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Understanding acrylamides in foods: mechanistic insights, exposure risks and technological approaches for reduction

Comprendiendo la presencia de acrilamida en los alimentos: conocimientos sobre los mecanismos subyacentes, riesgos de exposición y enfoques tecnológicos para su reducción

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ABSTRACT

Acrylamide is a compound with a broad spectrum of toxic effects according to the International Agency for Research on Cancer (IARC), which has classified it as 2A or possibly carcinogenic to humans; acrylamide is formed in food products that pass thermal processes, such as roasting, baking and frying. These processes lead to the Maillard reaction (nonenzymatic browning), which is an important source of flavor and aroma, and sensory characteristics that are appreciated by the consumers; however, from this reaction the formation of newly formed contaminants also occurs as is the case of acrylamide. Strategies presented in this review are based on the reduction of acrylamide formation by controlling the Maillard reaction. This review gathers research on the strategies that allow the reduction of acrylamide formation, one of these being the use of asparaginase to convert asparagine into aspartic acid, the control of the process, the use of vacuum technology, the addition of mono and divalent cations, and the addition of low, medium and high molecular weight polysaccharides. It was found that the technique used depends on the starting raw material, so that the treatment cannot be generalized. The potato blanching in conjunction with the addition of asparaginase is one of the most promising techniques for reducing the content of acrylamide in this type of product.

Keywords: acrylamide; Maillard; asparaginase; polysaccharides; food contaminant.

RESUMEN

La acrilamida es un compuesto con un amplio espectro de efectos tóxicos, según la Agencia Internacional para la Investigación del Cáncer (IARC), que la ha clasificado como 2A, es decir, posiblemente cancerígena para los seres humanos. Se forma en los alimentos sometidos a procesos térmicos, como el asado, el horneado y la fritura. Estos procesos generan la reacción de Maillard (pardeamiento no enzimático), que aporta sabor, aroma y otras características sensoriales apreciadas por los consumidores. Sin embargo, esta reacción también genera contaminantes, como la acrilamida. Las estrategias presentadas en esta revisión se basan en la reducción de la formación de acrilamida mediante el control de la reacción de Maillard. Se recopilan estudios sobre diversas estrategias para reducir la formación de acrilamida, como el uso de la asparaginasa para convertir la asparagina en ácido aspártico, el control del proceso, la aplicación de tecnología de vacío, la adición de cationes mono y divalentes, y la adición de polisacáridos de bajo, medio y alto peso molecular. Se concluye que la técnica más adecuada depende de la materia prima, por lo que no existe una solución generalizable. El blanqueo de la patata combinado con la adición de asparaginasa es una de las técnicas más prometedoras para reducir el contenido de acrilamida en este tipo de producto.

Palabras clave: acrilamida; reacción de Maillard; asparaginasa; polisacáridos; contaminante alimentario.

1. Introduction

Neoformed contaminants are compounds that are generated during the food heating or preservation processes and that show possible harmful effects for humans. Acrylamide is one of the most researched neoformed contaminants that has attracted the attention of the scientific community since it was added to the list of toxic substances found in food in 2002, when the Swedish National Food Administration discovered a relevant quantity of acrylamide in various foods rich in carbohydrates, which is considered potentially

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carcinogenic to humans (Zyzak et al., 2003; Tardiff et al., 2010; Alpözen & Üren, 2013; Ehlers et al., 2013; FAO, 2009; Chang et al., 2016).

The real effect of neoformed acrylamide in food on human health is not clear, but according to the ALARA recommendation (As Low as Reasonably Achievable), research institutions, authorities, and industries have made efforts to modify processes in order to reduce the acrylamide levels in food products (Boyaci Gunduz, 2023).

The main problem is that acrylamide formation also follows the mechanisms of the Maillard reaction (Zeng et al., 2020) which is responsible for the generation of desirable components essential for the pleasant taste and aroma of the product. These are relevant factors for consumer acceptance. This review provides a broad overview of the current knowledge on acrylamide, its effects, its formation mechanism, and the technological strategies to reduce its levels in food products. Controlling factors that influence the process, such as cooking temperature, pH, cooking time, pressure, addition of enzymes (asparaginase), and additives (mono and divalent salts), among others, aid in reducing acrylamide levels by inhibiting the formation of precursors responsible for the Maillard reaction (Kahkeshani et al., 2015; Matthaus & Haase, 2015; Lund et al., 2017; Adascălului et al., 2021; Champrasert et al., 2021).

