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REVIEW ARTICLE

Thermal processing methods and acrylamide formation in grain-based foods: a focus on temperature, time, and moisture

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Abstract

Acrylamide is a heat-induced chemical classified as a probable human carcinogen (Group 2A) and is widely detected in cereal-based foods subjected to high-temperature processing. Its formation primarily occurs through the Maillard reaction and is strongly influenced by processing parameters. This review aims to synthesize current evidence on how temperature, time, and moisture conditions during thermal processing affect acrylamide formation in grain-based products, with an emphasis on jointly evaluating these key processing parameters. Beyond describing formation mechanisms, the review highlights the dietary contribution of these products to consumer exposure and evaluates how processing parameters translate into variations in intake levels. By providing comparative evidence across various cooking practices, this work supports the optimization of processing conditions and identifies critical gaps in integrating"temperature–time–moisture" relationships and consumer exposure. Ultimately, this review offers a unified, process-based perspective, providing practical recommendations for both industrial stakeholders and public health optimization. Acrylamide levels generally increase with higher temperatures, longer heating times, and reduced moisture, particularly in dry-heat methods such as baking, frying, and roasting. Although some studies report a decline in acrylamide at extreme temperatures, these conditions typically compromise product quality, and research on this phenomenon remains limited. Moisture plays a critical role: lower-temperature, moist-heat treatments tend to inhibit acrylamide formation, while prolonged high-temperature exposure promotes it. Understanding the interaction between temperature, time, and moisture during cereal processing is crucial for effectively reducing acrylamide formation while maintaining product quality. This review not only highlights practical mitigation strategies applicable in industrial and home settings but also identifies key gaps in current knowledge, emphasizing the need for standardized, multidisciplinary research to optimize food safety and public health outcomes.

Keywords Acrylamide · Cereals · Cooking time · Temperature

Introduction

Cereals have played a vital role in human history as a basic food source. The agricultural revolution enabled the cultivation of grains such as wheat, barley, rice, and corn, contributing to the settlement of societies and the development of civilizations. Today, cereal grains such as wheat, rice, barley, and corn are extensively consumed not only as staple foods but also as ingredients in a wide range of processed products, including baked goods, breakfast cereals, and snacks. However, low-moisture, high-temperature cooking processes, such as baking, frying, and roasting, can form harmful compounds, including acrylamide, in cereal products [1]. Due to their high consumption rates, cereal-based foods are of particular importance from a food safety perspective.

Acrylamide (2-propenamide) was first identified by the Swedish National Food Authority in 2002 and has since become an important topic of study in food safety [2]. Acrylamide is a substance classified as a group 2 A carcinogen by the International Agency for Research on Cancer (IARC) and is also known to be neurotoxic in occupational settings [3, 4].

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Acrylamide exposure can also occur through foods cooked at high temperatures [4]. Acrylamide formation occurs via the Maillard reaction between reducing sugars and the amino acid asparagine during the thermal treatment of carbohydrate-rich foods, particularly at temperatures above 120 °C in low-moisture environments [5, 6]. The impact of cooking method, temperature, and time on acrylamide formation in cereal-based products is summarized in Fig. 1. Chips, coffee, bread, breakfast cereals, and bakery products rich in carbohydrates with high free asparagine content, especially those cooked at temperatures higher than 120 °C, have been identified by the Joint Expert Committee on Food Additives (JECFA) as important sources of acrylamide in the daily diet [7]. Dietary exposure to acrylamide primarily occurs through carbohydrate-rich foods that are processed at high temperatures, with cereal-based products making a significant contribution to overall intake [8].

The acrylamide content in cereal-based products can vary significantly depending on multiple factors such as cereal type, cooking method, moisture content, temperature, and duration of heat application [5]. Given the widespread consumption of cereal-based foods and the variability in acrylamide formation under different processing conditions, understanding how these factors interact is essential for effective risk mitigation.

This review not only compiles existing knowledge on how temperature, time, and moisture influence acrylamide formation in cereals under various cooking methods but also provides a comprehensive synthesis of research findings, emphasizing their practical application in both industrial processing and public health. By integrating updated experimental data and critically assessing mitigation strategies, this work provides actionable recommendations tailored to cereal-based food production, aiming to bridge the gap between scientific research and real-world implementation.

A literature search was conducted using Web of Science, PubMed, Scopus, and Google Scholar to identify relevant English-language studies on acrylamide formation in cereal-based foods. Keywords included acrylamide, cereals, cooking time, temperature, moisture, and processing methods. Studies covering different cooking techniques—including baking, frying, roasting, popping, puffing, and air frying—as well as dietary exposure were considered. Both original research articles and review papers published in English were included. Relevant articles were identified through title, abstract, and full-text screening, and the reference lists of identified articles were manually searched to capture additional pertinent studies. Acrylamide reduction strategies were also briefly reviewed.

