Mitigation Strategies to Reduce Acrylamide Formation in Fried Potato Products

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Potato products contain high amounts of acrylamide, which sometimes exceeds the concentration of 1 mg/L. However, many strategies for acrylamide reduction in potato products are possible. In this work, the different approaches for reducing acrylamide formation have been reviewed, keeping in mind that in the application of strategies for acrylamide formation, the main criteria to be maintained are the overall organoleptic and nutritional qualities of the final product.

Key words: acrylamide; potato; mitigation

Agronomic Strategies. Minimizing Reactants in the Potato Tuber

During the first studies of acrylamide formation in food, researchers reported that starch-derived products are very prone to the formation of acrylamide at concentrations up to 5 mg/kg.1 One of the first lessons we learned from the systematic analysis of acrylamide in food was that there is a large variability in acrylamide content between different final products from the same food commodities, even among different lots from the same commercial brand.1 This observation gives us some clues that there are opportunities to reduce acrylamide formation by first focusing on the raw material composition and second on the processing conditions.

The strong tendency for acrylamide to form in potatoes is because of the high levels of free asparagine (0.2–0.4% dry weight, representing 20–60% total amino acids content), compared to the amount of reducing sugars in the potato tuber, which actually represents the limiting factor. In addition, there is a significant relationship between acrylamide formation and reducing sugar (glucose, fructose) content, regardless of the potato tuber variety, under the same processing conditions.2–7 On the other hand, sucrose content has been found to have less correlation with acrylamide content.3

Reduction of sugar content in the potato tuber (Solanum tuberosum ssp. tuberosum L.) was proposed as the first strategy for acrylamide minimization because sugar is the limiting reactant. The results of studies have recommended using potato cultivars with a low reducing sugar content, such as Panda, Saturna, and Lady Clare, which are less susceptible to acrylamide formation when deep frying potato crisps, or the varieties Agria, Markies, and Fontane for French fries and hash browns.2,3,5,8 About 4000 cultivars are listed in the World Catalogue of Potato varieties, but only a few of them have acceptable sensory and nutritional quality after processing and should be considered for consumption. The sugar content of potatoes is determined by the genotype and several preharvest and postharvest factors. The major preharvest factors affecting sugar content are crop maturity, temperature during growth, mineral nutrition, and irrigation, while important postharvest factors are mechanical stresses and storage conditions.10 Aspartic acid, asparagine, glutamic acid, and glutamine show no significant correlation with the acrylamide concentration in the processed products.10

Potatoes used for roasting or frying should contain less than 1 g/kg fresh weight of reducing sugars.7,11 In this framework, a genetically modified potato variety was recently produced in the United States by inhibiting the expression of some specific genes that are responsible for low-temperature sweetening.12

However, other farming conditions could influence the sugar content of the same potato variety. A relationship between the fertilization method and the susceptibility to acrylamide

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Nitrogen appears to be indirectly related via its effects on dry matter and relative maturity of harvested tuber. Plants with adequate nitrogen fertilization produce tubers with lower reducing sugar concentration at harvest and accumulate less reducing sugars during storage. An excess in nitrogen intake by fertilization leads to the biosynthesis of more free asparagine, thus lowering the reducing sugar content since they are used by the tuber for the biosynthesis of amino acids. Consequently, decreasing nitrogen fertilization causes a reduced sugar content which reduces the potato’s quality for frying. However, there are other factors that must be considered regarding potato farming, and other conditions, such as type of soil, will influence nutrient uptake and metabolism by the plant.

Climatic conditions also affect the reducing sugar and asparagine content. Dry summers give rise to a lower reducing sugar content, and temperatures above 25°C result in elevated sugar levels because increased respiration has a negative effect on the rate of starch biosynthesis. Consequently, the level of reducing sugars will be lower at intermediate temperatures (15–25°C). Low temperatures during the final growing stage result in unacceptably high sugar levels, and excessive rainfall in the final stages of the growing season gives rise to a lower dry-matter content and to an increase in nitrogen uptake. Finally, it has been shown that weather conditions during the growing season influence biochemical reactions as well as nutrient uptake by the roots.

