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Acrylamide Formation and Different Mitigation Strategies during Food Processing – A Review

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ABSTRACT
Thermal treatment can initiate the production of some undesirable compounds in foods during processing. Acrylamide is one among such compounds that is produced (in starch-rich foods) as a result of Maillard reaction between reducing sugars and free amino acids. Acrylamide has gained much attention owing to its wide occurrence, dietary exposure, and toxicity. Its formation mechanism and mitigation has been an area of interest for numerous researchers since its discovery in foods. Some reviews have already been published on acrylamide where its formation and mitigation has been discussed with reference to some specific group of foods and/or some specific mitigation technique. In others, the mitigation section does not cover all the aspects of acrylamide attenuation reported in the literature. The present paper provides the updated and comprehensive information on formation, occurrence, dietary exposure, toxicity, and mitigation of acrylamide in foods during processing.

KEYWORDS
Maillard reaction; acrylamide; toxicity; mitigation

Introduction
Food commodities may undergo various heat treatments during processing (such as roasting, frying, baking, and pasteurization) with prime objectives of shelf-stability and desired sensory profile. These thermal treatments can initiate some reactions in foods (including Maillard reaction, lipid oxidation, and caramelization) that can produce various compounds, which can have both desirable (antimicrobial, antioxidant, and antiallergenic) and undesirable (cytotoxicity, carcinogenicity, and mutagenic responses) effects.\textsuperscript{[1,2]} Acrylamide is one among such compounds, which has gained much interest because of its toxicity and wide occurrence in processed foods.\textsuperscript{[3]}

Acrylamide (C\textsubscript{3}H\textsubscript{5}NO; prop-2-enamide) is a water-soluble, colorless, and odorless compound, and is vulnerable to bases, acids, oxidizing agents, and iron salts.\textsuperscript{[4]} Thermally, acrylamide decomposes to CO\textsubscript{2}, CO, and nitrogen oxides as well as ammonia.\textsuperscript{[5]} Being monomer, it is employed in organic synthesis, whereas the industrial processes such as paper making, cosmetics, textiles, and the treatment of waste water also find its applications.\textsuperscript{[4,6]}

Acrylamide was discovered in foods (processed at temperatures greater than 120°C) by Swedish National Food Authority and Stockholm University in 2002.\textsuperscript{[7]} The discovery of
acrylamide in foods urged the researchers to investigate various factors involved in acrylamide formation during processing. Consequently, numerous formation mechanisms were elucidated along with various mitigation strategies. Some reviews have already been published where acrylamide formation and mitigation has either been discussed with reference to some specific group of foods[8] and mitigation technique[9] or the mitigation section does not cover all aspects of acrylamide extenuation reported in literature.[3,10] The current work was aimed to present updated and comprehensive information on acrylamide formation, occurrence, exposure, associated risks, and mitigation in foods during processing.

Formation of acrylamide
Initially, the hypotheses discussed on formation mechanisms of acrylamide were focused on vegetable oils and lipids as the fried and baked starch-rich foods were found to be the main sources of acrylamide in foods. The main precursors reported for acrylamide formation included 3-aminopropionamide, decarboxylated Schiff base[11], decarboxylated Amadori product[12], acrylic acid, [13] and acrolein. [14] According to recent studies, two pathways are most accepted; Maillard reaction and acrolein pathway[15] (Fig. 1). Maillard reaction involves the reaction between free amino acids such as asparagine and reducing sugars. Chemical phenomena involved in acrylamide formation prefer short chain sugars that form cyclic hemiacetal and exposed to nucleophilic attack by alpha-amino acids. A Schiff base is formed by removal of water from sugar–protein conjugate, which further decarboxylates through the formation of oxazolidine-5-one. The decarboxylated product decomposes to acrylamide through the elimination of imine or after hydrolyzation to form 3-APA or 3-oxopropanamide. It has been found through continuous research that carbonyl compounds (2-deoxyglucose, 2,3-butanedione, octanal, and decanal) can produce results similar to reducing sugars.[10,16,17]

Acrolein, another precursor of acrylamide formation, is produced in oils when heated above their smoke point. [16] At this temperature, glycerol undergoes degradation resulting in the formation of acrolein. Acrolein further oxidizes to acrylic acid and produces acrylamide in the presence of asparagine where acrylic acid provides the carbon source and asparagine provides the amino group. Further, the peroxy radicals can initiate the polymerization of acrylamide in the presence of oxygen.[14,18]