2. Effects of acrylamide consumption on food

Toxicokinetic studies in humans, rats, and mice have been employed to explain acrylamide metabolism. In animals and humans, acrylamide is rapidly absorbed and distributed throughout the body after ingestion (Gargas et al., 2009; Enríquez & Sosa, 2010). It settles in organs such as the thymus, liver, heart, brain, kidneys, as well as breast milk and placenta, facilitating transfer to newborns (Pyo et al., 2020; Zhao et al., 2022). Research conducted in rodents indicates that acrylamide is a multi-organ carcinogen, potentially causing tumors in the lungs, uterus, skin, mammary gland, and brain (Rice, 2005; Koricanac et al., 2021). Its carcinogenicity stems from its conversion to glycidamide in mammals, which is mutagenic and genotoxic in various "*in vitro*" and "*in vivo*" test systems (Doroshyenko et al., 2009; Akagi et al., 2023). Acrylamide can also cause alterations in cardiomyocytes contraction behavior and eventually cardiac problems in mice (Walters et al., 2014).

Acrylamide and its metabolite glycidamide conjugate with glutathione and are excreted as subproducts from the mercapturic acid found in urine, which represents the primary metabolic excretion pathway for acrylamide in humans (Riboldi et al., 2014; Eisenbrand, 2020). Several cancer risk assessments in humans have been conducted based on acrylamide exposure, most of which rely on linear extrapolation of carcinogenicity data from medium- and long-term bioassays in rodents (Hogervorst et al., 2009). However, these carcinogenic potency estimates vary depending on the mathematical models used for extrapolation. Acrylamide, as a genotoxic carcinogen, has no exposure limit, meaning exposure to even a single carcinogen molecule may trigger the biological process leading to its pathogenicity. Therefore, acrylamide is regarded as a significant chemical hazard to food safety under the "As Low as Reasonably Achievable" principle, even though direct evidence of carcinogenicity in humans remains inconclusive (Eisenbrand, 2020; Koricanac et al., 2021).

The European Food Safety Authority (EFSA), in conjunction with the Joint FAO/WHO Expert Committee on Food Additives (JECFA, 2011), defined the margin of exposure (MOE) as an estimate based on the difference between the dose that causes a low but defined cancer incidence (typically found in animal bioassays) and the estimated human exposure (Lineback et al., 2012). Both EFSA and JECFA concluded that an MOE of 10,000 or more indicates a low concern from a public health perspective. Therefore, it is considered a low priority for risk management actions. In the case of acrylamide, they calculated an MOE of 300 for average consumers and 75 for high consumers, based on an acrylamide exposure of 1 mg/kg of body mass daily (average consumers) and of 4 mg/kg of body mass daily (high consumers). Consequently, the daily acrylamide intake for the Western population is considered a potential health risk (Benford et al., 2010; Lineback et al., 2012; Nguyen et al., 2022).

Riboldi et al. (2014) reviewed 1743 articles between 2000 and 2013 in their analysis of studies on human acrylamide intake and its associated risks. They found that the information obtained through investigations on the effects of acrylamide in animals is neither reproducible in humans nor consistent (Hogervorst et al., 2009; Pelucchi et al., 2011; Riboldi et al., 2014). Thus, even though carcinogenesis and acrylamide genotoxicity have been demonstrated in animals, the only confirmed effect in humans has been damage to the nervous system (Enríquez & Sosa, 2010; Kopańska, et al., 2022).

3. Acrylamide levels in various foods

The highest acrylamide levels have been found in fried potatoes, bread, bakery goods, and coffee, which together account for nearly a third of total intake (Lineback et al., 2012). However, acrylamide has also been detected in a variety of other food products as shown in Table 1.

The differences in acrylamide concentrations among various foods as well as the variation in concentrations reported for the same food by different authors are due to differences in sample composition. Even samples from the same batch can contain varying amounts of this contaminant. One reason for this variability is the susceptibility of the Maillard reaction to small changes in the process, such as temperature fluctuations (Boon et al., 2005; Matthaus & Haase, 2015).

