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Food Production, Processing and Nutrition (2024) 6:24
https://doi.org/10.1186/s43014-023-00212-6

Food Production, Processing and Nutrition

REVIEW

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Investigating influencing factors on acrylamide content in fried potatoes and mitigating measures: a review

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Abstract

Thermal processing of food has the potential to produce a number of unwanted chemical substances. One of these compounds that is created is acrylamide (in starch-rich foods). Additionally, it has a potential to cause cancer in rodents and in humans. Chocolate, potato, bakery foods, coffee, and chocolate products are the main dietary sources of acrylamide exposure. The fresh ingredient utilised most frequently in frying processes is potato, because of high global consumer demand. Ever since it was discovered in foods, acrylamide's mechanism and mitigation have drawn the attention of various investigations. Additionally, different frying techniques, such as deep frying, microwave frying, and air frying, have a direct impact on the development of acrylamide in products. In-depth details on acrylamide generation, incidence, dietary exposure, toxicity, and mitigation during the frying process are provided in the current work.

Keywords Acrylamide, Potato, Deep frying, Microwave frying, Air frying

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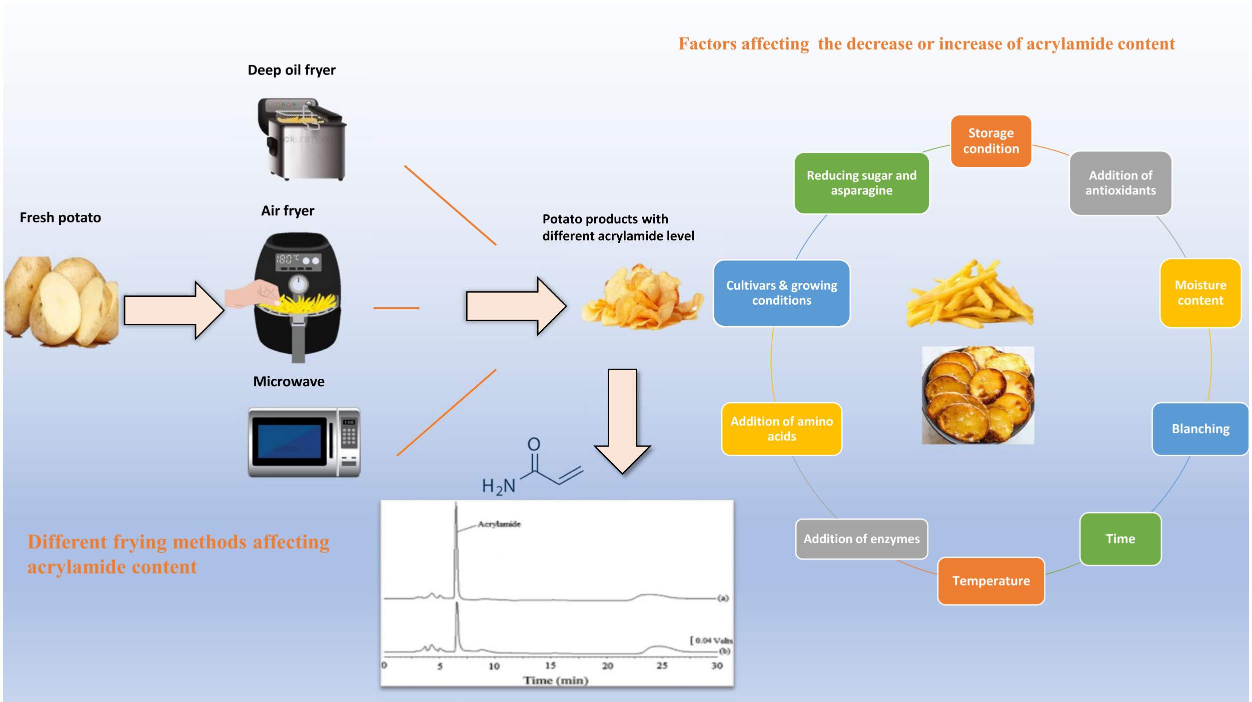
Graphical Abstract



Introduction

Potato "(*Solanum tube tuberosum rosum* L.) is the world's major non-grain food crop," coming in fourth place below wheat, maize, and rice (Gómez et al. 2021). With over a billion people dependent on the crop, yearly output already topping 350 Million Metric Tons produced on 17 million hectares of land (Bvenura et al. 2022). Potatoes are high in carbs and "have a 20% dry matter content and an average water content of 80% when freshly picked" (Singh et al. 2020). As the world's lifestyle changes and fast food becomes trendier, there is an increasing request for potato production. Newly, 50% of potato produce (e.g., in the USA and Europe) is directed to the food industries (Melito et al. 2017). Frying is an ancient and famous food preparation process. It is a rapid dehydration process that employs food heated to 150–200 °C as a medium to eliminate the moisture content of fruits and vegetables (Gertz 2014). Additionally, to achieve the desired texture, flavor, and taste preferred by customers, frying is employed to create a crisp outer layer while maintaining a tender interior, rendering it a favored culinary technique across a diverse range of dishes (Wang et al. 2022).

Furthermore, acrylamide formation has been linked to various frying methods due to its carcinogenic implications for human health. Consequently, acrylamide has garnered substantial attention in the realms of food science, technology, and environmental research since its discovery in 2002. Swedish researchers conducted preliminary studies on acrylamide development in carbohydrate-rich meals during the same year (Tareke et al. 2002). Acrylamide is produced during the preparation of carbohydrate-rich meals, and its level is affected by carbohydrate content, frying time, temperature, and other factors (Vinci et al. 2012). The toxicology of acrylamide which is created when food is cooked at high heat (over 120 °C), has attracted attention. Therefore, heated fried potatoes contained vast amounts of acrylamide. Consuming high-carbohydrate foods like bread, roasted cereals, and potato chips can expose consumers directly to acrylamide (Mekawi et al. 2019). This review concentrates on acrylamide generation, factors affecting it, and mitigation in potato products because these significantly affect the total amount of dietary acrylamide intake. Furthermore, this review enhances our understanding of heat treatment and its impact on food safety. It offers valuable insights that can serve as a foundation for creating guidelines and recommendations aimed at reducing acrylamide formation and ensuring the production of safer, superior-quality fried foods, benefiting consumers, food producers, and regulatory authorities.