Inadequate potato storage conditions also represent a risk; starch can be hydrolyzed, forming high concentrations of free sugars in the tuber, and this will lead to the formation of acrylamide and an excessive Maillard reaction upon frying. Senescent sweetening occurs with long-term storage after harvest, and this involves an increase in the sugar content inside the tuber. This process is enhanced at storage temperatures higher than 8°C, and it results in potato sprouting. Low temperatures mobilize sugars from starch in a process known as low-temperature sweetening. Sucrose can be used as an indicator for the reducing sugar potential in enzymatic cleavage and thermal breakdown, and the concentration of reducing sugars is used as a criteria for accepting or refusing potato batches at industrial plants. The level of sucrose should be low to minimize accumulation of reducing sugars, which is an index of tuber maturity. During cold-induced sweetening in stored potatoes, starch degradation occurs primarily through the action of starch phosphorylase. Use of sprout suppressant will limit the need to use low temperatures during storage. Low-temperature sweetening is partly reversible after reconditioning the cold-stored tubers for some weeks at 15°C.

Former variables are further affected if potatoes are not stored in the dark because light activates sugar metabolism. Finally, low oxygen levels in the storage atmosphere inhibit the cold-induced enzymes and consequently decrease the level of reducing sugars in the product.

### Processing Strategies. Controlling Variables during Deep Frying

Many stages prior to potato frying can be modified in order to reduce acrylamide formation. There are several minimization strategies related to pre-frying operations and most of them focus on the elimination of reducing sugars from the reaction media. It is well known that incorporation of aqueous pre-treatment steps (rinsing, soaking, blanching) of potato slices will lead to a reduction in acrylamide content. Treatment with various concentrations of citric acid before frying suppresses acrylamide in fried potatoes, but there are many concerns about sour flavors in the resulting products.

Soaking potato slices in distilled water for up to 90 min will reduce sugar content by about 30% from precursors leaching. However, blanching (soaking at moderate temperatures) is more effective and has been shown to reduce glucose by 76% and asparagine by 68%, which results in a very significant reduction in acrylamide and a significant loss of texture. Blanching induces gelatinization of the surface starch, reducing oil uptake, but a negative impact on the overall quality is expected.

Addition of certain additives, which reduce the pH of the water, will limit the formation of acrylamide. Immersion of potatoes in up to 2% organic acids (e.g., citric acid) decreases the pH, which reduces the formation of acrylamide at moderate temperatures of frying. Surprisingly, this effect was not observed at higher temperatures of frying. Several studies have demonstrated that pH modification has the potential to reduce acrylamide formation in food and model systems. Lowering the pH of food to reduce acrylamide generation results from protonation of the alpha-amino group of asparagine, which then cannot engage the nucleophilic addition to the available carbonyls. The acrylamide molecule contains an active double bond,
which may interact with food ingredients, mainly proteins. The addition of protein-rich components from meat will reduce acrylamide by 70%, and this is likely because of the reaction of protein nucleophilic groups (-SH, NH₂) with the acrylamide double bond.²³

Recently, an inhibition of acrylamide formation in asparagine–glucose model system by NaCl addition has been shown.²⁶ NaCl catalyzes the process of acrylamide polymerization and the subsequent formation of polyacrylamide. Addition of 1% NaCl (common additive in many foods) is enough to promote significant polymerization.²⁷

Recently, Pedreschi et al.²⁶ reported that soaking solutions of potato slices in NaCl before frying dramatically reduces acrylamide formation by about 90% compared to control chips. In contrast to the experiments with the potato model system²⁹ but in accordance with previous reports,²⁶,³⁰ Mestdagh et al.³¹ confirmed that soaking potato slices in NaCl solutions significantly decreases the acrylamide content and reported that the oil content is also significantly reduced (27%) by NaCl addition (0.1%) to the blanching water. Acrylamide formation has been shown to decrease upon lowering the oil content of the potato model system, probably from a lower heat transfer from the oil to the system.³² Therefore, decreased oil uptake seems a possible mechanism behind acrylamide reduction in the NaCl-treated crisps.

Recent studies have demonstrated that polyvalent cations also reduce acrylamide formation in thermally processed snack foods and bakery products.³³,³⁴ Gökmen et al.³⁵ investigated the potential formation and degradation of acrylamide during heating in the presence of monovalent and divalent cations. Dipping potatoes into calcium chloride solution inhibits the formation of acrylamide by up to 95% during frying without adversely affecting the sensory quality of fried potato strips (in terms of color and texture). The inhibition was attributed to the presence of monovalent or divalent cations rather than to the reduction of acrylamide precursors by dipping. Gökmen and colleagues postulated that the presence of Ca²⁺ would prevent the formation of the Schiff base of asparagines, and thus of acrylamide, during heating. Similar results were found by Mestdagh et al.³¹ who showed that dipping potato slices in CaCl₂ solution mitigates acrylamide formation, although only a marginal decrease was observed at the lowest concentration level (0.025 mol/L). As opposed to Gökmen et al.,³⁵ a more crispy texture and a bitter aftertaste at higher Ca²⁺ concentrations was perceived by panelists. It is interesting that several additives, such as organic acids, NaCl, and Ca²⁺, are able to lower the absorption of oil when frying. This fits perfectly with the ongoing consumer trend to move toward healthier and low-fat products in order to counteract obesity and coronary heart diseases. Some other questions, such as the rate of oil degradation during frying when salts are added³⁶,³⁷ and the consequent more rapid oil turnover rate, need to be further investigated because of the impact on process and production costs at the industrial scale.