The data presented in Table 1 show that the highest acrylamide levels were found in products such as potato chips, followed by instant coffee and cereals. These are therefore considered high risk products in terms of acrylamide intake. In potato-based products, acrylamide content is correlated with the levels of glucose and fructose present in the raw material. Studies by Hasse et al. (2004) and De Wilde et al. (2006) reported a correlation (r = 0.75 and r = 0.82, respectively) between acrylamide content and the amount of reducing sugars. In cereals, acrylamide formation is determined by the asparagine content, which depends on the genotype and cereal species (Matthaus & Haase, 2016). Although there is a notable incidence of acrylamide in these types of products, Powers et al. (2017) demonstrated that the average acrylamide content in potato chips in Europe decreased from 763 ng g^{-1} to 412 ng g^{-1} (46%) between 2002 and 2016, indicating an improvement in cooking processes aimed at avoiding the formation of this contaminant.

Table 1
Acrylamide content in different product groups

Food products		Acrylamide content µg/kg of food mass	Reference
Potatoes and potato products	Boiled mashed potatoes	16	Keramat et al. (2011)
	Baked potato	169	Keramat et al. (2011)
	Potato chips	752	Keramat et al. (2011)
		982	Bušová et al. (2020).
		537	Plaza (2015)
		412	Powers et al. (2017).
	Fried potato	334	Keramat et al. (2011)
		329	Mesías et al. (2020)
		203	Breitling-Utzmann & Hankele (2019)
	Baked sweet potato	324	Nguyen et al. (2022)
	Baked carrot	99	Nguyen et al. (2022)
Coffee	Pour-Over coffee	522	Matthaus & Haase (2016)
		13	Keramat et al. (2011)
	Instant coffee	288	Keramat et al. (2011)
	Decaffeinated coffee	668	Keramat et al. (2011)
Cereals, bread, and other bakery goods	Dulce de leche	24-112	Garzón (2014)
	Cereals and pastries, raw and boiled	15	Keramat et al. (2011)
	Cereals and processed pastries	123	Keramat et al. (2011)
	Breakfast cereals	298	Plaza (2015)
		161	Matthaus & Haase (2016)
		89	Bušová et al. (2020)
	Bread	446	Keramat et al. (2011)
		50	Plaza (2015)
	Cookies	77	Lambert et al. (2018)
		265	Matthaus & Haase (2016)
		343	Mesías et al. (2019)
	Pizza	33	Keramat et al. (2011)
	Popcorn	761	Bušová et al. (2020).
Others	Infant formula	18	Lambert et al. (2018)
	Fish	14	Lambert et al. (2018)
	Fruit Puree	7.3	Lambert et al. (2018)
	Fish based products	35	Plaza (2015)
	Chocolate powder	75	Plaza (2015)

3. Acrylamide formation mechanisms and its precursors

One way to extend food shelf life and impact their quality is to subject them to thermal processes. The increase in temperature during baking, toasting, frying, and sterilizing causes changes in food sensory properties such as palatability, taste, aroma, and texture. However, it can also lead to undesirable effects, such as acrylamide production, which is classified among the so-called "foodborne contaminants." The formation of this unwanted compound in food results from the Maillard reaction, a non-enzymatic browning, and depends on the presence of precursors such as reducing sugars, proteins, and food processing conditions like pH, temperature, and time (Echeverri et al., 2014; Matthaus & Haase, 2016; Stadler & Theurillat, 2017; Zeng et al., 2020). Studies by Becalski & Lewis (2003) and Mottram et al. (2002) show that the main route for acrylamide formation in food is the Maillard reaction with free asparagine as a precursor at temperatures between 175 ºC and 185 ºC in the presence of α-dicarbonyl compounds such as glucose or any reducing sugar (Keramat et al., 2011). The acrylamide formation reaction mechanism from asparagine and a reducing sugar is shown in Figure 1. Asparagine may decompose thermically by deamination-decarboxylation. However, when a source of carbonyl is present, the reaction favors acrylamide formation. This explains the high acrylamide concentration detected in foods rich in reducing sugars and free asparagine (Becalski & Lewis, 2003; Matthaus & Haase 2016; Quan et al., 2020). Glycoconjugate compounds such as N-glycosides and related compounds formed through the asparagine reaction with a reducing sugar, followed by dehydration (Schiff bases in their open-chain tautomeric form), act as intermediates in the formation of acrylamide. The formation of N-glycosides from glutamine and methionine produces lower acrylamide levels. The asparagine reaction with glucose or with 2,3-butanedione (one of several dicarbonyl compounds generated in the Maillard reaction) leads to the formation of substantial amounts of acrylamide in dry products, but only trace amounts are produced when asparagine is replaced with other amino acids (Mustafa, 2008; Plaza, 2015). Once the Schiff base is formed, which is susceptible to decarboxylation and the elimination of a substituted amine, it results in the formation of 3-aminopropionamide (3-APA, an intermediate in the Maillard reaction). In turn, this compound may form acrylamide through the elimination of ammonia (Musfata, 2008; Edna Hee et al., 2024). Therefore, the decarboxylated Schiff base and the decarboxylated Amadori compounds of asparagine are the direct precursors in the formation of acrylamide via the Maillard reaction (Keramat et al., 2011).