Acrylamide

Acrylamide "(C3H5NO; prop-2-enamide) is a water-soluble, colorless, and odorless compound, and is vulnerable to bases, acids, oxidizing agents, and iron salts" (Tepe & Çebi 2019). Even though the chemical properties of acrylamide are well known, however, its existence in food was recently discovered. Acrylamide was detected in meals that cooked at temperatures higher than 120 °C byby a team of Swedish scientists led by Dr. Margareta Törnqvist in 2002 (Tareke et al. 2002). In addition, drinking water is filtered using water-soluble polyacrylamide produced from acrylamide. It is also used in cosmetics compounds and food packaging, such as paperboard (International Agency for Research on Cancer 1994). According to studies reported by "The joint FAO/WHO Expert Committee on Food Additives (JECFA)," the findings show that cereals, coffee, and potato products are the prime dietary categories that contribute to acrylamide levels (Toda et al. 2005). Acrylamide was categorized as a "probable human carcinogen by the International Agency for Research on Cancer (IARC)". It was also defined as a chemical capable of causing various hazardous consequences. According to Mottram et al. (2002), the Maillard reaction, which includes free amino acid asparagine as well as reducing sugars such as glucose, fructose, maltose, lactose, and sucrose at high temperatures, is what causes acrylamide to develop in meals. Studies showed that cooked meals, including fried potato products, baked goods, and cereals, have an acrylamide maximum quantity and range between 50 to 4000 μg/kg in carbohydrate-rich foods and 5–50 μg/kg in protein-rich foods (Bušová et al. 2020; Liu et al. 2022; Tareke et al. 2002). There are several ways that acrylamide enters the body, including inhalation from cigarette smoking, ingestion through consuming cooked, high-carbohydrate foods, and penetration of cosmetics through the skin (Carere 2006). Consumption of food and acrylamide content both affect exposure to acrylamide. This can be interpreted to mean that acrylamide levels in products can vary greatly due to changes in ingredients and processing conditions. Thus, eating foods that have a low concentration of acrylamide, such as bread, leads to exposure to acrylamide, which increases the overall exposure to acrylamide (Abt et al. 2019; Matthys et al. 2005).

Mechanism of acrylamide formation

The reactions that occur during heating between the asparagine and reducing sugars lead to "dehydration and the formation of a Schiff base by corresponding N-glycosylation and decarboxylation reactions. Subsequent reactions of hydrolysis, decarboxylation, or deamination result in the formation of intermediate compounds with varying degrees of reactivity which can eventually lead to the formation of acrylamide" as shown in Fig. 1 (Vinci et al. 2012). Asparagine, fructose, and/or glucose, regarded as the main precursors, are used in studies based on model systems to initiate acrylamide generation.

Other acrylamide formation pathways are depicted in Fig. 2 (Stadler et al. 2003; Yaylayan et al. 2005).

- Acrylamide is formed when acrolein derived from the oxidative degradation of lipids or glycerol reacts with ammonia (Yaylayan et al. 2005). Moreover, other synthesis that can lead to the creation of acrylic acid "β-alanine, aspartic acid, carnosine, serine, or cystei (Eriksson 2005).
- The quantity of reducing sugars determines the amount of acrylamide in fried meals of potato (Elmore et al. 2015; Muttucumaru et al. 2014).
- Free asparagine may directly relate to variation of acrylamide, especially in cultivars with a high reducing sugar content (Halford et al. 2012). Modeling indicates that the concentration of free asparagine affects the structural diversity of acrylamide when the ratio of free asparagine to reducing sugars is less than approximately 2.3 (Muttucumaru et al. 2017). In potato tubers, fructose and glucose are the dominant reducing sugars, with very little maltose, also glucose-to-fructose ratio is essential. Therefore, these two sugars affect acrylamide development. However, unlike glucose, fructose has been demonstrated to favor acrylamide over color compounds during potato frying (Higley et al. 2012; F. Mestdagh et al. 2008). This agrees with a study that modeled the kinetics of acrylamide generation in French fries (Parker et al. 2012). Therefore, it is a common practice to blanch potatoes to eliminate the soluble carbohydrates (Halford et al. 2022).

Acrylamide in food

Most people acquire one-third of their daily caloric requirements from cereal and potatoes worldwide. Many societies are concerned about the content of acrylamide in meals. Table 1 lists the amount of acrylamide (μg/kg) contained in various food items as "determined by the European Food Safety Authority (EFSA) (2013)". Potato products represent 50% of the acrylamide content, while bread and its products contain only low values, constituting about 20%. This depends on the temperature to which these products are exposed. Acrylamide does not occur in raw foods, but when food is heated to a temperature