Occurrence, dietary exposure, and toxicity
Occurrence of acrylamide has been reported in a variety of foods including potato crisps, bread, biscuits, breakfast cereals, coffee, cereal-based (and jarred) baby foods, hazelnuts, almonds, olives, raw and processed fruits and vegetables, meat, fish, popcorn, cocoa products, green tea, oilseeds, condiments, sauces, alcoholic beverages as well as homemade potato products.[3,19,20] Recently, a study was conducted by Mesias et al.[21] on renowned food service establishments (trademark food restaurants) in Spain. The results indicated that mean acrylamide contents were in range with the EFSA (European Food Safety Authority) standards. However, 13.5% samples were found to breach the benchmark level (500 µg/kg) established by the European Commission for ready-to-eat French fries (EU Regulation 2158/2017).[21] Acrylamide contents in different brands of the same
product can vary due to the difference in concentration of acrylamide precursors (in raw materials), composition, process conditions, duration, and conditions of storage.[3,22] These factors, along with different eating habits, have resulted in variable dietary exposures of acrylamide among populations of different regions and age groups. Some selected studies are summarized in the following paragraphs.

Tawila et al.[23] reported an average daily intake of 0.51 µg/kg body weight/day in school-going children (consuming cafeteria foods) with 95th percentile value of about 1.71 µg/kg. A decrease in exposure was observed with an increase in the age of children. For primary school children, the exposure value was 0.65 µg/kg body weight/day which decreased to 0.37 µg/kg body weight for secondary school children. Wyka et al.[24] estimated the dietary exposure of acrylamide in teenagers and reported different values for males and females. The dietary intake values were 1.04 and 1.18 µg/kg body weight/day with 95th percentile for
females and males, respectively. Zając et al. estimated the exposure to different age groups and observed a decrease in exposure with age from 1.51 µg/kg body weight/day for the youngest group (6–12 years) to 0.67 µg/kg body weight/day for the oldest group (42–60 years). The exposure level for adults was found to be 0.85 µg/kg body weight/day with 95th percentile value of 1.70 µg/kg body weight/day. A study conducted to assess the acrylamide exposure to infants (aged 6–12 months) reported an average level from 2.10 to 4.32 µg/kg body weight/day. The maximum exposure, representing an isolated worst case, was reported to be 7.47–12.35 µg/kg body weight/day. Exposure assessment in adolescents (aged 10–17 years) has been reported to be 0.29 and 0.17 µg/kg body weight/day on the basis of food diary and food frequency questionnaire. Sirot et al. assessed the acrylamide exposure to adults and children among the French population and reported values of 0.43 and 0.69 µg/kg body weight/day, respectively. A study conducted on the dietary exposure of acrylamide to the Chinese population revealed an exposure level of 0.29 µg/kg body weight/day with 95th percentile value of 0.49 µg/kg body weight/day. In general, potato and cereal-based products are reported to be the major contributors to the exposure of acrylamide and account for about one-third of total acrylamide intake.

Acrylamide has been classified as “probable carcinogen” by the International Agency for Research on Cancer. When ingested, it is distributed to various body tissues (heart, kidneys, brain, liver, and breast) and can affect metabolism, reproduction, normal cell division, and dysfunction during developmental phases. During metabolism, the body converts it into glycidamide that can act as a potent DNA-damaging agent. Consumption of acrylamide at low dose for longer times can also affect the neurotransmission and axonal efficiency. Alghoraishi et al. have reported that acrylamide can significantly reduce the progressive and total sperm motility in mice. The California Office of Environmental Health Hazard Assessment has declared acrylamide as a male developmental toxin. Some of the females (mouse) treated with acrylamide presented an increased level of ROS (reactive oxygen species) causing reduction in DNA as well as histone methylation levels which consequently resulted in decreased oocyte fertility and quality.