Acrylamide formation

Acrylamide formation during thermal processing should be understood within the broader framework of Maillard reaction chemistry, which generates a wide spectrum of

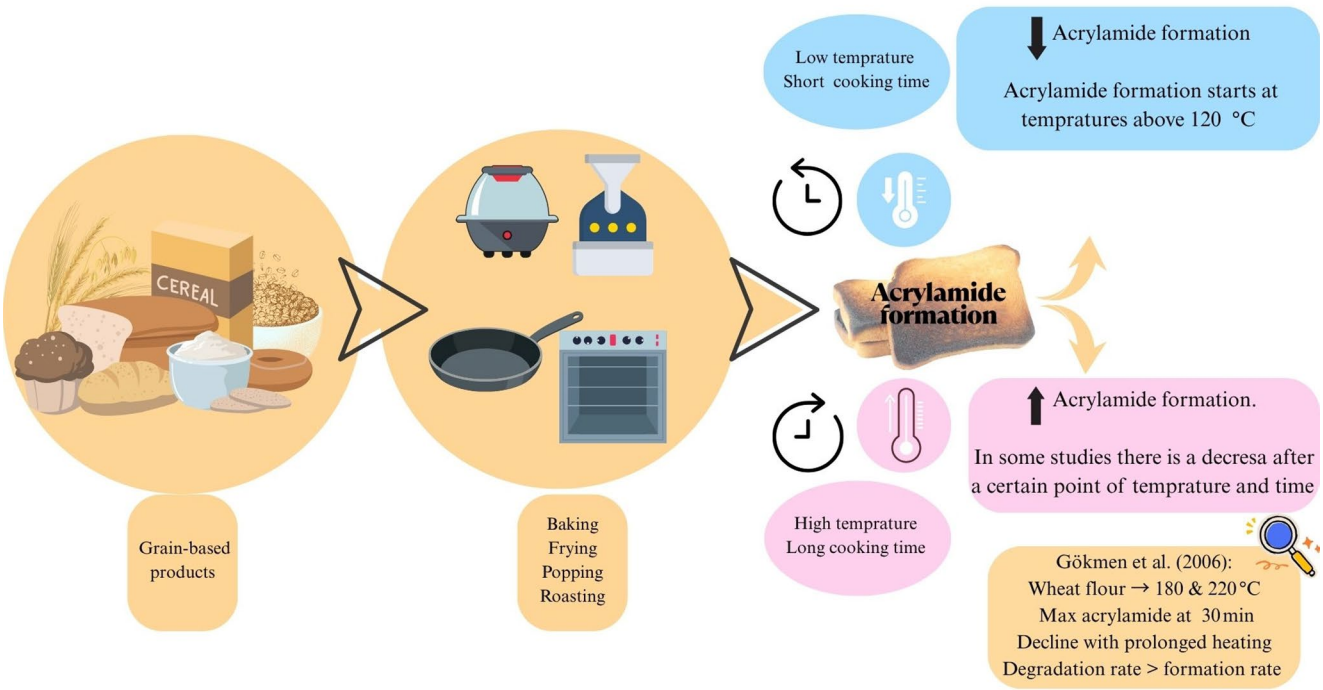


Fig. 1 Effect of temperature and processing time on acrylamide formation during thermal treatments of cereal-based products (compiled by the authors based on published literature)

reactive intermediates and end-products, extending beyond acrylamide alone. In addition to reducing sugars, dehydration products such as 5-hydroxymethylfurfural (HMF) are formed from hexoses under heat and can act as highly reactive carbonyl compounds [9]. Several studies have demonstrated that HMF may contribute to acrylamide formation from asparagine under high-temperature conditions, in some cases exhibiting a stronger promoting effect than reducing sugars [10, 11]. In addition to acrylamide, other Maillard reaction–derived compounds, such as advanced glycation end-products (AGEs) and reactive α-dicarbonyl compounds (e.g., glyoxal and methylglyoxal), are formed during thermal food processing [12]. Reactive α-dicarbonyl compounds such as methylglyoxal, glyoxal, and 3-deoxyglucosone are key intermediates formed during the Maillard reaction and have been identified as part of the complex reaction network that also produces acrylamide and advanced glycation end-products (AGEs) in heated foods [13, 14]. These α-dicarbonyls are generated alongside other Maillard intermediates under thermal processing conditions, and their high carbonyl reactivity may influence pathways leading to acrylamide formation, for example, through Strecker degradation mechanisms involving asparagine and reactive carbonyl species [15]. Taken together, these findings indicate that acrylamide formation should be viewed as part of a broader Maillard-derived reaction network, in which shared reactive carbonyl intermediates link acrylamide generation with the formation of other heat-induced compounds such as α-dicarbonyls and advanced glycation end-products.

Baking process in cereal products and its effect on acrylamide formation

Bread is one of the oldest processed food products. Tomb carvings from ancient Egypt, dating back to 3000 BC, depict bread baking. Throughout history, bread has been a fundamental food source for humanity and has played an important role in the development of civilization. Baking generally refers to the preparation of cereal-based foods such as bread, biscuits, and cakes [16].

Baking is a complex process in which simultaneous, interdependent heat and mass transfer occur, along with structural and compositional changes in the dough. As the temperature rises, gases evaporate, and the volume increases. In addition, starch gelatinizes, and proteins coagulate at higher temperatures, reducing the dough's elasticity. These changes contribute to the development of the dough's characteristic porous structure. In addition, at high temperatures, water evaporates, forming a hard outer crust in products such as bread [17]. The amount of acrylamide in cereals ranges from 62 to 803 µg/kg, with an average of 292 µg/kg recorded. Cooked grain products, especially wheat-based cereals and breakfast cereals, contain high levels of acrylamide [18].

Baking is the process of cooking in which heat is applied directly to the food. The high temperatures and low humidity during cooking trigger various chemical reactions among food components, resulting in specific changes in the final product. These outcomes are changes that improve the organoleptic properties of the food, such as flavor and color changes, which consumers appreciate for their sensory attributes. There is also the formation of products such as acrylamide [19].

