Application of Cations, Acids, and Antioxidants on Mitigating Acrylamide Formation in Food with a Special Focus on Potato and Cereal Based Foods - A Review

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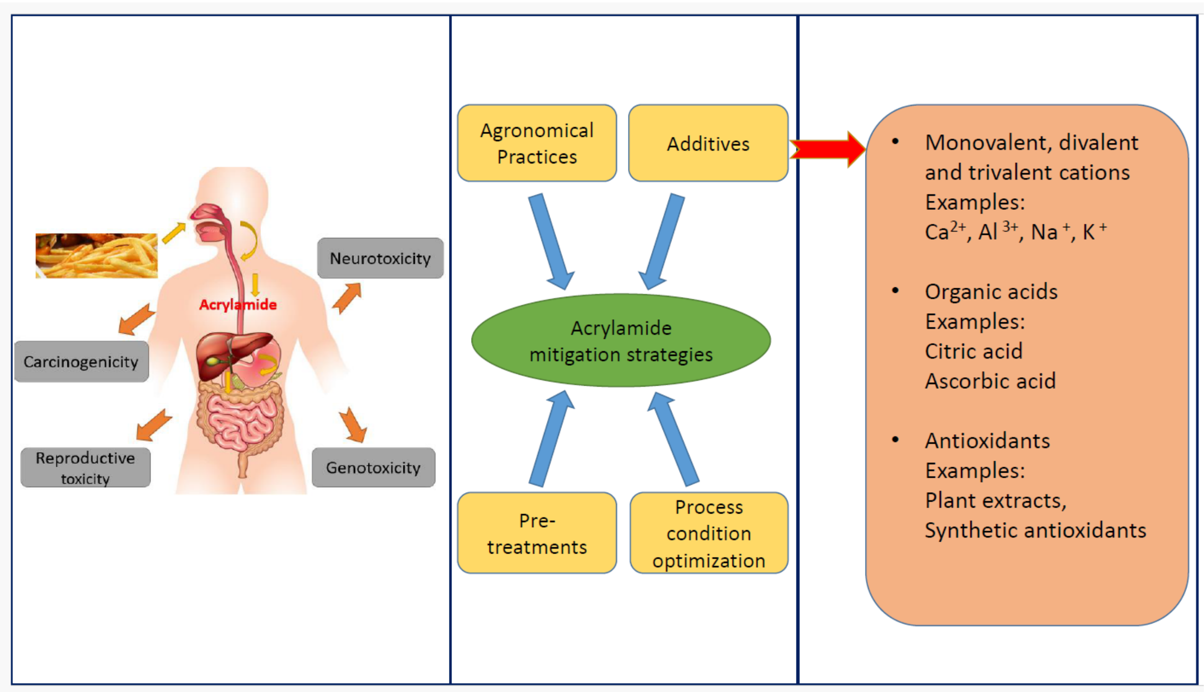

Abstract

Acrylamide is a toxic substance that forms in food during high-temperature processing methods such as deep-frying, baking, and roasting, through the Maillard reaction or the acrolein pathway. Since acrylamide has been identified for its carcinogenicity, genotoxicity, and neurotoxicity, global food authorities have established benchmark levels for different food categories. Consequently, researchers have proposed various mitigation strategies, focusing on agronomical, chemical, physical, and microbial approaches. However, most of these approaches are associated with high cost, technology, extended time, and poor sensory and nutritional quality. In this context, application of various additives such as metal cations, organic and inorganic acids, and antioxidants in optimum amounts have been effective in reducing acrylamide formation. Additives contribute to reducing acrylamide either by interacting with its precursors and/or intermediate products or by breaking down acrylamide into other non-toxic substances. Since cations can form thermostable asparagine/matrix intermediates through chelation reaction between asparagine and metal cations, asparagine will be unavailable to react with carbonyl compounds to form the Schiff base. Lower pH conditions inhibit the acrylamide formation by blocking the protonation of the α-amino group of asparagine and reducing any possibility for

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nucleophilic addition reactions with carbonyl groups. Toxicity associated with Maillard products can be reduced by using antioxidants in the frying oil or the food. Polyphenols are capable of reducing the acrylamide formation by directly trapping acrylamide at elevated temperature. It is essential to identify the most appropriate additive, its concentration and the optimum process conditions when applying additives to get an optimal acrylamide inhibition. This review article highlights the effect of various additive applications, their effectiveness and possible future advances in food to control acrylamide formation within the accepted level.