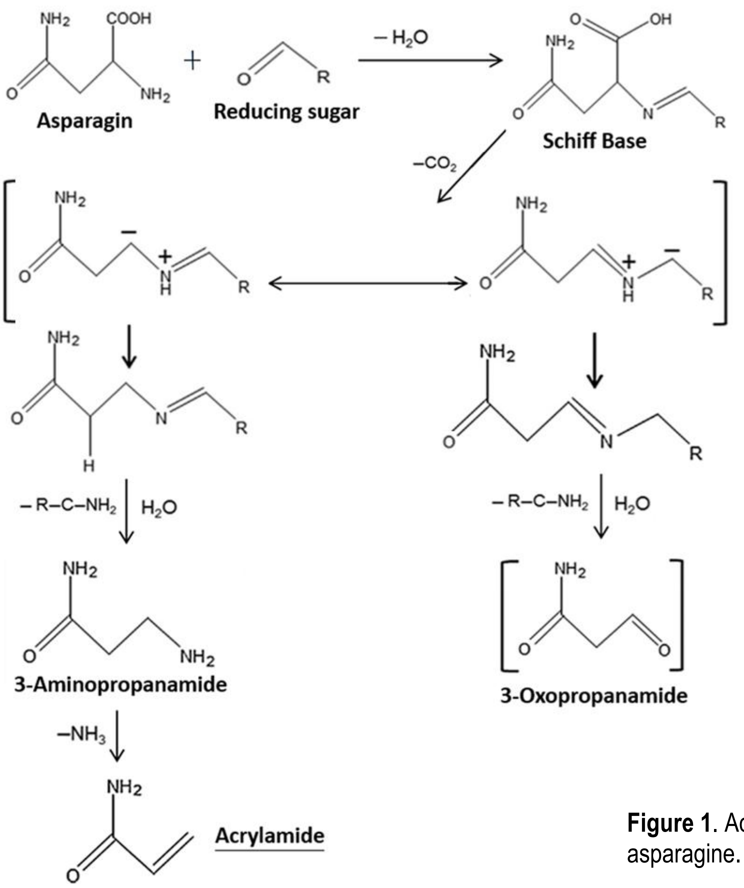

Figure 1. Acrylamide formation mechanism from asparagine. Adapted from Matthaus & Haase (2016).

In order to generate acrylamide through this pathway, the intermediate 3-oxopropanamide must be reduced to 3-hydroxypropionamide (the Strecker alcohol of asparagine), followed by a β elimination of water. Stadler & Scholz (2004) demonstrated that N-glicosil from asparagine generates approximately 2.4 mmol/mol of acrylamide, compared to 0.1 - 0.2 mmol/mol obtained with α-dicarbonyls and the Amadori compound of asparagine. This indicates that α-hydroxycarbonyls are much more efficient than α-dicarbonyls in converting asparagine into acrylamide, and that Strecker degradation appears to play a limited role in acrylamide formation (Stadler & Scholz 2004; Quan et al., 2020).