Another mitigation strategy for acrylamide formation in foods is the use of the enzyme asparaginase (L-asparagine amidohydrolase), which catalyzes the hydrolysis of asparagine in aspartic acid and ammonia. From a theoretical point of view, this approach seems to be more useful for cereal products where asparagine is known to be the limiting factor in acrylamide formation. In fact, in potatoes, the content of free asparagine does not correlate with potential acrylamide formation,⁴,⁹,³⁸ whereas a highly significant correlation between the content of reducing sugars and acrylamide has been observed.² In raw tubers, the molar concentration of asparagine exceeds that of reducing sugars, the latter are also consumed faster during heating.²,³,⁸,³⁹ Nevertheless, when Zyzak et al.³⁰ evaluated the effectiveness of the asparaginase treatment in a mashed potato product that had been cooked by microwave, they found that asparaginase pretreatment results in an 86% reduction in asparagine and greater than 99% reduction in acrylamide compared to samples prepared without the enzyme. A constraint of this approach in limiting acrylamide formation is the limited availability and high cost of asparaginase, while questions remain about the contribution of free asparagine and aspartic acid to the flavor profile (e.g., pyrazines) and to nutritional aspects, as well as country-specific regulatory approval of the enzyme. Two commercial products, Acrylaway® (asparaginase form Aspergillus oryzae) from Novozyme ( Bagsvaerd, Denmark) and PreventASe® (asparaginase form A. niger) from DSM (Delft, Netherlands), are on the market for food applications that have been proven to reduce acrylamide in dough-based products without influencing product taste or appearance.

Surface to volume ratio is also important because acrylamide formation is a surface phenomenon. Both home-made and industrially prepared French fries are usually cuts with different geometries. Matthäus et al.⁴¹ demonstrated that a surface to volume ratio of 3.3:1 cm⁻¹ results in a significantly lower amount of acrylamide than fine strips with a ratio of 5.4:1 cm⁻¹. Another factor to consider is the ratio of potato to oil mass, which is recommended to be less than 10%. This recommendation is important for catering services and home-frying processes.
where the ratio of potato to oil is not standardized and the heat load could be very different from one piece of potato to the other. Drying potatoes by microwave or hot-air treatment before frying results in a significant reduction in oil content, and, in these conditions, acrylamide is reduced by 44%.\textsuperscript{22,43} It should be stressed that moisture content is an important quality parameter of potato crisps, which should be crispy not only after frying but also during the shelf life of the product; many investigations have not considered this aspect.

The influence of temperature on the formation of acrylamide has been repeatedly demonstrated.\textsuperscript{44,45} Frying potatoes is based on heat transfer from the hot oil, which results in water removal and oil uptake by the potato. It has been shown that the acrylamide content of potato strips first increases exponentially with time, depending on temperature.\textsuperscript{23} After prolonged heating, a decrease in the acrylamide content is observed because acrylamide degradation predominates. The acrylamide yield is the net result of simultaneous formation and elimination reactants and it can be modeled by consecutive first-order reactions.\textsuperscript{46} Controlling the temperature and time of frying will have a major effect on acrylamide reduction in potato products, but this could have a negative effect on perceived product quality; it may also be difficult to introduce on a home scale. Temperature and time can be precisely controlled at industrial plants but only partly controlled at home. For instance, there are differences in the heat transfer inputs and electrical potency of domestic fryers, whereas these are exhaustively controlled at the industrial scale, and initial and end-frying temperatures of the process remain almost constant. It can be concluded that for home preparation, strategies concerning the choice of suitable potato varieties or cultivars will be more effective to reduce the acrylamide content.