Various studies have demonstrated that acrylamide formation in cereal-based baked products is strongly influenced by cooking temperature, duration, moisture, and the type of heating method used, as shown in Table 1. For instance, Ahrné et al. demonstrated that higher temperatures increased acrylamide concentrations [20]. They found that steam baking and low-temperature baking not only reduced acrylamide formation but also produced acceptable crust color. The lowest acrylamide content was achieved by steam baking while also maintaining ideal sensory quality [20].

Baking studies consistently show that acrylamide formation follows a non-linear thermal pattern: it increases with temperature and time to a maximum, then declines during prolonged or intense heating. This behavior has been noted in bread, wheat flour, and biscuits, where acrylamide peaked at 180–260 °C and then decreased with extended baking times due to competing degradation reactions [20–24]. Similar trends were reported in biscuits and maize-based products baked for more than 10–15 min at 180–220 °C [23, 24]. This decline is explained by the chemical instability of acrylamide at high temperatures, where evaporation, polymerization, and reactions with food matrix components become dominant over its formation via the asparagine–reducing sugar pathway [1, 22, 25–27].

Govindaraju et al. explained that at high temperatures, the amino group of free asparagine in foods reacts with the carbonyl group of reducing sugars to form Schiff base, an intermediate compound involved in acrylamide formation. Prolonged cooking degrades acrylamide, reducing its content. Thus, prolonged cooking of food products at lower temperatures reduces acrylamide content [1]. Specifically, at elevated temperatures, acrylamide undergoes secondary reactions, including polymerization, evaporation, and reactions with other food compounds. These processes reduce the acrylamide concentration [22].

Moisture and heat-transfer conditions strongly modulate this kinetic behavior. Steam baking and low-temperature baking were associated with significantly lower acrylamide formation while maintaining acceptable crust color, whereas dry, high-temperature conditions promoted higher

Table 1 Effect of baking method on acrylamide formation at different temperatures and times

Product	Cooking Method	Moisture	Temperature (°C)	Time (minutes)	Observation	Conclusion	Reference
Wheat bread	Baking	No steam applied	200–260	10–15	Acrylamide concentration increased with increasing temperature; at very high temperatures and low moisture levels, acrylamide decreased, but sensory quality deteriorated	Acrylamide formation increased with decreasing moisture content.	[20][a]
Wheat bread	Baking	High moisture due to steam application	200	5–15	Steam cooking and lower baking temperature reduced acrylamide formation	High moisture reduced acrylamide formation; peel color was sensory acceptable.	[20][a]
Wheat bread	Baking	No steam applied	260	15–20	Acrylamide peaked at 15 min and decreased with prolonged baking due to thermal degradation	Prolonged cooking led to acrylamide degradation, and the total acrylamide content decreased. The acrylamide content of the peel was lower than that of the core	[20][a]
Biscuits	Baking	No steam applied	180	7, 10, 13	30% of biscuits baked in 13 min exceeded the reference levels set by the European Regulation; those baked for a shorter time were below the reference values.	A shorter cooking time helped to keep acrylamide levels under control.	[23]
Biscuits	Baking Traditional and convection oven	No steam applied	175	18, 20, 22, 24, 26	In biscuits made from wheat flour, the acrylamide content increased with cooking time. Higher levels were measured after 20 min in the convection oven.	In convection ovens, the temperature increased faster due to uniform heat distribution, leading to greater moisture loss.	[28]
Biscuits Muffins Cakes	Baking	No steam applied	170–190	20	The highest acrylamide content was noted in biscuits (126.52 µg/kg), muffins (84.24 µg/kg), and cakes (71.21 µg/kg) baked at 190 °C. And these values were higher than the values formed at 170 °C at the same time	Acrylamide formation increased with temperature, and lower water activity in biscuits caused higher acrylamide levels.	[29]
Rye bread	Baking	No steam applied	230–260	45	Rye bread baked at 230 °C for 45 min had 25% less acrylamide than the samples baked at 260 °C for the same time.	Acrylamide formation increased with temperature	[30]

[a]Ahrné et al. [20] presented multiple observations under varying conditions

acrylamide levels [20, 21]. The formation of acrylamide in food is influenced not only by the cooking temperature, but also by the heat transfer method used. Schouten et al. found that biscuits baked in convection ovens developed more acrylamide than those baked in conventional ovens at the same temperature and duration. Convection baking resulted in a faster temperature rise, leading to higher acrylamide levels [28].

Product characteristics further influence acrylamide accumulation. Ahmad et al. investigated acrylamide content in bakery products and detected the highest values in biscuits, followed by muffins and cakes baked at 190 °C for 20 min. It was reported that higher acrylamide levels in biscuits may be associated with their lower water activity [29]. Although prolonged high-temperature baking can reduce acrylamide through degradation, this is often accompanied by excessive browning and unacceptable sensory quality, as exemplified by bread crusts baked at 260 °C [20].

Overall, the evidence suggests that acrylamide levels in baked cereal products are governed by the balance between formation and degradation kinetics, which is highly sensitive to temperature, moisture, heat transfer, and product structure.

Roasting method application in cereal products and its effect on acrylamide formation

Roasting is a dry heat cooking method that involves even distribution of heat over the product [30]. The temperature in the oven or equivalent heat sources used in this method is at least 150 °C [31], while the internal moisture is largely preserved in the roasting process, the changes that occur outside the product with heat are effective in making the product digestible, adding the desired taste and sensory

properties and making the product more acceptable to the consumer [30].