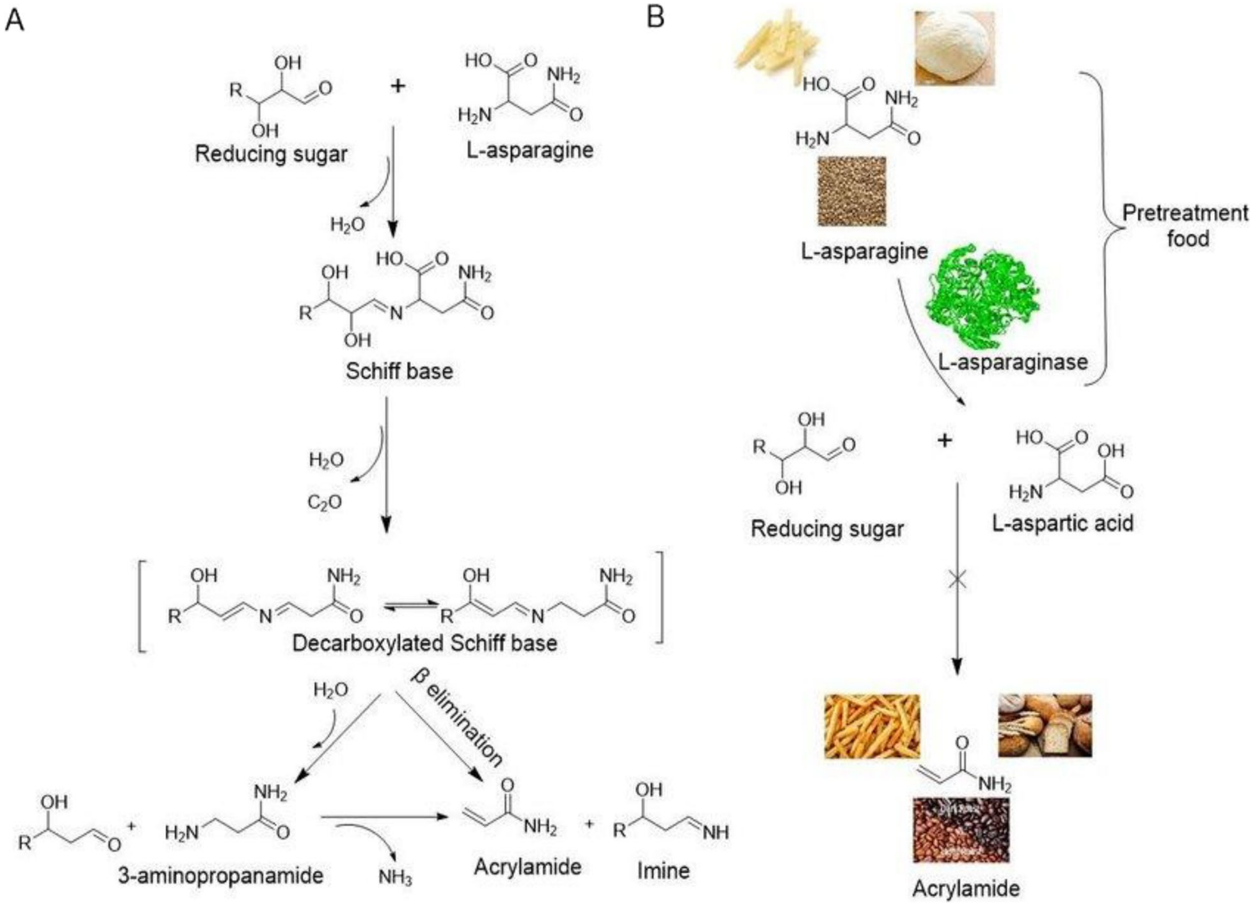


Fig. 1 The principal pathway of the acrylamide during frying (Jia et al. 2021)

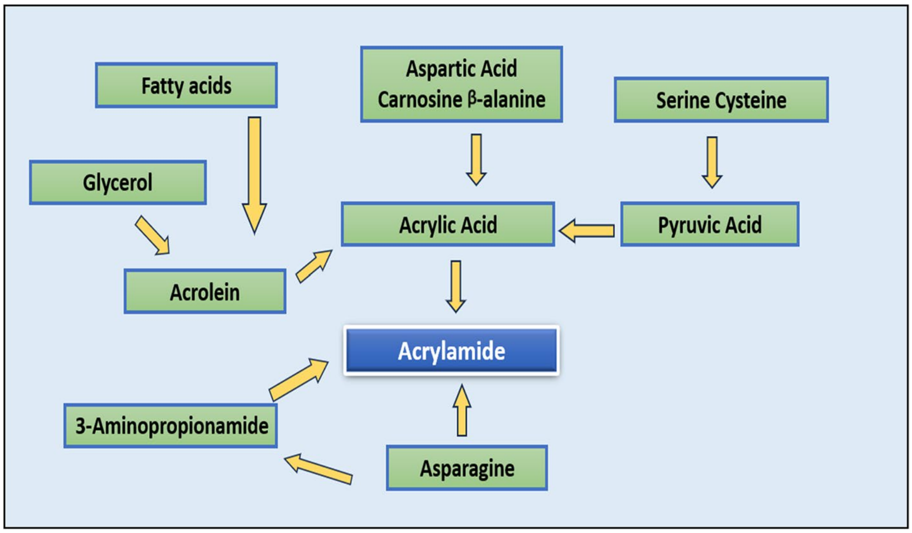


Fig. 2 Alternative acrylamide formation mechanism, Acrylamide is formed when acrolein derived from the oxidative degradation of lipids or glycerol reacts with ammonia

Table 1 Acrylamide level in various food items

Food item	Mean content µg/kg
Potato crisps	1000
Baby food (not cereal foods)	50 – 80
Instant coffee	900
Biscuits	500
Baby food (biscuits & rusks)	200
Roast coffee	450
Bread	80 -150
Breakfast cereal	200—400
French fries ready to eat	600

Source:(European Food Safety Authority, 2013)

of 120 °C or above. Furthermore, Acrylamide concentration in food products rises with temperature exposure. (Capuano et al. 2010; Rifai & Saleh 2020). According to studies, acrylamide may be found in a broad variety of meals that are rich in carbs and asparagine also heated at high temperatures (boiling or nonthermally processed foods are free of acrylamide) (Rifai & Saleh 2020), with the majority of the contribution coming from products made from cereal, potatoes, and coffee. Pastries, biscuits, bread, and processed cereal items make up the majority of cereal product consumption (Abt et al. 2019; Dybing et al. 2005; Fernandes et al. 2019; Rifai & Saleh 2020).

Even among same group of food products, acrylamide content varies. Moreover, there were 172 to 930 µg/kg in potato crisps and fries. Thus, that variability is caused by variances in raw material sources, processing circumstances, and analytical techniques (Williams 2005). Stadler et al. (2002) emphasized that diverse concentrations of reducing sugar and asparagine cause varying potential quantities of acrylamide production in potato cultivars. In addition, compared to asparagine, potatoes have a wide range of concentrations of glucose and fructose.

The effect of acrylamide on health

Human exposure to acrylamide is inevitable because it is a dietary contaminant in many commonly consumed foods (Rifai & Saleh 2020). When food is heated, chemical reactions produce dangerous heat-induced chemicals or "thermal process contaminants." Acrylamide is one of such chemical that has recently attracted much scientific attention (Adani et al. 2020). A qualitative similarity between the fate of acrylamide exposure in humans and animals has been noted. Acrylamide is absorbed by the mouse's gastrointestinal system through circulation and delivered to peripheral tissues following meal ingestion (Fennell & Friedman 2005). Acrylamide is metabolized after absorption by at least two major mechanisms. "It may be conjugated to N-acetyl-S-(3-amino-3-oxopropyl) cysteine by glutathione-S-transferase (GST), or it may be converted to glycidamide in a reaction catalyzed by the cytochrome P450 enzyme complex (CYP450), where this metabolite is known to be higher reactivity toward DNA and proteins than the primary acrylamide compound" (Sumner et al. 1999). These studies could indicate that acrylamide can enter any human tissue. According to World Health Organization (2020) this substance is reportedly cumulatively neurotoxic in rats and people. In rodent toxicity studies, it was discovered that the majority of experimental animal species experienced neuropathy after daily dosages of 10 to 50 mg/kg bw of acrylamide. Nevertheless, single dosages of 100 to 200 mg/kg proved fatal to most animals.

Moreover, mice were given single doses of acrylamide at 10, 20, and 30 mg/kg as well as repeated doses of 10 mg/kg for 1 and 2 weeks. This resulted in a considerable increase in DNA damage, as seen by the rise in micronuclei and chromosomal aberrations in animal bone marrow cells (Alzahrani 2011). Although there is adequate evidence to conclude that acrylamide is carcinogenic to experimental mice, there is currently no evidence of the substance's effects on human health according to the limited epidemiologic research that have been done on occupational and dietary exposure to it (Kumar et al. 2018). The International Agency for Research on Cancer (IARC) now categorizes acrylamide "as a probable human carcinogen and, by the US National Toxicology Program, as reasonably predicted to be a human carcinogen" (Rifai & Saleh 2020).