Keywords: *Acrylamide, Antioxidant, Carcinogenicity, Deep-frying, Maillard reaction*

Introduction

Acrylamide (CH_2=CHCONH_2) is a water-soluble, α, β-unsaturated vinyl monomer containing a carbonyl group. It forms in many foods during high-temperature heat treatments and is easily polymerized (Mogol et al., 2020). Acrylamide has a molecular weight of 71.08 g/mol, a melting point of 84.50 ºC, and a boiling point of 136 ºC. It dissolves well in polar solvents like methanol and water but is less soluble in non-polar solvents such as hexane and carbon tetrachloride (Nematollahi et al., 2019). The acrylamide monomer is stable under acidic conditions but decomposes readily under alkaline conditions at room temperature. When exposed to oxidation or ultraviolet light, acrylamide can easily polymerize at temperatures above its melting point of 84.50 ºC (Ke et al., 2020). In its pure form, acrylamide is an odorless, and colorless solid at room temperature. Polyacrylamide, derived from acrylamide, is widely used in the paper industry, water treatment, and the construction of sewerage and drainage systems (EFSA, 2015; Mogol et al., 2020).

According to the International Agency for Research on Cancer (IARC), acrylamide is classified as a category 2A compound, indicating it is a "probable human carcinogen" based on its carcinogenicity observed in rodents (Ofosu et al., 2019). This classification is rooted in extensive research on the formation and risks of acrylamide in foods (Ofosu et al., 2019). Acrylamide forms during high-temperature processing methods like frying, roasting, and baking, particularly in carbohydrate-rich foods with high asparagine content (Yang et al., 2016). It is also present in non-food items such as cigarette smoke and drinking water (EFSA, 2015). Mass spectral studies have shown that the nitrogen atom and the three carbon atoms of acrylamide originate from asparagine (Champrasert et al., 2021).

Many studies have focused on various strategies for mitigating acrylamide in foods, including agronomical practices and optimizing processing conditions (Esposito et al., 2020; Pérez-Nevado et al., 2018), adding enzymes such as asparaginase (Chi et al., 2021; Meghavarnam and Janakiraman, 2018), using fermentation (Di Francesco et al., 2019; Petka et al., 2022), and incorporating additives (Komprda et al., 2016; Negoiță et al., 2022). However, these methods can impact the texture, color, and taste of the food to varying degrees. Incorporating additives is a suitable solution for inhibiting acrylamide formation while preserving the original sensory properties of the food (Xu et al., 2016). Additives are often more cost-effective, feasible, and less complex in terms of time and technological requirements compared to other strategies for acrylamide reduction. Since most of previous review articles including Maan et al., (2020) and Rifai et al., (2020) have discussed, with limitations, the impact of different additives on acrylamide mitigation, our review focused to fill the gap and provide a detailed analysis on the impact of cations, acids, and antioxidants on mitigation of acrylamide formation in foods with a particular focus on fried potato and cereal based foods.

Effects of acrylamide on human health

Several studies have revealed that acrylamide causes various toxicities, including carcinogenicity (Areej et al., 2020), neurotoxicity (Jong-Su et al., 2021), genotoxicity (De Conti et al., 2019), and reproductive toxicity (Rifai et al., 2020). The tolerable intake levels of acrylamide for neurotoxicity and carcinogenicity are about 40 µg and 2.6 µg per kg of body weight per day,

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respectively (Pan et al., 2020; Saraji and Javadian, 2019). Acrylamide is readily absorbed into the bloodstream of both animals and humans through inhalation, skin contact, and ingestion (Wu et al., 2021). Once absorbed, acrylamide is rapidly converted into glycidamide, a carcinogenic metabolite, by the enzyme cytochrome P450 (Kacar et al., 2019). Acrylamide then circulates rapidly to various body organs, including the heart, brain, thymus, liver and kidneys (Khorshidian et al., 2020; Matoso et al., 2019; Sarion et al., 2021).