There are minor reaction pathways for acrylamide formation, such as the one proposed by Ehling et al. (2005), which is based on the degradation of lipids during heating. This process produces three-carbon units, such as acrolein and acrylic acid, which act as acrylamide precursors (Keramat et al., 2011; Echeverri, et al., 2014; Perera et al., 2021; Edna Hee et al., 2024).

5. Techniques for reducing acrylamide concentration in foods

5.1 Modification of process conditions

Baking, frying, and toasting operations are typically carried out at temperatures above 170 °C. High temperatures induce chemical reactions in foods and the formation of contaminants such as acrylamide (Echeverri et al., 2014; Mogol, 2015; Adascălului et al., 2021). The effect of time and temperature in the potato frying process was studied by Haase et al., (2004), who tested frying temperatures ranging from 150 °C to 190 °C and durations between 5 and 10 minutes.

Researchers found that acrylamide content increases with both frying time and temperature. Acrylamide levels remained relatively low at temperatures between 150 °C and 175 °C, but they rose sharply at temperatures ≥ 180 °C. Additionally, frying time showed a positive linear correlation with the amount of acrylamide formed in the potatoes.

González-Cuello et al. (2018) obtained similar results when analyzing the frying of cassava chips at different temperatures. For this reason, it is recommended to carry out the frying process for short durations and at temperatures below 180 °C in order to reduce the potential acrylamide content in the final product (Breitling-Utzmann & Hankele, (2019). One way to lower the operation temperature is vacuum technology food processing, preferably at (6.65 kPa). This technology works by reducing the boiling point of water through increased vacuum pressure, which allows food to be dried at lower temperatures (Zhang et al., 2011; Mogol, 2015).

Adascălului et al. (2021) studied homemade versus industrial potato frying. The results showed that homemade frying produced significantly less acrylamide (541.65 µg/kg) compared to industrial frying (684.37 µg/kg), which can be attributed to the lower temperatures typically used in homemade frying. In cookies baked under vacuum (500 mbar) at 200 ºC, the average acrylamide content ranged from 11 ng/g to 51 ng/g, whereas in conventionally baked cookies it ranged from 39 ng/g to 211 ng/g. However, in this study, vacuum-baked cookies lacked the characteristic brown surface, which is a limiting factor in terms of consumer product appeal (Mogol, 2015). Acrylamide formation has also been studied in bread baking, showing similar results: the hotter and longer the baking process, the higher the acrylamide concentration in the dough (Samadi Ghorbani et al., 2019).

In studies comparing conventional oil and air frying, results showed a significantly lower formation of acrylamide in chicken and fish when fried using hot air: from 79.40 ± 9.52 µg/kg to 60.00 ± 9.12 µg/kg in chicken, and from 64.40 ± 4.93 µg/kg to 60.75 ± 6.75 µg/kg in fish (Alkaç et al., 2024). However, the study by Navruz-Varlı & Mortas (2024) found no significant difference in acrylamide content when comparing immersion frying, hot air frying, or potato baking, unless a previous blanching process was applied.

5.2 Food acidity

pH is another relevant parameter that has been studied due to its influence on acidity levels and its correspondence with the increase or decrease of acrylamide amounts in foods. It has been demonstrated that lowering the pH leads to a reduction in acrylamide levels during frying and baking processes. In a model system, acrylamide content peaks when the pH is around 8, which is close to the pKa of asparagine. This leads to an improvement in the initial steps of acrylamide formation, possibly due to the inhibition of acrylamide formation as a result of the conversion of a protonated amine into a non-nucleophilic protonated amine (Matthaus & Haase, 2015). Several researchers have managed to reduce acrylamide formation by lowering pH using compounds such as citric acid (Gama-Baumgartner et al., 2004), even though the product quality varied due to the presence of a bitter taste in the final product (Echeverri et al., 2014; Xu et al., 2016). In a study by Negoiță et al., 2022, medium pH was reduced using citric acid, obtaining a reduction ranging from 77% to 97% when the pH reached 2.99 (0,05% citric acid) and 2.35 (1% citric acid), respectively.

5.3 Use of asparaginase

The main precursor in acrylamide formation is asparagine; therefore, reducing its concentration in food products may lower formed acrylamide levels. Asparaginase is an enzyme capable of converting asparagine into ammonia and aspartic acid (Lund et al., 2017). This enzyme can be obtained from a variety of microorganisms, including *Escherichia coli*, *Erwinia carovora*, *Bacillus* sp, *Enterobacter aerogenes*, *Corynebacterium glutamium*, *Pseudomonas stutzeri* and *Candida utilis* (Xu et al., 2016), as well as legumes such as soy (Liu et al., 2019).

