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REVIEW ARTICLE

Acrylamide mitigation in cereal-based foods: a comprehensive review of enzymatic treatments, additives and novel technologies

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Abstract

Acrylamide is a compound formed during the heat processing of carbohydrate-rich foods as a result of the Maillard reaction, and it poses significant health risks. It is classified as a potential carcinogen and neurotoxic agent, with long-term dietary intake raising serious public health concerns. As acrylamide is commonly found in a variety of processed foods, the development of specific and effective mitigation strategies is crucial to protect public health and meet regulatory requirements. Enzymatic methods, natural additives, and novel technologies have gained prominence in reducing acrylamide levels in cereals. The enzyme asparaginase prevents acrylamide formation by converting asparagine into aspartic acid before the Maillard reaction begins, while glucose oxidase inhibits acrylamide production by lowering glucose levels. Studies have shown that these enzymatic treatments provide effective and industry-compatible solutions with minimal sensory alterations. Certain natural additives, such as rosemary and green tea extracts, achieve similar effects by inhibiting the Maillard reaction or neutralizing free radicals. Innovative technologies, including microwave heating, radio frequency application, vacuum baking, infrared heating, and ultrasound, have demonstrated success in reducing acrylamide—provided that their use is carefully controlled to minimize impacts on sensory quality. Advances in food processing technologies continue to enhance the efficiency and scalability of these approaches. However, most studies have evaluated these strategies in isolation, with limited assessment of the economic feasibility and sensory impacts of integrated approaches. This review provides a comprehensive analysis of enzymatic, additive-based, and technological acrylamide mitigation strategies, focusing not only on their mechanisms of action but also on practical aspects such as industrial applicability, economic considerations, and sensory effects. The aim is to offer practical insights to guide future research and assist food producers in selecting the most suitable combination of strategies for acrylamide reduction. Future studies should focus on optimizing multi-strategy mitigation techniques and evaluating potential trade-offs in large-scale applications.

Keywords Acrylamide · Mitigation strategies · Enzymatic treatments · Additive applications · Novel technologies

Introduction

Acrylamide (AA, C_3 H_5 NO) is a food contaminant found in many foods, has carcinogenic and neurotoxic effects, and has become inevitable for human transmission. Acrylamide, a heat-induced contaminant, is classified as a probable human carcinogen by the International Agency for Research on Cancer [1]. Dietary exposure, especially through cereal-based products, has raised significant public health concerns due to its widespread presence and potential neurotoxic and genotoxic effects [2]. Therefore, methods are being developed to reduce acrylamide formation [3, 4]. These methods are shown in Fig. 1. Acrylamide, which causes neurotoxicity through central and peripheral neuropathy, has clinical findings such as numbness, skeletal muscle weakness, ataxia,

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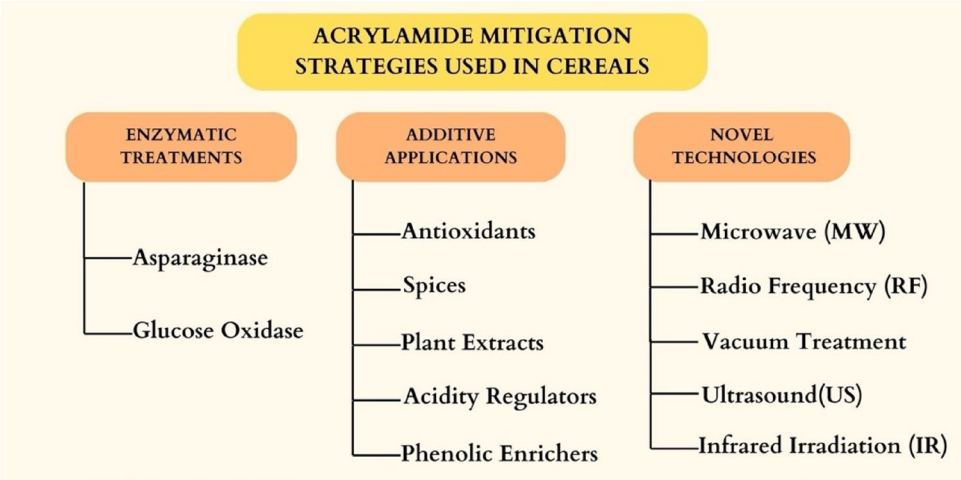


Fig. 1 Acrylamide mitigation strategies used in cereals

Table 1 Average, minimum, and maximum acrylamide levels in Cereal/Cereal-Based foods [9]

Cereal/Cereal-Based Foods	Average Amount (mcg/kg)	Minimum acrylamide (mcg/kg)	Maximum acrylamide (mcg/kg)
White Bread	–	< 10	130
Toast Bread	–	25	1,430
Cookies	–	< 20	7,834
Breakfast Cereals	96	11	1,057
Rice Crackers	–	< 3	67
Roasted Noodles	123	3	581

cerebellar ataxia, and hindlimb dysfunction [5]. Acrylamide is a typical process-related contaminant found in heat-treated foods (coffee, biscuits, etc.), especially starchy foods such as potatoes, bread, and cakes [6, 7]. The acrylamide content in heat-processed foods like baked goods is influenced by several factors, including the initial levels and ratios of its precursors, flour quality (e.g., milling intensity), fermentation conditions, and the type of thermal processing used (such as baking, frying, or toasting). Additionally, processing parameters like temperature, heating duration, pH, moisture content and activity, physical structure of the product, and the presence of additives also play a significant role [8]. Typical acrylamide concentrations in cereal-based foods vary within the following ranges: 10–1500 mcg/kg in bread products, 20–1000 mcg/kg in biscuits and cookies, 10–1000 mcg/kg in breakfast cereals [9, 10]. Table 1 illustrates the acrylamide content in various cereal-based foods [9].

Cereal-based products are a significant source of acrylamide exposure due to their widespread consumption [11]. While the maximum acceptable intake level of acrylamide for humans is 1 µg/kg body weight/day, it is estimated that the average acrylamide intake among consumers varies between 0.6 µg/kg body weight/day and 4 µg/kg body weight/day, which can be many times higher than this maximum level [12, 13].

The type of cereal grain and its growing conditions play a significant role in determining the acrylamide-forming potential of cereal-based products. Studies have shown that different wheat species exhibit variable levels of free asparagine, with hard wheats typically having higher concentrations than soft wheats [14]. Similarly, rye and oats tend to accumulate more asparagine compared to barley or rice, making them more susceptible to acrylamide formation during thermal processing [15]. Moreover, agronomic practices, such as high nitrogen fertilization, drought stress, and soil sulfur deficiency, have been linked to increased asparagine accumulation in cereals [16]. Therefore, the selection of cereal type and optimized cultivation conditions can be considered essential preventive strategies in minimizing acrylamide risks.

In cereal-based foods, acrylamide is formed through the Maillard reaction, where the free amino acid asparagine reacts with reducing sugars (such as glucose, fructose, and maltose) or carbonyl compounds. In the early stages of the Maillard reaction, the α-amino group of free asparagine reacts with a carbonyl source to produce a Schiff base. The amide group on asparagine's side chain is then incorporated into the amide bond of acrylamide [10].

Implementing strategies to reduce acrylamide formation in cereal-based foods is of critical importance for food safety and the preservation of sensory properties [17]. Many methods have been developed to reduce acrylamide in foods, such as enzymatic treatments, adding organic acids or antioxidants, and innovative approaches. The use of enzymatic treatments is recognized as an efficient approach to minimize acrylamide production in foods subjected to heat processing, with minimal impact on their quality [18]. Enzymatic depletion of key precursors like free asparagine and reducing sugars significantly lowers acrylamide levels, offering a targeted and effective approach [19].

Antioxidant additives, particularly plant polyphenols (such as rosemary extract, green tea, and grape seed), are

known to reduce acrylamide formation by inhibiting the Maillard reaction or by scavenging free radicals [9, 20]. The use of these natural additives in acrylamide mitigation is generally less expensive and more widely available compared to enzymatic and other technological methods, making them potentially more accessible for industrial applications [18]. Additives are typically applied to cereal-based products through direct incorporation into the dough, pre-treatment dipping, or surface coating [21–23]. However, their efficacy is less predictable, and higher doses may be required to achieve consistent results, which can potentially affect the product formulation [20]. In addition to, innovative mitigation strategies include a variety of pressure-, radiation-, and dielectric-based heating techniques. For instance, vacuum baking utilizes reduced pressure to lower the boiling point of water, facilitating moisture removal and limiting Maillard reaction-driven acrylamide formation at lower temperatures and shorter processing times [18]. Consequently, the selection of a mitigation strategy should be based on a cost-benefit analysis, considering the type of product, scale of production, and market demands [18].