According to the European Food Safety Authority (EFSA), both animal and human studies have shown that acrylamide, when not covalently bound to a food component, is readily absorbed in the gastrointestinal tract upon oral intake (EFSA, 2015). Acrylamide can cross the placenta and be excreted in breast milk to a small extent. Maternal intake of acrylamide during pregnancy has been linked to restricted intrauterine growth, indicated by low birth weight, small-for-gestational-age infants, and reduced head circumference at birth (Nagata et al., 2018). Acrylamide can damage the nervous system, causing infertility, irritability, and eye infections (Saraji and Javadian, 2019). Due to its electrophilic nature, acrylamide tends to react with nucleophilic groups such as thiols, carboxylates, and amines in biological matrices like DNA (Mogol et al., 2020).

Huang et al. (2018) examined the cardiac developmental toxicity (CDT) associated with acrylamide in zebrafish embryos and found that introducing acrylamide after fertilization caused heart shrinkage and abnormal morphological development. Additionally, acrylamide negatively affected gene expression by suppressing several genes involved in atrioventricular valve development. According to Katen et al, (2016), administering 1 µg/kg of acrylamide to male mice for six months, which is equivalent to a daily dose of 10.5 µg/kg body weight for humans, caused DNA damage in sperm without affecting overall fertility. However, the offspring exhibited a significant increase in sperm with damaged DNA and elevated levels of the CYP2E1 enzyme in germ cells, despite having no direct contact with acrylamide. Studies have shown that hemoglobin adducts from acrylamide can indicate internal doses and related exposures to acrylamide in the blood over a four-month period. More than 70 studies have assessed hemoglobin adducts from acrylamide in humans, demonstrating the feasibility of incorporating this biomarker into epidemiological research (Pedersen et al., 2022; Timmermann et al., 2021).

Given that acrylamide is a neurotoxin, Kopanska et al. (2017; 2022) studied its effect on acetylcholinesterase (AChE) enzyme activity in various tissues of mice, including the myocardium, hypothalamus, smooth muscle of the small intestine, and thigh skeletal muscle. The AChE activity was assessed based on malondialdehyde and thiol groups. The results showed a significant reduction in AChE activity in the hypothalamus and muscles, indicating that acrylamide directly impacts peripheral nerves, causing physiological alterations and structural damage. Additionally, different doses of acrylamide caused a deterioration of enzyme activity in a dose-dependent manner (Kopanska et al., 2022).

Wu et al. (2021) demonstrated that acrylamide alone could increase erythrocyte osmotic fragility, liver indexes, and malondialdehyde levels in the liver while causing a significant reduction in weight gain and glutathione levels in the plasma of mice. Interestingly, when both acrylamide and Maillard reaction products (MRPs) were present together, MRPs effectively mitigated the adverse toxicity imparted by acrylamide. The presence of MRPs, which are commonly generated alongside acrylamide in heat-processed foods, could lessen the acrylamide toxicity in mice.

Acrylamide mitigation strategies

The goal of acrylamide mitigation techniques is to reduce acrylamide levels below safe benchmark thresholds. For baking, toasting, and frying, it is crucial to select raw materials with low asparagine and reducing sugar levels to minimize acrylamide formation. Effective mitigation involves crop management, fertilization, optimal storage conditions, agronomic techniques, seasonal/weather considerations, and cultivar selection (European Commission, 2017; Liyanage et al., 2021).

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Storage conditions, such as duration, temperature, and humidity, significantly impact the amount of acrylamide formed in potatoes (Baskar and Aiswarya, 2018). Different cultivars of the same species contain varying amounts of asparagine and reducing sugars. Liyanage et al., confirmed that asparagine and reducing sugar contents in potatoes are genotype-specific, with lower amounts required to reduce acrylamide formation (Liyanage et al., 2021). Asparagine is the dominant free amino acid in potatoes, representing approximately one-third of the total amino acid content (Raffan and Halford, 2019). To prevent an increase in asparagine content, precise timing of nitrogen fertilizer application and avoiding excess nitrogen are crucial (Sarion et al., 2021).

