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Factors that influence Acrylamide Formation in Fried Foods: A Review

[1]Jibril, H., [2]Abdulkarim, S. M., [1]Iliyau, R and [1]Abubakar, S.A

[1] Department of Food Science and Technology,
Kano University of Science and Technology,
Wudil. Kano State, Nigeria

[2]Federal University Dutse,
Jigawa state. Nigeria

Email: hassanajibril24@gmail.com

Abstract
Acrylamide (AA) is an industrial chemical used in the production of polyacrylamides: It was discovered in food during the thermal processing (frying, baking, grilling, and roasting, among other things) of a wide range of foods (mostly starchy foods). Frying is one of the pathway for acrylamide formation, in which oil is heated to temperatures above the smoke point, which results in the production of acrolein known as the acrolein pathway. The formation of acrylamide during frying is influenced by a variety of factors. The article examines the factors contributing to the formation of acrylamide in various fried food products. These factors include processing time and temperature, type of oil, size of food, reused oil, food type and brand, storage conditions, presence of antioxidant in oil and so on.

Keywords: Acrylamide, Acrolein, Factors, Foods, Frying

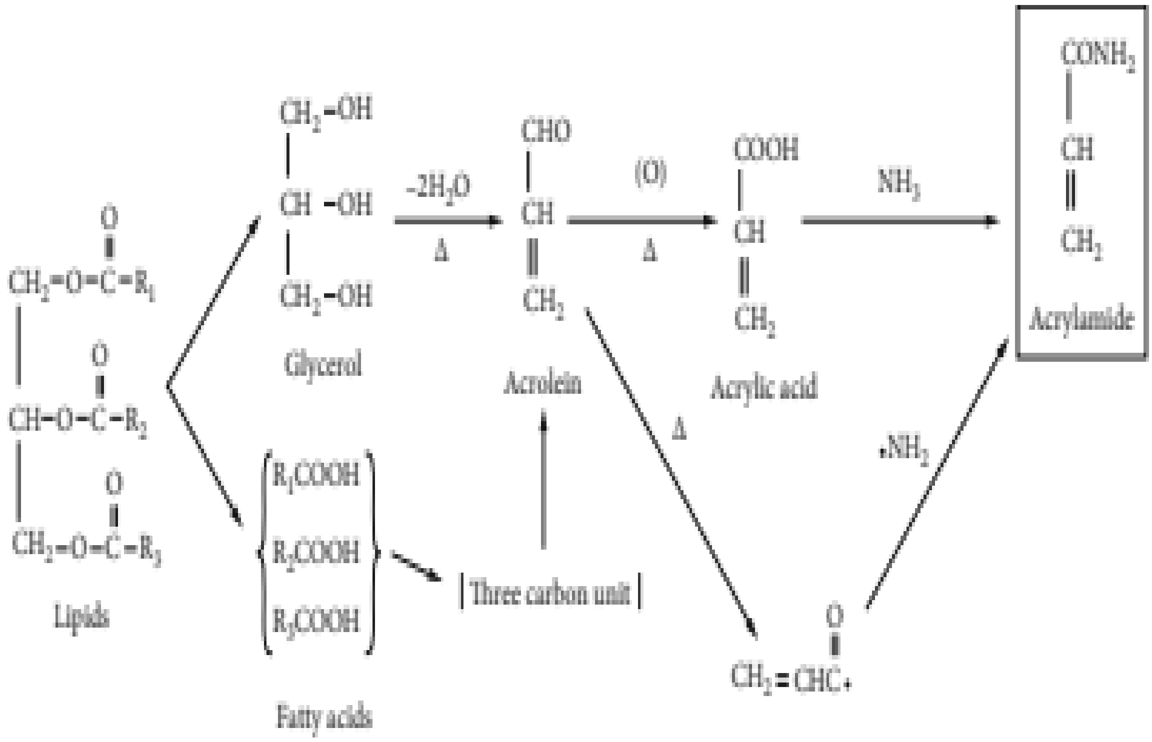
INTRODUCTION

Acrylamide (AA) is a common industrial organic compound that is a monomer of polyacrylamide and can be found in a variety of food products (Ubaoji and Orji, 2016). The molecular weight is 71.08gand the chemical formula is C_3H_5NO or (CH_2=CH–CO–NH_2) (Yelewicz*et al.*, 2010).It is a crystalline solid. That is white, odourless, and soluble in water, ethanol, ether, and chloroform (Kepekci-Tekkeli*et al.*, 2012). Acids, bases, oxidizing agents, iron, and salts are all incompatible with acrylamide. It decomposes non-thermally to form ammonia, and thermally to form carbon monoxide, carbon dioxide, and nitrogen oxides. The compound is primarily used as a building block in the production of polyacrylamide and acrylamide copolymers. Polyacrylamide and acrylamide copolymers are used in a variety of industrial processes, including the manufacture of paper, dyes, and plastics, as well as the treatment of drinking water and wastewater, including sewage (Ubaoji and Orji, 2016).

Acrylamide was first found in food by a group of Swedish researchers in 2002 (De Vleeschouwer *et al.*, 2010), in high concentrations, particularly in carbohydrate-rich foods like French fries and potato crisps. This discovery was made at the Swedish National Food