Although numerous studies have addressed general acrylamide reduction techniques, there remains a clear gap in the literature regarding the in-depth evaluation of various mitigation methods specifically within cereal-based matrices. This review aims to fill this gap by providing a comprehensive assessment of acrylamide mitigation strategies in cereals, including enzymatic applications, the use of additives, and innovative technologies. It not only focuses on their mechanisms of action but also examines the practical aspects of these interventions, such as industrial applicability, economic feasibility, and their impact on sensory properties.

The objective of this review is to offer practical insights that can guide future research and assist food producers in selecting the most appropriate combination of strategies for effective acrylamide reduction in cereal products.

Approaches for mitigating acrylamide formation in cereal-based products

Enzymatic treatment for mitigation of acrylamide in cereals

Acrylamide, a chemically toxic substance, is food-borne and formed by various mechanisms (such as the Maillard reaction, acrolein pathway, and free amino acid pathway), especially in heat processes [19]. The Maillard reaction initiates with interactions between the carbonyl groups of different sugars and the amino groups of amino acids or proteins, leading to the production of intermediate or polycarbonyl compounds [24]. During the Maillard reaction, reducing sugars react with amino groups to form a Schiff base, which rearranges into an Amadori compound that subsequently degrades into reactive dicarbonyls, promoting the development of color and aroma and ultimately resulting in the formation of brown polymers called melanoidins [24]. Acrylamide (AA) formation in foods is mainly linked to the Maillard reaction, which is the first feasible route that can be manipulated to reduce AA formation [4]. In the Maillard reaction, reducing sugars condense with amino acids, particularly asparagine, resulting in the formation of N-glycosides that subsequently rearrange into Amadori products; the decarboxylation of these intermediates or the transformation of 3-aminopropionamide under aqueous conditions ultimately leads to acrylamide formation, primarily accumulating in the crust or surface layers of foods where advanced Maillard reactions cause darker coloration [4].

Acrylamide, a small and hydrophilic molecule, passes through the tissues quickly after being taken into the body, enters the circulation, and is absorbed by various organs [2]. It has been reported that the amount of acrylamide in foods varies depending on the food content, processing stages, storage conditions, and many other factors [2]. Since acrylamide has many harmful effects on health (such as carcinogenicity and neurotoxicity), both traditional and innovative methods to reduce these adverse effects interest the scientific community [25]. Various approaches have been developed to minimize acrylamide content in food products. Among these, enzymes are more prominent in the food industry. Figure 2A and B respectively demonstrate in detail how asparaginase and glucose oxidase treatments reduce acrylamide formation in cereals. Asparaginase, glucose oxidase, acrylamidase, phytase, amylase, and protease enzymes prevent acrylamide formation in different ways or hydrolyzing already formed acrylamide [19].

Enzymes reduce acrylamide formation through specific catalytic mechanisms. There is an amide group on the side chain of asparagine, and this amide group is converted into aspartic acid and ammonia by the asparaginase enzyme [26]. As a result, aspartic acid does not engage in the Maillard reaction, thereby substantially reducing the formation of acrylamide [27]. Glucose oxidase, employs a tightly but noncovalently attached flavin adenine dinucleotidE as a redox cofactor to catalyze the oxidation of β-D-glucose into D-glucono-δ-lactone and hydrogen peroxide in the presence of oxygen, after which D-glucono-δ-lactone spontaneously hydrolyzes into gluconic acid without enzymatic assistance [28]. By enzymatically reducing the concentrations of free asparagine and reducing sugars through the action of glucose oxidase and asparaginase, acrylamide levels were substantially lowered, highlighting the effectiveness

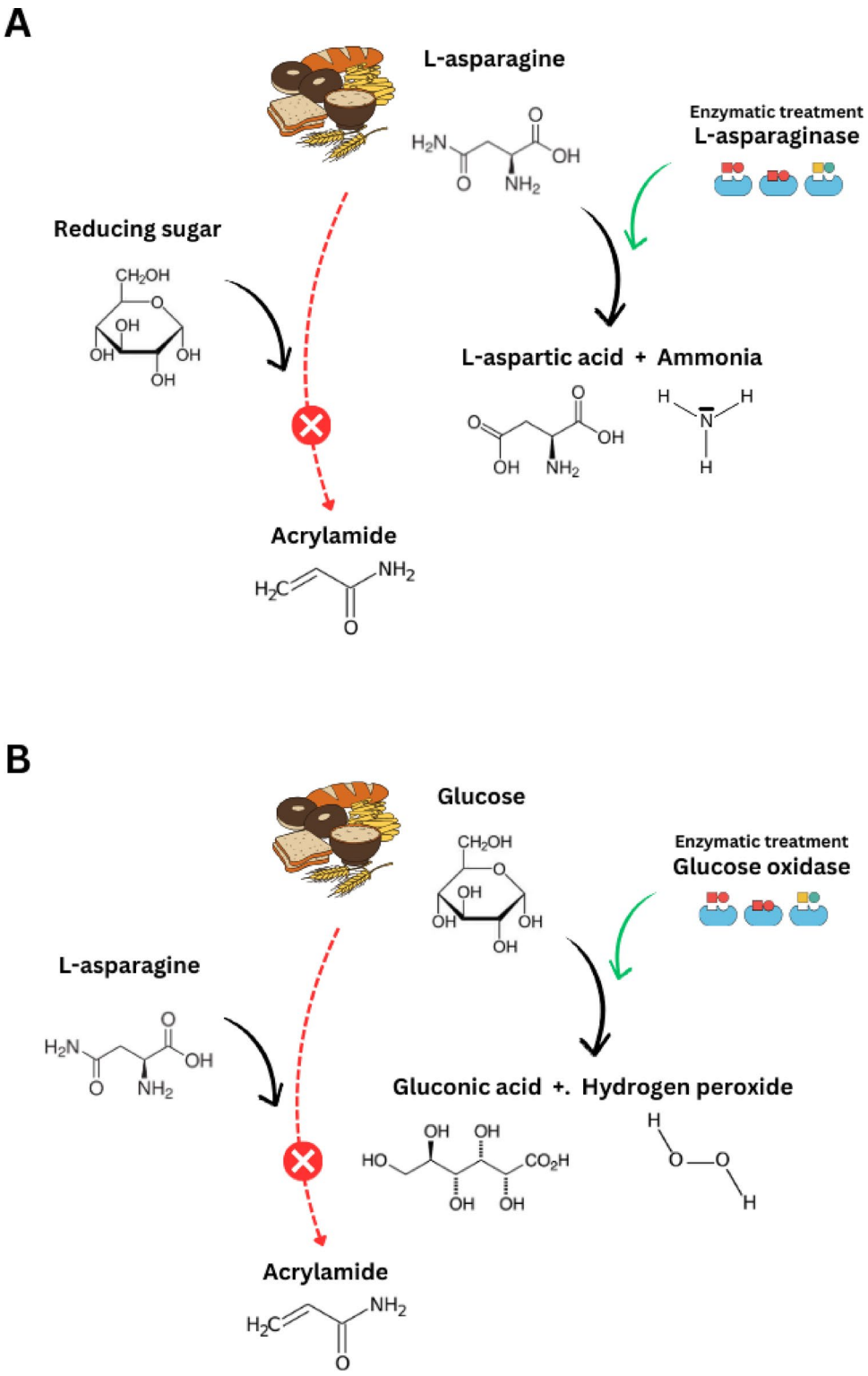


Fig. 2 Mechanisms of acrylamide reduction in foods by enzymatic treatments: **A** L-asparaginase application and **B** glucose oxidase application

of precursor depletion in minimizing acrylamide formation [19]. Since various food components (e.g., lipid-derived aldehydes, free amino acids, and other carbonyl-containing molecules) react with asparagine and contribute to the formation of acrylamide, it would be beneficial to reduce these compounds as much as possible in applications [29].

Acrylamide hydrolysis carried out by enzymes largely preserves other bioactive compounds and generally has minimal impact on the sensory and rheological characteristics

of the final product [19]. Table 2 presents various studies investigating the effects of enzymatic treatments on acrylamide reduction in cereal products.

In this section, we focused on asparaginase and glucose oxidase enzymes, which are used more by the food industry than others for various reasons such as stability under thermal conditions and cost.