Choice of the frying oil is an important aspect for deep frying. Frying oil not only acts as a heat transfer medium but also contributes to the taste and aroma of the potato fries. Some studies have focused on the effect of the type of frying oil on acrylamide formation in the product. Matthäus et al.\textsuperscript{41} did not find differences in acrylamide formation in French fries because of the type of frying oil, and similar results were reported by Mestdagh et al.\textsuperscript{32} However, Gertz and Klostermann\textsuperscript{47} found higher amounts of acrylamide in French fries fried with palmolein compared to rapeseed or sunflower oil. On the other hand, the type of oil has an influence on the shelf life and the stability of the frying medium during processing. Matthäus et al.\textsuperscript{41} did not find a relationship between acrylamide formation and the aging of the frying oil or the addition of silicon oil as an antifoaming agent. Recently, Mestdagh et al.\textsuperscript{38} reported that the heat transfer properties of the frying oil (from oxidative or hydrolytic oil degradation) change to such an extent that acrylamide formation during the preparation of French fries would be significantly influenced. In addition, oil degradation products (glycerol, monoacylglycerols, and diacylglycerols) do not influence acrylamide formation because acrylamide formation is independent of oil oxidation and hydrolytic status. This conclusion is important since it was suggested that triacylglycerols are partially hydrolyzed during frying, followed by dehydration of glycerol to acrolein. Acrolein may be oxidized to acrylic acid, which can finally react with ammonia to form acrylamide.\textsuperscript{47,49}

The consumer’s perception of color, flavor, and crispness should be unaffected by a reliable acrylamide mitigation procedure. Frying time should be adjusted to keep final moisture content below 3% to obtain desirable crispness. Lowering water activity at the surface of products for prefrying was proposed as a means of acrylamide reduction.\textsuperscript{30} It has been reported that low frying temperatures result in moderate acrylamide concentrations despite the longer frying times, whereas temperatures above 170°C enhance acrylamide formation and enhance color.\textsuperscript{31} On the other hand, frying at temperatures below 170°C will increase fat uptake, and the potato will become soft. It is suggested that the frying temperature should be below 175°C and the frying time should not be longer than necessary to obtain the right quality parameters of fried products. Therefore, a lower frying temperature will negatively influence the fat content and the moisture of crisps. Alternative heat treatments are under investigation. Granda et al.\textsuperscript{50} performed vacuum frying experiments between 118 to 140°C at a vacuum pressure of 1333 Pa. Vacuum frying reduces acrylamide formation by 94% without important changes in the organoleptic parameters of the potato.

Finally, post frying treatment has also been considered. Kita et al.\textsuperscript{31} reported that applying a postdrying step after frying results in a decreased acrylamide content in crisps. When crisps were fried in oil at 185°C, it was possible to obtain a 70% decrease of acrylamide content after 2 min of frying and 75 min at 105°C of postdrying.

Acrylamide is a very polar, low mass, and volatile substance. These particular properties could be used to eliminate it after processing. A combination of adequate temperature and vacuum after the frying process could be an alternative for removing acrylamide from the matrix. However, there are many
FIGURE 1. Acrylamide formation from asparagine and glucose. The R-NH2 group of asparagine participates in a nucleophilic-addition reaction with the aldehyde group of glucose to form a Schiff base, which then undergoes an Amadori rearrangement to the shown glucose–asparagine derivative (N-glycoside). The latter can then undergo decarboxylative deamination, losing the COOH and R-NH2 groups associated with asparagine to form acrylamide. Addition of glycine can reduce acrylamide level in two ways: (1) competing effectively with asparagine in the Maillard reaction or (2) reacting with acrylamide after its formation.

issues that should be overcome, such as loss of flavor or fragility of the potato crisp, which probably breaks. Such an alternative is possible, however, because even though the vapor pressure of acrylamide is low (i.e., 0.93 Pa at 25°C, 9.3 Pa at 50°C), it has been measured in air. On the other hand, it has been reported that acrylamide, added to foods before heating, is not completely recovered in analysis, so it appears that acrylamide is eliminated either by further reactions (addition reactions or polymerization) with food components or evaporates during heating.

Therefore, it is possible that adopting postfrying steps will reduce the concentration of acrylamide but may also reduce the concentration of many volatile products, thus affecting the sensorial quality of the final product.

