Indian Journal of
Nutrition

Open Science Publications

Volume 12, Issue 1 - 2025

www.opensciencepublications.com

Acrylamide in Food: from Formation to Regulation and Emerging Solutions for Safer Consumption

Review Article

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Article Information: Submission: 14/12/2024; Accepted: 06/01/2025; Published: 08/01/2025

Abstract

Acrylamide is a heat-induced chemical that was first identified in food in 2002. It is mostly created when reducing sugars and asparagine undergo the Maillard reaction, which occurs during high-temperature cooking techniques like roasting, baking, and frying. Its synthesis is also aided by other processes, including lipid breakdown. Crispy bread, coffee, baked foods, cereals, and potato items are common sources. Acrylamide has caused serious health concerns due to its neurotoxic, genotoxic, and carcinogenic qualities as well as the International Agency for Research on Cancer's designation of it as a potential human carcinogen. Epidemiological research indicates that eating acrylamide increases the risk of cancer, especially in high-exposure populations. Reduced acrylamide levels are the goal of regulatory initiatives by organizations like the FDA and EFSA, yet difficulties still exist because detection techniques are expensive. Using antioxidants like polyphenols, changing cooking methods, and applying enzyme treatments are examples of current mitigating tactics. This review emphasizes the need for creative solutions to improve food safety by highlighting the mechanics of acrylamide generation, health hazards, dietary sources, and detection and mitigation strategies.

Keywords: Acrylamide; Food Safety; Carcinogenic Risks; High-Temperature Cooking

Introduction

Following the discovery in food in 2002, acrylamide—a chemical molecule produced during high-temperature cooking methods like frying, roasting, and baking—has attracted a lot of attention. The main cause of its creation is the Maillard reaction, which occurs when reducing carbohydrates like glucose and fructose and the amino acid asparagine are heated beyond 120°C [1]. Acrylamide can also form through lipid degradation processes that involve intermediates like acrolein in addition to the Maillard reaction [2]. Bread, coffee, cereal items, and snacks made from potatoes are foods that are frequently linked to acrylamide [3]. Because of its neurotoxic, genotoxic, and carcinogenic qualities, the chemical has caused health concerns ever since it was discovered in foods in 2002. According to the International Agency for Research on Cancer, acrylamide is a likely human carcinogen (IARC, 1994). Epidemiological research has linked dietary acrylamide consumption to a higher risk of developing some types of cancer, especially in groups where exposure levels are high [4, 5].

Guidelines have been put in place by regulatory agencies including the U.S. Food and Drug Administration (FDA) and the European Food Safety Authority (EFSA) to monitor and reduce the amount of acrylamide in food products. For example, EFSA published Regulation 2017/2158, which outlines doable steps to lower acrylamide in foods such baked goods and products made from potatoes [6, 7]. Despite these initiatives, the high expense of analytical methods such as liquid chromatography-mass spectrometry makes it difficult to precisely measure the levels of acrylamide in various food matrices [8].

Using enzymes like asparaginase to reduce precursors in food and altering cooking techniques, including lowering frying temperatures and times, are the main focuses of mitigation measures. Furthermore, it has been discovered that antioxidants, such as dietary polyphenols, mitigate the toxicity caused by acrylamide, providing encouraging opportunities for risk mitigation. [8, 9]. Acrylamide in food is discussed in this review along with its production during high-temperature cooking, potential health hazards such as cancer and neurotoxicity, and detection and reduction techniques. Changing cooking techniques is one way to reduce acrylamide.

Formation of Acrylamide in Foods

When foods high in carbohydrates are cooked at high temperatures, acrylamide, a substance that is categorized as a possible carcinogen, is created. Let's see the various processes that led to its formation.