Asperaginase

Some enzymes contribute to us industrially. The most critical feature of asparaginase, which has attracted much attention by researchers, is its antineoplastic activity [30]. Recently, many developments have occurred in enzyme technologies; thus, it has become possible to benefit from the properties of enzymes at the highest level [31]. Asparaginase is widely used to reduce acrylamide levels in foods in various forms sourced from *Aspergillus oryzae* and *Aspergillus niger* [8]. L-asparaginase enzyme, which is extensively utilized in the

Table 2 The effect of enzymatic treatment on acrylamide reduction in cereals

Cereal Product	Method	Key Findings	References
Biscuit	0.5 g of asparaginase per kg of wheat flour	67.28% reduction in acrylamide levels The best conditions for acrylamide reduction are resting the dough at 37 degrees for 30 min	[28]
Biscuit	0.5 g of glucose oxidase per kg of wheat flour	63.93% reduction in acrylamide levels A decrease in carbohydrate content due to enzyme activity was reported	[28]
Biscuit	Application of 0.5 g (1 to 1 ratio) of asparaginase and glucose oxidase enzyme per 1 kg of flour	Decrease in both asparagine and sugar levels due to the combined action of enzymes 69.63% reduction in acrylamide levels	[28]
Biscuit	1000 ASNU asparaginase enzyme per 1 kg of wheat flour	68% decrease in asparagine levels 35% decrease in acrylamide levels	[35]
	2000 ASNU asparaginase enzyme per 1 kg of wheat flour	95% decrease in asparagine levels 65% decrease in acrylamide levels	
	3000 ASNU asparaginase enzyme per 1 kg of wheat flour	99% decrease in asparagine levels 80% decrease in acrylamide levels	
	3000 ASNU asparaginase enzyme per 1 kg of wheat flour 15 min resting time for the dough	100% decrease in asparagine levels 96% decrease in acrylamide levels	
Pizza (fried)	Frying Adding 3 U of asparaginase enzyme per 100 g of flour for 2 h	60% decrease in acrylamide levels	[48]
Pizza (wood oven)	Baking in the wood oven Adding 3 U of asparaginase enzyme per 100 g of flour for 8 h	40% decrease in acrylamide levels	[48]
Biscuits and bread	10 U *Rhizomucor miehei* L-Asparaginase (RmAsnase) per 1 mg of flour	81.6% reduction in acrylamide levels in biscuits 94.2% reduction in acrylamide levels in bread	[49]
Sweet bread	Asparaginase derived from *Cladosporium sp.* was utilized in wheat-based dough at a concentration of 300 U	97% reduction in acrylamide amount in the bread crust 73% reduction in acrylamide levels in the crumb region of bread	[50]
Gingerbread	Application of 100 U- 1000 U L-Asparaginase enzyme per 1 kg of dough	1000 U/kg L-Asparaginase enzyme treatment; 45% (30 min incubation) and 75% (60 min incubation) reduction in acrylamide levels 100 U/kg L-Asparaginase enzyme treatment; 80% (48 h incubation) reduction in acrylamide amount No adverse impacts on the gingerbread color, texture, or visual aspect were observed.	[51]

food and pharmaceutical sectors, breaks down asparagine into substances such as aspartic acid and ammonia, thus eliminating precursors that cause acrylamide formation [18, 27]. According to studies on bread and biscuits, asparaginase activity is affected by temperature, time, additional addition of asparaginase, and pH, but reducing acrylamide with this method does not make a difference in the sensory and textural attributes of foods such as bread and biscuits [32, 33].

Based on the findings of a 2019 study investigating the influence of duration, temperature, and asparaginase on the formation of acrylamide in bread and the physicochemical properties of bread, there was a positive relationship between temperature and baking time and acrylamide formation, while significant decreases in acrylamide levels were observed in samples treated with asparaginase [33]. In a research released in 2018, sweet bread was subjected to treatment with 300 U of L-asparaginase to investigate how L-asparaginase isolated from *Fusarium culmorum (ASP-87)* affected acrylamide formation in sweet bread. An 86% reduction in acrylamide level and a 78% reduction in asparagine content of baked sweet bread were reported [34]. In a study investigating the impact of asparaginase on the formation of acrylamide in different biscuit, cracker, and cookie doughs, acrylamide reductions of 96%, 80%, and 54% were achieved in biscuits, crackers, and cookies, respectively [35]. Nonetheless, the study has demonstrated that asparaginase requires a water activity exceeding 0.75 to reduce acrylamide in bakery products effectively and that asparaginase does not affect the color and spreading capacity of the products [35]. The latest study exploring the impacts of various enzyme applications on the content of acrylamide in biscuits, the application of 0.5 g L-aspaginase per kg for 30 min during the preparation of the dough caused a decrease of nearly 67% in the acrylamide presence of the biscuits [28].

However, the use of asparaginase also has different limitations, such as; production and economic applicability of L-asparaginase. Industrial production of L-asparaginase with different microorganisms was previously carried out by submerged fermentation (SF), which provides the advantage of easier monitoring and use, but this method has various disadvantages such as large amounts of wastewater production, difficulties in wastewater treatment processes and high production costs [27, 36, 37]. Several parameters—including carbon and nitrogen sources, temperature, pH level, duration of fermentation, agitation speed, and the amount of inoculum—can significantly affect the efficiency of submerged fermentation (SF) [38, 39]. Later, as an alternative to SF, solid state fermentation (SSF) was developed for L-asparaginase production by different microbes, and although this method is advantageous over SF in terms of wastewater production and cost, it has its own difficulties, for example; ensuring optimum L-asparaginase production for different microorganisms requires optimization of many parameters such as substrate selection, moisture content, pH, particle size and incubation time [27]. Additionally, there are also different regulations and restrictions in different countries regarding the use of asparaginase in the food industry; for example, according to EFSA, only enzymes included in the EU Union List can be used in food under certain conditions of use [40]. Within the European Union, L-asparaginase has received regulatory approval for use in certain food categories under Regulation (EC) No 1332/2008; however, applying it to other food types or at higher concentrations may necessitate further authorization processes, which could limit its widespread adoption [40].

Glucose oxidase

Glucose oxidase enzyme (GOX), naturally produced in the fungus *Aspergillus niger*, disrupts the formation pathways of reactive oxygen species by hydrolyzing glucose to hydrogen peroxide and D-glucono-δ-lactone [41]. Although the application frequency of glucose oxidase in the food sector is significantly lower compared to L-asparaginase, it is frequently used to prevent rancidity of oils, improve the taste or color characteristics of foods, deplete oxygen in fruit juices, and bleach milk [18, 42]. Glucose oxidase has also been used to reduce acrylamide levels in grains. Based on the findings of a study investigating the impact of adding 0.5 g of glucose oxidase per kilo to biscuit dough during the preparation phase on changes in acrylamide levels, a 63.93% decrease in acrylamide levels occurred in biscuits to which glucose oxidase was added, but a slight reduction in the sensory properties of the biscuits was reported [28].

An examination of the characteristics of glucose oxidase shows that the enzyme exhibits optimal activity at around 25 °C under pH 7.0 conditions, with a pH optimum between 4.0 and 6.0 at this temperature; however, thermal stability tests conducted by pre-incubating the enzyme at various temperatures (pH 7.0) for durations ranging from 2 to 60 min revealed a noticeable decline in activity above 55 °C, and complete loss of activity after 2 min at 85 °C [43]. Furthermore, glucose oxidase from natural origins often presents challenges such as low fermentation yield, complex downstream processing, and inconsistent activity, which restrict its widespread application [44]. Glucose oxidase expressed in hosts such as S. cerevisiae and H. polymorpha is often excessively glycosylated, which adversely affects its enzymatic activity [45]. Another limitation of the use of glucose oxidase is that glucose oxidase oxidizes β-D-glucose to D-glucono-1,5-lactone, reducing molecular oxygen to hydrogen peroxide [43]. Hydrogen peroxide produced by

glucose oxidase must be converted to oxygen and water by catalase enzyme [44]. Hydrogen peroxide, which is formed as a result of the reaction catalyzed by glucose oxidase, can inactivate many proteins—including enzymes—when accumulated in high concentrations [46] Hydrogen peroxide can disrupt the structure and functionality of proteins by causing structural changes in amino acid residues, breaking of peptide bonds, and cross-linking between proteins, which can affect the sensory properties of foods [46].

Like other food enzymes, the use of glucose oxidase in the food industry is subject to regulatory oversight [47] Prior to January 2009, food enzymes—excluding those classified as food additives—were either unregulated or governed by individual national legislations [47]. However, as of January 20, 2009, all food enzymes have been brought under the scope of Regulation (EC) No 1332/2008, as previously mentioned [47].

Additives for mitigation of acrylamide in cereals

Additives, particularly plant-derived antioxidants such as polyphenols, are effective in reducing acrylamide levels in cereal-based products. These compounds primarily act through their radical-scavenging properties, neutralizing reactive oxygen species and stabilizing free radicals that contribute to acrylamide formation [9, 20]. Unlike enzymatic strategies, which directly target acrylamide precursors in the Maillard reaction, additives offer mitigation by enhancing the antioxidant capacity of food matrices [18]. The use of these natural additives in acrylamide mitigation is generally less expensive and more widely available compared to enzymatic and other technological methods, making them potentially more accessible for industrial applications [18].

Commonly studied additives include rosemary extract, green tea polyphenols (EGCG), grape seed extract, and various spices such as thyme and cumin; all of which are known for their high phenolic content [22, 23, 52, 53]. As shown in Fig. 3, the impact of various additives on acrylamide formation is evident, demonstrating their role in inhibiting Maillard reaction intermediates and reducing acrylamide levels in cereal-based products.