Muttucumaru et al., (2017) noted that reducing sugar concentrations in potato tubers stored for 2-6 months period at 8 ºC, were increased in one cultivate while the same is decreased in another cultivars. Similarly, Sun et al., (2018) found that the glucose concentration increased in another cultivar of potato tuber stored at 7.2 °C for 9 months, which however, remained unchanged in the next year. These conflicting results indicated that growing season, environmental conditions, type of cultivar and storage period effect on reducing sugar levels and making predictions is difficult (Sun et al., 2020).

While optimal agronomical practices can effectively reduce acrylamide formation, they require specialized knowledge to develop and identify new genotypes (Alvarez-Morezuelas et al., 2021; Varzakas et al., 2016), continuous monitoring (Sun et al., 2020), technology, and capital (Alvarez-Morezuelas et al., 2021) may be the limiting factors for implementation. Additionally, consumer acceptance should be considered when adopting these traits.

Asparaginase enzyme can hydrolyze asparagine into aspartic acid and ammonia in raw foods under optimal conditions (Curtis and Halford, 2016). In industrial-scale fried potato production, safe reduction of acrylamide is achieved through treatments with L-asparaginase, and blanching step where potato slices are heat-treated in hot water at 85 °C for 3.5 minutes. This process reduces the amounts of reducing sugars and free amino acids (Di Francesco et al., 2019). However, this method is expensive due to the need for dedicated machinery and large quantities of recombinant asparaginase enzyme (Dias et al., 2017). Additionally, while the asparagine pre-treatment is effective in foods with an "aqueous" preparation step, it is less effective in foods with limited moisture content (Curtis and Halford, 2016).

Fermentation is the primary step in the process of bakery products due to the high sugar content present in cereals but not for potato-based products (Xu et al., 2016). Lactic acid bacteria such as *Lactobacillus plantarum, Lactobacillus bulgaricus, Lactobacillus acidophilus,* and yeast play significant roles in fermentation (Lopez-moreno et al., 2024). Abedi et al. (2022) observed significant reduction in sugar content when fermentation carried out using lactic acid bacteria and yeast, ultimately leading to reduced acrylamide formation.

Moreover, controlling over-frying time and oil temperature can reduce acrylamide content in fried foods. Yang et al., 2016 noted that temperature should not exceed 170-175 °C, while Mencin et al., (2020) mentioned that keeping frying temperatures below 120 °C can be considered safe. Bertuzzi et al. (2018) found that a combination of low temperature and longer frying time was the most favorable condition for acrylamide formation in potato snacks. Increasing frying time by a few seconds had a greater impact than increasing the temperature by 10-20 °C. However, changes in process conditions may significantly affect the flavor, texture, and mouth feel of the product. Therefore, further research is needed to develop methods that can reduce acrylamide content while preserving desirable sensory properties.

Acrylamide mitigation using additives

Pre-treatments such as soaking and blanching in water at various temperatures have been successful in reducing the development of acrylamide by removing a certain amount of precursors (Di

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Francesco et al., 2019; Negoiță et al., 2022). Sugars and asparagine concentrations can be efficiently reduced by blanching at temperatures between 50 and 90 ºC (Ledbetter et al., 2021). Since certain pre-treatments may affect sensory qualities and oil absorption during frying (Genovese et al., 2019; Korshidian et al., 2020), it's essential to identify the ideal soaking or blanching conditions to maintain the product quality.

A variety of soaking techniques, including the use of acids (Liu et al., 2020), antioxidants (Nagpal et al., 2021; Nan et al., 2021), amino acids (Cerit and Demirkol, 2021; Zhu et al., 2020), and food hydrocolloids (Champrasert et al., 2021) added to soaking water have proven successful in mitigating acrylamide in potato-based foods. Studies showed, application of additives imparted no or less alterations to the sensory and texture properties of food (Sansano et al., 2015; Zhu et al., 2020). It has been found that applying additives is relatively cost-effective (Morales et al., 2014; Yang et al., 2021), feasible (Morales et al., 2014), less complex (Morales et al., 2014; Yang et al., 2021), and requires less specific knowledge, technology and machinery to handle (Yang et al., 2021) compared to other mitigation strategies (Yang et al., 2021).