A joint committee of FAO (Food and Agriculture Organization), WHO (World Health Organization), and EFSA presented their guidance on the risk of exposure of different compounds that were thought to be carcinogenic or genotoxic. The previous recommendation was to present the exposure as ALARA (as low as reasonably achievable). But it was considered of limited use because there were not any carcinogenic potency or human exposure included. Therefore, the risk managers were recommended to use MOE (margin of exposure) approach for their priority setting as it was more informative than ALARA. The CONTAM panel of EFSA performed the risk characterization of acrylamide and established a BMDL10 (benchmark dose lower confidence limit) value of 0.43 mg/kg body weight/day for peripheral neuropathy (in rats) and 0.17 mg/kg body weight/day for neoplastic effects (in mice). Nonneoplastic effects were assessed using the MOE approach for neurotoxicity and it was concluded that MOE might be of concern for toddlers and other children. Acrylamide and its metabolites showed a positive response in a variety of genotoxic tests indicating its concern with genotoxicity. The carcinogenic processes which are facilitated by DNA reactive mode of action may not have any threshold value relative to dose–response relation. Therefore, the panel considered it inappropriate to establish a tolerable daily intake.
Increased awareness about the occurrence and toxicity of acrylamide has resulted in demand for legislation to ensure its information on food labels in some countries. Some benchmark levels and mitigation procedures were established and put into force (April 2018) under EU regulation No. 2017/2158 for the reduction of acrylamide in foodstuff. \[43\] In 2005 in California, a lawsuit was filed against some companies and restaurants for failing to fulfill the requirements (regarding acrylamide) of Safe Drinking Water and Toxic Enforcement Act of 1986 (proposition 65). This proposition regulates the chemicals causing carcinogenic and reproductive harms forcing the manufacturers to label their products with such chemicals or otherwise warn the consumers. As a part of settlement of lawsuit, acrylamide warning labels/notices are now being posted by a number of restaurant chains selling foods containing acrylamide to reduce its consumption and promote better public health. \[37,44,45\]

**Mitigation approaches**

Various approaches have been reported in literature for reducing acrylamide formation during food processing. Summary of the effects of these approaches on acrylamide reduction in various foods has been presented in Tables 1–5. Each of these approaches is suitable only for some specific group of foods as described in the following sections.

**Processing conditions**

Thermal processing (baking, frying, roasting, etc.) is the most common type of food processing. Since acrylamide formation is initiated (from its precursors) by heat; therefore, several researchers have evaluated the effect of thermal processing variables (i.e. processing temperature and time) in relation to acrylamide formation. Frying, broasting, and allied processing techniques are among common cooking methods in restaurants and at home, which result in acrylamide production in foodstuff in response to the availability of precursors. \[85–87\] Williams \[88\] found that time–temperature combination during frying was a decisive factor (among others such as type of frying oil, potato cultivar, soaking) affecting acrylamide formation in potato fries. Daniali et al. \[46\] investigated the acrylamide formation in frying oils using palm olein and soybean oils at different times and temperatures. They reported a direct correlation between time, temperature, and amount of acrylamide formation. The maximum amount of acrylamide was observed when both oils were heated at 200°C for 7.5 min, and the minimum amount was observed at 160°C for 1.5 min. Matthäus et al. \[89\] reported that time duration is a key factor especially at frying temperatures above 175°C. They reported a radical increase in acrylamide concentration at 180–190°C compared to lower temperatures (150°C and 175°C). Increase in the concentration of acrylamide with respect to time followed linear function; however, for frying temperature, a nonlinear relation was observed. Van Der Fels-Klerx et al. \[90\] evaluated the effect of baking time and temperature on acrylamide contents in biscuits at 180°C, 190°C, and 200°C. The acrylamide contents increased with increasing temperature with the highest concentration observed at 200°C. At each temperature, the acrylamide concentration increased with baking time; whereas at 200°C, a linear relationship was observed between baking time and acrylamide concentration. Claus et al. \[47\] studied the effect of baking temperature on acrylamide contents and sensory properties of bread. Nearly, same
results were obtained regarding color, odor, and flavor of the bread samples baked at 240°C for 50 min and 200°C for 70 min. However, higher acrylamide concentration was seen in the samples baked at higher temperature (124.1 µg/kg) compared to lower temperature (92.4 µg/kg). Mustafa et al. have also reported a direct relation between the concentration of acrylamide and baking parameters (temperature and time). Mizukami et al. investigated different roasting conditions for green tea to reduce the acrylamide
concentration without doing any compromise over the quality of the product. The sample was subjected to roasting process at 180°C for 15 min and at 160°C for 30 min to produce the desired Houjicha flavor. In the green tea infusions, 4.0 and 2.0 µg/L of acrylamide were detected by the roasting process at 180°C for 15 min and 160°C for 30 min, respectively. Degradation of catechins was also inhibited at 160°C compared to 180°C. Summa et al. \[52\] subjected different coffee samples to a roasting temperature of 236°C for different time periods. A decreasing trend in acrylamide level was seen with increasing roasting time. Contrary to this, Lukac et al. \[53\] evaluated the acrylamide contents in almonds (roasted at 145°C and 165°C) and reported an increase in acrylamide concentration with roasting time. A similar trend has been reported by Farah et al. \[54\] for roasting of cocoa beans at 130°C. The contrasting trend of acrylamide formation in coffee beans might be due to the use of high roasting temperature (236°C).