The role of antioxidants

Among the most effective strategies for reducing AA levels is applying natural antioxidants [54]. As shown in Fig. 3, polyphenols have gained attention due to their strong antioxidant activity, free radical-scavenging properties, and other biological functions [4, 55].

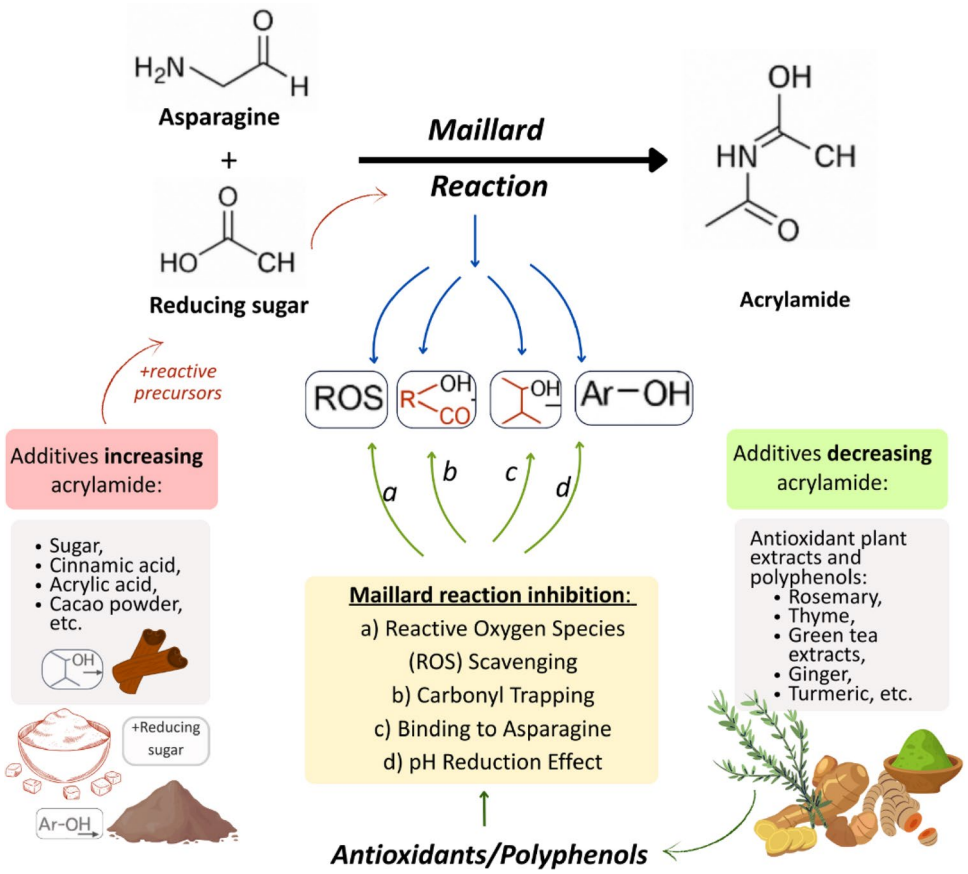


Fig. 3 Effects of additives on acrylamide formation and Maillard reaction

Specific compounds such as phenolic acids and flavonoids interact with carbonyl groups during Maillard reactions, suppressing acrylamide formation [56]. For instance, green tea catechins, including epicatechin and epigallocatechin gallate, have been shown to reduce acrylamide formation in controlled systems [52]. Similarly, bioactive compounds derived from spices and plants have demonstrated notable efficacy in mitigating acrylamide formation [56]. Polyphenols can also contribute to the preservation of sensory properties during the processing of cereal-based products [17]. However, some antioxidants, such as chlorogenic acid, may promote the formation of 5-hydroxymethylfurfural (HMF), which under certain conditions could indirectly enhance acrylamide formation, highlighting the importance of careful antioxidant selection [57].

Table 3 Effects of Plant-Based and additives on acrylamide formation in cereals

Cereal Product	Method	Key Findings	References
Wheat-flour-based products	Addition of citric acid	Acrylamide formation was reduced by 30%.	[70]
Bread	Addition of green tea polyphenols	Acrylamide levels decreased by 48%.	[23]
Cookie	Addition of ginger powder	Acrylamide levels decreased by 6.2%.	[61]
Bread	Addition of EGCG	Acrylamide levels decreased by 37%.	[52]
Cookie	Addition of spices (thyme, cumin, anise)	Acrylamide levels decreased by 45%, 35%, and 50%, respectively.	[22]
Pita	Addition of mint, fennel, turmeric	Acrylamide levels decreased by 45%, 38%, and 29%, respectively.	[21]
Rye bread	Addition of folic acid	Acrylamide levels were reduced by 25%.	[68]
Wheat bread	Addition of thyme	Acrylamide levels decreased by 25%.	[71]
Wheat-based products	Addition of apple polyphenols	Acrylamide formation was reduced by 15%.	[17]
Bread	Addition of turmeric	Acrylamide levels increased by 20% at 150–200 °C.	[66]
Buckwheat ginger cakes	Various spices (cloves, nutmeg, fennel, anise, cinnamon, coriander)	Acrylamide levels decreased by 23% with cloves, 20% with nutmeg, 17% with fennel, and 18% with anise. Increased by 29% with cinnamon and 18% with coriander.	[62]
Wheat flour bread	Addition of grape seed extract	No significant reduction in acrylamide formation observed.	[67]
Bread	Addition of rosemary	Acrylamide levels decreased by 62%.	[58]

Spices and plant extracts

Plant-derived compounds and various spices can reduce acrylamide formation by capturing carbonyl groups during Maillard reactions, thanks to their content of phenolic acids and flavonoids [58]. Table 3 summarizes studies examining the effects of various plant-based additives on acrylamide levels in cereal-based products.

Spices with high antioxidant capacity, such as thyme and cumin, have been shown to reduce acrylamide levels in baked goods by 45% and 35%, respectively [22]. Anise is the most effective spice in this category, providing a 42% reduction in acrylamide levels [22]. Green tea catechins, particularly epigallocatechin gallate (EGCG), have been found to reduce acrylamide levels by up to 40% in baked goods [52]. These compounds effectively interact with carbonyl groups, inhibiting Maillard reactions [52]. Similarly, the phenolic components of rosemary (Rosmarinus officinalis), such as carnosic acid and carnosol, added to bread and cookies, have resulted in a 62% reduction in acrylamide levels [58, 59]. Additionally, one study showed a further 6% reduction in acrylamide levels under humid baking conditions when rosemary extract was incorporated into these products [60].

The bioactive compound 6-Gingerol found in ginger can reduce acrylamide formation by inhibiting protein glycation [61]. Ginger powder added at levels of 1–5% to cookies has been associated with a 6.2% reduction in acrylamide levels and improved sensory properties [62]. On the other hand, acidic spices such as cinnamon and turmeric may have dual effects on acrylamide formation, containing both inhibitory and promotive compounds [63, 64]. While the phenolic components of cinnamon reduce acrylamide formation, its cinnamic acid content can promote acrylamide production at high temperatures [63]. Ultimately, the mechanism of action of cinnamon depends on its chemical composition and specific processing conditions [63, 65]. Similarly, the active component in turmeric, contains carbonyl groups that can react with asparagine and potentially contribute to acrylamide formation [66]. Additionally, under low sugar and high asparagine concentrations, curcumin has been observed to increase acrylamide formation [66].

Grape seed extract (GSE), rich in phenolic compounds such as epicatechin and proanthocyanidins, has been suggested as a potential natural additive for mitigating acrylamide formation in cereal-based products [17, 67]. It was hypothesized that the polyphenols in grape seed extract could scavenge reactive carbonyls or stabilize the food matrix, thereby reducing acrylamide formation [17, 67, 68]. However, despite being rich in phenolic compounds, the effect of grape seed extract on acrylamide reduction in cereal-based products appears limited under specific baking conditions.

In a study simulating crust formation, the addition of grape seed extract at levels of 0.1% and 0.5% to wheat flour did not result in a significant reduction in acrylamide levels after baking at 180 °C for 30 min [67]. This suggests that, despite its antioxidant potential, grape seed extract may lack the necessary interaction with acrylamide precursors such as free asparagine and reducing sugars under high-temperature conditions. However, in this study, the ineffectiveness of these mechanisms may be due to the thermal degradation of polyphenols or the limited accessibility of reactive sites in the crust-like model [54, 56]. These findings indicate that the effectiveness of phenolic-rich additives like grape seed extract may be highly dependent on the food matrix and specific processing conditions.

On the other hand, the combined use of spice mixtures in cereal products can further suppress acrylamide formation through their phenolic content and radical-scavenging properties [21, 22, 62]. As presented in Table 3, spices such as coriander, mint, thyme, and anise have demonstrated notable efficacy in reducing acrylamide levels in wheat-based products, highlighting their potential role in Maillard reaction modulation. However, variability in the phenolic composition and extraction methods of plant-based additives often leads to inconsistent results across different studies, making their standardization in industrial applications challenging [69].