Commercially, this enzyme derives from *Aspergillus niger* or *Aspergillus oryzae*, molds that have been used in commercial products and deemed safe by JECFA (2007) (Xu et al., 2016). Di Francesco et al. (2019) studied the use of the yeast *Aerobasidum pullulans* in potato chips to reduce asparagine, precursor of acrylamide, achieving a reduction of 16% in asparagine and 83% in acrylamide in fried potatoes. In the case of the usage of the L-asparaginase gene from Acinetobacter soli, expressed in *Escherichia coli*, it showed high activity in asparaginase elimination, resulting in a 55.9% reduction in acrylamide formation in potato chips (Jiao et al., 2020). Asparaginase obtained from soy demonstrated notable antitumor activity as well as effectiveness in preventing acrylamide formation in fried products (Liu et al., 2019).

Pedreschi et al. (2011), on the acrylamide level reduction in fried potatoes, applied the following treatments: (I) blanching with hot distilled water at 85 ºC for 3.5 min; (II) immersion in an asparaginase dissolution (10000 ASNU/L; amount of asparaginase produced by a micromole of ammonia per minute under standard conditions at pH 7 and 37 ºC) at 50 ºC for 20 min, and (III) blanching with hot distilled water at 85 ºC for 3.5 min, combined with immersion in an asparaginase dissolution (10000 ASNU/L) at 50 ºC for 20 min as control. The experimental results showed that both the blanching treatment and the asparaginase immersion had a similar effect to the acrylamide reduction, obtaining in both cases a 17% acrylamide initial concentration reduction. However, combining both methods reduced acrylamide levels by nearly 90%. Researchers attributed this to structural changes in the potato tissue during blanching, which facilitates asparaginase diffusion and effectiveness (Pedreschi et al., 2011).

Other studies have reported 69% reductions of acrylamide initial content in cookies using *A. orzyae* asparaginase at 900 U/kg and 200 ºC until reaching 2% moisture (Anese et al., 2011); 80% in fried potatoes treated with *Bacillus licheniformis* asparaginase at 30 IU/mL and 175 ºC for 15 minutes (Mahajan et al., 2012); 90% in tortilla chips using *A. orzyae* asparaginase at 190 ºC for 60 seconds (Hendriksen, et al., 2013); and 94.2% in bread, using *Rhizomucor miehei* asparaginase at 05-10 U and 250 ºC for 15 minutes. Similar results were obtained in bread baking following a pretreatment with asparaginase (Samadi Ghorbani et al., 2019). According to recent investigations, the use of asparaginase is a highly effective technique for reducing final acrylamide levels in food products (Edna Hee et al., 2024).

5.4 Use of antioxidants from natural sources

The addition of antioxidants found in rosemary, bamboo leaves, turmeric, and green tea extracts influences the Maillard reaction and may reduce acrylamide presence in heated foods, as demonstrated by previous studies (Pelucchi et al., 2011; Kahkeshani; 2015). Kamkar et al. (2015) investigated the efficiency of vitamins B3 and B6 as well as autolyzed yeast in reducing acrylamide formation in fried potatoes. The results indicated a reduction of 58%, 50%, and 33% in acrylamide formation, respectively, without impacting the original flavor and the crispy texture of the fried potatoes (Kamkar et al., 2015; Constantinou et al., 2016). Abdel-Daim et al. (2020) studied the effect of thymoquinone, a compound present in the Nigella sativa plant to prevent hepatic damage in mice due to acrylamide through the monitoring of various biomarkers. The results showed that the thymoquinone has a significant effect in preventing adverse effects of acrylamide on the liver.

According to Kahkeshani et al. (2015), antioxidant activity is not the main factor responsible for the reduction of acrylamide content. Antioxidant compounds can interfere at different stages of the Maillard depending on their molecular structure and functional groups. This interference may increase or decrease acrylamide production, regardless of the antioxidant activity (Edna Hee et al., 2024).