Acrylamide mitigation using monovalent, divalent, trivalent cations

The addition of cations can serve as an effective tool in reducing acrylamide levels while providing additional nutritional value to the food (Seyyedcheraghi et al., 2023; Wen et al., 2016). Salts such as Ca^{2+} can block the nucleophilic reactions of amino groups in amino acids by forming complexes that stabilize the zwitterionic form of the amino acids, rendering them protonated and unavailable for nucleophilic reactions on carbonyl compounds (Tas et al., 2016). The above study further demonstrated that the effectiveness of mineral salts in acrylamide mitigation is temperature-dependent, with the efficacy of salts negatively correlated with temperature (Tas et al., 2023). In their study, $CaCl_2$ was the most effective than NaCl, KCl, and calcium lactate under all tested conditions such as heating at 160, 180, and 200 °C in an oil bath. Calcium lactate and magnesium lactate exhibited a notable buffering effect through lactate anions, which hindered the protonation of amines at elevated pH levels, thereby reducing the inhibitory impact of cations on the Maillard reaction. This may explain the reduced acrylamide mitigating effect observed with calcium lactate in every treatment, unlike $CaCl_2$, which showed the highest reduction in acrylamide percentage. Particularly at higher temperatures, the ability of Ca^{2+} to stabilize the zwitterionic form of amino acids might have been counter balanced by the buffering impact of lactate ions (Tas et al., 2023). Therefore, achieving the desired outcome while avoiding counterbalancing effects requires considering both the cation and the anion incorporating into a food product.

Arámbula-Villa et al. (2018) demonstrated the effectiveness of divalent cations, specifically calcium and magnesium chloride, in reducing acrylamide levels in tortilla chips made from nixtamalized maize. The treated samples resulted in a reduction of 52-67% and 69-74% in acrylamide content for $CaCl_2$ and $MgCl_2$, respectively. $MgCl_2$ was more successful than $CaCl_2$ in this application. Even though the same concentrations of cations were applied, the highest reductions in acrylamide content, 67% and 74%, were achieved with samples containing 0.08 M and 0.12 M of $CaCl_2$ and $MgCl_2$, respectively. Results indicated that different cations may exhibit varying effectiveness when applied to the same food at different concentrations. Therefore, identifying the most suitable cation and concentration is crucial for effective acrylamide mitigation. However, it is noteworthy that in this study, a bitter aftertaste was observed in chips treated with 0.12 M $MgCl_2$ (Arámbula-Villa et al., 2018). Since the addition of metal ions can significantly affect food structure in numerous ways, it is essential to conduct a detailed analysis of sensory properties to ensure that the desired flavor profile and overall quality of the food product are maintained.

In an asparagine-glucose aqueous model system, Wen et al. (2016) found that low-valent metal cations required higher concentrations to reach their maximal inhibition, while high-valent cations required

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lower concentrations. This finding suggested that application of high-valent cations such as Al^{3+} and Fe^{3+} may be more economical and feasible than low-valent cations like K^{+}. However, it is important to note that higher concentrations of cations may impart undesirable taste, color, and texture, so using lower cation concentrations while still achieving lower acrylamide content may be preferable.

Wen et al. (2016) observed that the effectiveness of Ca^{2+} in reducing acrylamide generation was only up to 20 µmol/L. Beyond that level a progressive decrease in effectiveness was noted. It has been reported that progression in acrylamide formation in potato chips made using different potato cultivars following a blanching step in either 0.1 M NaCl or $CaCl_2$ salt solutions. This progression in acrylamide formation was likely due to the relatively high cation concentrations which altered the acrylamide synthesis pathway by shifting it from the dominant asparagine-glucose reaction to deoxidation of asparagine by 5-hydroxymethylfurfural (HMF).

Moreover, Wen et al. (2016) revealed that elevated metal cation concentrations promoted the formation of furfural and HMF, which are considered harmful compounds. Glucose not only reacts with asparagine to form acrylamide but also degrades to form HMF. Asparagine rapidly reacts with HMF, accelerating acrylamide formation, with this occurrence being more pronounced with Ca^{2+} ions than with Mg^{2+} ions.

Therefore, the addition of metal ions for acrylamide mitigation appears to have limitations, and further studies on various foods are needed to fully understand their effects and ensure a safe food. Conducting adequate preliminary studies to confirm a safe acrylamide level before introducing these methods to large-scale manufacturing is essential.