**Author for Correspondence*

Authority and Stockholm University (Rosen and Hellas, 2002; Tareke *et al.*, 2002). The primary parameter for the formation of acrylamide is high temperature (often greater than 120 ^{o}C) and low moisture content (Stojanovska and Tomovska, 2015). According to Gökmen and Palazoglu (2008), AA is largely created during high-temperature processing via the Milliard reaction pathway. It is develops when carbohydrates are fried, deep fried, or baked, particularly when asparagine is present. The second most well-known route is the acrolein pathway. Oil is formed with AA when heated over the smoke point (Liu *et al.*, 2015). Oil is first degraded into acids, then glycerol and fatty acids remove the water from glycerol, which causes acrolein to be produced through a heterolytic acid-catalyzed carbonium ion mechanism (Das and Srivastav, 2011; Katragadda*et al.*, 2010).



Source: (Krishnakumar and Visvanathan, 2014)
Figure 1 Acrolein Pathway for acrylamide formation

Factors Contributing to Acrylamide Formation in Fried Food
The availability and consumption of foods that are heavily fried has shown that frying is one of the cooking methods (Pankaj and Keener, 2017). During the frying process, oil and food ingredients are exposed to moisture and oxygen at high temperatures, which causes important chemical reactions such oxidation, hydrolysis, and polymerization. These reactions may lead to the buildup of lipid degradation chemicals and the production of acrylamide, both of which are harmful to human health (Vieira *et al.,* 2017; Ghasemian *et al.*, 2014). Many researchers have determined that lipid oxidation encourages the synthesis of acrylamide (Jin *et al.,* 2013; Capuano *et al.*, 2010). Acrylamide can be created by oxidizing lipids from its precursor, acrolein, which is created by dehydrating glycerol and then oxidizing it to create acrylic acid. Acrylamide can then be produced when asparagine is present (Zhang *et al.*, 2015; Mestdagh *et al.*, 2007). Another suggested mechanism is that two common amino acids, alanine and aspartic acid, immediately decompose to create acrylic acid.

In this review, factors that have been implicated in contributing to the formation of acrylamide formation are extensively discussed below:

i)Time and Temperature during Frying

Along with other variables including frying oil type, potato cultivar, and soaking, time and temperature combination during frying are significant elements that impact the development of acrylamide in potato fries (Williams, 2005). The amount of acrylamide produced during frying palm olein and soybeans is directly correlated with time and temperature. According to these researchers, frying temperatures and time are the key elements that affect the synthesis of acrylamide in potato chips, and the concentration of acrylamide increases as the frying process progresses at high temperatures of 180–190 °C (Kita and Lisinska, 2005; Jackson and Al-Taher, 2005). The acrylamide generated in frying oils, palm olein and soybean oil, at varied times and temperatures was studied. A high concentration of acrylamide was seen when both oils were heated at 200 °C for 7.5 minutes and the lowest concentration was observed at 160 °C for 15 minutes. (Daniali *et al*., 2018).