Pathway of the Maillard Reaction

One of the main processes for the production of acrylamide is the Maillard reaction, which occurs particularly in meals high in reducing sugars and amino acids, like coffee, cereals, and potatoes. Acrylamide is one of the several intermediate compounds that are produced by this intricate, non-enzymatic browning reaction, which takes place at high temperatures (over 120°C). Acrylamide is produced during this reaction when asparagine combines with reducing carbohydrates such as fructose and glucose. This is especially noticeable in dishes like roasted coffee beans or fried potatoes that contain a lot of carbohydrate. Although the process is essential for giving cooked foods their flavour and colour, it also produces toxic byproducts like acrylamide. According to studies, altering the cooking time and temperature might lessen the severity of the Maillard reaction and minimize the generation of acrylamide [11-12].

Decomposition of Asparagine

An amino acid called asparagine is essential for the synthesis of acrylamide. Acrylamide is a byproduct of asparagine's breakdown under heat, especially when it interacts with reducing sugars. In starchy foods like potatoes, where high asparagine levels lead to increased acrylamide formation, asparagine breakdown is essential to the Maillard process. Acrylamide generation can be considerably decreased by lowering asparagine concentrations in raw dietary ingredients prior to cooking, either by genetic selection or agricultural techniques. Pre-cooking techniques like blanching or soaking may also diminish asparagine levels and, consequently, acrylamide in the finished product, according to studies [3, 14].

Interactions between Amino Acid and Lipids

Lipid and amino acid interactions, especially during frying, provide another avenue for the production of acrylamide. Frying's high temperatures cause lipids to break down, producing volatile chemicals that can react with amino acids—especially asparagine—to produce acrylamide. Fried snacks and other foods high in fat are more likely to have this pathway. When lipids and oils used in deep-frying combine with amino acids found in starchy foods like potatoes and cereals, research shows that the resulting chemicals can aid in the creation of acrylamide [15, 16].

The impact of the Food Matrix

Acrylamide production is significantly influenced by the food matrix, which consists of the food's structure and substance. Food's pH, moisture content, and starch content all have a big impact on how much acrylamide formed. High-heat cooking techniques like frying and baking tend to increase the production of acrylamide in foods with a high starch-to-water ratio, like potatoes. Because water slows down the Maillard reaction and lessens the synthesis of acrylamide, the moisture content is crucial. Additionally, because the Maillard reaction proceeds more quickly in meals with a higher pH (alkaline foods), acrylamide generation may be enhanced [17, 18].

Different Cooking Conditions

Temperature, cooking duration, and moisture content are some of the variables that affect the development of acrylamide during cooking. Acrylamide is produced as a result of the Maillard reaction between sugars and amino acids, especially asparagine, which is facilitated by higher temperatures, particularly at 120°C. Acrylamide levels are considerably raised when meals like potatoes are fried at temperatures higher than 170°C [18]. Furthermore, cooking time is important since longer cooking times can raise the amounts of acrylamide, while overcooking can cause it to break down into different components [19]. Because they cook in a drier environment, foods with lower moisture content—like baked goods or fried potatoes—tend to produce more acrylamide. On the other hand, acrylamide levels are typically reduced when foods with a high moisture content are boiled or steamed. Acrylamide formation is also significantly influenced by the type of diet and its composition, especially its starch content, with foods high in starch being more likely to produce it. Therefore, controlling the cooking process can assist prevent the development of acrylamide while preserving the quality of the meal [20].

Sources of Acrylamide in the diet

Many foods, particularly those prepared at high temperatures using techniques like frying, roasting, and baking, contain acrylamide. The following are the primary foods that increase exposure to acrylamide.

Potato Products

Foods made from potatoes, especially those that are fried, roasted, or baked at high temperatures, are a major source of acrylamide in the diet. One of the main sources of acrylamide is fried potato products, such as French fries and potato chips. When potatoes are cooked at temperatures higher than 120°C, the Maillard reaction takes place, resulting in the formation. Temperature and cooking time both raise acrylamide levels. Crispy or browned potatoes typically contain the most acrylamide [22, 23].

Cereal Based Foods

Acrylamide is frequently found in bread, biscuits, breakfast cereals, and cereal-based crackers. High temperatures during baking trigger the Maillard reaction, which results in the formation of acrylamide in the meal. Products that are roasted or darker tend to have higher quantities of acrylamide. The amount of acrylamide in various foods can vary depending on the kind of cereal and the particular baking circumstances [22].