Changes in physical and chemical characteristics throughout frying process

Immersion or deep-oil frying is the most traditional and well-known way to cook potatoes. This method modifies fried potatoes' physical, chemical, and sensory properties. The three main characteristics that define fried potatoes' quality are their oil content, color, and texture. Potato chips and French fries are palatable and have a distinctive flavor when fried in fat or oil, enhancing their organoleptic properties. Therefore, the amount of fat absorbed during immersion frying determines the quality of the fried potatoes (Mellema 2003). Since acrylamide is generated during the final phase, frying conditions significantly impact the products acrylamide levels when consumed.

The structure of French fries is made up of two distinct regions: a core that is fried and humid on the outside and crispy oil-free on the inside (Asokapandian et al. 2020). Color, mechanical characteristics (hardness, crispness, and so on), porosity, volume, and roughness are among French fries' essential physical properties. In addition, French fries oil and moisture content are two critical chemical characteristics (Pedreschi 2012). Therefore, various processes as well as chemicals absorbed by the frying oil impact the color, texture, and taste of fried meals. Moreover, the primary determinants of color and flavor changes during processing are the temperature and duration of frying, moisture content, oil type, size and characteristics of the food surface, heat variations during storage and frying, pre-frying procedures, and the product's interfacial tension with the oil (Fellows 2009).

The most crucial visual quality factor for how people judge the quality of food is thought to be color. Customers primarily base their food selections on visual perception (Abdullah et al. 2004). Color development in French fries commences after adequate drying has taken place and is dependent on the evaporation rate and coefficient of heat transfer through various stages of frying. Thus, it is the result of a Maillard reaction that is dependent on the surface reducing sugar concentration as well as frying time and temperature. According to certain research, the Maillard reaction is the mechanism for the development of acrylamide and color. Traditionally, colorimeters were used to measure the color of vegetables instrumentally. Recently, digital image processing technologies have started to be used to measure fried potato color (Pedreschi 2012). The sensory properties of potatoes fried using two different techniques, namely air frying and vacuum frying, were studied and evaluated. In addition, deep oil frying was also included for comparison. The sensory properties assessed included color, flavor, taste, texture, and general acceptability. Upon evaluation, it was found that deep oil frying resulted in improved appearance and general acceptability of the potatoes. The deep-fried potatoes exhibited a perfect yellow-golden color and desirable texture attributes, which were superior compared to those achieved through air frying and vacuum frying methods (Basuny & Al oatibi 2016).

According to Fellows (2009), the creation of texture inside the product occurs due to changes in lipids, carbohydrate polymers, and proteins during the frying process—Maillard reaction and caramelization, which both result the evolution of colors ranging from gold to brown. In addition, changes in the meals' surface might result from the evaporation of surface water, which also impacts crust development and the texture of the food (Reda 2004). Therefore, the texture and color of potato chips are two essential aspects that influence their quality.

Moisture content is an important aspect of sustaining product quality. In addition, water partially evaporates during potato frying due to the high heat, which flows away from the meal and via the surrounding oil. Thus, the food absorbs oil which compensates for part of the water lost. Therefore, heat and mass transfer phenomena happen simultaneously during the process. Moreover, the moisture content in fried meals, typically represented as a percentage, refers to "the quantity of water per unit mass of wet or dry product"., however, the moisture and oil content are affected by temperature. Thus, the moisture content of the meals decreases throughout the frying process as frying time and temperature increase (Liu et al. 2021).

The Maillard reaction, which causes browning, texture, and flavor development, occur concurrently with acrylamide synthesis during frying. In view of the fact that the Maillard reaction influences acrylamide formation and color development, as well as frying variables (time and temperature), which have a similar effect on each, a correlation has been found. Thus, French fries that have been fried for a longer period of time at a higher temperature have more acrylamide (Gökmen & Mogol 2010). Based on a study by Bignardi et al. (2019) regardless of the variables (time and temperature), a correlation was confirmed between acrylamide content and product color. Table 2 reviews recent studies conducted to measure acrylamide content in fried potato products by different frying methods. In the present study, we bring out other frying methods to highlight their impact on potato products as the following.

Deep oil frying

"Deep frying is a conventional food processing technique dating back as early as sixteen centuries B.C., and still widely utilized today at both domestic and industrial scales." Foods ought to be tasty, crispy, and more attractive after deep frying in cooking oil. Uncooked food is thoroughly immersed in hot oil and can attain temperatures up to 200 °C (Nawaz et al. 2019). Deep-fat fried products are popular because they offer a desirable flavor, color, and crisp texture. Also, frying oil serves as a heat transmission medium and helps to improve the texture and taste of fried food (Casal et al. 2010). The oil acts as a heat transmission medium during deep-frying, forcing water from the product to be displaced to absorb the oil. Due to the simultaneous occurrence of heat and mass transfer, this results in migrations of oil and water to produce the desirable and distinct quality of the fried meal. Therefore, deep-fried meals are crispy on the outside and safely cooked inside. Moreover, this process is incredibly fast and, when executed correctly, eliminates microorganisms. Water in food evaporates fast when it comes in touch with extremely hot oil, turning into superheated steam that expands quickly and gives food a crispy quality (Asokapandian et al. 2019). Frying dehydrates foods by gelatinizing starch, denaturing protein, oil absorption,