Acidic environment and phenolic enrichers

The suppression of acrylamide formation through acidic additives is a crucial area of study, particularly for enhancing food safety in thermally processed starchy foods. A summary of the mechanisms and effects of these additives is provided in Table 3. While numerous additives have demonstrated the ability to reduce acrylamide formation, the extent of their effectiveness is highly variable and depends on several factors, including food matrix composition, processing parameters, and the specific chemical nature of the additive. For example, studies on the use of green tea polyphenols show reductions in acrylamide levels ranging from 20 to 60% depending on the concentration, application method, and baking conditions [23, 52]. However, other research has reported minimal impact under certain conditions, suggesting that polyphenol stability and interaction with food components may limit efficacy [17].

Additionally, while acidic additives like citric acid are effective in lowering pH and inhibiting Maillard intermediates, their impact is also dependent on buffering components in the dough. Excessive use may impair yeast activity or alter product texture [68]. Moreover, some studies suggest that citric acid's impact plateaus beyond certain concentration thresholds, providing no further acrylamide reduction [70].

The proposed mechanisms for additive action, including carbonyl scavenging, free radical neutralization, and pH modulation, are often supported by model system studies but lack robust validation in complex food systems. For instance, while polyphenols are known to bind reactive carbonyls, their degradation at high temperatures might negate their inhibitory effects [65].

Furthermore, the combination of multiple additives can yield unpredictable outcomes [4]. Some combinations may produce synergistic reductions in acrylamide, while others may result in antagonistic effects due to competing interactions within the Maillard reaction network.

Citric acid is one of the most widely studied acidic additives and has been reported to significantly reduce acrylamide levels during food processing [70]. Firstly, it interacts with carbonyl groups involved in Maillard reactions, which play a key role in the formation of acrylamide precursors [4]. Secondly, citric acid significantly lowers the pH of the food matrix, creating an environment less favorable for the progression of Maillard reactions [56]. This dual mechanism has been consistently demonstrated in various studies, reinforcing citric acid's potential as a practical solution for acrylamide suppression in different food systems [54]. However, while citric acid effectively reduces acrylamide by lowering pH, excessive acidification may negatively affect dough fermentation and the sensory qualities of baked goods [68].

Additives are typically applied to cereal-based products through direct incorporation into the dough, pre-treatment dipping, or surface coating [21–23]. However, their efficacy is less predictable, and higher doses may be required to achieve consistent results, which can potentially affect the product formulation [20]. Consequently, the selection of a mitigation strategy should be based on a cost-benefit analysis, considering the type of product, scale of production, and market demands [18].

Novel technologies for mitigation of acrylamide in cereals

Reducing acrylamide levels in these products is crucial for minimizing dietary exposure. Various mitigation strategies and regulatory guidelines have been developed, aiming to lower acrylamide levels to the minimum feasible across different food categories, thereby reducing the population's overall acrylamide intake [11].

There is an increasing demand for new technologies that have a less negative impact on the nutritional value of products, as food quality is better preserved with non-thermal methods [72]. In recent years, various emerging

and innovative techniques such as radiofrequency and microwave heating, pulsed electric fields, ultrasounds, high hydrostatic pressure, supercritical fluids, and cold plasma technologies have been employed to reduce acrylamide levels in different food products [73]. Table 4 presents studies investigating innovative technologies employed to reduce acrylamide in cereals.

Microwave application on cereals

Microwave energy, a type of electromagnetic radiation ranging from 300 MHz to 300 GHz, enables heating by allowing materials to absorb this energy throughout their volume, converting it directly into heat [74]. The microwave works by generating heat through the vibration and collision of polar molecules within the food. This method leads to faster heating and a more even heat distribution throughout the food. Microwave techniques are commonly employed in the food industry and home cooking for various purposes, such as drying, sterilization, baking, and heating.

Some studies suggest that microwave processing can promote Maillard reactions like conventional heating methods. This raises questions about whether the acrylamide formation mechanism is the same as traditional heating methods and which process (microwave or conventional) produces more acrylamide. However, there is still limited information on the effects of microwaves on acrylamide formation and the interactions between food ingredients. Some researchers have proposed that microwave heating may lead to higher acrylamide formation than conventional heating methods [75]. However, short exposure to microwaves at low power (such as during blanching and thawing) may help limit acrylamide formation during final heat treatment [76].

The literature also includes studies where microwave baking is widely used in food thermal processing to mitigate thermal processing hazards [77, 78]. In a survey conducted by L Dong et al. [78], the impact of microwave power and duration on the formation of thermal processing hazards and their precursors in microwave-baked biscuits was investigated. Compared to conventional baking (190 °C for 7 min), microwave baking at 440 W for 3 min effectively reduced the content of methylglyoxal, 3-deoxyglucosone, acrylamide, and 5-hydroxymethylfurfural by 60.75%, 30.19%, 30.87%, and 61.28%, respectively.

In a study designed by I Barutcu et al. [77], chicken samples were coated with soy, chickpea, and rice flours, while a batter made with corn and wheat flours served as the control group for acrylamide comparison. Acrylamide levels were assessed exclusively in the coatings of the chicken samples. The coated products were cooked using both conventional deep frying (180°C, 5 min) and microwave frying (180°C/350 W/2 min) methods to evaluate the effect of cooking technique on acrylamide formation. The results showed that microwave frying was more effective in reducing acrylamide levels, with the highest reduction (34.5%) observed in rice flour-containing batters, while the control sample showed a 13.8% decrease. This reduction was mainly attributed to the shorter frying time in microwave processing. Interestingly, although soy flour-based batters produced lighter-colored samples, their acrylamide levels were similar to those of other formulations, indicating that color parameters may not always reliably reflect acrylamide content.

Similarly, W Al-Ansi et al. [79]'s study examined the effects of incorporating fennel seeds (FS) and black cumin seeds (BS) into biscuit formulations baked by conventional and microwave methods. Microwave-baked biscuits demonstrated higher antioxidant activities and lower acrylamide levels compared to conventionally baked ones. The addition of BS reduced acrylamide content by up to 61% in conventional baking and 68% in microwave baking. Notably, FS addition led to acrylamide levels dropping to the minimum quantifiable limit in microwave-baked biscuits and reductions of 38%, 61%, and 78% in conventional baking at 2%, 4%, and 6% FS concentrations, respectively. These findings suggest that microwave baking, combined with FS or BS incorporation, can enhance antioxidant properties while significantly reducing acrylamide formation in biscuits.

Unlike findings from other studies, J Michalak et al. [75]'s research demonstrated that microwave heating results in the highest acrylamide formation among common household cooking methods. The study investigated ten commercially available, pre-cooked croquettes -primarily made of wheat flour and meat- reheated using roasting (10 min at 200°C), pan-frying (5 min at 180°C), deep-frying (5 min at 180°C), and microwave treatment (10 min at 200°C, 700 W), all performed according to the instructions on the packaging. Acrylamide concentrations, were significantly higher in microwave-treated samples (average 420 µg/kg) than those prepared by roasting (360 µg/kg), deep-frying (298 µg/kg), or pan-frying (285 µg/kg) ($p < 0.05$). The elevated acrylamide levels observed in J Michalak et al. [75]'s study, compared to other research [77–79], are likely attributable to the application of higher microwave durations and temperatures.

According to the findings from various studies, acrylamide formation levels during microwave cooking of cereal-based products can vary depending on the temperature, duration of application, and the specific characteristics of the products being treated. Promising results have shown that microwave cooking has the potential to reduce acrylamide levels when optimal conditions are achieved; however, further research is needed to clearly define these conditions.