In contrast to lower temperatures of 150 °C and 175 °C, a rapid increase in AA concentration was found at 180-190 °C frying temperature by Matthäus *et al*. (2004). Frying temperature at or above 175 °C is a significant component. High temperatures and low moisture content promote the synthesis of acrylamide because acrylamide creation increases as temperature and moisture content do. Generally speaking, the colour of the food product gets darker the higher the acrylamide content (Emmanuel, 2010).

Yu *et al*. (2009) looked into the impact of temperature and duration on acrylamide generation in fried rice and potatoes, it was postulated that heat an time have a direct influence on the acrylamide formed on the fried products. In fried potatoes and rice, heating and cooking time were found to directly affect the synthesis of acrylamide, with a considerable amount of acrylamide formed at temperatures above 120 °C, primarily at 150 to 180 °C and decreasing at higher degrees (Osman *et al*., 2015). The fact that acrylamide is a byproduct of the Maillard reaction may help to explain the decrease (Mikulikova and Sobotovab, 2007). The average rate of acrylamide production increased with temperature and was highest for potato chips that were cooked at 180 °C (approximately 6.06 ppb/s). Given that measurable levels of acrylamide were generated at temperatures above 100 °C, especially at 120 °C, it is evident that the concentration of acrylamide rises with increasing temperature (Ubaoji and Orji, 2016). Long-term, high-temperature frying is a key contributor of acrylamide contamination (Yang *et al*., 2016).

The acrylamide formed decreased slightly under severe frying conditions in all types of oils, but the difference was not statistically significant. Red palm oil and corn oil showed a significant increase in acrylamide formation with increasing frying time from mild to moderate frying conditions, but yellow palm oil did not (Kamarudin *et al*., 2018). French fries made with red palm oil had an acrylamide content that dramatically increased from 740 µg/g in the mild condition to 852 µg/g in the intermediate condition and only slightly decreased to 828 µg/g in the severe condition (Kamarudin *et al*., 2018).

According to Napolitano *et al*. (2008), the concentration of acrylamide in potato crisps increased quickly as frying time at 180 °C increased. While Pedreschi *et al.* (2005) found that the amount of acrylamide significantly increased as the frying temperature increased from 150 to 190 °C and that after 7 minutes at 150 °C, the acrylamide content of potato slices was around 500 µg/kg compared to around 4500 µg/kg for frying for 3.5 minutes at 190 °C. The generation of acrylamide in potato chips (Atlantic variety) fried for a maximum of 6 minutes in a conventional fryer was tested, and it was discovered that the acrylamide level increased significantly with frying duration for all frying temperatures of 150, 165, and 180 °C (Granda *et al.,* 2004). Nyabaro *et al.* (2019) research has shown that cooking at high temperatures causes acrylamide levels to rise.

It was found that rice and potatoes absorb acrylamide at various times when the frying temperature raised from 110 to 175 °C. Additionally, as the period increased from 15 to 20 minutes, the amount of acrylamide in the fried foods increased at the same temperature (Osman *et al*., 2015). According to the authors, fried rice heated at 175 °C for 20 and 15 minutes had the highest acrylamide level of 3221. 24 µg/kg and 2567.20 µg/kg respectively, whereas rice heated at 110 °C for 15 minutes had the lowest amount of 756.06 g/kg. Fried rice significantly increased all acrylamide readings at 110 °C for 15 minutes compared to potatoes (Osman *et al*., 2015).