Table 2 Recent studies of acrylamide content in different frying methods

References	Results	Frying conditions	Methods	Potato product
Yaseen et al. (2020)	(136, 522, 989, 1523, 2416 μg/kg)	(100, 130, 150, 170, 180 °C) For 4 min	Deep frying	Potato chips
Hamid et al. (2019)	85 μg/kg	180 °C for 3.5 min	Unthawed and deep frying	French fries
	84 μg/kg	180 °C for 3.5 min	Deep frying after thawing at room temperature	
	77 μg/kg	180 °C for 3.5 min	Deep frying after thawing at 5 ºC overnight	
	106 μg/kg	180 °C for 3.5 min	Deep frying after thawing in microwave for 5 min	
Sansano et al. (2018)	21 -231 μg/kg	180 °C From 1 to 8 min	Deep frying	French fries
	46 -182 μg/kg	180 °C From 1 to 10 min	Microwave frying 315W	
	44–337 μg/kg	180 °C From 1 to 8 min	Microwave frying 430W	
	23 -172 μg/kg	From 1 to 6 min	Microwave frying 600W	
Elfaitouri et al. (2018)	542—895 μg/kg	160 °C From 30 to 150 s	Microwave frying 200W	Potato chips
	669 -1739 μg/kg	170 °C From 30 to 150 s	Microwave frying 400W	
	1139 -11,423 μg/kg	180 °C From 30 to 150 s	Microwave frying 800W	
Dong et al. (2022)	42.12 ng/g to 1598.41 ng/g, increased as the temperature and time extended	(180,190,200 °C) for (12,15,18,21,24 min)	Air frying	French fries
	649.75 ng/g	180 °C for 6 min	Deep frying	
Haddarah et al. (2021)	63.1 ng/g	175 °C for 15 min	Air frying	French fries
	1384.79 ng/g	200 °C for 4 min	Deep frying	
Antunes-Rohling et al. (2018)	279.3 ± 75.1 μg/kg Acrylamide reduction of 90%	171 °C for 10 min	Deep frying after an Ultrasound pretreatment	Potato slices
	1649.7 ± 122.3 μg/kg	171 °C for 10 min	Directly deep-fried potatoes	
Meghavarnam and Janakiraman (2018)	690 μg/kg^{-1} to 4475 μg/ kg^{-1} enzyme reduced to 94%	170 °C, 180 °C 90 s	Deep frying after treatment with L-asparaginase	Potato slices
		170 °C, 180 °C 90 s	Directly deep-fried potatoes	
Adascălului et al. (2021)	541.65 μg/kg to 764.58 μg/kg	103 °C 13—15 min	Deep frying, Home Conditions (pan)	French fries
	684.37 μg/kg	170 °C, for 11 min	Deep frying, Fast food conditions (fryer)	
Al-asmar et al. (2018)	2089 μg kg^{-1}		Deep frying	French fries
	Acrylamide reduction equals 48% for PEC, > 38% for CH, ≥ 37% for GPF + TGase, and > 31% for GPF, respectively	170 °C for 6 min	Treatment with hydrocolloid coating solutions: (GPF), (TGase) (GPF + TGase), (CH), (PEC)	
Aykas et al. (2022)	52.0 to 812.8 g/kg	180 °C 1 to 5.5 min	Deep frying	French fries
Perez-Lopez et al. (2021)	**in extra virgin olive oil** at 175 and 185 ºC (1050 and 1771 μg kg – 1 respectively) **in sunflower oil** (555 and 1236 μg kg – 1, respectively)	175 and 185 °C For 4 min	Deep frying	French fries
Larissa et al. (2021)	765.46 to 3673.87 ng/g	160 °C for 7 min	Air frying	Four different sweet potato varieties
	719.44 to 3557.67 ng/g	160 °C for 2 min	Deep frying	

Table 2 (continued)

References	Results	Frying conditions	Methods	Potato product
Champrasert et al. (2021)	Acrylamide content was 27.88 ng/ml at conventional heating and was 3.5 times higher after 60 s of microwave heating (800 W, 98.02 ng/ml). Alginate, pectin, and chitosan coatings significantly reduced acrylamide production by 54%, 51%, and 41%, respectively	170 °C for 3 min and at 800 W for 4 min	Heating block and microwave Treatment with (alginate, pectin and chitosan)	Potato chips
Mousa & Mousa (2018)	In control, the sample was 934.0 ± 8.5 mg/kg	170 °C for 5 min	Deep frying	Potato strips
	112.1 to 560.4 mg/kg	170 °C for 5 min	Deep frying after treatment with antioxidants	
Zhang et al. (2021)	1929.10 ± 0.77 ng/g	160 °C for 5 min	Directly deep frying	French fries
	Acrylamide reduction of 18% to 20%		Pulsed electric field (PEF) with blanching pretreatment	
Ahmed et al. (2023)	27.28, 36.74, 43.96 ppm respectively	3,5,7 min at 160 °C	Deep frying	French fries
	21.8, 33.86, 48.16 ppm respectively	8,10,12 min at 170 °C	Air frying	
	30, 38.67, 46.44 ppm respectively	160,180,200 s at 180 °C	Microwave frying	

and aromatizing and coloring through Maillard processes (Porta et al. 2012).

Oil uptake can represent more than 40% of the fried food mass. Moreover, because this oil content is considered relatively high in fried foods, it is not recommended to consume fried foods as a daily practice (Moumtaz et al. 2019). In several research, French fries are the most common example of fried food. Due to their popularity, they have become a staple in many cuisines and are enjoyed by people of all ages. Moreover, flavor and texture of the external shell are also affected by the quality of the frying oil (Santos et al. 2018). Therefore, the crispy texture of French fries depends on the water evaporation and oil absorption during the frying process. On the other side, fried meals with high oil absorption may have adverse health effects, including increased risk of cancer, cardiovascular and cerebrovascular illnesses, and obesity (Ghidurus et al. 2010). Additionally, the fatty medium's extensive physical and chemical modifications, such as polymerization, oxidation, and hydrolysis, led to the progressive formation of hazardous chemicals, which significantly negatively affect health (Saguy & Dana 2003). Some evidence suggests that during several frying cycles in French fries, using frying oils can generate ingredients that degrade food quality and encourage the formation of compounds with negative nutritional repercussions and potential health hazards.

Moreover, vegetable oils such as soybean, sunflower, maize, or rapeseed contain polyunsaturated fatty acids, making them unsuitable for frequent frying. Changes occur in the physical parameters of oil as well, like color, density, and viscosity, as the oil becomes darker in color after repeated deep frying (Lisa et al. 2022). In addition, when oil is used on regular basis, the quality of oil degrades from fresh to deteriorating.

On the other hand, the effect of frying oil on the acrylamide production in French fries was investigated. According to Becalski et al. (2003) and Gertz and Klostermann (2002) palm oil has a higher acrylamide level than rapeseed and sunflower oils. Also, olive oil in comparison to corn oil. In terms of acrylamide content, the fried product's acrylamide concentration is influenced by the oil type and lipid oxidation profile. In general, palm olein outperformed the other oils in terms of frying performance because it contains a balanced proportion of saturated and unsaturated fatty acid content making it less susceptible to oxidation (Abd Razak et al. 2021). 'Nevertheless, other researchers found out that in finished products, the acrylamide content was unaffected by the type of oil (Santos et al. 2018).

Air frying

It is considered a revolutionary cooking method for producing fried foods with minimal oil content while retaining the color and texture of deep-fried food (Ghaitaranpour et al. 2018). Moreover, "it is a technology for producing fried food by bringing an external emulsion of oil droplets in heated air and the product into direct contact in a frying chamber. The product is continually in motion to encourage a homogenous connection between both phases". As a result, the product dehydrates and eventually creates a distinctive fried product crust. Because the quantity of oil used is significantly lower than that used in deep oil frying, the products are low in fat. Nowadays, household equipment on the market is designed to generate low-fat fried products (Shaker 2014).

Consumer preference for low-fat foods has motivated manufacturers to develop meals with a lower quantity of oil that retain the desired flavor and texture (Pinthus et al. 1993). According to the data provided by Santos et al. (2017) for a comparison of deep frying with oil versus air frying, the results emerged in French fries of air frying operations, which were represented by a rate of 70% less fat, resulting in a loss of 45% in calories per 100 g. Thus, a direct comparison of deep oil frying and air frying technologies demonstrated that air frying is a healthier alternative to deep frying. The air-frying procedure provides health benefits for consumers owing to reduced fat absorption and less fat oxidation, especially when using olive oil, as well as economic and environmental benefits due to decreased oil consumption and no effluents after frying.