Acrylamide mitigation using acids

Maintaining an unfavorable pH for acrylamide formation is a key strategy to reduce its presence in food. Organic acids can help reduce the acrylamide generation by lowering the pH, thereby blocking the nucleophilic addition reaction between asparagine and carbonyl groups in reducing sugars. This inhibition prevents the generation of the Schiff base, a crucial intermediate in both acrylamide formation and the Maillard reaction (Di Francesco et al., 2019; Negoiță et al., 2022). A lower pH inhibits acrylamide generation by blocking the protonation of the α-amino group of asparagine, thus stopping its involvement in nucleophilic addition reactions with carbonyl groups (Negoiță et al., 2022).

Various α-hydroxy organic acids, such as citric, ascorbic, and lactic acids, have been effective in reducing acrylamide levels (Liu et al., 2020). It is proposed that the hydroxyl group next to the α-position of the carboxylic group plays a crucial role in the inhibition mechanism of acrylamide generation (Slinde et al., 2020). Sivasakthi et al. (2019) observed a significant reduction in acrylamide content in potato chips (540 μg/kg) when the slices were immersed in 1% lemon juice and fried at 160 °C for 7 minutes. This suggested that lemon juice is an excellent natural ingredient for mitigating acrylamide and could be applied on an industrial scale for potato chip production. In addition to reducing precursor content, the residual acids on the potato slices may have further decreased acrylamide formation by lowering the pH. Slinde et al. (2020) extensively described the effect of different acids and the impact of two-step treatment with dipping potato slices in various acid solutions before and after par-frying French fries. A single dip in a lactic acid (44 mM, 0.4%) solution, either before par-frying and freezing or by immersing par-fried frozen pieces, reduced the acrylamide content by about 40%. However, a two-step immersion treatment decreased the acrylamide content by about 60%, demonstrating its effectiveness in precursor reduction and inhibition of acrylamide formation.

According to Slinde et al. (2020), applying HCl as an acidifier directly lowered the pH, resulting in a 64% reduction in acrylamide level. The highest acrylamide inhibition was achieved with α-hydroxy acids such as lactic acid, malic acid, and glycolic acid (at 100 mM), showing more than 80% reduction. Conversely, acidified alcohols like ethanol and butanol did not exhibit any inhibitory

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effects beyond pH reduction. These results illustrated that α-hydroxy acids are more effective in reducing acrylamide than mere pH reduction with HCl, formic acid, or acetic acid. The same article mentioned that lactic acid has the highest potential for acrylamide mitigation, with pH reduction below its pKa. Although glucono-delta-lactone contains a α-hydroxy group, the ring structure may hinder its effectiveness in reducing acrylamide. Thus, the structure of the acid is critical for achieving substantial acrylamide inhibition in food. This study also found that low concentrations (10 mM) of lactic acid were less effective at inhibiting acrylamide formation than higher concentrations (40 mM).

Negoiță et al. (2022) demonstrated that immersing potato strips in citric acid solution for 30 minutes significantly mitigated acrylamide formation by lowering the pH from 7 to 3.99 with 0.05% citric acid and to 2.35 with 1% citric acid. This treatment resulted in a notable acrylamide mitigation in French fries by approximately 77% and 97% reduction, respectively. Additionally, immersing the fries in citric acid brightened the samples, enhancing their L* value parameter. Nguyen et al. (2022) found that immersing sweet potato and carrot fries in 5% acetic acid at a ratio of 1:10 (fries: vinegar, w/w) at room temperature for 15 minutes reduced acrylamide content by 90% and 73%, respectively, compared to control samples. Interestingly, prolonged immersion of potato slices in acetic acid did not lead to further acrylamide reduction, suggesting that high concentrations of acetic acid could achieve substantial acrylamide reduction within a short period.

Liyanage et al. (2021) reported that blanching potato slices in a 0.5% ascorbic acid solution significantly increased acrylamide content in potato chips made from three different cultivars; Atlantic, Snowden and Vigor. The promotion of acrylamide formation may be due to the thermal decomposition products of ascorbic acid reacting with amino groups. Furthermore, prooxidant action of ascorbic acid when applying in high concentration was reported by Jayasinghe et al, (2013). Additionally, blanching slices in a 1% acetic acid solution increased acrylamide formation in chips made from the Atlantic and Snowden cultivars, while it reduced acrylamide levels in the Vigor cultivar. These findings indicate that the same pre-treatment can have varying effects on acrylamide formation depending on the potato cultivar used.