Inhibition of the Reaction by Competitive Compounds toward Reducing Sugars Instead of Asparagine

It is well known that acrylamide is mainly formed from asparagine and reducing sugars through the Maillard reaction (Fig. 1). The first step is the...
TABLE 1. Effect of the addition of glycine or other amino acids on acrylamide formation in the potato model system or potato-based foodstuffs

<table>
<thead>
<tr>
<th>Authors</th>
<th>Amino acids used</th>
<th>Effect on acrylamide content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kim et al.</td>
<td>Glycine, lysine, cysteine</td>
<td>Addition of 0.1 and 0.5% glycine to pallets reduced acrylamide concentration by 43% and by more than 70%, respectively; soaking potato slices in a 3% solution of either lysine or glycine reduced the formation of acrylamide by more than 80% in potato chips fried for 1.5 min at 185°C</td>
</tr>
<tr>
<td>Claeys et al.</td>
<td>Cysteine, lysine, alanine, and glutamine</td>
<td>Addition of cysteine and lysine to the asparagine–glucose model system heated at 140–200°C lowered acrylamide yield. Alanine has no effect while glutamine increased acrylamide yield</td>
</tr>
<tr>
<td>Rydberg et al.</td>
<td>Various amino acids or protein-rich components</td>
<td>Addition of several amino acids or a protein-rich component to potato slurries decreased acrylamide content by more than 80%; glycine and glutamine were almost twice as effective as alanine, lysine, and glutamic acid in suppressing acrylamide levels at low concentrations</td>
</tr>
<tr>
<td>Brathen et al.</td>
<td>Glycine and glutamine</td>
<td>Addition of glycine and glutamine to a starch model system, reduced acrylamide formation by 30% compared to no addition while no effect was found in French fries</td>
</tr>
<tr>
<td></td>
<td>Glycine</td>
<td>Addition of glycine to a model system consisting of starch, asparagine, and glucose decreased acrylamide content upon prolonged heating treatment</td>
</tr>
<tr>
<td>Low et al.</td>
<td>Glycine</td>
<td>Addition of glycine to a potato model system reduced acrylamide content, increased the total volatile yield by promoting the formation of certain alkylprazines</td>
</tr>
<tr>
<td>Mestdagh et al.</td>
<td>Glycine and lysine</td>
<td>Addition of glycine and lysine reduced acrylamide formation in potato slices (up to 85%) by addition to the blanching water. No effects on pH and oil content. Strong effect on browning</td>
</tr>
</tbody>
</table>

reaction between the alpha-amino group of the free asparagine and a carbonyl source, forming a Schiff base. Results from mechanistic studies indicate that the side-chain amide group of asparagine is incorporated in the amide bond of acrylamide.\(^4,30,56\)

From this reaction pathway, it is clear that one possibility for reducing acrylamide formation is to use compounds able to compete with asparagine for carbonyl groups; this means, in particular, other free amino acids (e.g., glycine) or proteins. As a matter of fact, among the several patent applications for the reduction of acrylamide in heat-treated foodstuffs, applications based on the addition of amino compounds, including amino acids, have been proposed.\(^37,38\)

Amino acids may compete effectively with asparagine in the Maillard reaction or may react with acrylamide after its formation (FIG. 1). Acrylamide has two reactive sites, the conjugated double bond and the amide group, and can thus be eliminated by reaction with numerous food constituents. In this sense, other nucleophilic compounds could work in this way and lead to a reduction in acrylamide content.

In a model system consisting of starch, asparagine, and glucose, acrylamide content decreases upon prolonged heating,\(^23\) indicating that acrylamide reacts with amino acids. The reaction of acrylamide with the amino group of glycine was demonstrated previously,\(^59\) and the effects of amino acids on acrylamide formation and elimination have been extensively studied (see TABLE 1).

Claeys et al.\(^46\) reported that the addition of cysteine and/or lysine to the asparagine–glucose model system and heated at temperatures between 140 and 200°C significantly lower the acrylamide yield. According to the activation energies for acrylamide formation and elimination when these amino acids are added, Claeys and colleagues concluded that lysine would act mainly by competing with asparagines in the Maillard reaction while cysteine would increase the elimination rate of acrylamide by reacting with its SH group and forming cysteiny1-S-β-propionammide. SH groups are reported to be 100–300 times more reactive than amino groups with conjugated vinyl compounds,\(^59\) while cysteine is classified as an amino acid with low reactivity in the Maillard reaction.\(^60\) As such, sulfur amino acids or sulfhydryl compounds could reduce acrylamide content in heated foods. Unfortunately, their use is restricted by the unpleasant off-flavors they can generate in foods. The same authors reported that addition of alanine to the same model system has no effect on acrylamide yield, while glutamine increases the rate
et al. used homogenized potato slurries and found that the addition of glycine reduced the formation of acrylamide by more than 80% in potato chips fried for 1.5 min at 185°C; however, a significant reduction (more than 40%) is obtained by using 0.1 or 0.5% lysine and glycine solutions. Of course, the overall inhibitory effect results from both the leaching of acrylamide precursors and the competitive action of amino acids. The same authors reported that the addition of lysine and glycine to potato model snacks before frying reduces the acrylamide content upon heating. In particular, the addition of 0.1 and 0.5% glycine to potato slices reduces acrylamide concentration by 43% and by more than 70%, respectively.

