 MPa, highlighting the reinforcing effect of groundnut shell powder in the composites. As the proportion of groundnut shell powder increases, the flexural strength generally trends upward. This is evident from Samples 4 (S40G60) and 5 (S20G80), which display higher flexural strengths of 8.08 MPa and 10.17 MPa, respectively. Conversely, Sample 1 (S100), consisting of 100% sisal fibre, displays the lowest flexural strength of 5.18 MPa among all the composites, suggesting that groundnut shell powder significantly enhances the composite's flexural properties as shown in Figure 7.

The research findings emphasize the significance of composite composition in achieving enhanced flexural strength. The incorporation of groundnut shell powder as a reinforcement in the epoxy matrix enhances the flexural performance of the composites, making them potentially suitable for applications requiring high flexural load-carrying capacity. The comparative analysis of flexural properties helps optimize the composition of sisal fibre-groundnut shell powder-reinforced epoxy composites for specific engineering applications[53–55]. Table 5 represents mechanical properties and standard deviations.

The fibre content is 40 weight per cent sisal fibre. The proportion of nut shell ash as an ingredient ranged from 5 to 20% by weight. Changed from fifty-five per cent to forty per cent by weight in the epoxy matrix. In order to guarantee statistical dependability, six samples were analyzed for each structural attribute per combination. The Dispersion of fibres, arrangement of particles, and full activity of the material are microstructural elements that significantly impact the physical properties of epoxy materials supplemented with walnut shells and polyamide

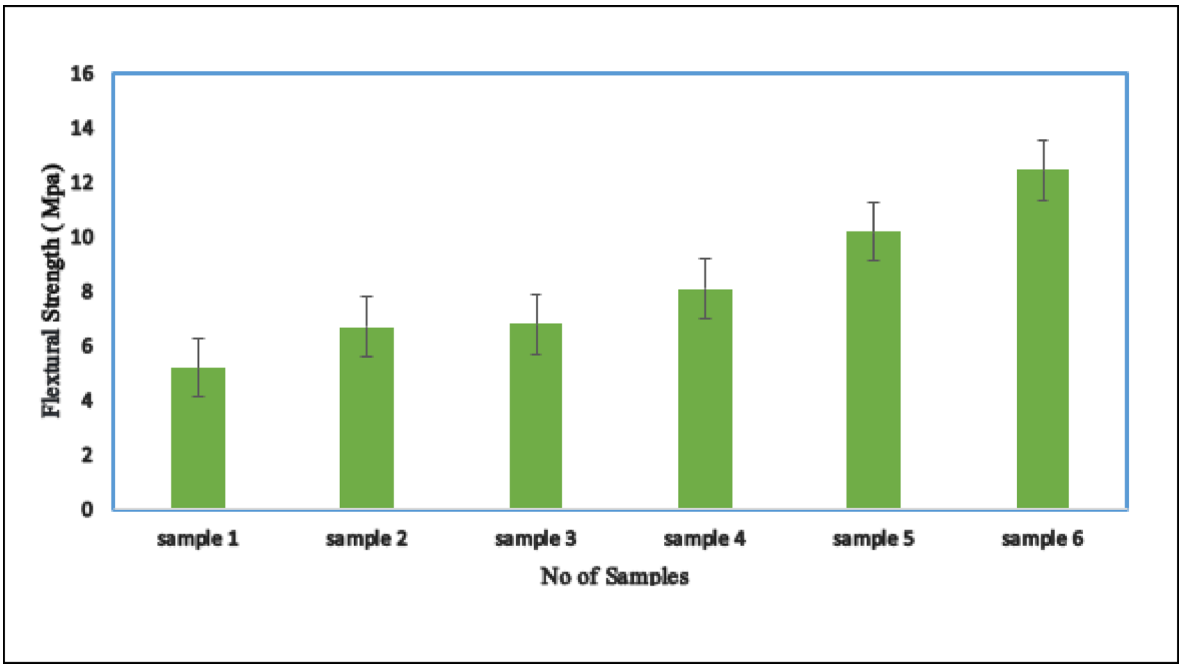

Fig. 7. Flexural strength.