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Coffee

Roasted coffee beans are a significant source of acrylamide, with the levels varying based on the roasting process. During roasting, the beans are exposed to high temperatures above 200°C, which triggers the Maillard reaction, leading to the formation of acrylamide. Darker roasts, which undergo longer roasting times, typically contain higher levels of acrylamide compared to lighter roasts. This is due to the prolonged heat exposure, which intensifies the chemical reactions within the beans. As a result, regular consumption of coffee, especially dark roasts, can contribute to increased acrylamide intake, a concern for individuals mindful of its potential health risks [22, 23].

Baked Products

Baked goods such as cakes, cookies, pastries, and toasted bread are common sources of acrylamide in the diet. The Maillard reaction, which takes place at high temperatures typically above 120°C, is responsible for acrylamide formation during baking. Foods that are baked until golden brown or crispy tend to have higher levels of acrylamide. This is particularly evident in products that undergo longer baking times or are cooked at higher temperatures, as the heat promotes the reaction between sugars and amino acids like asparagine. Therefore, baked goods with a darker, crispier texture generally contain higher acrylamide levels, making them a significant dietary source of this compound [22].

Fried Foods

Fried foods, including deep-fried snacks and meats, represent another major source of acrylamide. The high temperatures involved in frying, often exceeding 170°C, accelerate the Maillard reaction, which results in acrylamide formation. Fried foods that are golden brown or have a crispy exterior are particularly high in acrylamide. This is because the longer foods are exposed to heat, and the more they brown or crisp up, the greater the formation of acrylamide. Therefore, it is advisable to fry foods at lower temperatures or for shorter durations to reduce acrylamide formation, although this may affect the texture and taste of the food [23].

Biscuits and Crackers

Another significant source of acrylamide in the diet is dry baked foods like biscuits, crackers, and etc. High temperatures are usually used to bake these foods in order to give such a crunchy texture, which promotes the Maillard process and forms acrylamide. The amount of acrylamide in the product increases with its colour. Additionally, the usage of refined flours and sugars raises the levels of acrylamide [22, 23].

Crispy Bread and Toasted Bread

Acrylamide can also be found in considerable quantities in crisp breads like rye and toasted bread. Bread is subjected to high temperatures during the toasting process, which triggers the Maillard reaction and promotes the production of acrylamide. Acrylamide levels are higher in darker-toasted bread than in lightly toasted bread [23].

Health Implications of Exposure to Acrylamide

According to national dietary patterns and food preparation methods, varying levels of acrylamide (AA) have been reported in foods across different countries. Potato-based products, coffee, and baked goods are identified as the primary sources. Direct exposure to AA typically occurs through the consumption of high-carbohydrate foods such as potato crisps, chips, roasted cereals, and bread. Additionally, indirect exposure to AA can result from food packaging containing polyacrylamide, which may leave residual monomers [25]. Acrylamide is commonly ingested through oral routes, such as dietary intake, drinking water, or smoking. Studies have shown that rats have demonstrated that its bioavailability through diet ranges between 30% and 40% [26]**.** Once absorbed, acrylamide undergoes metabolism through the cytochrome P450 oxidase system, specifically CYP2E1, resulting in the formation of glycidamide (GA). Alternatively, it can directly react with glutathione to produce N-acetyl-S-(2-carbamoylethyl) cysteine (AAMA) [27]. Exposure of this is associated with neurotoxicity, impaired fertility, and cancer risk and so on.

Carcinogenicity

In 2015, 17.5 million cancer cases and 8.7 million deaths were reported globally, with 208.3 million disability-adjusted life years (DALYs) lost. Cancer incidence rose by 33% between 2005 and 2015 [28]. Acrylamide is believed to cause cancer by converting to the genotoxic compound glycidamide through the enzyme cytochrome P4502E1[29, 30]. While animal studies have shown a dose-response relationship between acrylamide and cancer, particularly in hormone-sensitive organs [31], human studies have mostly found no clear link between dietary acrylamide and cancer, except for a potential increased risk of pancreatic cancer in workers exposed to acrylamide [30]. Some studies have suggested that there is a possible link between dietary acrylamide(AA) intake and a cancer risk such as Oesophageal Cancer had a higher risk among overweight or obese individuals with higher AA intake[32], risk Lymphatic malignancies especially in smoking men [33].