Acrylamide mitigation using antioxidants

Strecker degradation, Maillard reaction, and the hydrolysis of esters and glycosides reactions occurr during frying. These reactions release some antioxidant compounds while destroying others, leading to changes in antioxidant activity (Tian et al., 2016). The toxicity of Maillard products can be reduced by using antioxidants in the frying oil, which inhibit lipid oxidation and extend the oil's shelf life (Nagpal et al., 2021). Various food combinations and plant polyphenols, such as rosemary extract, bamboo leaf antioxidants (Liu et al., 2015), tocopherols, tertiary butylhydroquinone (TBHQ), butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA), can reduce acrylamide formation in deep-fried foods (Ke et al., 2020).

Research has demonstrated the effectiveness of powdered spices and plant materials in reducing acrylamide levels in various food systems (Huang et al., 2020; Lotfy et al., 2018; Yuan et al., 2019). For instance, adding vitamin E (0.1 mg/kg) to cookie dough reduced acrylamide formation by 49.6%. Furthermore, water-soluble antioxidants found in virgin olive oil were observed to inhibit acrylamide formation in crisps across various frying conditions. (Kamarudin et al., 2018). Similarly, Nan et al. (2021) reported that adding 0.1 M quercetin to an asparagine-glucose model system heated at 180 °C for 30 minutes resulted in a 51.38% reduction in acrylamide. The kinetic curve indicated that quercetin's inhibitory activity was most significant during the acrylamide formation phase, with a negligible effect during the degradation phase. This inhibition might result from reactions between quercetin decomposition products and intermediate compounds from the Maillard reaction, rendering them unavailable or converting them into compounds with little or no association with acrylamide formation. However, as the exact inhibition pathways remain unclear, further studies are needed to reach a definitive conclusion.

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Mekawi et al. (2019) effectively used lyophilized pomegranate peel nanoparticles extract (LPP extract) at 1.00 g/kg in sunflower oil to inhibit acrylamide formation in potato chips by 54%, also enhancing the oil's oxidative stability. The antioxidant activity of LPP surpassed that of synthetic antioxidants α-tocopherols and BHT in sunflower oil during frying at 180 ºC over 20 cycles. In the finished fried food, lipids became the primary source of carbonyls, which reacted with asparagine to form acrylamide. The superior antioxidant activity of LPP limited the carbonyl accumulation in the oil, significantly reducing the acrylamide formation.

Yuan et al. (2019) demonstrated that rosmarinic acid (RoA) effectively mitigated acrylamide, with a direct reaction observed between the hydroxy groups of RoA and the vinyl group of acrylamide through Michael-type addition. Rottmann et al. (2021) noted that the nucleophilic centers of phenylacrylic acids (such as ferulic, p-coumaric, and caffeic acids) include phenolic hydroxyl groups and electron-rich carbon atoms at the ortho position, which may react as nucleophiles with acrylamide. In contrast, cinnamic acid, lacking a hydroxyl group, was not expected to engage in such reactions.

Xingyu et al. (2019) suggested that the carboxylate groups of phenylacrylic acids tend to react as nucleophiles in an oxa-Michael addition at elevated temperatures and lower water activity. However, Rottmann et al. (2021) found that applying hydroxyphenyl acrylic acids such as ferulic, p-coumaric, caffeic, and cinnamic acids was ineffective in reducing acrylamide content in fried potato and sweet potato. Their study showed no adduct formation in non-supplemented samples, with only low acrylamide levels (17-264 μg/kg) in fried products. The study concluded that the acrylamide mitigation effect of plant extracts observed in other studies with phenols were not due to the abundant phenylacrylic acids but rather other potential constituents. Therefore, it is essential to identify the most suitable phenols and phytochemicals before applying them to specific foods, as the reaction products and mechanisms are unique to each additive.