Studies on potato products proved that the content of acrylamide (a known pollutant in French fries) in air frying decreased to 85–90%. In a study conducted by Basuny & Al oatibi (2016) the effects of different frying processes on potato chips, including novel technologies such as air frying and vacuum frying, were compared to traditional frying processes. The results revealed that air frying and vacuum frying methods resulted in potato chips with significantly lower acrylamide content than conventionally fried chips. Specifically, the acrylamide contents of potato chips after deep-frying (atmospheric), vacuum frying, and air frying were found to be 290 ppm, 100 ppm, and 78 ppm, respectively.

Based on the findings of Dong et al. (2022), it was concluded that air frying was generally healthy and might lessen the development of food hazards. The potato slices were cooked for 12 to 24 min at a range of temperatures (180 to 200 ˚C). The results of the study indicate that "as air frying temperature and time increased, so did the amount of browning, hardness, and Maillard hazards (acrylamide, 5-hydroxymethylfurfural, methylglyoxal, and glyoxal)". Therefore, compared to conventional method (180 ˚C- 6 min), air frying reduced acrylamide and 5-hydroxymethylfurfural by 47.31 and 57.04%, respectively. Therefore, air and vacuum frying might be ideal for making potato chips for modern consumers who use too much oil and search for healthier and higher-quality products.

Microwave frying

Microwaves are "electromagnetic waves ranging from 300 MHz to 300 GHz. The corresponding wavelengths range from 1 mm to 1 m, demonstrating microwaves' intermediate location between infrared and radio waves. Domestic microwave appliances generally operate at a frequency of 2.45 GHz". To prevent interference with communications systems, industrial microwave systems operate at 915 MHz and 2.45 GHz (Datta & Anantheswaran 2001). Since the 1940s, electromagnetic waves (microwaves) have been employed. Therefore, microwave ovens heat food quickly and are used in food preparation processes such as drying, frying, defrosting, heating, baking, and blanching (Sumnu & Sahin 2005). Recently, new technologies, for instance, microwave warming, have grown in popularity as substitutes for traditional methods. The rising usage of microwaves is also because it significantly improves the performance of traditional methods (Ekezie et al. 2017).

Microwave heating is generated by a product's capacity to absorb and transform power into heat. Dipolar and ionic mechanisms primarily cause microwave heating of foods. Water is the primary component that allows microwaves to heat meals. The more water content of the meal, the speedier it warms up (Guo et al. 2017). Food components, polar particles are also subjected to strong electromagnetic field effects, which causes polar molecules to rotate at an exceptionally high rate. Because of this rapid collision of water molecules with polar particles, heat is produced by friction between the molecules. The food warms up due to heat being transferred through the meal by "conduction, convection, or radiation". Cooking is among popular applications for microwave ovens due to the rapid rise in temperatures in the meal. Microwave ovens are suitable for preparing small amounts of food, particularly in houses. As a result, microwave ovens have become popular in homes and have been established as daily equipment. Their primary purpose is still to reheat previously cooked or prepared foods (Kalla 2017).

Microwave heating systems offer various advantages, including rapid heating, volumetric heating, and fast processing times. Furthermore, they are energy efficient, have a quick startup time, simple to install and clean, easy to operate and control, etc. Because of these advantages, microwave ovens are already standard household equipment. Based on this, the food industry has been manufacturing microwaveable items for consumers and the food service sector. The food industry has successfully used microwave heating for other purposes as well, such as drying pasta and vegetables, thawing bulk frozen meals, blanching vegetables, sterilization of products, preserving hams and sausage emulsions, inactivating enzymes, and pasteurization of bread.Generally, a standard microwave includes drying, thawing, sterilizing, tempering, blanching, pasteurizing, baking, and cooking (Devi et al. 2020; Guo et al. 2017).

Microwave heating could produce more acrylamide than traditional heating. This might be explained by microwaves rapidly raising food temperature because they can generate thermal energy within the meals without needing a medium to transfer heat. Products with poor thermal conductivity can heat up quickly, which is not the case with traditional heating methods. Thus, microwave heating provides a suitable environment for the acrylamide and probably has a significant impact on its kinetics and formation. In many studies, it has been found that microwave-heated potato products can produce significant amounts of acrylamide (Michalak et al. 2017). Hamid et al. (2019) compared various methods of defrosting French fries. They discovered that thawing conditions had no effect on acrylamide generation. Thus, microwave thawing was the optimum approach considering to the (relatively) low acrylamide and oil levels in meals as well as their attractive color features. Sansano et al. (2018) indicated that when compared to deep-oil frying, microwave frying reduced acrylamide by 37 to 83%. Moreover, it depends on the treatment duration. In theirstudy, raising the power of microwave from 430 to 600 W led to a roughly two-fold decrease in acrylamide levels.

On the other hand, Elfaitouri et al. (2018) confirmed that acrylamide content increased when the microwave heating power was raised for more than five minutes and decreased when the process continued for extended periods, indicating that this compound was degraded. Additionally, increasing the power from 200 to 800 W (while also raising the temperature from 160 °C to 180 °C) more than doubles the amount of acrylamide Table 2.

Effect of repeated frying on acrylamide formation

The effect of repeated frying on acrylamide formation is a significant concern as it can lead to the accumulation of decomposition products and increased levels of free fatty acids, both of which contribute to the generation of acrylamide during subsequent frying cycles. The quality and condition of the frying oil play a crucial role in influencing acrylamide formation. Mihai et al. (2021) conducted a study on the acrylamide content of fried potatoes during repeated frying processes. They observed that when sunflower oil was used for frying, the level of acrylamide in the potatoes increased from 1279.89 to 1651.44 μg/kg in the first three frying cycles. Similarly, when palm oil was used, acrylamide content increased from 1129.58 to 1419.07 μg/kg in the first four frying cycles. Generally, potatoes fried in palm oil exhibited lower acrylamide levels compared to those fried in sunflower oil, likely due to the more stable fatty acid composition of palm oil during frying.

The type of oil used also plays a role in acrylamide formation, with oils high in unsaturated fatty acids (e.g., soybean oil and sunflower oil) promoting higher acrylamide levels compared to oils higher in saturated fatty acids (e.g., coconut oil and palm oil). Research by Uchida et al. (1998) and Ewert et al. (2014) revealed that polyunsaturated fatty acids in oil at high temperatures accelerate the formation of acrolein, with linoleic acid being a major contributor. Additionally, Daniali et al. (2016) reported the conversion of glycerol to acrolein when frying oils were exposed to high temperatures. Various studies have highlighted the chemical changes occurring in oil during repeated frying, leading to an increase in acrylamide levels in fried potatoes. The elevated levels of primary and secondary fat oxidation products in the oil after repeated frying result in the formation of hydroperoxide and aldehyde. When these compounds interact with asparagine, typically present in fried foods, acrylamide is generated (Kuek et al. 2020; Matthäus et al. 2004; Pedreschi et al. 2008; Zamora & Hidalgo 2008).