Rydberg *et al*. (2005) made the claim that prolonged heating would lessen the synthesis of acrylamide due to a degradation process and the exhaustion of one of the reactants. When potato slices were deep-fried, acrylamide production increased with rising temperature up to 185 °C (Gertz and Klostermann 2002). Because there isn't any water to evaporate when frying potato crisps, as the core zone disappears, the pressure reduces and the heat transfer swiftly rises the material's temperature to above 100 °C (Gertz *et al*., 2003). The temperature rises until it hits 120 °C when no more water can escape through the crust, at which point acrylamide starts to develop at temperatures between 170 and 180 ^{o}C, this reaction is at its optimum (Gertz *et al.,* 2003)

The cooking temperature of a meal is a crucial factor to monitor since it directly affects the development of acrylamide. For example, high frying temperatures raise the concentration of acrylamide (Sivasakthi *et al*., 2019). According to the same authors, potato slices without any pretreatment had an acrylamide level of between 2256 µgKg^{-1} (160 ^{o}C for 7 min.) and 2473 µgKg^{-1} (180 ^{o}C for 4mins). It was also discovered that, with increasing frying time, acrylamide production in sweet potato French fries rises linearly (Truong *et al*., 2014).

The samples' acrylamide concentration was 482 µg/kg after 3 minutes at 180 °C against 678 µg/kg after 10 minutes at 220 °C (Michalak *et al*., 2011). Fry food in fresh oil produced high concentrations of acrylamide, and vice versa. Since acrylamide levels are unaffected by the use-life of the frying oil, the primary determining factors are the applied temperature and frying time (Gertz, 2014).

According to Gokmen *et al*. (2007), raising oil temperature led to higher amounts of acrylamide after the same amount of time was spent frying potato strips at 150 ^{o}C, while frying duration had little to no impact on acrylamide generation. After 3 minutes of frying at 190 ^{o}C compared to 9 minutes at 150 ^{o}C, the amount of acrylamide was around 40 times higher. With longer frying times, acrylamide production also decreased (Ridzala *et al.,* 2020). The amount of acrylamide generated depends on the dietary matrix, temperature influences the quantity of acrylamide formed as the production typically increases beyond 120°C (Yang *et al.,* 2016). It was also reported by Lu *et al*. (2016) and Mariotti-Celis *et al*. (2017), that acrylamide concentration was influence by increase in frying time and temperature.

ii) Oil type and repeated frying

The type of oil used also affects the concentration of acrylamide production in foods. Numerous investigations have discovered that the type of oil used influences how much acrylamide forms in food samples (Zhang *et al*., 2015; Daniali *et al*., 2016). Different types of oil's capacity to convey heat to meals has an impact on acrylamide production (Gertz *et al*., 2003; Becalski*et al*., 2003; Matthaus*et al*., 2004). It was proposed by Mestdagh *et al*. (2005), varying concentrations of molecules like mono- and diacylglycerols and short- and medium-chain fatty acids alter the surface tension between non-polar oils and foods that contain water, which alters how much heat is transferred from the oil to the food.

According to Gökmen's (2015) research, the amount of acrylamide present influenced by both the level of lipid unsaturation and the rate of oxidation. Less unsaturated triacylglycerol-containing oils are more stable for frying (Arslanet *al.*, 2016). It is believed that when oil becomes more unsaturated, the production of acrolein rises, lowering the smoke point. In light of this, oils with a higher concentration of saturated fatty acids and a lower concentration of polyunsaturated fatty acids have a higher smoke point (Lingnert *et al*., 2002).

In comparison to oils like rapeseed oil, sunflower oil, or groundnut oil, palm olein and beef tallow were discovered to contain more polar substances such mono and diacylglycerols or medium chain triacylglycerols (Gertz, 2014). They added that more polar chemicals may lessen the surface tension between the oil and food surface. According to the surfactant concept of frying, additional surfactant components are created when oil deteriorates, increasing the amount of contact between oil and food. These materials improve heat transfer at the oil-food interface, allowing the water in the food to evaporate faster and the temperature to rise above 100-104 ^{o}C for a shorter period of time (Gerzt, 2014).