Neurotoxicity

Acrylamide (AA) is proven to cause neurotoxicity in humans through occupational exposure, leading to peripheral neuropathy symptoms such as numbness and tingling in the limbs. In laboratory animals, chronic AA exposure causes skeletal muscle weakness and ataxia. While the exact mechanism of AA neurotoxicity remains unclear, proposed mechanisms include[34, 35]**.** Impairment of nerve growth occurs when AA interacts with kinesin motor proteins in neuron, disrupting fast anterograde transport of nerve growth factor resulting in death. And it also inhibits neurotransmitter uptake into synaptic vesicles, potentially through interactions with sulfhydryl groups.[36]

Reproductive and Developmental Effects

Research on laboratory animals indicates that high doses of AA can cause reproductive toxicity, although no such effects have been documented in humans [25]. In rats, the No Observed Adverse Effect Level (NOAEL) for reproductive toxicity is estimated at 2–5 μg/kg/day, which is four times higher than the doses associated with neurotoxicity and 2000 times greater than typical dietary exposure [25], [37]. In rats, administering 0.5–10 mg/kg of AA resulted in growth retardation, reduced sperm reserves in the epididymis, and testicular lesions. In male rats, doses of 20 mg/kg led to dose-dependent reductions in testosterone and prolactin levels. Similarly, studies on female mice showed that oral exposure to AA decreased body and organ weights, reduced the number of corpora lutea, and lowered serum progesterone levels in a dose-dependent manner [38, 39].

Method of Detection and Quantification

Biomonitoring for Acrylamide Exposure

Acrylamide exposure can be assessed using human biomonitoring, analyzing either blood or urine samples. Acrylamide (AA) and its metabolite glycidamide (GA) form hemoglobin adducts by attaching to the N-terminal valine of hemoglobin. These adducts, such as acrylamide-hemoglobin (AA-Hb) and glycidamide-hemoglobin (GA-Hb), are reliable biomarkers of cumulative exposure, reflecting the lifespan of red blood cells (~120 days). Advanced techniques like gas chromatography-tandem mass spectrometry (GC-MS/MS) and liquid chromatography-tandem mass spectrometry (LC-MS/MS) are employed for their detection. Furthermore, glycidamide-derived DNA adducts, including N7-(2-carbamoyl-2-hydroxyethyl) guanine, are investigated as indicators of genotoxicity. The ratio of GA-Hb to AA-Hb provides insights into individual metabolic differences influenced by genetic variants in enzymes like CYP2E1 [40, 41].

In urine, acrylamide metabolites are excreted as mercapturic acid conjugates: N-acetyl-S-(2-carbamoylethyl)-L-cysteine (AAMA) for acrylamide and N-acetyl-S-(2-hydroxy-2-carbamoylethyl)-L-cysteine (GAMA) for glycidamide. These metabolites reflect short-term exposure within 48 hours. Urinary biomarkers are particularly valuable for population studies due to non-invasive collection. Techniques like high-performance liquid chromatography (HPLC) coupled with tandem mass spectrometry (MS/MS) are commonly used for their sensitivity and accuracy [42].

Dietary Exposure and Genetic Influence

Dietary acrylamide exposure is evaluated by integrating data on food concentrations and consumption patterns. While a probabilistic approach offers precise estimates, deterministic methods serve as effective initial screening tools. Genetic polymorphisms in enzymes like CYP2E1 and glutathione S-transferases influence acrylamide metabolism. Individuals with specific genotypes may exhibit elevated glycidamide formation, as indicated by higher GA-Hb levels, correlating with increased genotoxicity risk. Combining genetic data with biomarker analysis provides a comprehensive understanding of individual susceptibility to acrylamide's adverse effects [42, 43].

