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Formation, Properties, and Reduction Methods of Acrylamide in Foods: A Review Study

Arezou Khezerlou[1], Mahmood Alizadeh-Sani[2], Nasim Zolfaghari Firouzsalari[3], Ali Ehsani[4*]

1. Talented Students Center, Students Research Committee, Department of Food Sciences and Technology, Faculty of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz, Iran
2. Students Research Committee, Department of Food Sciences and Technology, Faculty of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz, Iran
3. Students Research Committee, Department of environmental health engineering, faculty of health, University of Medical Sciences, Tabriz, Iran
4. Nutrition Research Center, Department of Food Sciences and Technology, Faculty of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz, Iran

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ABSTRACT

Introduction: Acrylamide is a chemical compound that may form in various starchy foods, such as potatoes, bread, and bakery products at high temperatures (above 120°C) and during cooking processes. This compound has been identified by the International Agency for Research on Cancer as a potential cancer-causing compound. The present study aimed to investigate the formation of acrylamide from food components during heat treatment as a result of the Maillard reaction between amino acids and reducing sugars.
Methods: A comprehensive literature review was conducted via searching in databases such as Google Scholar, Science Direct, Pub Med, and SID using English or Persian keywords, such as acrylamide and food.
Results: Since acrylamide is found in food products, there have been several reports on the presence of acrylamide in fried and oven-cooked foods, which have led to worldwide concern. Acrylamide has been classified as a possible mutagenic and carcinogenic compound in humans. Moreover, several reports have indicated that asparagine (a main amino acid found in potatoes and cereals) is a decisive contributor to the production of acrylamide through reducing sugars. In this review, we investigated the formation of acrylamide and various methods for its prevention and reduction.
Conclusion: Considering the toxicity of acrylamide and its health risks for humans, and given the importance of food safety and health issues, a few methods could be used to decrease the formation rate of this harmful compound in susceptible food products.

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Introduction

Acrylamide is a compound with the chemical formula of C_3H_5NO, which is actually a unit of polyacrylamide and acrylamide copolymers. Polyacrylamides and acrylamide copolymers are used in several industrial processes, such as the production of paper, paints, and plastic, gel electrophoresis, soil softening, and treatment of drinking water and sewage (1, 2).

Acrylamides or 2-prophenamides are solid, odorless compounds in the form of white crystals, which have high water solubility at room temperature. These compounds are formed during the Maillard reaction in heated foods(3). The carbonyl group of reducing sugars with amine group of amino acids (especially free asparagines) react and create a Schiff base, leading to the formation of acrylamide during the subsequent decarboxylation. These compounds could also

* *Corresponding author:* Ali Ehsani, Department of Food Sciences and Technology, Faculty of Nutrition and Food Sciences, Tabriz University of Medical Sciences, Tabriz, Iran. Tel: 00984133357581-3; Email: ehsani@tbzmed.ac.ir

be generated in food packaging and adhesives; however, only a few of them remain in these products.

Previous studies have assessed the chemical properties and toxicity of acrylamides. Furthermore, high-dose animal studies have indicated that acrylamide is a carcinogenic, genotoxic, and neurotoxic compound, which is considered to be the main cause of peripheral neuropathy. These properties are often attributed to the metabolites of acrylamide, such as glycidamide, 5-hydroxymethylfurfural (HMF), and N-acetyl-S-(3-amino-3-oxopropyl) cysteine (2, 4-7).

In the animal studies in this regard, the International Agency for Animal Health has classified acrylamides in group 2A carcinogens, while the European Union (EU) has categorized it in group two of carcinogenic and mutagenic substances. In addition, the Food and Drug Administration (FDA) and World Health Organization (WHO) have suggested the daily intake of acrylamide to be 0.3-0.8 μg/bw/kg. However, the recommended limit of acrylamide in fried potatoes has been reported to be 400-1500 μg/kg.

The evidence provided by the National Nutrition Institute of Sweden has shown the high concentration of acrylamide in fried, cooked, and deep-fried foods and coffee(4, 8).Following the first report published by the University of Stockholm, many European countries, as well as the United States, reported similar findings on the formation of acrylamide mainly in the high-carbohydrate foods that are prepared at high temperature (2). Therefore, the current literature and mentioned findings represent a global concern (2).