For example, roasting oats is preferred because it improves the product's sensory properties, but it also leads to acrylamide formation. In their study, Schlörmann et al. reported that the acrylamide content of raw oat samples was below the detection limit (10 µg/kg), but increased significantly when samples were roasted at temperatures between 140 °C and 180 °C, in 10 °C increments, for 20 min using a drum roaster. Lower acrylamide contents were found in kernels compared to thin and thick oat flakes, while the acrylamide contents of products were 449 µg/kg, 651 µg/kg, and 875 µg/kg, respectively, at 180 °C. These values exceed the European regulatory limit of 150 µg/kg for oat-based breakfast cereals; therefore, oats should be roasted at lower temperatures [32]. Consistent with the oat data documented by Schlörmann et al., Kraboun et al. showed in broken rice that roasting at 200 °C increased acrylamide approximately fourfold compared with unheated samples, while Mizukami et al. demonstrated in barley that acrylamide peaked at 180–240 °C and then declined at higher temperatures as darker-colored grains formed, indicating competing degradation processes at excessive thermal loads [33, 34]. Hu et al. demonstrated that preheating oats at 90 °C followed by low-temperature roasting at 110 °C (≤ 120 °C) effectively prevented acrylamide formation, whereas direct roasting at 160 °C for 30 min produced very high acrylamide levels (507.4 µg/kg), exceeding the European benchmark of 300 µg/kg [35].

Taken together, the roasting studies consistently demonstrate that acrylamide formation is strongly enhanced by high temperature and surface dehydration, particularly in products with high surface area, such as oat flakes and broken rice. Preheating and low-temperature roasting (< 120 °C) have been documented to effectively suppress acrylamide formation, whereas excessive roasting intensities promote rapid accumulation. However, as demonstrated in barley, acrylamide does not increase indefinitely; instead, it may decline at very high temperatures (≥ 240 °C) due to thermal degradation and the formation of darker-colored grains. Despite these insights, substantial variability exists across studies due to differences in grain type, particle size, initial moisture, and roasting equipment. The absence of standardized roasting protocols, moisture control, and kinetic modeling limits the transferability of laboratory findings to industrial practice.

Effect of frying, popping, puffing, and air frying of cereal products on acrylamide formation

Frying is a cooking method that exposes food to high temperatures, causing physical and chemical changes such as starch gelatinization, protein denaturation, browning, and crust formation, which result in desired taste and texture changes in the final product [36]. Unlike baking, frying applies heat indirectly through a heat-transfer medium, such as oil, rather than directly to the product [37]. This is a frequently preferred cooking method, especially in the processing of snack products [38]. Frying typically occurs at temperatures between 150 and 200 °C, and the high heat promotes acrylamide formation via the Maillard reaction [39].

In their study, Wu et al. found that a positive correlation between cooking temperature and acrylamide content in dough twist samples fried at 170 and 180 °C, with acrylamide levels increasing as cooking time extended. The highest acrylamide content was recorded in samples baked at 170 °C for 12 min, while a decrease in acrylamide formation was observed at 180 °C for 10 min or more [26]. Similarly, in another study on fried dough twists, higher processing temperatures and longer frying times were associated with increased acrylamide content. It was concluded that when the frying temperature exceeded 160 °C, acrylamide formation increased rapidly, and that optimal acrylamide levels and organoleptic properties were achieved by cooking at 160 °C for 3 min [40].

Popping and puffing are dry-heat cooking methods commonly used in the food industry to produce snacks and breakfast cereals. Products such as popped/puffed rice, maize, sorghum, and wheat are ready-to-eat snacks that are widely consumed worldwide. Popping involves briefly exposing grains to high temperatures using techniques such as sand roasting, salt roasting, hot air, or microwave ovens [41]. Significant differences in acrylamide content have been documented between flaked and puffed breakfast cereals, with puffed formulations generally exhibiting higher levels [42]. A study on the production of breakfast cereals found that products produced by the puffing process (167 µg/kg) had a higher acrylamide content than those produced by the flaking method (79 µg/kg). These differences are primarily attributed to variations in processing conditions, including temperature distribution, higher moisture content, and additional drying and tempering steps required for puffed products, all of which can influence and potentially accelerate acrylamide formation [42]. This is because in the flaking process, the grains are first boiled (80–95 °C), dried (220 °C), and fried (160–200 °C), whereas in the puffing process, the products are first cooked at 140–180 °C,

dried by sudden pressure reduction, and then fried at temperatures that can reach 330 °C. Temperature and humidity differences between the processes are believed to affect the acrylamide content [18].

Air frying is a cooking method that uses rapid hot air circulation to cook food with minimal oil, typically operating at temperatures ranging from 140 °C to 200 °C, which are sufficient to induce Maillard reactions [43, 44]. In a study conducted in South Korea, acrylamide levels were determined after cooking 22 grain-based products in an air fryer. The exposure values obtained were classified as "a cause for concern" according to the limit values set by health authorities. It was noted that air fryers, which operate on the principle of hot air circulation and reduce humidity of food during cooking, could be a significant factor in acrylamide formation within the scope of this study [45].

Cereal products as contributors to dietary acrylamide intake

Dietary acrylamide exposure shows considerable variation across geographical regions, reflecting differences in dietary patterns, food processing practices, and regulatory frameworks. In European countries, population-based exposure assessments have generally reported relatively higher acrylamide intakes compared to those in Asian countries. National dietary surveys indicate substantial international variation in acrylamide exposure. In China, a nationwide Total Diet Study estimated the mean dietary acrylamide intake at approximately 0.175 µg/kg body weight (bw) per day, whereas in Japan, the corresponding mean intake was about 0.15 µg/kg bw per day in men and 0.19 µg/kg bw per day in women [46, 47]. In the United States, the estimated mean dietary acrylamide exposure for individuals aged two years and older is approximately 0.36 µg/kg bw per day, while much higher values, reaching about 1.42 µg/kg bw per day, have been indicated for children under two years of age, reflecting their greater food intake relative to body weight.