Analytical Methods for Acrylamide Detection

The quantification of acrylamide in food remains a priority, with advancements in analytical techniques offering improved precision and efficiency. Traditional methods like high-performance liquid chromatography (HPLC) and ultra-performance liquid chromatography (UPLC) are reliable, delivering fast and reproducible results but requiring optimized sample preparation. Gas chromatography (GC), particularly when coupled with mass spectrometry (GC-MS), is widely used for acrylamide analysis. To enhance precision, derivatization techniques such as bromination or silylation are applied [44, 45].

Novel methods, including capillary electrophoresis, immunoenzymatic tests, and biosensors, are gaining prominence. Biosensors, particularly electrochemical variants like amperometric and potentiometric sensors, detect acrylamide with high sensitivity in complex food matrices. Techniques like cyclic voltammetry and ion-selective electrodes enable trace-level detection. Immunochemical methods offer rapid, cost-effective alternatives for acrylamide quantification [45, 46].

Challenges and Limitations

A universal procedure for acrylamide analysis across all food types remains elusive due to the complexity of sample preparation and the high cost of reagents. Instrumental methods often require specialized equipment and labour-intensive protocols, limiting widespread application. These challenges drive the development of faster, simpler, and more cost-effective techniques [45].

Strategies to Mitigate Acrylamide Formation

Mitigating acrylamide formation in food is critical due to its classification as a probable human carcinogen. Strategies are broadly categorized into modifying ingredients, optimizing processing conditions, and exploring pre-process interventions to minimize its formation during cooking and food preparation [47].

Modifying Ingredients

Ingredient-based strategies involve reducing the precursors of acrylamide. The enzyme asparaginase is widely used to lower the concentration of asparagine, a key precursor in the Maillard reaction that produces acrylamide. The application of asparaginase has shown reductions of up to 80% in processed foods such as baked goods and potato-based products [48]. Selecting raw materials with naturally low levels of reducing sugars and asparagine is another effective approach. For example, specific potato varieties with lower sugar content are preferred for frying and baking to reduce acrylamide levels [49]. Other ingredient modifications include adding amino acids like glycine or cysteine, which compete with asparagine in the Maillard reaction, thereby reducing acrylamide formation. The addition of natural antioxidants, such as rosemary extract or green tea polyphenols, has also demonstrated potential in mitigating acrylamide levels by reducing oxidative stress during cooking [50].

Optimizing Processing Conditions

Processing conditions significantly impact acrylamide formation. Lowering cooking temperatures and reducing cooking times are among the simplest and most effective measures. Techniques such as vacuum frying and baking allow cooking at reduced temperatures, which can lower acrylamide levels by 50–90% while maintaining product quality. Vacuum baking, combined with conventional methods, has demonstrated reductions of up to 95%, while only vacuum baking has shown reductions as high as 98% without compromising sensory properties [49].

Surface treatments like blanching are also effective. Blanching potatoes in hot water or acidic solutions before frying removes

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significant amounts of acrylamide precursors. For example, blanching at 70–80°C for 5–15 minutes can reduce acrylamide by 50–70% [51]. Steam-blanching is another method that minimizes water usage while achieving similar reductions.

Combining innovative technologies like infrared heating or microwave-assisted frying with traditional cooking methods has also shown promise in reducing acrylamide levels while maintaining texture and flavor [52].

Exploring Pre-Process Interventions

Pre-process interventions such as soaking treatments effectively reduce acrylamide formation by depleting precursor compounds or altering reaction conditions. Soaking potatoes in cold water for 15–120 minutes has shown reductions of 42–89% in pan-fried products and up to 47% in deep-fried French fries. Hot water blanching, performed at 60–80°C for 5–15 minutes, has achieved even higher reductions of up to 97% depending on the temperature and duration [50].