Careful choice of processing variables can be used as an effective tool to reduce acrylamide in thermally processed foods. Changes in process variables might result in slight changes in sensory characteristics of the product. However, through careful selection of time and

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**Table 3. Effect of blanching on acrylamide reduction in various foods.**

<table>
<thead>
<tr>
<th>Blanching conditions</th>
<th>Food product</th>
<th>Acrylamide reduction (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blanching for 3 min at 80°C</td>
<td>Potatoes</td>
<td>73%</td>
<td>[70]</td>
</tr>
<tr>
<td>Blanching for 10 min at 70°C</td>
<td>Potato crisps</td>
<td>70%</td>
<td>[71]</td>
</tr>
<tr>
<td>Water blanching and soaking (in 0.5% sodium acid pyrophosphate then strip soaking in 0.4% calcium chloride solution)</td>
<td>Sweet potato</td>
<td>92.16%</td>
<td>[72]</td>
</tr>
<tr>
<td>Blanching (with 10 U/mL of L-asparaginase at 80°C for only 4 min)</td>
<td>French fries</td>
<td>80.5%</td>
<td>[73]</td>
</tr>
<tr>
<td>Blanching at 68.7–75°C for 8.8–9.7 min</td>
<td>Potato chips</td>
<td>61.3%</td>
<td>[74]</td>
</tr>
</tbody>
</table>

**Table 4. Effect of fermentation on acrylamide reduction in various foods.**

<table>
<thead>
<tr>
<th>Type of fermentation</th>
<th>Food product</th>
<th>Acrylamide reduction (%)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Submerged fermentation (SMF) and Solid-state fermentation (SSF)</td>
<td>Biscuits with Flaxseeds (through SMF) and lupine (through SSF)</td>
<td>78% and 85%, respectively</td>
<td>[75]</td>
</tr>
<tr>
<td>Fermented <em>Helianthus tuberosus</em> L. Tuber</td>
<td>Wheat bread</td>
<td>54%</td>
<td>[76]</td>
</tr>
<tr>
<td>Fermentation with Baker's yeast (<em>Saccharomyces cerevisiae</em>, 1–2% w/v)</td>
<td>Instant coffee</td>
<td>70%</td>
<td>[77]</td>
</tr>
<tr>
<td>Lactic acid bacterial fermentation with <em>Aspergillus niger</em> glucoamylase</td>
<td>Mixed rye bread</td>
<td>59.4% (in 500 g loaf) and 40% (in 1000 g loaf)</td>
<td>[78]</td>
</tr>
<tr>
<td>Fermentation with <em>Pediococcus acidilactici</em>, <em>Lactobacillus brevis</em>, <em>Lactobacillus plantarum</em>, and <em>Pediococcus pentosus</em></td>
<td>Bread</td>
<td>84.2%, 55.6%, 49.2%, and 39.2%, respectively</td>
<td>[79]</td>
</tr>
</tbody>
</table>