The level of dietary acrylamide exposure also varies markedly across Europe (0.4 µg/kg body weight per day reported by EFSA), with European populations often having higher intakes (1.4–3.4 µg/kg body weight per day) [48, 49]. Children, relative to their body mass, consume a large amount of starchy foods, such as cereal and baked products, leading to an estimated dietary acrylamide intake that is 2–3 times higher than that of adults [48].

In Europe, urinary biomarkers of acrylamide exposure indicate that population-level exposure increased from the early 2000 s until around 2017, with particularly pronounced rises among children, whereas trends among adults were less consistent [50]. Regulatory actions addressing acrylamide in food developed in parallel with the progressive rise in population exposure suggested across Europe. In the early 2000 s, the food industry introduced voluntary mitigation tools, including the Acrylamide Toolbox and the FAO/WHO Codex Code of Practice, to reduce acrylamide formation during food processing [51, 52]. Binding benchmark levels for acrylamide in food were established by the European Commission under Commission Regulation (EU) 2017/2158, adopted in 2017 and becoming applicable in April 2018 [53]. Subsequent biomonitoring data from the HBM4EU programme show that this upward trend stabilised or slightly declined thereafter, suggesting that the tightening of regulatory limits contributed to a measurable shift in exposure patterns [54]. In recognition of the associated health risks, the European Commission established benchmark levels for acrylamide in cereal products: 50 µg/kg for wheat-based bread, 100 µg/kg for non-wheat bread, and up to 800 µg/kg for gingerbread. For breakfast cereals, limits range from 150 to 300 µg/kg depending on the grain type [53]. Current knowledge on the potential risks associated with dietary acrylamide intake is limited, and international food safety authorities agree that further research is needed. Although the neurotoxic effects of low-level dietary acrylamide exposure are considered minimal, there is still uncertainty regarding long-term consumption and its association with cancer risk [55].

Cereal-based products are a significant source of dietary acrylamide, owing both to their acrylamide content and their frequent consumption [8]. The widespread consumption of these products contributes significantly to overall human exposure to acrylamide. Overall, approximately 29% of the acrylamide consumed comes from bread, pastry, and breakfast cereals [56]. However, acrylamide exposure is not limited to cereal products; other widely consumed thermally processed foods, including fried potato products, coffee, chocolate, and tea, can make substantial contributions, depending on regional dietary habits [56–60]. In China, vegetables and cereal products account for the largest share of total intake, whereas in Japan, green tea is the predominant contributor [46, 47, 61]. In the United States, potato-based foods, particularly French fries and other fried potato products, contribute significantly to acrylamide exposure. In Germany, the highest mean acrylamide concentrations have been reported in vegetable crisps, while in Canada, potato products and French fries likewise have the greatest acrylamide content [62, 63]. This indicates that acrylamide exposure should be evaluated in the context of overall dietary intake rather than attributed solely to individual food groups.

Bread, in particular, is highlighted as a principal contributor; despite its lower acrylamide concentration compared to some other cereal-based foods, the sheer volume

consumed translates into a significant contribution—studies report that bread may account for anywhere from 10% up to nearly 50% of total daily acrylamide intake [60, 64]. Differences in acrylamide exposure across age groups further highlight the role of cereal products. In EFSA assessments, soft bread contributes between 0.1% and 31% of acrylamide exposure, depending on age group, with the highest contribution observed in toddlers, where exposure from processed cereal-based baby foods can reach up to 30% [65]. In Türkiye, the combined contribution of bread, simit, and local breakfast cereals ranges from approximately 10% in good exposure scenarios to 23% in worst-case scenarios, underscoring the importance of cereal products in total dietary acrylamide intake [60].

Breakfast cereals are a major source of acrylamide in Western countries [66]. In Spain, the average acrylamide content in commercial breakfast cereals ranged from less than 62 to 803 µg/kg, with an average of 292 µg/kg and a median of 258 µg/kg [42]. This resulted in an estimated daily acrylamide intake from breakfast cereals of 2.68 µg per person per day [42]. In a 2019 reassessment of the Spanish market, the mean acrylamide content of breakfast cereals was 118 µg/kg, representing a 60% decrease since 2006 [18]. Flaked breakfast cereals contained significantly lower acrylamide levels compared to puffed products, with 85% of cereals remaining below benchmark limits [18]. Other studies have measured varying levels of acrylamide in breakfast cereals. For example, in a study analyzing 12 breakfast cereal products in Italy, 33% exceeded the European Commission's indicative benchmark levels of 200–400 µg/kg, depending on their composition [67]. In a study conducted in Türkiye, the average acrylamide content of breakfast cereals was 138 ± 14 µg/kg, and the average daily acrylamide exposure from breakfast cereal consumption was 0.08 ± 0.06 µg/kg body weight/day [68]. The acrylamide content of breakfast cereals and granola varies considerably depending on the type of grain and the manufacturing process. In the analyzed products, acrylamide levels reached up to 556 µg/kg, with the highest levels detected in puffed cereals and the lowest in extruded products [69]. Among cereal types, wheat-based products had the highest average acrylamide levels, followed by oats, corn, and rice. Granola products showed levels of up to 121 µg/kg [69]. These findings indicate that both the type of grain and the processing method significantly influence acrylamide formation, highlighting the importance of product selection and processing control to minimize dietary exposure.