Rydberg et al. examined the effects of various amino acids on the formation of acrylamide in homogenized potatoes heated at 180°C for 25 min. The addition of glycine, alanine, lysine, glutamine, and glutamic acid at a concentration of 35 mmol/kg was found to reduce acrylamide levels by 42% to 70%. They also demonstrated that glycine and glutamine are almost twice as effective as alanine, lysine, and glutamic acid in suppressing acrylamide levels at low concentrations. Rydberg and colleagues also investigated the effect of protein addition (lean fish) to potato patties. Like free amino acids, proteins were found to significantly lower acrylamide content, as already reported by several authors working on different matrices. Proteins could act both by inhibiting acrylamide formation reaction and eliminating acrylamide formed via reaction with amino and/or sulfhydryl groups of amino acid side chains. For that purpose, Rydberg et al. added different amounts of minced cod to potato slurries and obtained a reduction of up to 70% of acrylamide content after heating.

Similar results were found by Vattem et al., who used chickpea butter to coat potato chips during frying. They postulated that proteins might also be involved in complexing starch on the surface of the slices and stabilizing the complex even at higher temperatures, making the sugars in the starch less available for the Maillard reaction. The legume proteins may also be involved in delocalizing the electrons from the sugar carbonyl via their aromatic amino acids. This delocalization prevents the keto-enolization of the sugars and, therefore, the breakdown of the six-carbon chain to hydroxyacetone, which eventually may form acrylamide through a series of condensation reactions.

Bråthen et al. found that the addition of glycine and glutamine during blanching of crisps reduces the amount of acrylamide by 30%, but no effect was found on French fries. Furthermore, they found that glycine is more effective than glutamine in reducing acrylamide, while Rydberg et al. found comparable effects for both amino acids. This apparent discrepancy could be explained by the different systems used. Rydberg and colleagues used homogenized potato slurries with amino acids added during the homogenization, which ensured that the amino acids were evenly distributed. On the other hand, in common industrial conditions, potato crisps are made from sliced potatoes and are not reconstituted. In the nonreconstituted potato crisps, the amino acid has to enter the potato tissue, and glutamine, being larger than glycine, will be transported more slowly into potato tissues. All in all, glycine is known to be more reactive in the Maillard reaction than glutamine, which may be of importance if the effect from the addition of glycine is caused by competition in the Maillard reaction. However, a reaction between glycine and the acrylamide previously formed seems to be the more likely cause of the decrease in measured acrylamide content when glycine is added.

As the Maillard reaction plays a major role in acrylamide formation, its suppression would, therefore, reduce the levels of acrylamide. However, the Maillard reaction is also a major route for the generation of desirable flavors and colors in food, ensuring the sensory quality expected by consumers. It is important to study the relationship between flavor generation, taste, and acrylamide production to develop a strategy to minimize acrylamide without adverse effects on the flavor and taste of foods. In this respect, Low et al. studied the effect of treatment with citric acid or glycine on the volatile profile and acrylamide levels in a potato model system. After cooking at 180°C for 10–60 min, these treatments were found to affect the volatile profiles and, in particular, Strecker aldehydes and alkylpyrazines, key flavor compounds of cooked potato. Citric acid limits the generation of volatiles, particularly the alkylpyrazines. Glycine increases the total volatile yield by promoting the formation of certain alkylpyrazines, namely 2,5-dimethylpyrazine, trimethylpyrazine, 2-ethyl-3,5-dimethylpyrazine, tetramethylpyrazine, and 2,5-diethyl-3-methylpyrazine. However, the formation of other pyrazines and Strecker aldehydes is suppressed. The authors concluded that a combined treatment of lower levels of citric acid and glycine would have less impact on the flavor profile than a higher
TABLE 2. Effect of the addition of antioxidants on acrylamide formation in different matrices and food models