It is evident that changes in the composition of oils during repeated frying contribute significantly to the rise in acrylamide levels, emphasizing the importance of monitoring and managing frying oil quality to mitigate acrylamide formation (Başaran & Turk 2021).

Factors influencing acrylamide production in food

Cultivars and growing conditions

Figure 3 illustrates thefactors and methods affecting the production of acrylamide. Due to variations in concentrations of reducing sugar and asparagine, different potato cultivars have varied range for potential acrylamide generation. Additionally, potatoes have a variety of glucose and fructose levels than asparagine (Amrein et al. 2003). Larger groups of reducing sugars relative to asparagine in various cultivars were proposed to be the source of asparagine's more significant role in acrylamide production. They also observed that asparagine had an effect on acrylamide formation in 20 potato cultivars grown in two locations after two and six months of storage when its level was 2.257 lower than that of reducing sugars (Muttucumaru et al. 2017).

Reducing sugar and asparagine

According to Mottram. (2002), in a dry system and buffer at temperatures below 120ºC asparagine combines with reducing sugar to generate acrylamide. Therefore, depending on the kind of amino acid, the quantity of acrylamide varies. Also, the ratio of amino acids to reducing sugar is crucial for acrylamide generation.

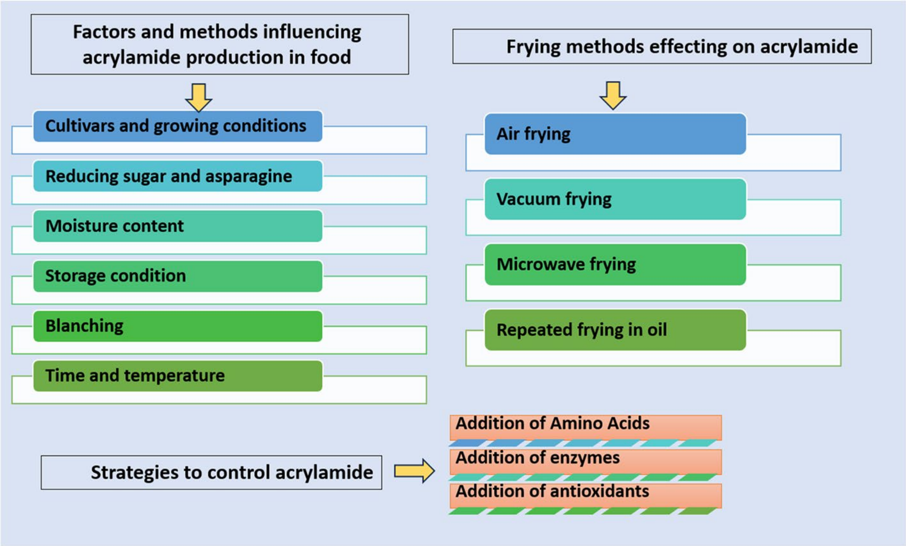


Fig. 3 Factors and methods affecting the production of acrylamide in food

The asparagine proportion of total amino acid in potato, wheat, and rye was determined to be 40%, 14%, and 18%, with 940, 167, and 173 µg/kg respectively (Ekezie et al. 2017). Liyanage et al. (2021) indicate that minimal quantities of asparagine and reducing sugars are necessary to reduce acrylamide formation in potato chips.

Moisture content

According to Amrein et al. (2004) acrylamide production is influenced by the moisture level. For instance, foods with a high moisture content have a higher acrylamide concentration. According to the results obtained by Ciesarová et al. (2006) least quantity of acrylamide formation in starch matrices was shown at water contents between 25 and 40%; beyond this range, the acrylamide level was significantly larger. Therefore, water concentration in food, along with reaction time and temperature, is a major factor in the synthesis of acrylamide.

Storage condition

Storage conditions may impact the raw matrix's acrylamide content due to the hydrolysis of carbohydrates which raises the amounts of reducing sugar. However, the amount of asparagine and other amino acids are unaffected. For instance, keeping potatoes below 10 °C expands the amount of acrylamide during cooking (Grob et al. 2003). Matsuura-Endo et al. (2006) found that storage practices significantly affect reducing sugars and thus acrylamide production. They investigate the impact of storage conditions on potato components. Five cultivars of potatoes were stored for eighteen weeks at different temperatures. After that, the concentrations of sugars and free amino acids in cultivars and the acrylamide content in chips after frying were determined. In all cultivars, the reducing sugar content rose significantly, as did the acrylamide content. Moreover, free amino acids exhibited minimal change and fluctuated within defined ranges characteristic of each cultivar. When the fructose/asparagine molar ratio in the tubers was 2 the quantity of reducing sugars strongly linked with the level of acrylamide. When the fructose/asparagine ratio was more than 2 during low-temperature storage the asparagine concentration was determined to be the major limitation factor for acrylamide generation rather than the reducing sugar concentration.

Blanching

Blanching is a food industry unit practice that involves "submerging food items in hot water, steam, boiling solutions of acids and salts, or a microwave applicator". This technique is frequently employed to preserve color and inactivate enzymes in various fruits and vegetables before further processing (freezing, drying, frying, canning, or sterilization) (Kalla 2017). Among other benefits, it produces a layer of gelatinized starch that significantly improves the finished product's texture, as well as a more uniform color and reduced oil absorption. Furthermore, it has been demonstrated that blanching potatoes before frying significantly lowers the amount of acrylamide.

Acrylamide generation was studied by Pedreschi et al. (2007) in response to different processing conditions, after potato slices were immersed in water for 120 min, they demonstrated that acrylamide production was reduced by 33%, 21%, and 27% at 150, 170, and 190 °C, respectively, compared to the control sample. On the other hand, strips blanched at different temperatures and times (at 50 °C for 80 min) and fried at the same temperature had the minimal acrylamide level (135, 327, and 564 g/kg for 150, 170, and 190 °C, respectively).