Practical recommendations for reducing acrylamide formation

It is a challenge to reduce acrylamide levels without reducing the organoleptic properties and consumer acceptability of foods. Commission Regulation (EU) 2017/2158 addresses acrylamide mitigation in cereal-based products through a multi-stage approach encompassing agricultural practices, product formulation, and processing conditions [53]. In cereal crops, efforts to mitigate acrylamide formation begin with controlling the accumulation of key precursors, especially free asparagine and reducing sugars, during plant growth. Analyses of commercial cereal flours have demonstrated a strong positive relationship between free asparagine concentration and the amount of acrylamide formed during baking, indicating that asparagine level is the dominant predictor of acrylamide-forming potential in cereal matrices [23, 70, 71]. At the agricultural level, particularly in contract farming systems, good agricultural practices are recommended to limit free asparagine levels in cereals, including balanced sulfur and nitrogen fertilization and effective plant health management [68]. Organic agricultural practices have been reported to reduce the potential for acrylamide formation in cereal products compared with conventional farming systems [72]. In a field trial on wheat, fertilizer management—particularly the nitrogen-to-sulfur balance—was noted to markedly affect the accumulation of free asparagine in the grain, which in turn was closely associated with acrylamide levels in baked cereal products [73]. Based on this field study, a high nitrogen supply was associated with increased free asparagine in wheat grain and higher acrylamide formation in baked products. In contrast, maintaining a nitrogen-to-sulfur ratio of approximately 10:1 was sufficient to keep free asparagine levels under control [73]. Providing sufficient sulfur through fertilization, particularly in sulfur-deficient soils, can effectively reduce free asparagine concentrations—at application rates around 20 kg S ha^{-1}—and therefore lower the acrylamide-forming potential of cereal grains [74].

During product formulation, key mitigation strategies include the partial or complete replacement of ammonium bicarbonate with alternative leavening agents, the reduction or substitution of fructose and other reducing sugars with non-reducing sugars, the use of asparaginase under appropriate conditions, and, where feasible, the replacement of wheat flour with cereals exhibiting lower asparagine levels, such as rice or maize [53].

During product formulation, several practical strategies are proposed to reduce acrylamide formation in cereal-based foods. For example, partial replacement of ammonium bicarbonate with alternative leavening agents, such as sodium bicarbonate, can significantly lower acrylamide levels in

baked products. This is demonstrated by factorial design experiments, where reducing ammonium bicarbonate while adjusting the leavening system led to acrylamide reductions of over 80% in biscuits [75]. In addition, the inclusion of the enzyme asparaginase during dough preparation has been found to dramatically reduce acrylamide formation across a variety of cereal flours; in oat, corn, and rice cookie formulations, asparaginase treatments achieved reductions of up to approximately 97%, 95%, and 92%, respectively, compared with untreated controls, while maintaining acceptable color and texture properties [76]. Replacing fructose and other highly reducing sugars with non-reducing sugars can further limit the availability of acrylamide precursors during thermal processing [77]. Additionally, the use of cereal flours with intrinsically lower free asparagine content, such as wholemeal flours made from maize or rice, has been shown to result in lower acrylamide formation compared with high-asparagine flours under identical processing conditions [78]. Moreover, prolonged proofing in bakery products can significantly reduce acrylamide levels, as demonstrated by lower crust acrylamide levels in breads with extended fermentation times [79].

At the processing stage, optimization of time–temperature combinations, maintaining a higher moisture content in the final product, and preventing excessive browning are identified as critical control measures. Several studies indicate that food processing methods, such as cooking temperature and time, are effective in controlling acrylamide formation. Increased temperatures above 120 °C and extended cooking times have also been associated with increased acrylamide formation [20, 23, 34]. Therefore, changes in temperature and application time may be effective in reducing acrylamide formation.

Heat treatments applied to products also alter their color, and it is reported that acrylamide formation increases in parallel with browning in certain foods [24]. For this reason, the color of baked products, such as bread and cookies, can also give us an idea about the acrylamide level [21, 80]. To reduce consumers' exposure to acrylamide, the U.S. Food and Drug Administration (FDA) recommends that when baking or toasting bread and other bakery products, the color should be light brown, and that consumption of cereal-based products with excessively dry crusts should be avoided [81]. Similarly, Health Canada recommends that bread and baked goods be toasted to the lightest possible colour and that overcooked and burnt products be avoided [82]. The European Food Safety Authority (EFSA), in line with other authorities, recommends that cereal-based products should be lightly toasted rather than burned [58]. However, this feature is not observed in all cereal-based products; for example, there are no recommendations on the relationship between color and acrylamide content for corn-based snack products [83]. The acrylamide content of breakfast cereals and granola varies depending on factors such as the type of grain used (e.g., wheat, oats, corn, rice) and the manufacturing process [69]. For consumers, attention to product type and portion size can help reduce acrylamide exposure from cereal-based products. Puffed breakfast cereals generally contain higher acrylamide levels than flaked cereals due to the high temperatures and rapid processing steps involved in puffing, and therefore should be consumed in moderation [42]. Therefore, ensuring variety in consumption may be a suitable approach to reducing acrylamide intake. Despite the potential for dietary acrylamide intake from cereal consumption, the FDA does not recommend reducing intake of healthful grain products, such as whole grain cereals, which are a good source of whole grains and fiber [57].