If frying time is not taken into account, frying with palm olein and tallow can produce a higher level of acrylamide than frying with vegetable oils like sunflower or rapeseed (Gertz, 2014). Foods cooked in palm olein were found to have increased acrylamide contents (Gertz *et al*., 2003). When comparing potato chips that were fried in unrefined oils, like virgin olive oil, to those that were cooked in refined oils, it was discovered that the generation of acrylamide was higher in olive oil than in corn oil (Becalski *et al.*, 2003).

It was suggested that the polyunsaturated fatty acid ratio of frying oil has an anti-acrylamide effect. Higher concentrations of polar substances, silicone, or diglycerides in frying oils resulted in higher concentrations of acrylamide. This result might be brought on by food moisture evaporating, which accelerates heat transfer (Gertz *et al.,* 2003). It was shown that the acrylamide level may be decreased by more than 50% by using specific adsorbents to bind the moisture during the frying process according to these authors.

Unrefined oils have greater quantities of acrylamide, according to Becalski *et al.* (2003); this may be because crude or virgin oils include unidentified chemicals that promote the formation of acrylamide in foods that are fried. In accordance with the findings of Jin *et al.* (2013), Zamora *et al.* (2008), and Capuona *et al.* (2010), there was a high concentration of acrylamide in unrefined oils. They theorized that this high concentration of acrylamide is caused by the loss of oxidized products and/or carbonyl compounds in such oils.

The amount of acrylamide formed in fried potatoes depends on the type of frying oil used (Bakhtiary *et al.,* 2013). The amount of acrylamide contamination in fried food may be affected by the type of frying oil used as high acrylamide was formed in palm oil products used for frying, which was most likely due to the higher amount of diacylglycerols present emulsifying the mixture, but more research is needed to verify these findings (Gertz *et al.,* 2003).Daniali *et al.* (2018) reported that palm oil with 1422 µg/g of acrylamide had less acrylamide than soya bean oil 2447 µg/g. These authors also hypothesized that Soya bean oil, which is vulnerable to oil oxidation due to its high un-saturation level, produced more acrylamide because acrolein can be created as a consequence of lipid oxidation.

Ahmad *et al*. (2021) found out that oil type significantly affected the levels of acrylamide in beef nuggets but frying cycle had no effect. Among the oil types studied, Palm olein was discovered to have the lowest acrylamide concentration of all the oil types examined, making it the ideal oil for frying (Ahmad *et al*., 2021). Additionally, these authors further submitted that when Palm olein (327 µg/g) was used instead of Sunflower oil (521 µg/g), soya bean oil (613 µg/g), and red palm olein (808 µg/g), the average level of acrylamide was considerably lower. The highest concentration of acrylamide was found in red palm olein, while palm olein had the lowest amount. AlsoKuek *et al.* (2020) in their finding established that the Palm olein gave the lowest acrylamide content. Acrylamide formation increased during 20 deep-frying sessions of potatoes (Urbančič *et al.*,2014).

Using red palm oil, which is high in carotene, to fry french fries decreased the generation of acrylamide. On the other hand, the impact of red palm oil's fat-soluble antioxidants on the production of acrylamide was more pronounced under the same consecutive frying settings as opposed to different frying conditions (Kamarudin *et al.,* 2018). The result indicated that using red palm oil in deep-fat frying for french fries can reduce acrylamide formation. The authors advocate more research on the effect of different types of fat-soluble anti-oxidants on acrylamide formation prevention.

Gertz and Klostermann (2002) reported that palm oil produced considerably greater acrylamide in french fries than other deep-frying oils. Furthermore, Becalski *et al.* (2003) showed that olive oil induced greater formation of acrylamide than corn oil. The authors reiterated further that the maximum amount of acrylamide was discovered in palm oil samples, which was 1140 ppb, while the lowest concentration was in sesame oil samples, which was 860 ppb, and the amount of acrylamide in fried samples from the blended oil as 952 ppb. As a result, the lower formation of acrylamide concentration in fried potatoes using sesame oil in comparison to samples for palm olein and blended oil is due to sesame oil's higher thermo oxidative stability in comparison to both other oils (Bakhtiary *et al*., 2013). Capuano *et al.,* 2010) reported that the reaction between carbonyl compounds derived from lipid thermoxidation products and free asparagine of potato results in the formation of acrylamide by oils used in frying.