Raw foods (e.g., raw potatoes) lack or contain only a limited amount of acrylamide. As stated earlier, acrylamideis formed in foods containing high levels of carbohydrates, which are prepared at high temperatures (≥120°C). It is also formed during various cooking processes, such as frying, boiling, toasting, and grilling(2, 4).Plant-based food products (e.g., potatoes and cereals)may have high levels of acrylamide due to the presence of the precursors required for the reaction, including glucose, fructose, and asparagine (2, 9-11). On the other hand, meat products often lack or have extremely low acrylamide levels due to the absence of precursors. Exposure to acrylamide through diet depends on the acrylamide levels in foodstuff, as well as the amount of food intake. Therefore, even if food products contain a small amount of acrylamide and are consumed in high dietary amounts (e.g., coffee), they may lead to health consequences. The major sources of acrylamide formation are the foods that are produced at home and in restaurants, commercial centers, and caterings. Acrylamide is found in a wide range of food products that are consumed on a daily basis(11, 12).

Table 1. Acrylamide levels in different food groups

Food groups	Analytical method	range	References
potato chip	HPLC	269.21-1405.30 (μg/kg)	(31)
Milk-based beverage	LC-MS/MS	2.6-5.3(μg/kg)	(32)
Cereals based food		11-17	
Milk based dessert		2-5	
Soup, Puree		14-15	
Fruit Puree		5.7-7.3	
Vegetable-based ready-to-eat meal		19-20	
Meat/fish-based ready-to-eat meal		14-14	
Chip and toast	HPLC	10-300(μg/kg)	(33)
Bread crust and cracker	SPE-HPLC[1]	0.05-500	(34)
Potato crisps	RP-DISDME[2]	100-10000	(35)
Roasted coffee	HPLC-MS/MS	2-100	(36)
Cheese Snack	GC-MS	1-100(μg/kg)	(37)
Fried banana		10-100	
Fried eggplant		10-100	
Boiled potato		0.2-100	

Potato chips	Mn-Doped ZnS Quantum Dots	453.2(g kg^{-1})	(38)
Corn flakes		77.8	
Instant coffee		265.8	
Diet cracker		356.8	
Cracker		384.1	
Bread		296.1	

Table 1 shows the concentration of acrylamide in various food products. Exposure to acrylamide is not only limited to the type of foods; it is a common nutritional problem. In the United States, it has been estimated that acrylamide-based foods supply 38% of daily calories, 36%of fiber, 33%of carbohydrates, and more than 35% of specific nutrients per day. As such, it is difficult to estimate the acrylamide contents in various foods due to the differences in the concentration of acrylamide in a specific food group (e.g., potato chips) (13). These differences are observed in various products of a particular manufacturer. Furthermore, the products that are made from raw materials of different varieties, which have been sown at different times under different climatic conditions, may generate variable amounts of acrylamide due to the differences in the content of reducing sugars and asparagine levels. These factors have made it difficult to determine the exact level of acrylamide exposure through diet.

With regard to carcinogenicity, acrylamide has been reported to cause cellular mutation, neurological disorders, and fertility defects in men, while weakening the immune system. In addition, the adverse effects of acrylamide have been confirmed in experimental animal and human studies (14, 15).On the other hand, the development of potato product industries and high consumption of the foodstuffs have necessitated the use of various methods to reduce the acrylamide concentration in fried potato products through preserving their quality, taste, color, and nutritional value. Some of the approaches in this regard include the optimization of soil cultivation and cultivating varieties with low levels of acrylamide precursors (i.e., reducing sugars and asparagine), reducing the temperature and time of storage, preventing enzyme contamination, optimizing the frying process in terms of temperature and processing time, selecting proper frying oils, potato flake blanching, treatment with organic acids and salt minerals, lactic fermentation of potatoes before processing, and using antioxidants during the frying process(4, 14, 16-18).

The present study aimed to investigate the formation of acrylamide, as well as the methods to reduce and prevent its formation.

Material and methods

Mechanism of Acrylamide Formation in Food

Acrylamide is formed through various processes, which are mainly associated with the Maillard reactions in food products (Figure 1).