SNo	Property	Filler Content	Average Value Mpa	Standard Deviation Mpa	Trend Observed
1	Hardness	16 wt%	79	± 2.2	increased with filler content
2	Impact Strength	12 wt%	41	± 0.5	Peak at 10%, falls at higher filler
3	Tensile Strength	22 wt%	39	± 2.8	Increased up to 15%, slight drop at 20%
4	Flexural Strength	21 wt%	66	± 3.5	Increased up to 15%, slight drop at 20%

Table 5. Mechanical properties and standard deviations.

S.No	Negative effects	Positive effects	Microstructural factor
1	Porosity and Poor wetting,	Toughness and Adhesion	Matrix Saturation
2	Clustering and stress concentration	Strength and Load transfer	Fiber Dispersion
3	Voids and Agglomeration	Hardness and Stiffness	Particle Distribution

Table 6. Sisal fiber groundnut shell powder structural behaviour.

fibres. The distributed Fibres are evenly distributed, and the load is consistently transferred from the substrate to the filaments. The tensile and bending strengths are diminished as a result of anxiety concentration zones formed by filament aggregation caused by deficient dissemination. Although evenly dispersed, connected and intermittent connections considerably increase strength-to-weight proportions, according to investigations. The dispersion of particles in ground walnut shell powder by limiting the mobility of polymers results in a uniform arrangement of nutshell granules, which increases rigidity and toughness. With just five to fifteen per cent padding by weight, small fragments micro-reinforce the material, making it stronger in both compressive and torsional tests. Multifunctional stability is negatively affected by voids along with poor attachment between surfaces caused by fragmentation at high contents of filler by weight. Matrix concentration reduces with increasing filler material, which results in the filaments and nanoparticles not fully moistened to enhance permeability and spaces. Excessive padding of the loadings is associated with decreased influence and elasticity, as confirmed by scanning electron microscopy (SEM) findings of microvoids and inefficient connections. Table 6 represents factors affecting structural behaviour for sisal fibre groundnut shell powder.

Impact strength

The impact strength analysis of the sisal fibre-groundnut shell powder-reinforced epoxy composites provides crucial information about their ability to withstand sudden loads and impacts. The data presented in the research paper demonstrates that the impact strength of the composites varies with the composition. Sample 1 (S100),

comprising 100% sisal fibre, exhibits the highest impact strength of 0.4 joules among all the composites. This suggests that sisal fibre contributes to the composite's ability to absorb impact energy effectively[56,57].

Samples 2 (S80G20) and 5 (S20G80) both exhibit an impact strength of 0.3 joules, indicating that the combination of sisal fibre and groundnut shell powder in the epoxy matrix still provides reasonable impact resistance. On the other hand, as shown in Figure 8. concerned to Samples 3 (S60G40), 4 (S40G60), and 6 (G100) display similar impact strengths of 0.2 joules. This suggests that the presence of groundnut shell powder in the composites does not significantly impact the material's ability to absorb impact energy. The findings from the impact strength analysis reveal that sisal fibre plays a crucial role in enhancing the impact resistance of the composites[58,59]. The variation in impact strength with changes in composite composition is essential for optimizing the material for specific applications that require good impact resistance, such as automotive components and protective equipment. Understanding the impact behaviour of sisal fibre-groundnut shell powder-reinforced epoxy composites is vital for their successful implementation in practical engineering applications[60,61].

Hardness strength

The hardness strength analysis of the sisal fibre-groundnut shell powder-reinforced epoxy composites provides valuable information about their resistance to indentation and wear. The data presented in the research paper shows that the hardness strength of the composites varies with the composition. Sample 3 (S60G40) exhibits the highest hardness strength of 104.3 HRL among all the composites, indicating that the combination of 60% sisal fibre and 40% groundnut shell powder in the epoxy matrix results in a material with excellent resistance to indentation. Sample 5 (S20G80) also exhibits a relatively high hardness strength of 101.7 HRL, indicating that even with a higher proportion of groundnut shell powder, the composite retains good hardness properties[14,18]. Figure 9. indicates hardness analysis.