Capuano *et al*. (2010) stated that the amount of acrylamide in final products is significantly influenced by the oil's heat stability. By altering the fatty acid composition and including antioxidants, oil's thermooxidative stability can be increased. Saturated fats, which are less vulnerable to thermoxidation, are likely to create less acrylamide (Capuano *et al.,* 2010). The development of acrylamide in french fries was significantly influenced by the frequent use of frying oil (Basaran and Turk, 2021). The repeated frying cycle was also shown to cause acrylamide formation in French fries (Gertz, 2004) and sweet potatoes (Lim *et al*., 2014), but other studies by Matthäus*et al.* (2004), William (2005), and Zhang *et al.* (2015) established that the frying cycle has no adverse effects on acrylamide formation.

iii) Rate of Oil Oxidation

It was also known that the quantity of acrylamide generated was influenced by the rate of oxidation. Due to an increase in the oxidative byproducts of frying oil, the amount of acrylamide in fried chops gradually increases during the frying process. It was stated that after six days of frying, the final acrylamide concentrations of the chops were 1.41 and 1.82µg/g for oil water frying and pure oil frying, respectively. The acrylamide content was significantly reduced $p<0.05$by oil water frying (Ma *et al*., 2016)

iv) Food type or brand

Acrylamide concentrations can also vary depending on the type of food and, in some cases, the brand of a particular food. For example, French fries contained a high concentration of acrylamide (Kepekci-Tekkeli *et al.,* 2012). It was discovered that potatoes contain high quantities of acrylamide, up to 3000 or even 4000 g/kg in potato chips and fries (Amit and Prem, 2012; Shamla and Nisha, 2014). Over 1,000 parts per billion (ppb) is a typical acrylamide content in potato chips, or roughly 28 micrograms of acrylamide in a one-ounce snack-size bag of potato chips (Ubaoji and Orji, 2016).

González-Mulero *et al* study's from 2021 brought attention to the vast range of acrylamide levels present in the diverse food preparations consumed in Spain. According to these scientists, French fries (chips) are one of the main causes of acrylamide exposure in the diet because they had the greatest levels of this pollutant. Hash browns, French fries, and potato chips all contained high quantities of acrylamide, which were above 2000 lig/kg (Ono *et al.,* 2003; Health Canada, 2003). Within a given food category, such as potato chips and some other brands of foods, the acrylamide concentration might differ dramatically between different brands (US FDA, 2004).

Research has shown that potato chips and French fries are very acrylamide-rich (EFSA 2011; Sirot *et al*., 2012). These authors suggested that the high amounts of acrylamide in meals were caused by the free asparagines present in potatoes. The two fried foods that contribute the most acrylamide are potato chips and french fries. These goods include between 100 mg*kg-1 in pale yellow items and 2000 mg*kg-1 in well-done, brown potato crisps (Capuano and Fogliano 2011).

v) Size of the food

The size and shape of the product (surface to volume ratio) will have an impact on the ultimate acrylamide concentration because acrylamide is generated on the surface of foods like potatoes (Ibrahim *et al*., 2019). As a result, the thinner and smaller cut sizes, the more acrylamide formation during the final frying process (Foot *et al.,* 2007). Larger French fries (20 mm) contained slightly less acrylamide, which is likely due to the crust's lower proportion of the total mass (Grob *et al*., 2003). The amount of acrylamide in a foodstuff was influenced by its size because it was discovered to be more prevalent in thin slices or sticks of food (Biedermann *et al.,* 2009).