Time and temperature

According to Stadler et al. (2002) temperature influences acrylamide formation in meals. The most crucial technique to limit acrylamide formation is controlling processing variables like heating temperature and time. Yuan et al. (2007) discovered that expanding the period of frying caused acrylamide concentrations to increase. On the other hand, Belgin et al. (2007) proved that following a microwave pre-cooking step, the acrylamide concentration in the entire potato strip was reduced by 36%, 41%, and 60% for frying temperatures of 150, 170, and 190. The decrease was caused by the combined impact of lower frying time and surface temperature. Furthermore, when the microwave heating power was raised for more than 5 min, the acrylamide concentration rose but reduced as the process continued, showing that this chemical was degraded (Elfaitouri et al. 2018). Yaseen et al. (2020) also explained the effect of different temperatures on the structure and estimation of acrylamide and found that deep-frying was done at various temperatures (100, 130, 150, 170, and 180 °C). The results of the acrylamide contents were (136, 522, 989, 1523, and 2416 μg/kg) for a frying period of 4 min. According to, a wide range of acrylamide levels was produced by cooking par-fried French fries at 180 °C for 1 to 5.5 min. Thus, acrylamide content in potato varied from 52.0 to 812.8 g/kg according to spectra of samples taken using portable FT-IR equipment (Table 2).

In the research study conducted by Ahmed et al. (2023), an investigation was carried out to assess the variation in acrylamide content resulting from three different frying methods. The study utilized three frying techniques, namely Deep Frying (DF), Air Frying (AF), and Microwave Frying (MF). The acrylamide content was measured in parts per million (ppm) for each method and at various frying durations. In the DF method, the average acrylamide content was found to be (27.28, 36.7, 43.96) ppm after (3, 5, and 7) minutes of frying, respectively, at a temperature of 160 °C. Conversely, the AF method exhibited average acrylamide values of (21.8, 33.86, 48.16) ppm after (8, 10, and 12) minutes of frying, respectively, at 170 °C. Finally, in the MF method, acrylamide values were measured at (30, 38.67, 46.44) ppm after (160, 180, and 200) seconds of frying, respectively, at 180 °C. Notably, it was observed that higher frying temperatures and extended frying times across all methods resulted in a significant increase in acrylamide content generated in the French fries. This finding highlights the importance of considering frying conditions to mitigate potential health risks associated with acrylamide consumption.

Strategies to control acrylamide

Addition of amino acids

Acrylamide production can be reduced by using particular amounts of several different amino acids that compete with asparagine while maintaining flavor (Food Drink Europe 2011). In a dietary model system, Wedzicha et al. (2005) demonstrated that amino acid content and asparagine proportion are essential determinants in acrylamide formation. The use of competitive chemicals capable of competing with asparagine for carbonyl groups might inhibit the Maillard reaction, lowering acrylamide generation in meals. Moreover, adding amino acids before heat processing foods has been proposed as a feasible technique to limit acrylamide formation by competing with asparagine in the Maillard reaction or interacting with acrylamide after it has formed. In one investigation, soaking potato slices in a 3% solution of either lysine or glycine before frying decreased the generation of acrylamide by more than 80% (Rifai & Saleh 2020).

Addition of enzymes

This improvement was explained by Zyzak et al. (2003) as a way to decrease the development of acrylamide in starchy foods. Asparagine levels in potatoes and cereals can be reduced by the asparaginase enzyme, which hydrolyzes aspartic acid and ammonia. Sun et al. (2016) investigated the efficacy of a new bacterial type II L-asparaginase abASNase2 from Aquabacterium sp. A7-Y to remove acrylamide from fried potato strips as compared to untreated potato strips (acrylamide content: 0.8230 ± 0457 mg/kg). The abASNase2-treated group released 88.2% of the acrylamide (acrylamide content: 0.0970 ± 0157 mg/kg). Thus, according to these findings, the novel L-asparaginase abASNase2 is a “potential candidate for applications in the food processing industry”.

Moreover, Meghavarnam and Janakiraman (2018) found in a study on potatoes and bread thatASP-87 a pure l-asparaginase from *Fusarium culmorum*, was tested for its potential to prevent acrylamide production. The findings indicated the acrylamide content of the samples ranged from 690 g/kg-1 to 4475 g/kg-1. Asparaginase reduced l-asparagine content by 85% and 78%, respectively, whereas acrylamide concentration was lowered by 94% and 86%.

Addition of antioxidants

Antioxidants are compounds that can help reduce oxidative stress. They can be (1) endogenous (reduced glutathione and antioxidant enzymes including catalase, superoxide dismutase, glutathione peroxidase, and reductase) or (2) exogenous (antioxidant vitamins like vitamins A, C, and E) (Maroof & Gan 2022). It has been proven that the antioxidants could limit acrylamide production, and the reduction reached 25% by frying French fries and adding rosemary, indicating that rosemary inhibits acrylamide generation (Becalski et al. 2003). In addition, according to the results revealed by Haddarah et al. (2021) "that borage, fennel, and ginger extracts had significant amounts of TPC (298.607 mg/100 g; 117.79and 97.363 mg/100 g GAE, respectively) and relatively high scavenging activity (86.09%, 89.11% 93.67% respectively)". As a result, pretreatment of potatoes with the percentages have mentioned above plant extracts reduced acrylamide generation in all samples (67.99%, 73.36%, 59.67%, and 66.29%, 29.15%, 21.91% for borage, fennel, and ginger in air frying and deep frying respectively), using natural extracts that negatively influence lipid oxidation. Borage was able to minimize acrylamide generation by more than 60% in both fryers. Even for the control samples, air frying inhibited this hazardous chemical more than deep frying. Indeed, frying variables such as oil level and temperature play a significant role in this variation in fryer techniques highlighting the probable relationship between "antioxidant activities of plant extracts and frying conditions" in the regulation of acrylamide synthesis.

Conclusion

Acrylamide content in fried potato products might change based on the temperature or time of heating, the frying method used, controlling storage conditions, or pretreatments such as bleaching, adding enzymes, or adding antioxidants, as formerly discussed. The main obstacle in potato frying will be reducing acrylamide significantly as long as it remains acceptable product qualities like flavor and color "generated by similar Maillard reaction pathways". Reducing acrylamide levels and oil content are critical problems with potato products. Air frying is supposedly an option for producing fried potatoes with low levels of acrylamide and oil. Therefore, air frying is a healthier alternative for deep fat frying. Based on the available data, process variables and product characteristics determine whether acrylamide forms in microwave-heated food similarly to how it does in traditional heating. Therefore, it is important to conduct more research in this area. Since likely, acrylamide cannot be eliminated from fried products. Customers need detailed instructions on how to make their meals to reduce the hazard of the development of excessive amounts of hazardous substances, including acrylamide.

Acknowledgements
Not applicable.

Authors' contributions
Zahraa Adil Ahmed: Conceptualization, Resources, Writing – original draft. Nameer K. Mohammed: Conceptualization, Investigation, Project administration, Data curation, Validation, Writing – review & editing. All authors read and approved the final manuscript.

Funding
The authors received no specific funding for this work.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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Received: 23 January 2023 Accepted: 15 November 2023

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