Table 4 The effect of innovative technology applications on acrylamide formation in cereals

Cereal Product	Method	Key findings	References
Leavened cakes and short-dough biscuits	Radiofrequency heating	The most optimal results were achieved when the RF process was applied to products with relatively high residual moisture (approximately 10%).	[81]
Rice flour-coated fried chicken	Microwave frying (180°C/350 W/2 min) Conventional deep frying (180°C, 5 min)	In deep frying, 111 µg/kg of acrylamide was found, while microwave cooking resulted in 73 µg/kg.	[77]
Biscuit	The biscuits were subjected to vacuum treatment under different pressure, temperature, and time combinations.	Acrylamide removal from biscuits was successfully achieved (43%) under vacuum treatment at 6.67 Pa pressure and 60 °C for 5 to 15 min, with the process effective only in samples with a water activity value above 0.83.	[88]
Partially baked cookies	Radiofrequency heating (partially baking cookies for 8 and 9 min in a 27.12 MHz RF tunnel oven) Conventional baking (205°C for 11 min)	RF post-drying 8 min: 51.1 ng/g RF post-drying 9 min: 74.6 ng/g Conventional baking: 107.2 ng/g	[100]
Biscuit	Effect of combining conventional baking with vacuum post-baking	Vacuum baking generates less acrylamide than conventional baking preventing HMF formation and limiting browning.	[87]
Pre-cooked flour-based croquettes	Pre-cooked Pan-frying 180°C/5 min Deep frying 180°C/5 min Roasting 200°C/10 min Microwave 200°C(700 W)/10 min	190 µg/kg 285 µg/kg 298 µg/kg 360 µg/kg 420 µg/kg The highest levels of acrylamide were detected with microwave heating.	[75]
Corn grit	Vacuum-microwave: 5, 7.5 and 10 min Infrared Irradiation (IR) 76 and 90 °C 10 s 4800 W/m^2 densed	The acrylamide content was found to be lower in IR-treated grits compared to those treated with vacuum microwave. However, the acrylamide content in corn grits cooked using traditional methods was found to be the lowest among all.	[99]
Biscuit	Fennel and black cumin seeds were added to conventional microwave-baked biscuit formulations; the microwave baking was performed at 700 W for 90 s.	Microwave-baked biscuits had higher antioxidant activity, moisture, and breaking strength, with lower acrylamide content compared to conventional ones. BS reduced acrylamide, and FS further lowered it, especially in microwave-baked biscuits, where levels were undetectable	[79]
Cake	Ultrasound application before baking (at 70% and 100% intensity; 0, 4, 6, 8 min)	Ultrasound application at 100% intensity and processing for 6 min has been identified as the optimal condition to reduce acrylamide formation by up to 70% and produce higher-quality baked cakes.	[72]
Fried dough twist	Infrared-assisted deep-frying	Compared to deep-frying a dough twist made with sucrose, infrared-assisted deep-frying of a dough twist made with maltitol resulted in a 61.8% reduction in acrylamide.	[98]
Wheat Bread	Vacuum modification after partial-baking yeast-leavened wheat bread	Acrylamide levels in vacuum-modified bread were 59.8% lower compared to the control group.	[89]
Biscuits	Microwave baking, (2, 2.5 and 3 min) (440,480, and 520 W) Traditional baking (190°C, 7 min)	Compared to the traditional baking method, the microwave baking method at 440 W for 3 min showed a 30.19% reduction in acrylamide formation.	[78]

Radio frequency (RF) application on cereals

Radio frequency (RF) treatment is a type of dielectric heating technology that utilizes specific electromagnetic wave frequencies—13.56, 27.12, and 40.68 MHz—for both household and industrial use [80]. This technology works by generating heat volumetrically within dielectric materials like food [81]. Heat is produced through molecular friction caused by ion movement and polarized molecule rotation under an alternating electric field, resulting in more efficient heat transfer [82] and allowing volumetric drying—heat is generated where moisture is highest without raising surface temperature [83]. The longer wavelength of RF compared to microwaves allows for deeper penetration, more uniform internal heating, and the ability to cook larger samples effectively [80, 82].

RF heating has been effectively utilized in the food industry for various applications, including drying, baking, thawing, defrosting, disinfestation, pasteurization, sterilization, enzyme inactivation, enhancement of gelling properties, and modification of starch structure [81, 82]. Notably, RF heating is commonly used as a post-baking method to quickly reduce the residual moisture in bakery products without causing additional color changes, and it can minimize baking times by up to 30% [81]. This technology, applicable to both liquid and solid foods, offers advantages such as uniform heat distribution, contactless heating, faster drying, and energy efficiency. Additionally, the installation of large-scale systems is relatively easier. However, high initial investment costs and complex system design—due to factors like the dielectric properties of the food and electrode placement—limit the widespread adoption of the technology [82].

When combined with conventional heating processes, radio-frequency is another promising technique to reduce acrylamide formation in food [83]. The use of RF technology to reduce acrylamide formation in cereal products has been explored in only a limited number of studies in the literature [81, 84]. M Anese et al. [81] demonstrated the reduction of acrylamide formation in leavened cakes and short dough biscuits through RF post-baking. demonstrated the reduction of acrylamide formation in leavened cakes and short dough biscuits through RF post-baking. In this study, the application of RF heating after conventional baking significantly reduced acrylamide formation in leavened cakes, especially at lower moisture levels. Compared to conventional baking alone, combining it with 6% and 10% RF heating resulted in 20% and 50% lower acrylamide levels, respectively, in cakes with 4% moisture. This reduction is attributed to RF heating's ability to limit surface temperature increases, thereby preventing excessive Maillard reactions. M Anese et al. [81] Anese et al. (2008) reported that as product moisture falls, conventional ovens lose efficiency—dry foods conduct heat poorly—and longer baking times for the core cause surface overbrowning. To prevent this, items leaving tunnel ovens with higher moisture are moved to RF heaters to complete baking without additional color changes.

In the study conducted by T Kocadağlı et al. [84], the aim was to reduce acrylamide formation in cookies by lowering the baking temperature and making recipe modifications. By lowering the temperature, the baking time was extended, and to shorten the time, conventional baking was combined with a radio frequency post-drying process. Browning occurs during the later stages of baking at high temperatures, and since the Maillard reaction is responsible for both surface browning and acrylamide formation, applying a lower thermal load not only reduces acrylamide levels but also limits browning and flavor development. To compensate for the lack of surface browning during low-temperature baking, Maillard reaction products (MRP) were added to the dough. The MRP was obtained by heating a mixture of arginine and glucose at 100 °C for 6 h or overbaking thin dough disks. As a result, acrylamide formation was reduced by up to 50% with this method. Furthermore, the addition of MRP to the dough provided the desired browning in the cookies.

Although studies on the use of radio frequency heating in cereal processing are limited, the results obtained so far are promising, highlighting the need for further research in this area.

Vacuum treatment on cereals

In recent years, research on vacuum baking has accelerated due to its advantages over conventional methods, such as lower baking temperatures and shorter processing times [85]. For instance, D Grenier et al. [86]'s study have shown that vacuum facilitates the movement of dissolved gases within the dough toward gas cells, promoting better product expansion. The simultaneous application of heat and vacuum reduces the boiling point of water, helping to preserve color and flavor. Additionally, vacuum influences water distribution in the dough, affecting the availability of water for starch gelatinization [85].

More broadly, vacuum techniques have been successfully implemented across a variety of food processes—including evaporation, packaging, filtration, conveying, drying, cooking, cooling, frying, freeze-drying, and impregnation—delivering numerous benefits in both processing efficiency and product quality [85]. Beyond these conventional applications, vacuum treatments can be applied either during the thermal process to remove harmful compounds as they form or after they are present [83]. As another novel mitigation

method, researchers have explored using vacuum treatments to remove thermal process contaminants such as furfural, HMF, and acrylamide from products like biscuits, potato chips, and coffee [87]. Vacuum treatments can be applied either during the thermal process to remove harmful compounds as they form or after they are present. This method relies on the low molecular weight of the compound, such as acrylamide (71 Da), allowing its potential removal from food in vapor form during vacuum treatment [83].

Vacuum treatments have been effectively used to eliminate acrylamide from biscuits that were previously hydrated to a high water content [83]. According to the study carried out by M Anese et al. [88], acrylamide removal was successfully achieved only in samples with a water activity value above 0.83, and the highest removal was observed when the vacuum treatment was applied for 5 to 15 min at 6.67 Pa pressure and 60 °C temperature. With these conditions, 43% of acrylamide was removed from the biscuits.

Also, BA Mogol, V Gökmen [87]'s study revealed that acrylamide and HMF were undetectable in biscuits processed using a combined baking method, which involved short-time conventional pre-baking at 220 °C followed by vacuum post-baking at 180 °C and 500 mbar. In contrast, both compounds were present in conventionally baked samples. In vacuum baking, the partial removal of oven air significantly reduced convective heat transfer, while conduction and radiation remained active; this resulted in a lower overall thermal load, which was the main reason for the limited browning reactions observed in the biscuits. The combined approach enabled effective moisture reduction while minimizing contaminant formation, highlighting its potential as a safer and more efficient alternative for biscuit production.

According to the results of a study conducted by S Tuta Şimşek [89], vacuum modification applied after partial-baking significantly reduced acrylamide content in yeast-leavened wheat bread. The most effective condition was applying 60 s of vacuum at 70 kPa, which resulted in a 59.8% reduction in acrylamide compared to the control, without compromising bread texture or color. These conditions also promoted beneficial structural changes in the bread crumb. The quality of bread can be improved through enhanced vacuum management in combination with traditional ovens, which has a significant impact on the key characteristics of the bread. Vacuum-combined baking is an alternative method that promotes bubble inflation in bread, reduces required baking temperature and time, and enhances storage stability. Vacuum cooling and vacuum baking are techniques applied to partially baked bread. While vacuum cooling is usually performed on fully baked bread, it can also be used until the bread reaches an internal temperature of 35 °C [89].

However, further research is needed to fully understand the mechanisms of vacuum baking and to optimize its parameters, as it remains a promising approach for the reduction of thermal contaminants such as acrylamide in cereal products.