According to the FDA's 2016 guidance for manufacturers, it is recommended to reduce thermal input through temperature and time controls, and to maintain the final product's moisture level at higher levels. It is also emphasized to monitor the acrylamide level of the product, taking into account color changes specific to each product [81]. For roasted cereal products, acrylamide formation can be reduced by preferring lower roasting temperatures (below 120 °C), applying pre-heating steps prior to roasting, and avoiding very small particle sizes that increase surface area exposure [33, 35]. It is recommended that cereal-based baked products be cooked at lower temperatures for longer periods. To minimize acrylamide in grain products, strategies such as maintaining high relative humidity during baking have proven effective [84]. In addition, it is suggested that high temperatures should be applied in the early stages of cooking, when product moisture is still high, and acrylamide formation is at low levels, and that the temperature should be reduced in the final stages of cooking as a practice to keep acrylamide content under control [81]. Maintaining a high relative humidity during baking has also been associated with an effective reduction in acrylamide levels in bakery products by slowing surface drying and delaying the progression of the Maillard reaction. For instance, baking bread at 200 °C for 20 min with steam application during the last 10 min resulted in approximately a 50% reduction in acrylamide. Lowering the oven temperature after the first 5 min of baking decreased acrylamide levels by up to 67% [20]. Furthermore, for low-moisture cereal products such as biscuits or crackers, the use of deck ovens that transfer heat mainly by conduction and radiation, rather than convection ovens with forced air circulation, can reduce acrylamide formation which may be attributed to slower heat transfer, lower surface temperatures, and better moisture retention in the dough, all of which are critical factors in limiting acrylamide formation during baking [28, 33].

Table 2 Cooking conditions associated with lower acrylamide formation in cereal-based products

Product	Cooking Method	Moisture	Temperature (°C)	Time (min)	Recommendation	Reference
Bread	Baking	High moisture due to steam application	180–200	20	Baking at moderate temperatures is recommended for high-moisture doughs, with crust development monitored to limit acrylamide formation.	[20]
Biscuits	Baking	No steam applied	170–180	7–20	Short-duration baking preserves sensory attributes while minimizing acrylamide formation.	[23] [29] [28]
Oat flour	Roasting	Moisture conditions not reported	110–120	20–40	Roasting at temperatures below 120 °C is recommended to minimize acrylamide levels; higher temperatures substantially increase its formation.	[35]
Oat	Roasting	Moisture conditions not reported	< 160	20	Higher temperatures and longer roasting times significantly increased acrylamide levels. To preserve sensory quality while minimizing acrylamide formation, roasting temperatures should not exceed 160 °C.	[32]
Fried Dough Twists	Frying	Moisture conditions not reported	160	3	Short frying at moderate temperature achieves a balance between minimal acrylamide formation and acceptable organoleptic properties.	[40]

While precise recommendations cannot be universally applied due to differences in product type, moisture content, and formulation, Table 2 summarizes cooking conditions from published studies that are associated with comparatively lower acrylamide formation in cereal-based products.

Emerging strategies to reduce acrylamide formation in cereal products

Beyond conventional temperature and moisture control, a wide range of mitigation strategies has been developed to reduce acrylamide formation in cereal-based foods. Enzymatic approaches, particularly the use of asparaginase, have proven highly effective in converting free asparagine to aspartic acid before Maillard reactions [85]. The application of asparaginase prior to baking has been associated with reductions of up to 97% in acrylamide levels in gingerbread, without adversely affecting sensory quality [86]. In another study, the addition of L-asparaginase to biscuit formulations reduced acrylamide levels by approximately 67.63% compared with untreated samples [87]. Glucose oxidase provides an additional enzymatic pathway by lowering glucose availability, thereby limiting another key precursor of acrylamide [88]. In a model biscuit system, glucose oxidase alone reduced acrylamide concentrations by 54.16%, while a 1:1 mixture of glucose oxidase and asparaginase achieved a higher reduction of 69.94% compared with untreated samples, highlighting the potential of glucose oxidase–based treatments as practical mitigation tools in cereal-based bakery products [87].

Based on available evidence, incorporating polyphenol-rich plant extracts such as green tea, vine tea, rosemary, sorghum bran, and Tartary buckwheat is particularly effective at lowering acrylamide formation in bakery products by modulating Maillard reaction pathways [89]. Furthermore, natural plant extracts from Coriandrum sativum, Nigella sativa, and Thymus species, as well as probiotic strains such as Lactobacillus casei subsp. rhamnosus, have demonstrated strong mitigation effects in wheat, barley, and maize, with Nigella extracts reducing acrylamide by up to 100% in corn, 87% in barley, and 60% in wheat [90].

Several alternative processing technologies have been explored experimentally as means to mitigate acrylamide formation by modifying heat and moisture dynamics during thermal processing. For example, in microwave-baked biscuits, microwave baking at 440 W for 3 min produced ≈ 60.75% lower acrylamide levels than conventional baking at 190 °C for 7 min [91]. However, some studies report higher acrylamide formation under prolonged or high-power microwave exposure, highlighting the need to optimize processes when using microwave treatments to mitigate acrylamide [92]. In a study, vacuum modification applied after partial baking of yeast-leavened bread decreased acrylamide levels by nearly 59.8%, suggesting its potential as a promising new mitigation strategy [93].

In conclusion, beyond traditional control of temperature and moisture, various emerging strategies—such as enzymatic treatments, plant extracts, and innovative processing technologies—show promising potential for effectively reducing acrylamide formation in cereal-based products. However, further optimization for industrial applications and careful evaluation of their impact on sensory quality are essential.