**Table 5. Effect of plant extracts on acrylamide reduction in various foods.**

<table>
<thead>
<tr>
<th>Type of extract</th>
<th>Food product</th>
<th>Acrylamide reduction (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proanthocyanidins extracted from sorghum, cranberry, and grape seeds (0.01–1 mg/mL for 15 min)</td>
<td>Fried potato crisps</td>
<td>44.2%</td>
<td>[80]</td>
</tr>
<tr>
<td>Green tea extract (3%)</td>
<td>Chicken drumsticks and chicken wings</td>
<td>43% and 34%, respectively</td>
<td>[81]</td>
</tr>
<tr>
<td>Aqueous extracts from green tea, cinnamon, and oregano (1 g/L for 1 min)</td>
<td>Fried potatoes</td>
<td>62%, 39% and 17%, respectively</td>
<td>[82]</td>
</tr>
<tr>
<td>Rosemary extract (50 mg/kg)</td>
<td>Fried potatoes</td>
<td>38%</td>
<td>[83]</td>
</tr>
<tr>
<td>Bamboo leaves antioxidant (0.2 g/kg) and tea polyphenols (0.1 g/kg)</td>
<td>Cookies</td>
<td>63.9% and 43%, respectively</td>
<td>[84]</td>
</tr>
</tbody>
</table>
temperature, one can reduce acrylamide content in the product without negotiating on quality.\textsuperscript{92} Process optimization while addressing both, acrylamide contents and the sensorial characteristics of the product, should be a prerequisite for adopting such approaches.

**Processing techniques**

Various integrated processing methods have been reported to reduce acrylamide formation in products. Erdoğdu et al.\textsuperscript{55} studied the impact of microwave precooking with subsequent frying of French fries at 190°C, 170°C, and 150°C. Different microwave treatments used were 10, 20, and 30 s at 840 W of power. A noticeable amount of reduction in acrylamide was observed on the surface of microwave-treated samples, whereas in the inner core, a minute increase was detected. A 50% decrease in acrylamide formation has been reported by Anese et al.\textsuperscript{56} in coffee beans processed through roasting with integrated vacuum treatment compared to conventional roasting without affecting the color and other sensory properties. Anese et al.\textsuperscript{57} have reported a decrease of 43% (in biscuits) and 18% (in potato chips) by combining the vacuum with baking and frying, respectively. Similar results for acrylamide reduction through vacuum-combined baking have also been reported by Palazoğlu et al.,\textsuperscript{93} and Yıldız et al.\textsuperscript{94} Granda et al.\textsuperscript{58} experimented using vacuum frying of potatoes and reported a considerable decrease (up to 94%) in acrylamide contents. Belkova et al.\textsuperscript{95} have also reported a noticeable decrease in acrylamide and other undesirable by-products of Maillard reaction in potato crisps through vacuum combined frying.

Apart from integrated processing techniques, the use of novel processing methods (either alone or as a pretreatment) has been reported to reduce acrylamide contents in a variety of foods. In a study conducted by Antunes-Rohling et al.,\textsuperscript{59} high-intensity ultrasounds were applied on potatoes immersed in water as a pretreatment to mitigate the acrylamide level. They reported a decrease of 90% in acrylamide contents in potatoes fried after ultrasonic treatment and attributed this reduction to decreased reducing sugar contents. Barutcu et al.\textsuperscript{60} evaluated the effect of microwave frying on acrylamide contents in coating materials comprising different types of flours. Microwave frying produced 34.5% less acrylamide compared to conventional frying in rice-based coating material. Sansano et al.\textsuperscript{61} compared the effect of air frying and deep oil frying on acrylamide formation and reported a decrease of 90% through air frying.

Mitigation through integrated approaches or pre- and posttreatments results in increased processing steps and processing time with subsequent increase in processing cost. This can affect the cost of the product and its marketing. Therefore, cost evaluation of the process/product needs to be carefully assessed while adopting such strategies on a commercial scale.

**Additives**

Various additives (added either during processing or as a pretreatment agent) have been reported as effective against acrylamide formation in model as well as real food systems. Lime is an important additive used in the nixtamalization process where corn flour is used for tortilla chips production. A study by Salazar et al.\textsuperscript{62} reported a decrease of 36–52% in acrylamide owing to lime content (1.5–2 g/100 g). The study further indicated that lime concentration can play a vital role in mitigating acrylamide during nixtamalization through inhibition of Schiff Base. Zou et al.\textsuperscript{63} investigated the effect of cysteine alone
and in combination with glycine in asparagine/glucose and biscuit models. A significant decrease (93.2–97.8%) in acrylamide contents was observed using cysteine (0.36 g/100 g) and glycine (0.2 g/100 g). It was reported that cysteine and asparagine reduce acrylamide by competing with asparagine or through Michael adduction.