Ultrasound application on cereals

Research on cost-effective processing technologies to obtain high-quality food with minimal acrylamide content in products exposed to high temperatures is a promising field. Some of these strategies focus on reducing Maillard reaction precursors or increasing food moisture. Ultrasound is considered one of these potential strategies [90]. Ultrasound devices are widely available and recognized as sustainable and environmentally friendly technologies [91]. The cost-effectiveness of ultrasound processes stems from their low energy demands and minimal maintenance needs [92]. For instance, in a study conducted by N Ashar et al. [93], cooking broiler meat in a 70 °C ultrasonic bath reduced both cooking time and temperature; as a result, the process was found to be both economical and eco-friendly.

Ultrasound waves, a new technology with applications in analytical and culinary refinement, are one of the latest physical techniques for efficient aeration [72]. It is an innovative technological method widely used in the food industry for various purposes, including processing, analysis, and quality control [25]. Ultrasound treatment can disrupt cell walls and enhance mass transfer, thereby reducing asparagine availability and subsequently lowering acrylamide formation [18]. Recent research reveal that it has garnered more attention than other innovative methods due to its positive impact on food components' physicochemical and functional properties [94].

Depending on the application, ultrasonic technology operates at either low or high energy levels [25]. Low-frequency, high-intensity ultrasound treatment (UST) enhances the extraction of intracellular components from vegetable matrices. Applying this method to wash waters can expedite sugar leaching, reducing acrylamide formation during frying [95]. In a study conducted by R Esmaeilzadeh Kenari, A Nemati [72], the effect of sounding the cake batter with two types of baths and two different intensities (70% and 100%) of ultrasound probes for 0, 4, 6, and 8 min was examined. The application of ultrasound at 100% intensity for 6 min was the optimal condition for reducing acrylamide formation by up to 70% and producing higher-quality baked cakes. There is a need for further studies on the effect of ultrasound on acrylamide formation in cereals.

Infrared irradiation (IR) application on cereals

Infrared (IR) heaters generate heat by converting electrical energy into infrared radiation, which warms objects within a closed environment. In food processing, the heat is primarily transferred through the rapid vibration of water molecules at frequencies ranging from 60,000 to 150,000 MHz. This method does not require direct contact with the material being heated [96]. Infrared (IR) heating offers numerous advantages over traditional methods, such as shorter heating times, uniform heat distribution, minimized quality degradation, prevention of solute migration in food, and compact, versatile, and straightforward equipment, all while achieving notable energy savings. It is a versatile technology applicable to various food processing operations, including drying, baking, roasting, blanching, pasteurization, and sterilization [97].

Some studies based on cereal products have shown that infrared (IR) heating can reduce acrylamide formation compared to other heating methods. For example; Z Han et al. [98]'s study analyzed the impact of ingredients and infrared-assisted deep-frying on acrylamide, HMF, and oil content in fried dough twist. Using low-gluten flour and maltitol significantly reduced acrylamide and HMF levels while optimizing the infrared-assisted frying process decreased oil content. Compared to traditional deep-frying with sucrose, infrared-assisted frying with maltitol lowered acrylamide, HMF, and oil content by 61.8%, 63.4%, and 27.5%, respectively. Although infrared pretreatment has the potential to increase the formation of acrylamide and HMF, this processing method shortened frying time, which led to a further reduction in acrylamide and HMF levels. The results show that ingredient selection and infrared-assisted frying are key to improving fried dough twist quality.

In a different study by G Juodeikiene et al. [99] examining the effects of infrared irradiation (IR) and vacuum microwave (VM) methods on corn grits processing, it was found that both IR and VM treatments significantly reduced microbial contamination but the acrylamide levels increased by 75.5% and 91.6%, respectively, compared to the initial levels in untreated corn grits. In this study, vacuum–microwave (VM; 10 min at 60 °C) and infrared (IR; 10 s at 90 °C) stabilization of corn grits caused a rapid 26% drop in moisture, which intensified Maillard reactions both on the surface and throughout each particle. However, no comparison was made with conventional cooking methods. Protein-rich grit particles were used in breadmaking, and it was found that IR processing provided better physicochemical properties and higher acceptability compared to microwave treatment. The highest quality and acceptability were observed in bread made from protein-rich corn products processed with IR.

Although studies on reducing acrylamide formation in cereal products using infrared (IR) heating are quite limited, the available findings suggest that IR has the potential to reduce acrylamide levels more effectively than other heating methods. Further research is needed to determine the optimal application conditions.

The working principles of these innovative methods and their effects on acrylamide are illustrated in Fig. 4.

Sensory and nutritional impact of mitigation strategies

Acrylamide mitigation strategies must not only be effective in reducing toxic compound levels but also preserve the sensory attributes and nutritional integrity of the final food product. For enzymatic strategies, asparaginase is widely recognized for its minimal impact on the sensory characteristics of bakery products, such as bread, biscuits, and crackers [33–35]. Additive-based strategies can simultaneously affect sensory quality while mitigating acrylamide formation. For example, rosemary extract enhances natural aroma and color in baked goods, while also contributing to significant acrylamide reductions due to its high phenolic content [17, 53, 58]. Similarly, ginger powder has been shown to improve both flavor and texture, while achieving a measurable reduction in acrylamide levels [61]. Innovative technologies such as advanced thermal (e.g. microwave, infrared) and non-thermal (e.g. ultrasound) methods aim to reduce acrylamide in cereals while preserving the essential sensory properties (texture, flavour) of the final product [18]. In this section, the effects of acrylamide mitigation strategies on the sensory and nutritional properties of cereals are discussed.

Enzymatic treatments: Applying asparaginase for acrylamide reduction typically causes minimal changes in the sensory attributes of treated foods [101]. Since asparagine is selectively broken down by asparaginase and is not regarded as a primary factor in the flavour and colour development of baked goods, the use of asparaginase is considered to have minimal impact on sensory properties [102]. The findings indicated that incorporating asparaginase significantly decreased the asparagine levels in dough, while causing only minor changes in the volatile organic compounds profile and the colour of shortbread biscuits [102]. Asparaginase application had little impact on the color and texture of cookies, and sensory evaluations revealed no noticeable differences [101]. In wheat and rye cookies, the use of asparaginase offered an easy and efficient method to lower acrylamide content without compromising the sensory quality of the products [101]. The enzymatic application of L-asparaginase offers a straightforward and efficient

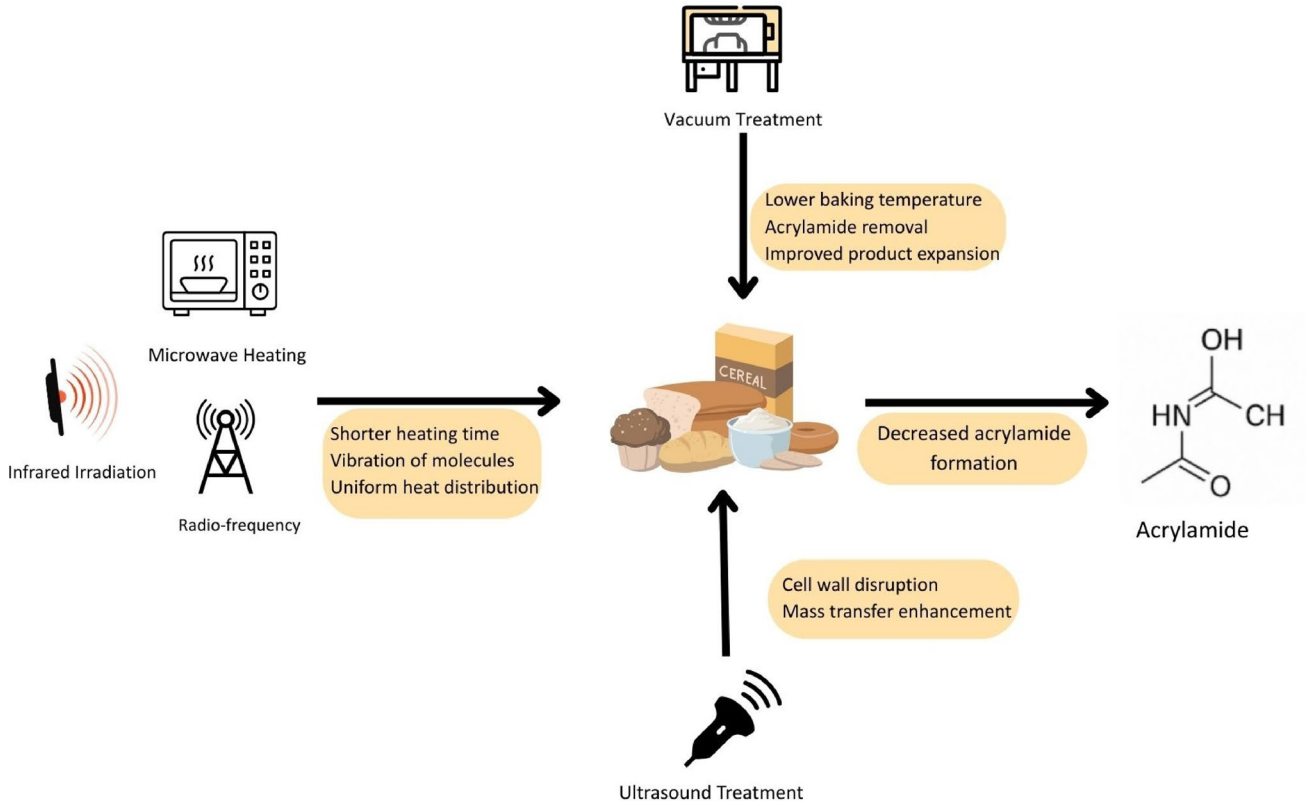


Fig. 4 Innovative approaches to mitigate acrylamide formation in cereals

approach to lowering acrylamide levels in foods, without altering the sensory characteristics or nutritional value of the final product [103]. Using asparaginase to reduce acrylamide formation appears to be a promising strategy for preserving sensory quality, though further investigation is needed to fully understand any potential negative impacts on the sensory attributes of cooked foods [104].