Soaking in solutions of NaCl can reduce acrylamide formation by 40–61% due to its ability to lower pH and alter heat transfer properties. Citric acid soaking has been even more effective, achieving reductions of up to 97% by significantly lowering the pH, thereby inhibiting the Maillard reaction [53].

Other innovative approaches include treating foods with calcium salts, which have shown to inhibit acrylamide formation by forming stable complexes with asparagine. Spraying potato slices with solutions containing green tea extract or rosemary extract before frying has also been found to reduce acrylamide by up to 60%, due to the antioxidant properties of these natural compounds [54].

Additional Cooking Strategies

Steaming or Boiling: Cooking methods like steaming and boiling are acrylamide-free as they occur at lower temperatures below 120°C, where the Maillard reaction does not proceed significantly [55].

Air Frying: Air frying has been shown to produce lower acrylamide levels compared to deep frying, particularly when coupled with pre-treatment methods like soaking or blanching [56].

Short-Time High-Temperature (STHT) Cooking: This method applies high heat for a very short duration, reducing acrylamide while preserving sensory qualities of the food.

pH Adjustment: Incorporating mild acids like vinegar or lemon juice in marinades for potatoes or baked goods can effectively reduce acrylamide levels by inhibiting the Maillard reaction [53].

Sous Vide Cooking: Cooking food in vacuum-sealed bags at low temperatures (<100°C) prevents acrylamide formation by avoiding the high heat required for the Maillard reaction, preserving flavor and nutrients [57].

Microwave Pre-Cooking: Microwaving starchy foods like potatoes before frying or baking reduces acrylamide by depleting precursors such as reducing sugars and asparagine, lowering acrylamide levels by up to 40% [58].

Insights and Implications

Acrylamide forms in foods primarily through the Maillard reaction, where reducing sugars react with asparagine at temperatures above 120°C, especially in carbohydrate-rich foods like potatoes and cereals [1, 2]. High asparagine levels in starchy foods further enhance its production, but pre-cooking methods like blanching or soaking can reduce acrylamide formation by up to 97% [3, 4]. Lipid degradation during frying also contributes via reactions with amino acids in fat-rich foods [5]. Factors such as pH, moisture, and starch content in the food matrix significantly influence acrylamide levels, highlighting the importance of controlling cooking conditions and food composition to mitigate its formation [6, 7].

Dietary acrylamide exposure mainly comes from high-carbohydrate foods cooked at high temperatures, such as French fries, potato chips, cereal-based products, coffee, baked goods, and

Figure 1: The burden of disease due to dietary exposure to acrylamide.

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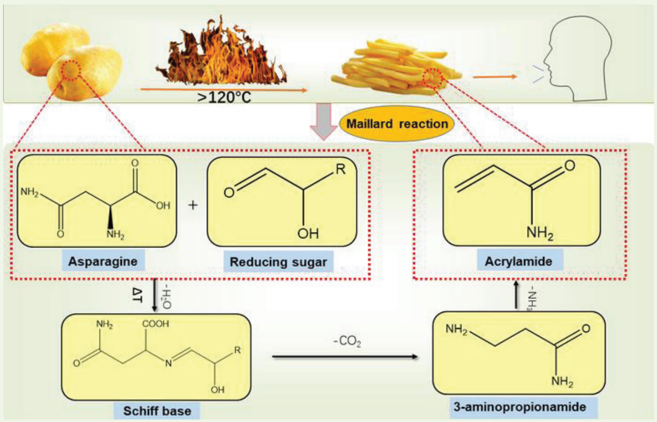

Figure 2: Mechanism of acrylamide formation in food.

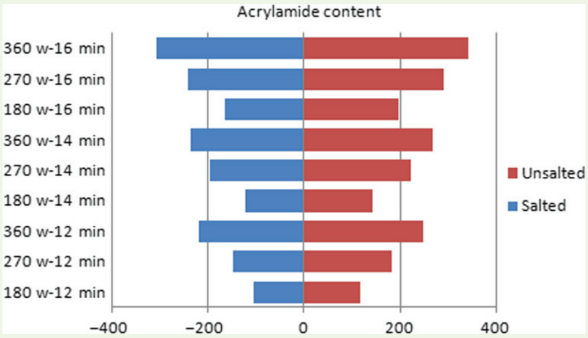

Figure 3: Effects of power and time in MW roasting on acrylamide formation amount in salted and unsalted pistachio types.