On the other hand, Sample 2 (S80G20) displays a hardness strength of 96.6 HRL, indicating that the addition of 20% groundnut shell powder to the composite slightly reduces its hardness compared to Sample 3. Samples 1 (S100), 4 (S40G60), and 6 (G100) show hardness strengths of 100.2 HRL, 88.3 HRL, and 84 HRL, respectively. These results suggest that the hardness strength of the composites is influenced by the ratio of sisal fibre to groundnut shell powder, with higher proportions of groundnut shell powder leading to a decrease in hardness. Understanding the hardness behaviour of sisal fibre-groundnut shell powder-reinforced epoxy composites is crucial for assessing their suitability for applications that require wear resistance and durability, such as in structural components and manufacturing tools[62,63]. The hardness strength analysis aids in selecting the optimal composition of the composites based on specific engineering requirements.

Conclusion

In conclusion, this study highlights the significance of composite composition in determining the mechanical properties of sisal fibre-groundnut shell powder-reinforced epoxy composites. These composites represent a promising and environmentally friendly alternative for various engineering applications that require specific mechanical strengths and wear resistance. The findings will help optimize the composition of these composites for tailored applications in industries such as automotive, construction, and manufacturing. The ratios of sisal fibre and groundnut shell powder used to create the composites were 100:0, 80:20, 60:40, 40:60, 20:80,

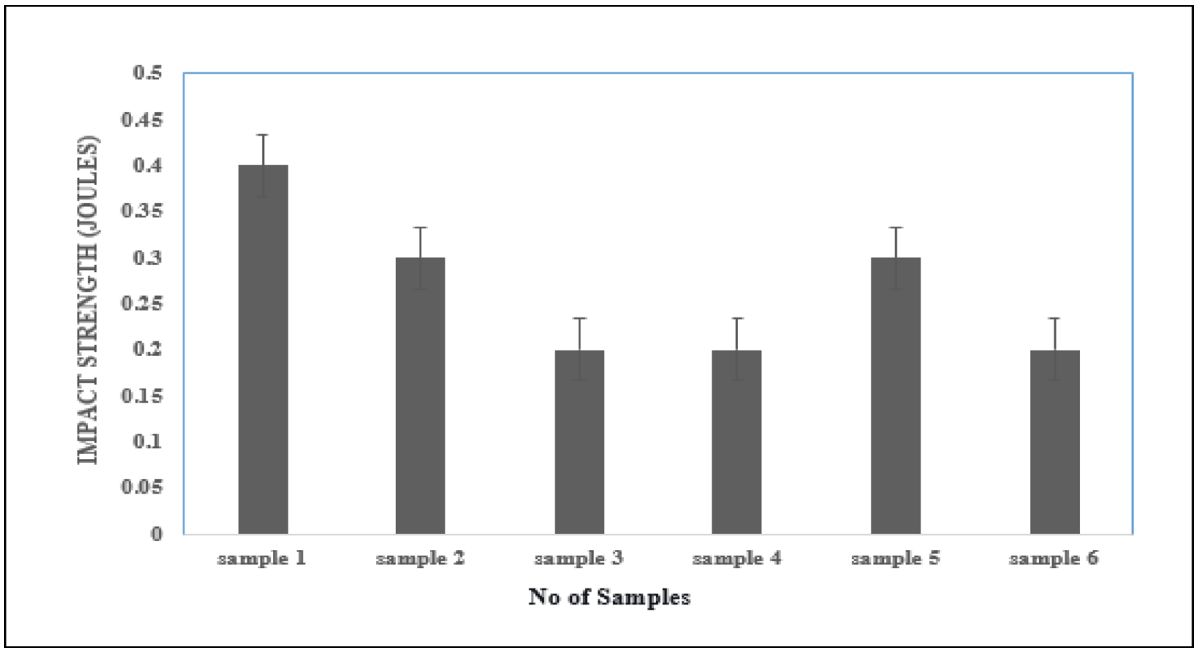

Fig. 8. Impact analysis.