Yuan et al. (2019) conducted a study revealing intriguing findings regarding the effect of rosmarinic acid (RoA) on acrylamide formation in asparagine-fructose and asparagine-glucose model systems. In the asparagine-fructose system, the optimal acrylamide inhibition (59.45%) was achieved with the addition of 10^{-4} mM RoA. However, concentrations of 10^{-3} and 10^{-5} mM RoA resulted in increased acrylamide levels, with 10^{-5} mM showing no significant difference from the control. This dual behavior of RoA, acting as both an antioxidant and a prooxidant, suggests that its effectiveness is concentration-dependent (Yuan et al., 2019). Antioxidants, which possess carbonyl groups, might directly react with asparagine to form acrylamide. Thus, increasing RoA from 10^{-4} to 10^{-3} mM might lead to higher acrylamide formation. Conversely, when RoA concentration was further increased from 10^{-3} to 10^{-1} mM, acrylamide content decreased, likely because the higher concentration acted as a strong prooxidant, enhancing acrylamide polymerization. Kinetic data identified the addition reaction between the adjacent hydroxyl groups on the double-ring structure of RoA and the vinylic double bond of acrylamide, as the main direct scavenging pathway for acrylamide mitigation (Yuan et al., 2019). Given the complexity of these reactions and the concentration-dependent effects, further studies are needed for a complete understanding.

While some studies have reported acrylamide inhibition, several have not found a significant impact, showing a dose-dependency without an absolute correlation, and some have even shown acrylamide acceleration (Rifai et al., 2020). For instance, Mousa et al. (2019) found that adding 3% green tea, thyme, garlic, and anise effectively reduced acrylamide in crust bread, whereas cinnamon doubled the acrylamide levels compared to the control sample. Similarly, Morales et al. (2014) found that treating potatoes with thyme and bougainvillea did not reduce acrylamide content in fried potatoes. The higher reducing sugar content in bougainvillea (2.8 g/100 g) might have favored acrylamide formation, resulting in no net reduction due to the combined effects of antioxidant activity and reducing sugars.

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Akgun et al. (2022) studied the effect of soaking potato slices in various wild edible plant extracts and found contradictory results. Some applications reduced acrylamide formation in potato crisps, while others promoted it with increased concentration and soaking time. Extracts from sow-thistle, milk thistle, garden sorrel, and shepherd's-needle either increased acrylamide content or caused no change, whereas ribwort plantain extract significantly reduced acrylamide content by 57%. This reduction might be attributed to the high levels of chlorogenic acid, p-coumaric acid, and p-hydroxybenzoic acid in ribwort plantain compared to other extracts. Thus, the performance of plant extracts or powders in acrylamide mitigation is highly dependent on their chemical constituents, can interfere with the acrylamide formation mechanism. Additionally, the reducing sugar content of plant samples should be analyzed and controlled before application to get the maximum benefit out of the antioxidants (Akgun et al., 2022).

Apart from mitigating acrylamide, antioxidants can impact the final quality of the product. Therefore, their reactions during heat treatment should be further studied to fully understand their effectiveness. Nonetheless, plant polyphenols may be more reliable and acceptable to consumers compared to synthetic antioxidants. Further research is needed to identify more thermally stable natural antioxidants and more benign synthetic antioxidants that can be incorporated into frying oil or food in commercial production.

Conclusions

Various studies on reducing food toxicant acrylamide have attracted attention over several years due to its prevalence in various food products causing negative health impacts. Under this perspective, various mitigation strategies including agronomical, physical, chemical and microbiological measures have been suggested and have been successful. Out of these strategies, the addition of additives has been found to be easier, feasible, cheaper, less time consuming and more promising in comparison to other possible approaches. The application of inorganic cations, weak acids, plant based and synthetic antioxidants are more effective in preserving the expected food quality with reduced acrylamide content. Since the effect of additives on acrylamide reduction depends on the properties of the food system, the need to focus more on food matter instead of asparagine- sugar model systems have emerged. Future research should focus on potential natural additives instead of synthetics to inspire greater consumer preference due to their harmless impact. However, studies on combined strategies have shown the highest effectiveness in acrylamide reduction compared to single treatments. Therefore future studies should focus on identifying the most suitable treatment combination for an optimal acrylamide reduction.

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