The therapeutic effect of inorganic vanadium against various diseases is well documented. Kalita and Jayanty pretreated the potato strips with various concentrations of vanadyl sulfate solutions. The pretreated strips were subjected to the preparation of French fries and chips. Acrylamide contents were decreased (up to 90%) with increasing the concentration of vanadyl sulfate. It was postulated that VO$^{2+}$ binds to asparagine and hinders its role in acrylamide formation. Yuan et al. explored the impact of some additives including allicin, cysteine, NaHSO$_3$, NaCl, and ascorbic acid on acrylamide reduction during microwave heating. Each of the foresaid additives proved good, but cysteine and NaHSO$_3$ performed excellently. NaHSO$_3$ was reported to play its role by preventing the formation of Schiff base through its reaction with the carbonyl group of reducing sugars. In another study related to ripe black olive, NaHSO$_3$ incorporation did not affect the acrylamide production at 1.5 mM but 100% inhibition at 25 mM concentration was reported. Sansano et al. pretreated the potatoes with 1% citric acid, glycine, nicotinic acid, and 2% NaCl. They reported a decrease of acrylamide up to 80–90%. Similar reduction (around 90%) has also been reported by pre-treatments in acidic (citric and acetic) solutions. Organic acids reduce acrylamide through protonation of asparagine amino groups at low pH. The same researchers also evaluated the effect of post-frying drying treatment (through drying of potatoes immediately after frying in hot air oven) and reported 80% reduction of acrylamide.

Since L-asparagine is considered to be one of the major precursors of acrylamide, various studies have evaluated the effect of enzyme L-asparaginase as a potential in reducing acrylamide formation. Studies have shown that L-asparaginase catalyzes the hydrolysis of L-asparagine into ammonia and aspartic acid. The enzyme L-asparaginase can be obtained from various sources including plants, animals, and microorganisms. Microbial source is considered as the most suitable option for its applications in the food and medical industries. In a study by Jia et al., potato slices were treated with L-asparaginase from Bacillus subtilis at a concentration of 8000 U/L to immerse potato slices before frying and acrylamide contents were reduced by 82%. In a recent study, Meghavarnam and Janakiraman performed a series of experiments, where 50, 100, 200, and 300 U/mL concentration of L-asparaginase were incorporated in dough and acrylamide risk was lessened up to 42%, 66%, 77%, and 86%, respectively. Dias et al. removed 72% and 92% acrylamide using L-asparaginase obtained from Aspergillus oryzae (Strain# CCT 3940) and commercial enzyme, respectively.

Although a variety of additives have been investigated with proven effectiveness against acrylamide formation, their industrial applications will depend on the type of the product, their effectiveness against acrylamide formation without affecting the product quality and safety.

**Blanching**

Blanching is a preparatory procedure where a food sample (such as potato chips) is dipped in hot water for few minutes for a variety of reasons. It is basically done to obtain more uniform color, less oil absorption, and a gelatinized layer of starch which greatly improves the texture of the product. The blanching of potatoes prior to frying has been found very
effective in minimizing acrylamide contents.\textsuperscript{49} Blanching helps to extract sugars from potatoes, thus reducing the amount of acrylamide precursors.\textsuperscript{70}

Viklund et al.\textsuperscript{70} determined the blanching impact on three potato clones (namely Saturna, Hulda, and SW 91102) and reported a decrease ranging between 51\% and 73\% in acrylamide production; possibly due to decline in the diffusion of precursors to the surface of slices. Blanching temperature has been reported to be the key factor in acrylamide reduction as well. Mestdagh et al.\textsuperscript{71} investigated the effect of blanching conditions (time and temperature combinations) on acrylamide formation in French fries and reported that blanching for a short time at high temperature proved to be more effective than blanching at low temperature and for a long time. Zuo et al.\textsuperscript{73} studied the blanching of potatoes combined with treatment with a thermostable enzyme (L-asparaginase) in one step and reported a significant decrease in acrylamide formation. While comparing with control treatment, Al-Bachir et al.\textsuperscript{102} achieved 61\% of acrylamide reduction in potato strips by blanching at 85 ± 0.5°C for 5 min compared to treatment with gamma irradiations (20–54\%). A decrease of 78\% was achieved with a combined treatment of blanching and gamma irradiations.