<table>
<thead>
<tr>
<th>Authors</th>
<th>Antioxidant used</th>
<th>Foodstuff</th>
<th>Effect on acrylamide content</th>
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<tbody>
<tr>
<td>Becalski et al.</td>
<td>Rosemary herb</td>
<td>Oil used to fry potato slices</td>
<td>Reduction of acrylamide formation</td>
</tr>
<tr>
<td>Fernández et al.</td>
<td>Liquid spice mix rich in flavonoids</td>
<td>Potato slices before and after frying</td>
<td>Reduction by up to 50%</td>
</tr>
<tr>
<td>Biedermann et al.</td>
<td>Ascorbic acid</td>
<td>Potato-based model system</td>
<td>Weak inhibition</td>
</tr>
<tr>
<td>Zhang et al.</td>
<td>Different solutions of antioxidant of bamboo leaves (AOB)</td>
<td>Potato crisps and French fries</td>
<td>Reduction of 74.1% and 76.1% when AOB addition ratio was 0.1% and 0.01% (w/w); no significant effects on crispness and flavor</td>
</tr>
<tr>
<td></td>
<td>Different solutions of AOB or extract of green tea (EGT)</td>
<td>Fried chicken wings</td>
<td>Nearly 57.8 and 59.0% reduction with addition ratios of 0.1 and 0.5% (w/w), respectively</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fried bread sticks</td>
<td>Nearly 82.9% and 72.5% reduction with AOB and EGT addition levels of 1 and 0.1 g/kg, respectively; no significant effects on crispness and flavor</td>
</tr>
<tr>
<td>Tareke et al.</td>
<td>Butylated hydroxytoluene, sesamol, Vitamin E</td>
<td>Meat</td>
<td>Enhancement of acrylamide formation</td>
</tr>
<tr>
<td>Vattem et al.</td>
<td>Phenolic antioxidants from cranberry and oregano</td>
<td>Fried potato slices</td>
<td>Slight increase</td>
</tr>
<tr>
<td>Rydberg et al.</td>
<td>Ascorbyl palmitate and sodium ascorbate; benzoil peroxide and hydrogen peroxide</td>
<td>Homogenized potato heated in an oven</td>
<td>Effect on acrylamide content small or nonexistent</td>
</tr>
<tr>
<td>Levine et al.</td>
<td>Ferulic acid, ascorbic acid</td>
<td>Model system based on wheat flour and water; resembled crackers</td>
<td>Reduction of acrylamide formation; increasing acrylamide elimination</td>
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</tbody>
</table>

level of either treatment on its own, which would be needed to achieve the same reduction in acrylamide. Low and colleagues also suggested the possibility of using a combination of different amino acids to boost the desired Strecker aldehydes and alkylpyrazines and at the same time mitigate acrylamide levels.

In a similar way, Mestdagh et al. investigated the effect of the addition of free glycine and L-lysine to potato crisp blanching water at different concentration levels. They showed that the addition of these components did not markedly change the pH of the potato at a low concentration (0.05%) as they had previously pointed out. At this concentration level, these additives markedly influence the final oil content of the crisps, compared to the control. L-lysine appeared to more efficiently reduce the formation of acrylamide (by up to 85%), although the differences are less pronounced at the 0.05 and 0.025 mol/L concentration levels. However, the authors found that this treatment strongly affects the color of the final product. Darker products are obtained upon frying when glycine or L-lysine is added to the blanching water. This difference is most pronounced for L-lysine, which is not surprising because L-lysine is known to be very reactive in the Maillard reaction. Moreover, at the applied concentrations, both amino acids could counteract the inhibition of browning caused by the addition of acetic or citric acid.

Many other authors have reported an increased browning of their potato model system when glycine was added, and the same effect has been reported by several authors for bread and cereal products. All in all, it is possible to conclude that the use of amino acids, and particularly of glycine, represent an attractive and promising strategy to reduce acrylamide formation in potato-based products.

Affecting Some Steps of the Reactions by Addition of Chemically Reactive Compounds that are Able to React with Intermediates

A significant part of mitigation research has consisted of studies testing the effects of the addition of chemically reactive compounds to potatoes. Most of these compounds are antioxidants, which are used in pure form, added as vegetable extracts, or present in whole spices.
It is difficult to draw firm conclusions from these studies as the reports published thus far have reported conflicting evidence. In some cases, retarding effects have been demonstrated with spice extracts, but it is clear that the effect is not necessarily a result of antioxidative properties of those additives. The main studies dealing with the effects of antioxidants on acrylamide formation are summarized in Table 2.