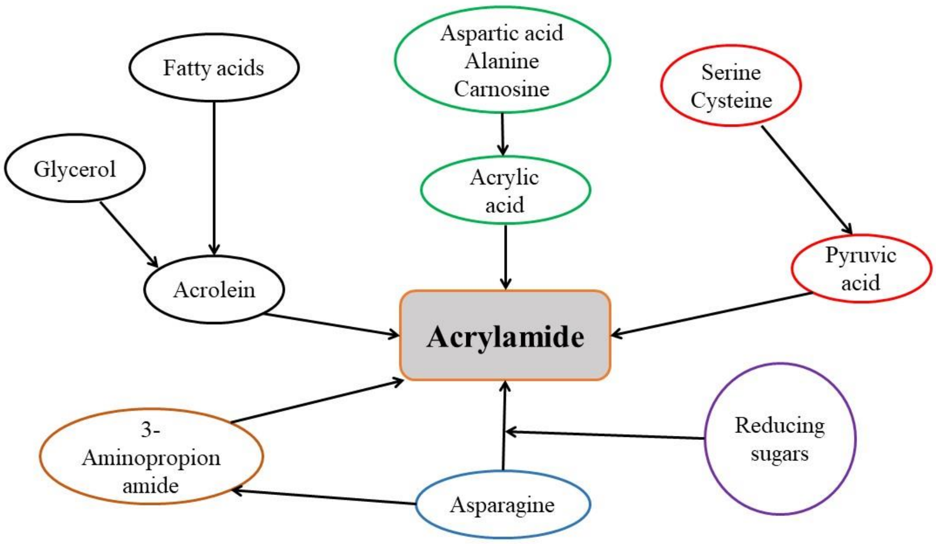

Fig. 1. The main mechanisms of acrylamide formation

During the normal heating of foods, reducing sugars react with amino acids, resulting in the Maillard chain reactions. The Maillard reaction is a non-enzymatic, brown reaction that occurs during the cooking and heating of food. This reaction is the result of a combination of carbohydrates, fats, and proteins, which causes the desired color and flavor in food products (19).

Asparagine metabolic path way is also a route through which acrylamide is formed. Asparagine is an amino acid found in potatoes, and carbohydrates are required for the formation of acrylamide. Asparagine amino acid could independently produce acrylamide through direct decarboxylation and deamination with an extremely low response rate. However, asparagine produces acrylamide in the presence of reducing sugars (especially glucose and fructose) or dicarbonyl compounds. The potential for acrylamide formation largely depends on the concentrations of glucose and fructose (2, 9, 13, 18).

Although the formation of acrylamide is mainly due to the combination of asparagine and reducing sugars, other pathways through acrolein and ammonia have also been proposed for the formation of acrylamides. For instance, in the absence of asparagine in the foods that are rich in fat, acrolein and ammonia play the role of asparagine. Acrolein and acrylic acid compounds are formed at high temperatures from the degradation of fats (i.e., triglycerides). In addition, amino acid destruction by ammonia may lead to the formation of acrylamides through thermal decomposition (13, 14, 20, 21).

Acrylamide Reduction Methods

Significant efforts have been made to reduce acrylamide formation in foods. Reducing the level of acrylamide in food products at home and in industrial sections not only reduces the health risks associated with this compound, but it also leads to the understanding of food safety. Considering the maximum formation of acrylamide in fried potato products and their high consumption, methods such as selecting proper varieties, storage at an ambient temperature (8°C), frying under vacuum or at temperatures below 120°C, lactic fermentation, and soaking potatoes in acetic acid, citric acid, glycine, hydrocolloids, salts, asparaginaseenzymes, vitamins, and antioxidants could minimize acrylamide formation in fried potato products(11, 22-24). In the following sections, we have introduced some strategies to prevent the formation of acrylamide in foods.

Effects of Raw Materials

Due to the mechanism of acrylamide formation, it is optimal to prevent acrylamide formation through controlling the precursor materials of this reaction. Therefore, selecting varieties with lower levels of reducing sugars and asparagine amino acids could be effective in this regard. Moreover, climatic conditions, time of harvest, storage conditions, and type of the varieties could influence the levels of asparagine and reducing sugars(4).

According to the literature, if the soil has a low sulfur level, lower amounts of asparagine acid are formed in potatoes, while lower amounts of acrylamide are formed during the production phase. In addition, if the soil contains more nitrogen, the amounts of free amino acids and protein increase, and more acrylamide is generated during processing (18).

During potato storage, caution is required in order to ensure that the storage temperature does not lead to the formation of reducing sugars. In such case, potatoes could be stored at room temperature so as to decrease the level of reducing sugars. In this respect, previous studies have also indicated that extremely high temperatures during summer may diminish acrylamide formation in potatoes.

Fertilizers may have a significant impact on acrylamide formation. Fertilizers with low nitrogen content have been reported to increase regeneration sugars, thereby incrementing acrylamide formation. Certainly, the effects may vary inbakery products; for instance, the level of sugars in wheat is not affected by the type of fertilizers. Typically, potatoes are preserved for several months after harvest, and the storage conditions may affect the level of reducing sugars, as well as the potential for the formation of acrylics during thermal processes. Therefore, if potatoes are preserved at low temperatures (<8°C), enzyme activities could increase, along with the level of regeneration sugars, increasing the formation of acrylamide in the product. To reduce the formation of acrylic amides in potato products, the optimal storage temperature has been set at 8°C(4).