Discussion

Across baking, roasting, frying, puffing, and air frying, the general trend is that higher temperatures and longer processing times lead to greater acrylamide formation. However, several studies have indicated that in baking and roasting, acrylamide may reach a maximum at intermediate thermal loads and then decline due to thermal degradation mechanisms, including evaporation, polymerization, and reactions with food matrix components [1, 20–24]. For example, in bread and wheat flour processed at 180–260 °C, acrylamide peaks before decreasing, and similarly, in barley and oats roasted at around 240 °C, darker grains are formed with lower acrylamide levels [32–34]. Nevertheless, such conditions severely impair color, flavor, and texture, rendering them impractical as mitigation strategies.

Roasting poses a high risk of acrylamide formation due to its dry-heat nature and pronounced surface dehydration. Products with larger surface areas, such as oat flakes and broken rice, accumulate substantially more acrylamide than intact kernels and often exceed European benchmark levels when roasted at temperatures of 160–200 °C [32, 33, 35]. Frying, puffing, and air-frying are characterized by high temperatures, rapid moisture loss, and intense heat transfer, and are therefore associated with acrylamide formation in cereal products. Puffing processes—where final frying temperatures may exceed 300 °C—consistently generate higher acrylamide levels than flaking [18, 42]. Air-frying produces a comparable risk profile by rapidly reducing water activity and accelerating Maillard reactions, with exposure levels in cereal products classified as a public health concern [45]. Accordingly, processes characterized by high temperatures, low water activity, and intense heat flux are inherently more prone to acrylamide formation than moisture-moderated or steam-assisted baking [20, 21, 28].

Because most studies are product-specific and rely on single-factor designs, it is not possible to define a universal temperature–time–moisture window applicable to all cereal products. This represents a major research gap, limiting the translation of laboratory findings into robust industrial mitigation strategies. The public health relevance is substantial, as bread, breakfast cereals, and cereal-based snacks account for roughly one-third of total dietary acrylamide intake in many populations, with children experiencing disproportionately higher exposure [48, 56, 60, 65]. The stabilization of biomarker-based exposure levels in Europe after 2017 demonstrates that regulatory and technological interventions can yield measurable benefits for the population [50, 54].

Emerging mitigation strategies—including enzymatic treatments (asparaginase, glucose oxidase), polyphenol-rich plant extracts, and novel technologies such as microwave and vacuum-assisted baking—can reduce acrylamide by 50–97%, exceeding the effectiveness of temperature–time control alone [85–93]. However, their industrial application remains constrained by formulation compatibility, scalability, and potential impacts on sensory quality. Together, these findings support the need for integrated mitigation approaches that span agriculture, formulation, and processing conditions, rather than relying on any single control point [53, 73, 76, 81].

Conclusions and recommendations

This study reviewed the effects of temperature, time, and humidity applied during different cooking methods on acrylamide formation in cereal products, as well as strategies to reduce acrylamide content. The evidence suggests that minimizing acrylamide formation requires careful control of processing parameters, including low cooking temperatures, high humidity, and short cooking times.

High temperatures and low moisture levels significantly increase acrylamide formation, whereas moist cooking methods, such as steam cooking, can help reduce its levels. Reducing the temperature towards the end of cooking is also recommended to limit acrylamide accumulation. Cooking above 120 °C generally increases acrylamide levels, while very high temperatures or prolonged cooking may degrade acrylamide, albeit at the cost of negatively affecting sensory properties such as color and texture.

Controlling the crust color is important, as excessive browning correlates with higher acrylamide content. Therefore, avoiding overly dark crusts and maintaining appropriate moisture levels in the final product are recommended practices for manufacturers.

Beyond traditional processing controls, emerging strategies, such as enzymatic treatments, plant extracts, and novel processing technologies, hold promise for reducing acrylamide levels. However, these methods require further optimization for industrial applications and assessment of their effects on sensory properties.

Regulatory frameworks, such as Commission Regulation (EU) 2017/2158, provide a comprehensive, multi-stage approach to mitigating acrylamide through agricultural practices, product formulation, and processing controls. Industries should closely follow these guidelines to ensure food safety and compliance.

From a public health perspective, acrylamide exposure is influenced not only by processing but also by dietary patterns. Although cereal-based products such as bread and breakfast cereals contribute substantially to acrylamide intake, simply limiting cereal consumption is neither practical nor nutritionally advisable. Instead, encouraging dietary

diversification within cereal foods—promoting a variety of grains and preparation methods—can help reduce acrylamide exposure while maintaining the nutritional benefits of cereals. Educating consumers about cooking practices, such as avoiding excessive browning and favoring moist cooking techniques, can further reduce acrylamide intake at home. Ultimately, acrylamide exposure should be assessed in the context of the overall diet rather than attributing risk solely to individual food groups, which supports balanced, varied dietary habits for improved health outcomes.

Despite the extensive and rapidly growing body of literature on acrylamide formation, several critical knowledge gaps and methodological inconsistencies remain. Visual indicators such as crust color or surface dryness, although frequently recommended, may not reliably predict acrylamide formation across all cereal-based products, particularly those formulated with alternative ingredients such as corn flour. Similarly, while high humidity and lower temperatures are generally associated with reduced acrylamide levels, these conditions may compromise product quality, safety, or consumer acceptance, limiting their practical implementation. Moreover, a major limitation of the current literature is the substantial methodological heterogeneity among studies, including differences in raw material composition, moisture control, heating profiles, and analytical approaches, which hampers direct comparison and synthesis of results. Consequently, the development of optimized, product-specific cooking recommendations that are applicable to both public health guidance and industrial processing remains a notable gap in the current literature.

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Declarations

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