Zhang et al. observed that 74.1% and 76.1% of acrylamide is reduced in potato crisps and French fries, respectively, dipped into different solutions of antioxidants of bamboo (AOB), a pale brown powder extracted from bamboo leaves. The reduction depends on the AOB addition:product ratio and on immersion time. Sensory evaluation results showed that organoleptic features of products are not affected by the treatment; the crispness and flavor of the potato crisps and French fries processed by AOB solutions are not significantly different from the normal potato matrix when the AOB solution to product ratio is <0.05%. Similar results were found by the same authors in other foodstuffs, such as fried chicken wings and fried bread sticks. Thus, the addition of plant extracts could be a possible technique for reducing acrylamide in many products. Becalski et al. found that acrylamide could be reduced when adding rosemary herb to the oil used for frying potato slices. It should be noted, however, that these findings could not be confirmed by others. Rosemary is known for its antioxidant content, but this effect could also be a result of many other factors. A decreasing effect of a flavonoid spice mix has also been reported by Fernández et al. A liquid spice mix was added to potato slices before frying, and a powder spice mix was also added to the potato slices after frying. The acrylamide levels were reported to be reduced by up to 50% by the spice-mix treatment. Biedermann et al. showed a weak inhibition effect upon addition of ascorbic acid to a potato-based model.

The ability of ferulic acid to inhibit acrylamide formation was attributed to its ability to react with acrylamide precursors or intermediates in the chemical process of its generation. The same authors reported that ascorbic acid is effective in increasing acrylamide elimination and decreasing the net amount of acrylamide formed in a wheat–water model system when baked at 180°C. In one pivotal study, Tareke et al. found that the addition of antioxidants (butylated hydroxytoluene, sesamol, vitamin E) to meat before heating enhances the formation of acrylamide. This author introduced the hypothesis that antioxidants might protect the acrylamide from further radical-initiated reactions. On the other hand, studies of the effect of the antioxidant compounds present in the oil on acrylamide formation are scarce. It is possible that the minor oil components tocopherols, phenols, and sterols can influence acrylamide formation during the exposure of potatoes to these oils at high temperatures.

Vattew et al. reported that formation of acrylamide in fried potato slices previously treated with phenolic antioxidants from cranberry and oregano or cooked in chickpea batter is not reduced but actually increases when exogenous phenolic is present. Based on these results, authors hypothesized a nonoxidative model for the formation of acrylamide in fried products. Rydberg et al. to investigate the effects of antioxidants on acrylamide formation, used two antioxidants, ascorbyl palmitate and sodium ascorbate, as well as oxidants, such as benzoil peroxide and hydrogen peroxide, in homogenized potato heated in an oven. They found that the effect on acrylamide content is small or nonexistent, thus suggesting that involvement of radicals or peroxidation in the formation of acrylamide may be of some, but only minor, importance; low levels of antioxidants cause a small increase, probably via protection of the acrylamide formed.

Conclusions and Future Perspectives

Many studies have attempted to find strategies to minimize the levels of acrylamide in different food commodities. This objective can be achieved either by modifying processing parameters, such as pH, temperature or time of heating, acting on precursors or key intermediates, or reducing concentration of reactants in the raw material as formerly discussed. Strategies to reduce acrylamide formation should maintain the overall organoleptic, nutritional properties, and microbiological safety of the food during its shelf life. Different approaches have been investigated to reduce the formation of acrylamide in food, but, in reality, only few of them could be implemented without any significant alteration of the food product.

It is very likely that the total elimination of acrylamide from fried products cannot be achieved. Then, the ALARA principle (as low as reasonably or technically achievable) should be applied by the different actors. And, as outlined in this review, there are many different opportunities to reduce acrylamide in fried potatoes. However, potential negative effects on the sensory characteristics of the final product have to be carefully evaluated. In this context, there will not be a unique strategy, and a combination of agronomical selection and lighter processing conditions will significantly
reduce the levels of acrylamide in the final product at an industrial level. Additional strategies should be implemented on the domestic scale, mainly focused on processing conditions. We should keep in mind that the overall objective is to reduce the acrylamide intake, and many sources of acrylamide come from foods processed at home. Consumers must be aware that it is important not to fry in excess and to limit the excessive intake of over-fried products. Also, information on potato varieties particularly suitable for frying and recommendations about potato home storage should be released.

In conclusion, the reduction of the overall intake of acrylamide is not only a food company’s task; in fact, companies must implement an intensive mitigation strategy for different food items. The onus also falls on the final cooks who should be aware that it is their responsibility to serve customers and/or relatives foods having a low acrylamide content.

Conflict of Interest
The authors declare no conflicts of interest.

References

Acrylamide in Potato Products