The incorporation of glucose oxidase into baking processes has been shown to enhance dough stability and facilitate easier handling [105]. This enzyme operates by oxidizing β-D-glucose into D-glucono-δ-lactone and hydrogen peroxide when molecular oxygen is present [44]. The degradation of D-gluconolactone leads to the formation of gluconic acid (C6H12O7), which lowers the pH of the solution and, along with hydrogen peroxide (H_2O_2), contributes to the inhibition of glucose oxidase (GOX) activity [42]. Moreover, the use of glucose oxidase in various food manufacturing processes, especially in bakery applications, improves dough structure and reduces the need for chemical oxidizers [105]. The removal of glucose by glucose oxidase also increases the shelf life and enhances microbial resistance of food products [106]. However the accumulation of hydrogen peroxide generated by glucose oxidase activity, if not properly controlled, can not only inhibit enzyme functionality but also lead to oxidative damage in sensitive food components, including the degradation of vitamins such as A, E, and folic acid, thereby reducing the nutritional value of food products [42, 107]. Although glucose oxidase is effective in reducing acrylamide levels, it is important to carefully adjust processing conditions to maintain the sensory and nutritional quality of foods.

Additives: Additive-based strategies not only reduce acrylamide formation but also have the potential to affect sensory quality either positively or negatively. For rosemary extract, the effective dose range has been identified as 0.25–0.5% (w/w) [53]. However, when used above 0.5%, biscuits exhibited bitterness, excessive darkening, and unpleasant odors [53]. Ginger powder, at 1% (w/w), made biscuits yellower and darker while reducing acrylamide by 6.2%, and remained within an acceptable range in sensory evaluation. In contrast, ginger powder used above 1% (w/w) resulted in sharp odor and bitterness, reducing consumer acceptability [61]. In buckwheat ginger cakes containing cinnamon or coriander, acrylamide levels were reported to increase by up to 29% [62]. Furthermore, the use of cinnamon in bakery products at optimal doses (0.5–4% w/w) has been associated with enhanced aroma, whereas its application at higher concentrations (above 4–6% w/w) has been linked to bitter taste and the development of a drier texture [108, 109]. The addition of soluble dietary fiber and green tea polyphenols

(EGCG) to cereal-based bakery products has been shown to reduce acrylamide levels in starch-based models by up to 38% [23, 52]. Additionally, this additive significantly reduced starch digestibility and lowered available glucose levels [23]. In the study by Fu et al., more than 40% of EGCG added to bread remained in the product after baking. Moreover, the structure and appearance of the bread were altered by the addition of EGCG [52].

These findings suggest that EGCG could be beneficial for developing healthier starch-based bakery products with low acrylamide content and low glycemic index, in line with new dietary trends [23]. However, previous studies have reported that EGCG addition to bread reduced brightness and sweetness, while increasing hardness, stickiness, and astringency [110, 111]. In the study by Torres et al., 3.3 g/kg EGCG added to dough was identified as the optimal level, achieving 30.2% acrylamide reduction with minimal sensory changes. Higher doses (6.6–9.9 g/kg) provided greater acrylamide reduction but resulted in undesirable color and texture changes [23]. These results demonstrate that plant-based additives must be used at appropriate doses to be effective, and process optimization is essential to ensure both acrylamide mitigation and sensory quality.

Novel technologies: Conventional hot-air baking achieves optimal browning and texture, but microwave-only baking cannot develop adequate surface color or crust [76]. Unlike convection ovens, microwave ovens do not heat the surrounding air, so they cannot brown most food surfaces. As a result, microwave-cooked products retain a moist exterior, which limits the development of desired flavors, colors, and acrylamide formation [77, 112]. In W Al-Ansi et al. [79]'s study microwaved biscuits exhibited a hard center, soft edges, and irregular, bulging surfaces—especially in the control group—indicating textural and appearance issues that warrant further research to optimize formulation and processing conditions. Similarly, L Dong et al. [78] found that sensory evaluations clearly favored traditionally baked biscuits over microwave-baked ones, primarily due to their superior taste and richer color.

On the other hand, in studies where vacuum technology was combined with conventional baking methods, improvements such as reduced formation of harmful thermal contaminants and the preservation—or even enhancement—of key sensory properties like taste, aroma, color, and texture were observed. These combined approaches thus offer a promising route to produce safer and higher-quality baked products without compromising overall product acceptability [87, 89]. Alternatively, Kocadağlı et al. (2012) preserved sensory attributes by combining conventional baking with a radio-frequency post-drying step and incorporating pre-formed Maillard reaction products—created by heating an arginine–glucose mixture or overbaking thin dough disks—directly into the dough, thereby restoring surface browning and desirable flavor in low-temperature–baked cookies while reducing acrylamide formation by up to 50%.

Ultrasound has been investigated as another promising method, with several studies focusing on its effects on cake properties [113, 114]. M Tan et al. [113] found that ultrasound reduced batter density, increased viscosity and size, and produced softer, fluffier cakes. Similarly, M Tan et al. [114] reported that ultrasound improved egg-free cakes with whey protein, increasing size by 18% and reducing density and hardness by 18% and 65%, respectively, with more stable air bubbles.

In the food industry, IR energy shows strong potential for processing high-value food products particularly due to its positive effects on the sensory qualities -such as flavor, texture, and appearance- of food components, further supporting its adoption in food processing [96]. Products cooked by infrared irradiation exhibited a more uniform, tender texture, a less oily mouthfeel, and a clean aroma. Their color appeared lighter and their flavor remained natural. While microbial load was markedly reduced, specific volume and consumer acceptance both increased. Additionally, the infrared-assisted method lowered fat content and produced a crisp structure; however, if temperature and exposure time are not properly controlled, acrylamide formation may increase slightly [98, 99].

Therefore, in order to minimize acrylamide formation while preserving desirable sensory and nutritional qualities, especially in baked cereal products, it is recommended to adopt a harmonized baking protocol that applies optimized low-temperature/time profiles, incorporates plant-derived antioxidants (such as fennel or black cumin seed extracts), and utilizes advanced processing techniques like infrared irradiation or vacuum-assisted baking.

Conclusions

This review has synthesized current strategies for acrylamide mitigation in cereal-based foods, including enzymatic, additive, and technological approaches. L-asparaginase and glucose oxidase remain the most efficient enzymatic tools, with consistent reductions across bakery matrices. Plant-based additives such as rosemary and green tea extract provide cost-effective and sensory-friendly alternatives. The combination of innovative technologies with conventional methods has shown great potential in both reducing acrylamide levels and preserving sensory qualities. However, each method carries limitations—ranging from regulatory challenges to high production costs and process sensitivity. For instance, enzymatic methods demand narrow temperature

and pH ranges, while high-tech methods may not be feasible for small-scale producers.

Although this review offers a comprehensive overview of acrylamide mitigation strategies in cereal-based products, several limitations exist. Heterogeneity in study designs, food matrices, and processing conditions complicates direct comparisons, and many studies rely on model systems that may not fully represent industrial practices. Research has largely focused on individual strategies, with limited evaluation of combined effects. The lack of standardized methods for measuring acrylamide reduction and sensory impacts further contributes to variability. Additionally, few long-term studies assess product stability and consumer acceptance, and detailed compositional analyses of natural additives are often missing. Finally, the review primarily covers English-language, indexed publications, possibly overlooking regional studies.

Future research should prioritize:

- • Combined strategies (e.g., enzyme + vacuum baking).
- • Long-term safety of mitigation byproducts.
- • Matrix-specific efficacy studies.
- • Industrial scalability.
- • Sensory evaluation and consumer acceptability studies.

Bridging these gaps will enable the development of scalable, safe, and consumer-friendly products that comply with regulatory standards and public health goals.

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Declarations

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