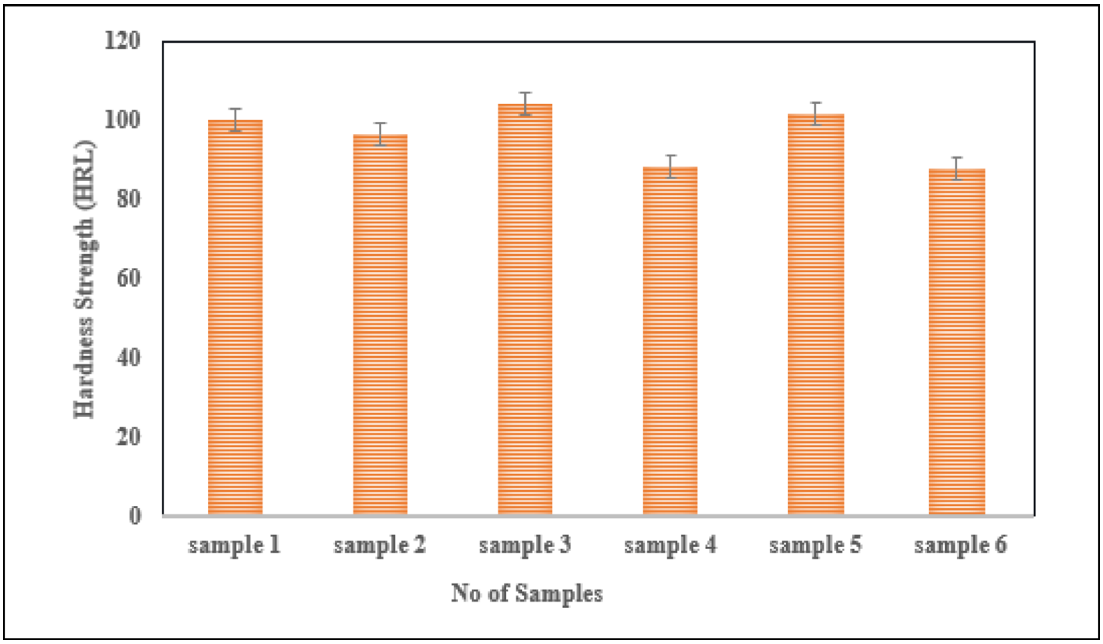

Fig. 9. Hardness analysis.

and 0:100. The composites were fabricated using the hand-laying method. Various tests, including elasticity, flexibility, impact, and hardness tests, were conducted to evaluate their durability. The samples exhibiting the best tensile, flexural, and impact strengths were then subjected to comprehensive scanning electron microscopy examinations of their internal structures, interior cracks, and surface characteristics on their fractured surfaces.

Based on the mechanical characterization of sisal fibre-groundnut shell powder-reinforced epoxy composites, the following conclusions were drawn: The polymer composite with a sisal fibre-to-groundnut shell powder ratio of 20:80 demonstrated the best tensile strength. In contrast, the 100:0 ratio exhibited the highest flexural strength. The laminate reinforced with 100% sisal fibre showed improved impact strength, whereas the 60:40 ratio displayed the maximum hardness.

- A comparative analysis of the structural evaluations of raffia fibre-groundnut shell powder-reinforced epoxy composites highlighted their potential as environmentally conscious materials for engineering applications. The incorporation of groundnut shell powder and sisal fibres in varying ratios significantly influenced the mechanical properties of the composites, including tensile, flexural, impact, and hardness strengths.
- Among the tested composites, the one with a 20:80 sisal fibre to groundnut shell powder ratio achieved the highest tensile strength. In contrast, the composite with 100% sisal fibre reinforcement demonstrated superior flexural strength. The impact strength analysis revealed that the composite with 100% sisal fibre exhibited the highest impact resistance, while the other composites containing groundnut shell powder showed comparable impact absorption.
- Furthermore, the hardness strength analysis indicated that the composite with 60% sisal fibre and 40% groundnut shell powder (S60G40) displayed the highest hardness strength, making it suitable for wear-resistant applications.
- The hardness behaviour of sisal fibre-groundnut shell powder-reinforced epoxy composites is crucial for assessing their suitability for applications requiring wear resistance and durability, such as in structural components and manufacturing tools. Composites (Samples 2 to 5) displayed a steady increase in tensile strength, with Sample 5, containing a ratio of 20% sisal fibre and 80% groundnut shell powder (S20G80), achieving the highest tensile strength of 16.78 MPa among all tested composites.
- Samples 3 (S60G40), 4 (S40G60), and 6 exhibited similar impact strengths of 0.2 joules. This suggests that the inclusion of groundnut shell powder in the composites does not significantly affect the material's ability to absorb impact energy.

Data availability

Data will be made available upon request. contact the corresponding author if someone wants to request the data from this study.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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