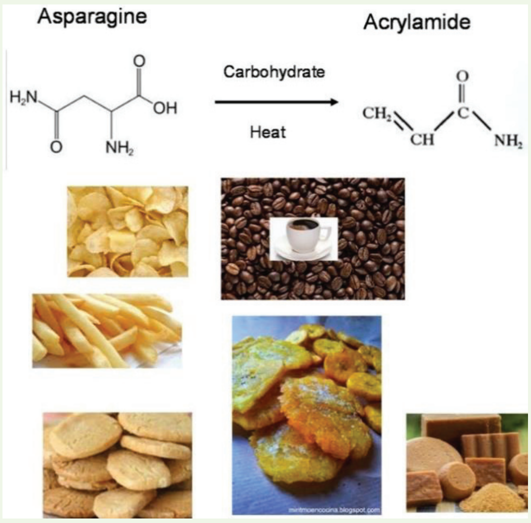

Figure 4: Various foods contributing to Acrylamide in the diet.

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toasted bread [8, 9]. Darker, more roasted products typically contain higher acrylamide levels [10].

Acrylamide, classified as a probable human carcinogen by the IARC (International Agency for Research on Cancer, 2024) [11], has been linked to cancer in animal studies, particularly in hormone-sensitive organs [12]. While human studies show mixed results, high dietary intake may elevate the risk of cancers such as esophageal cancer in obese individuals and lymphatic malignancies in smoking men [13, 14]. Neurotoxic effects, including peripheral neuropathy, have been observed, especially in occupational exposure, with mechanisms involving disruption of neuronal transport and neurotransmitter uptake [15]. Animal studies also show reproductive toxicity at high doses [16], but human studies have not confirmed similar effects at typical dietary levels [17].

Strategies to reduce acrylamide formation include using asparaginase to lower asparagine levels and selecting low-precursor ingredients [18]. Process modifications like vacuum baking and frying reduce acrylamide by minimizing thermal stress, with surface treatments such as blanching potatoes further lowering precursor levels [19, 20]. Pre-process interventions, like soaking in hot water or citric acid solutions, have shown significant reductions, with hot water blanching achieving up to 97% reduction [21]. These techniques offer scalable solutions for both domestic and industrial applications [22].

Conclusion

Acrylamide formation, driven primarily by the Maillard reaction between asparagine and reducing sugars during high-temperature cooking, poses notable health concerns due to its neurotoxic and probable carcinogenic properties (IARC, 2024) [11]. Major dietary sources include fried, roasted, and baked products such as potatoes, cereals, and coffee, with darker, more roasted items typically exhibiting higher acrylamide levels [8, 10]. While animal studies have demonstrated a strong link between acrylamide and cancer, human studies remain inconclusive, with some evidence of increased risks in specific groups, such as smokers and obese individuals [12, 13].

Reducing acrylamide levels in foods requires a combination of ingredient modifications and optimized processing techniques. Effective strategies include blanching, acid soaking, enzymatic treatments, and innovative methods like vacuum frying, which collectively can reduce acrylamide formation by up to 97% [3, 21]. Additionally, public health interventions such as regulatory guidelines, consumer education, and widespread adoption of these practices in industrial and domestic settings are essential to mitigate risks [22, 40].

In conclusion, addressing acrylamide exposure necessitates a multifaceted approach that balances food safety with quality. Advancing research, refining detection technologies, and promoting awareness are critical for achieving meaningful reductions in dietary acrylamide and protecting public health [18, 38].

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Citation: Abhigna S, Kulkarni MR, Khandalkar N, Patil AV. Acrylamide in Food: from Formation to Regulation and Emerging Solutions for Safer Consumption. Indian J Nutri. 2025;12(1): 306.