Blanching is a common unit operation during commercial processing of a variety of potato products and therefore the acrylamide content of such products can be expected to be at lower level. However, consumer practices at households can cause serious acrylamide threat especially when one-stage processing is performed. Mesias et al.\textsuperscript{103} conducted an observational study on 73 Spanish houses to evaluate the effect of consumer practices on acrylamide formation during the preparation of French fries from fresh potatoes. Acrylamide contents were found above the benchmark level of European Commission (500 µg/kg) for French fries in some 45\% of the analyzed samples,\textsuperscript{43} whereas the contents exceeded the concentration of 2000 µg/kg in about 7\% samples. For this category, the obtained average and median values were also found to be more than the report of scientific opinion of EFSA on acrylamide showing that domestic preparation of French fries is not well controlled and can result in increased exposure of population to acrylamide. Blanching seems to be the most simple and applicable treatment which can be practiced at households to reduce acrylamide threat from domestically prepared potato products, if coordinated properly.

\textbf{Fermentation}

Fermentation is an important process in the preparation of leavened baked products from wheat flour. Fermentation with yeast has been reported to reduce asparagine and subsequently the acrylamide formation in bread. Wang et al.\textsuperscript{104} have reported that about 40–60\% asparagine can be reduced with yeast fermentation while the contents of reducing sugars are increased. However, sourdough fermentation negatively affects the utilization of asparagine by yeast and can result in increased amounts of acrylamide.\textsuperscript{105} Acid fermentation in potatoes increases asparagine contents and reduces the contents of reducing sugars, thus resulting in decreased acrylamide contents.\textsuperscript{106} The fermentation process, type of microorganisms and their interactions are important factors that affect the amount of acrylamide reduction. Bartkiene et al.\textsuperscript{75} evaluated the acrylamide reduction in biscuits (supplemented with flaxseeds and lupine) through solid-state (SSF) and submerged (SMF) fermentation. For this purpose, different types of microorganisms (including \textit{Lactobacillus sakei}, \textit{Pediococcus pentosaceus}, and \textit{Pediococcus acidilactici}) were evaluated. The type of fermentation process and microbial strain significantly influenced the acrylamide...
formation. For instance, *Pediococcus acidilactici* was found to be more effective in reducing acrylamide contents in flaxseed, through SMF by 78% and lupine, through SSF by 85%. Other reports of acrylamide reduction through fermentation have been published by Akkılıoğlu and Gökmen\[77\] and Bartkiene et al.\[107\] for coffee and lupin-supplemented bread, respectively.

**Plant extracts**

Various plant extracts (rich in phenolics and antioxidants) have been investigated as inhibitors of acrylamide formation in model and food systems. However, contrasting results of their effects on acrylamide inhibition have been reported. This might be due to specific roles played by factors arising from different types of food ingredients. Vattem and Shetty\[108\] have proposed that acrylamide formation is non-oxidative in nature and thus the presence of exogenous phenolics can increase the formation of acrylamide. However, most of the studies on plant extracts have reported a significant decrease of up to 60% in acrylamide from various plant extracts including green tea, bamboo, mint, berry, and pomegranate flower.\[80,81,109,110\] Their inhibitory role mainly depends on the type of antioxidants in the extracts, their concentration and purity.\[111\]

**Conclusion**

Since the detection of acrylamide in foods, significant progress has been made in understanding its formation mechanism during processing, sources of occurrence in different foods as well as their exposure assessments. Exposure varies with age-group and decreases with increasing age, where potato and cereal-based products are reported to be the major contributors to exposure. Continuous exposure for longer times can affect metabolism, reproduction, and normal cell division. It can also lead to neurotoxicity and cancer. Reduction of acrylamide in different food products through various approaches has been extensively explored. For this purpose, process variables, novel and integrated processing techniques, use of additives, and different pre- and post-processing treatments have been reported in several studies. However, approaches useful for one product might not be applicable to other products due to variable compositions and different product technologies. Hence, there is a need to identify the most appropriate solution for respective products. Moreover, public awareness and sensitization about dangers of acrylamide along with possible ways to reduce its formation needs to be increased.

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