Effects of Additives

Asparaginase converts asparagine into ammonia and aspartic acid, thereby decreasing acrylamide formation. This method is useful for bakery products and potatoes; however, it is more expensive compared to other approaches. On the other hand, the glucose oxidase enzyme could oxidize glucose and prevent acrylamide formation. Evaluation of the effects of enzymes has confirmed that the inhibition of acrylamide precursors (i.e., asparagine amino acid and reducing sugar) may diminish acrylamide formation in food products.

Water plays a complex role in the formation or removal of acrylamide. In low moisture content, the activation energy for the formation of acrylamide is greater than its amount for the browning process; consequently, the formation of acrylamide decreases. Another study in this regard has demonstrated that acrylamide formation increases at higher temperatures and humidity, while browning mostly appears in the middle water activity (a_w) At high moisture content, acrylamide formation and browning reaction have been reported to decrease.

Some studies have denoted that the addition of amino acids (e.g., cysteine and methionine), high-protein materials could reduce the level of acrylamide. Furthermore, antioxidants (e.g., phenolic antioxidants, cranberry, ferulic acid, epigallocatechingallate, and oregano)(16, 25)are effective in the formation of acrylic amides, as well as preventing the Maillard reactions. However, the exact mechanism remains unknown since they appear to react with active aldehydes and largely prevent the oxidation of acrolein.

Addition of single and double cations to dough could significantly diminish the effects of additives on the production of acrylic amides. Moreover, multivalent cations (e.g., NaCl and $CaCl_2$) could decrease the production of acrylamides during thermal processes. Several studies have also reported the significant effects of sodium chloride on acrylamide formation through polymerization. Hydrocolloid coatings (e.g., alginic acid and pectin) could reduce the formation of acrylamide, while carbohydrates, carrageenan, dihydroxypropyl diphosphate, and xanthan gum stimulate acrylamide formation.

Antioxidants could be effective in the reduction of acrylamide formation in non-oxidative systems. However, the oxidative products that are derived from antioxidants may degrade acrylamide and its precursor (asparagines), thereby preventing the formation of acrylamide.

Fat-soluble vitamins are not effective in reducing acrylamide. Among water-soluble vitamins, vitamins B_2, B_5, and B_6have been shown to be more effective in decreasing the acrylamide content. This phenomenon suggests that the terminal functional group of the side chain at the four-position (i.e., primary amino, hydroxyl or aldehyde) might play a key role in affecting the capability of vitamins to interrupt certain steps of the pathway to the formation of acrylamide. On the other hands, vitamin E is considered to be a strong antioxidant, and antioxidant activity has been proposed as a major mechanism to inhibit acrylamide formation (16, 19, 22, 23, 26-28).

Statistical Analysis

The most important influential factors in the formation of acrylic amides are temperature and time of thermal processes, blanching, and frying. Several studies have denoted a significant association between the temperature and time of thermal processes with the level of acrylamide formation. Blanching is the most important inhibitor of acrylamide formation, which acts through removing the reducing sugars from the environment before the frying process. Other factors such as radiant heat transfer, optimizing the baking conditions (e.g., increasing relative humidity or reducing environmental pressure), and surface frying may also be highly effective in the reduction of acrylamide.

Among the other methods to decrease acrylamide in food products are pH reduction, increasing $a_w$in the excess of 18, and increasing the duration of fermentation. Furthermore, frying potatoes under vacuum and at temperatures below 120°C, deep frying instead of surface frying, avoiding the pH of 8-6,pre-processing or soaking potatoes in amino acids (e.g., glycine and lysine), acetic acid, and NaCland $CaCl_2$ saline solutions, treatment with pectin, alginate hydrocolloids, and vitamins, pre-treatment, lactic fermentation, and using antioxidants during the process could effectively decrease the formation of acrylamide in food products (4, 9, 11, 17, 24, 29, 30).

Conclusion

Considering the toxicity of acrylamide and the associated health risks for humans, and given the importance of food safety and health issues, a few methods could be used simultaneously (e.g., the Hurdle technology)in order to reduce the rate of acrylamide formation in susceptible food products. Furthermore, considering the maximum formation of acrylamide in fried potato products and their high consumption (especially chips), approaches such as selecting proper varieties, storage at an ambient temperature (8°C), frying under vacuum or at temperatures below 120°C, lactic fermentation, and soaking in acetic acid, citric acid, glycine, hydrocolloids, salts, asparaginase, glucose oxidase enzymes, vitamins, and antioxidants could minimize the level of acrylamide in fried potato products.

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Conflict of interest

None declared.

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