5.5 Use of monovalent and divalent cations (Na+ y Ca2+ o Mg2+)

Polyvalent cations can also reduce acrylamide formation during heating. These ions may interact with asparagine to prevent the intermediate formation of a Schiff base, and thus acrylamide generation. Studies have shown a reduction in acrylamide content in foods due to the use of NaCl. Negoiță et al. (2022) studied the application of diverse pretreatments to reduce acrylamide formation. In the case of NaCl, they achieved a significant reduction of up to 57% in the formation of this compound in comparison to the control.

The addition of divalent cations has also proven to be an effective method for reducing acrylamide formation (Kahkeshani et al., 2015). During the traditional cooking of corn grains in a calcium hydroxide dissolution before milling, nixtamalization is commonly used in tortilla preparation. The influence of lime concentration ($Ca(OH)_2$) used during the nixtamalization process in the physicochemical properties of nixtamalized corn flour has been analyzed, as well as its effects on acrylamide content in tortilla chips made from it. Tortilla chips made from nixtamalized corn had a lime concentration of 1.5 and 2.0 g / 100 g, leading to reductions of acrylamide content of 52% and 36%, respectively. Therefore, the authors suggest that the $Ca(OH)_2$ concentration control during nixtamalization can serve as an effective strategy when reducing acrylamide formation in fried products made from nixtamalized corn flour (Rannou et al., 2016), similar results obtained by Topete-Betancourt et al. (2019).

5.6 Use of polysaccharides

Sung et al. (2018) analyzed the acrylamide concentration in combined and heated mixtures containing 1% glucose, 1% asparagine, and 1% chitosan. Their study showed a high acrylamide concentration (9180 ng/mL) in the dissolution containing glucose (G) and asparagine (A). When chitosan (C) of low, medium, and high molecular weight was added to the mixture, no acrylamide formation was detected. This suggests that chitosan may promote the formation of Maillard reaction products without leading to acrylamide formation. The fructose mixture heated with chitosan of low, medium, and high molecular weight resulted in acrylamide concentrations of 37.8 ng/mL, 36.9 ng/mL, and 31.5 ng/mL, respectively. This implies that fructose (ketose) at 1% can react with chitosan to form acrylamide. However, glucose (aldose) would not react with chitosan under the same heating conditions (Chang et al., 2016).

In the model system developed by Chang et al. (2016), the addition of low molecular weight chitosan resulted in a 46.8% reduction in acrylamide formation due to a possible competition between the amino groups of chitosan and those of asparagine. Champrasert et al. (2021) demonstrated that, to achieve acrylamide reduction using chitosan, concentrations above 0.3% m/v were necessary as only a 9.46% reduction was observed at that level. In contrast, greater reductions were achieved with sodium alginate (64.9%) and pectin (55.9%) at the same concentration. The authors suggest that using lower molecular weight chitosan may enhance the reduction, as shown by Chang et al. (2016). This was supported by similar results obtained by Champrasert et al. (2022) and Mousa (2019), who observed significant acrylamide reductions in cookies when using pectin, acacia gum, and carboxymethyl cellulose as additives at different concentrations, while maintaining good sensory characteristics in the product.

Since neoformed acrylamide in foods poses a potential health risk to consumers, a regulation came into force in the European Union in April 2018. This regulation established mitigation measures and reference levels aimed at reducing the presence of acrylamide in foods. Its objective is to ensure a high level of consumer protection in relation to food safety (Unión Europea [EU], 2017).

6. Current and future challenges

One of the main challenges faced by the food industry is preventing the formation of undesirable compounds such as acrylamide during food processing. The reaction between asparagine and reducing sugars may lead to acrylamide formation, a compound that can negatively affect human health, particularly in processes involving high temperatures and prolonged heating. Therefore, developing alternative processing methods that inhibit the formation of such compounds without compromising functional, sensory, or nutritional properties of food products remains a significant challenge.

In the coming years, the food industry will face the significant challenge of developing processing methods that prevent the formation of such compounds whether through modifications to production processes, the addition of new ingredients, or pretreatments that inhibit the acrylamide formation reaction. For this reason, research in food biochemistry becomes essential to identify new, innovative, and efficient processes that not only aim to prevent the formation of undesirable compounds but also promote better resource use and a more sustainable food industry.

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