vi) Storage conditions and glucose/fructose ration

The storage conditions of foods relate to the amount of glucose to fructose concentration of such foods, as highlighted by Noti *et al*.(2003), potato tubers stored at 2 °C had higher glucose and fructose concentrations than tubers stored at 20 °C. As a result, when potatoes from low-temperature storage were fried into chips, the resulting product was darker and had higher acrylamide concentrations than chips made from potato tubers stored at 20 °C. When sun-damaged potatoes (green) were fried, the amount of reducing sugar was significantly higher and the amount of acrylamide was 3 to 8 times higher (Biedermann *et al*., 2003).

The cultivar of potato used has a significant impact on how much acrylamide is produced (Eriksson, 2005). Asparagine and reducing sugar content varied significantly between cultivars, despite the fact that acrylamide is not present in raw potato (before cooking or processing) (Jackson and Al-Taher, 2005), emphasizing the significance of the initial raw material on the potential for acrylamide formation in later processing stages. De Wilde *et al*. (2004) stated that reconditioning may be an alternative for cold storage but has limitations, making low temperature potato storage unsuitable for frying.

In another study, storing potato tubers at 8 °C or lower will result in a phenomenon known as "low-temperature sweetening," which raises the levels of AA by increasing the concentration of reducing sugar and enhancing the brown colour after frying (Chuda *et al.*, 2003). To prevent this rise in decreasing sugar content after heat processing, potato tubers should be kept in storage between 8 °C and 12 °C (De Wilde *et al.*, 2005). Lowering of the storage temperature from 8 to 4 °C resulted in an increase of the concentration of reducing sugars in the raw material, which led to a higher potential of acrylamide formation in the products (Matthaus *et al*., 2004)

vii) Presence of asparagines

A vital component in the production of acrylamide is asparagine (Omotosho *et al.*, 2016; Kumar *et al*., 2014). Many theories have been put up to explain the process by which acrylamide is created in fried food. Asparagine has been identified as the acrylamide's nitrogen source. Asparagines are abundant in wheat, corn, potatoes, green beans, and peanuts. Acrylamide cannot be efficiently produced by heating asparagine alone, but it can be produced more quickly when mixed with reducing sugars and other products of fat oxidation (Gerzt, 2014).

Since potatoes contain more free asparagine than reducing sugars, these two substances are principally required for the production of acrylamide (Amrein *et al*., 2004; Becalski*et al*., 2004; De Wilde *et al.*, 2005). Asparagine content may be the limiting factor for acrylamide synthesis when the molar ratio of reducing sugars to asparagine content is more than two, indicating an abundance of reducing sugars (Matsuura-Endo *et al*., 2006). In contrast, a different study found no link between the presence of precursors (asparagine and sugars) and the production of acrylamide (Skog *et al.*, 2008). The necessity to research the concentration of asparagine in connection to various aspects, such as production parameters and maturity stage, is driven by the fact that asparagine is the limiting element for the creation of acrylamide in plantain chips (Kansci *et al*., 2016). It was shown that raw unripe plantains had a higher content of asparagine than raw ripe one (Omotosho *et al*., 2017).

Asparagines content in plantains dropped as the fruit ripened, as was seen in raw and unripe plantain samples (Lilia *et al*., 2007; Bassama *et al*., 2011). Unripe plantains created less acrylamide when they were fried than ripe plantains, signifying that unripe plantains were healthier (Omotosho*et al*., 2017). In a different study, a correlation calculation showed that asparagine was a critical factor for acylamide concentration in fried items, although ascorbic acid had less impact while sugar content and dry matter (DM) did not significantly correlate with acrylamide (Larissa *et al*., 2021)

Conclusion

The temperature and duration of the fry are the two main frying-related variables that affect the development of acrylamide. The article analyzed additional elements, such as oil type, repetitive oil use, storage conditions, acrylamide precursors (asparagines, sugar), food size, food kind or brand, among others, that promote the development of acrylamide in fried foods.

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