



Acrylamide Formation and Concentration in Plantain Chips: A Comprehensive Review

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ABSTRACT

Acrylamide, a heat-induced pollutant produced by the Maillard reaction, raises public health concerns because to its carcinogenic potential. Plantain chips, a favorite snack in tropical locations, are especially prone to acrylamide generation due to their carbohydrate amino acid composition and frying methods. This study summarizes current research on acrylamide levels in plantain chips, with an emphasis on the effects of raw material composition, processing conditions, and pre-treatment procedures. Analytical methods such as HPLC and LC-MS/MS reveal varying amounts, which are frequently comparable to potato chips. The health implications, regulatory viewpoints, and mitigation techniques are examined, with a focus on balancing safety and product quality. Future study should focus on region-specific studies, novel processing methods, and consumer education to limit acrylamide dangers while retaining local dietary traditions.

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INTRODUCTION

Acrylamide is a pollutant produced when carbohydrate-rich meals are cooked at high temperatures, such as frying, baking, or roasting. Its growth is mostly tied to the Maillard reaction, in which reducing sugars interact with the amino acid asparagine, producing chemicals important for flavor and browning while also releasing acrylamide (Rasool *et al.*, 2025; Friedman, 2015; Aghvami *et al.*, 2023). Although this process improves sensory properties, the presence of acrylamide has caused concern. Since its discovery in food products in 2002, the molecule has been categorized as a potential carcinogen, prompting substantial research into its presence in commonly consumed foods (FDA, 2023).

Plantain chips are a popular snack in tropical places like Africa and Latin America, where they are both a dietary staple and a culturally and economically significant crop (Quintero-Castaño *et al.*, 2020; Pérez-Donado *et al.*, 2023). Ripe or unripe plantains are commonly sliced and deep-fried in oil at temperatures above 150 °C, which promotes acrylamide synthesis (Herman-Lara *et al.*, 2019; Okon *et al.*, 2022). Recently, acrylamide concentrations in fried ripe plantain chips were measured to be as high as 894.40 ± 56.35 µg/kg using advanced analytical methods such as solid-phase microextraction and gas chromatography. According to Díaz-Ávila *et al.* (2024), plantain-based snacks may pose a dietary exposure risk, as their levels are comparable to those seen in potato chips.

Several factors influence acrylamide concentrations in plantain chips, including ripeness, sugar and amino acid profiles, frying temperature, oil type, and pre-treatments like blanching or soaking (Su *et al.*, 2022). These characteristics account for the variability observed among research and manufacturing regions. Given the extensive consumption of plantain chips, monitoring acrylamide levels is critical for food safety, regulatory compliance, and public health protection. This study summarizes new findings, describes

analytical procedures, and assesses mitigation strategies for limiting acrylamide generation while keeping the nutritional and cultural value of plantain chips.

Acrylamide Formation Mechanisms

The Maillard reaction, in which the amino acid asparagine interacts with reducing sugars such as glucose and fructose under elevated thermal conditions, is the most common pathway for acrylamide formation in foods (Stadler *et al.*, 2002; Stadler *et al.*, 2004; Wang *et al.*, 2019; Piskov *et al.*, 2020; Hosen *et al.*, 2021). While this reaction is necessary for the development of desired flavor and color in cooked foods, it also produces acrylamide, a toxicologically significant chemical. The enormous body of research spanning two decades demonstrates the consistency of this mechanism across many food matrices, emphasizing its importance in food safety and public health.

The Maillard reaction is a complicated series of non-enzymatic chemical reactions that take place when food is heated. Unstable Schiff bases are created when the amino acid asparagine condenses with the reactive carbonyl groups of reducing sugars, mainly glucose and fructose (Xing and Yaylayan, 2021). Amadori compounds are created when these intermediates undergo Amadori rearrangement in an acidic environment (Raffan *et al.*, 2020; Aarabi and Seyedain-Ardebili, 2020). Reductones and deoxyosones are produced by other reactions, such as enolization, and they eventually polymerize into melanoidins, which give cooked meals their distinctive brown color and scent. Simultaneously, decarboxylation of Schiff bases produces dicarbonyl compounds that promote acrylamide production and drive Strecker degradation, generating Strecker aldehydes (Stadler *et al.*, 2002; Aalaei *et al.*, 2019). This mechanistic pathway demonstrates how the Maillard reaction both improves sensory quality and raises issues with food safety.

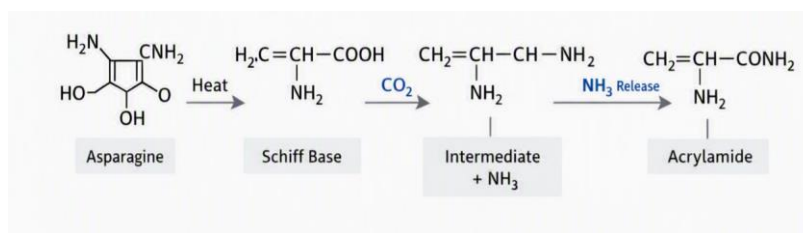


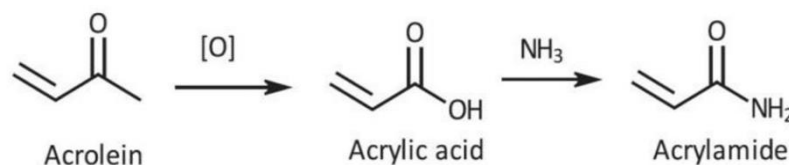
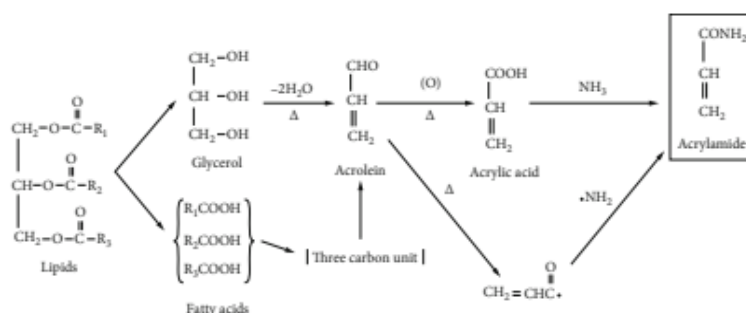
Figure 1: Maillard Pathway for Acrylamide formation

Table 1: Steps of Acrylamide Maillard formation

Step	Reaction	Product
Schiff base formation	Asparagine reacts with a reducing sugar	Schiff base
Decarboxylation	Schiff base loses CO ₂	Intermediate compound
Hydrolysis	Intermediate releases NH ₃	Acrylamide precursor
Rearrangement	Acrylamide precursor rearranges	Acrylamide

In addition to the traditional Maillard route, foods exposed to high temperatures and low moisture levels can also produce acrylamide by a number of other methods. These include asparagine oxidative degradation, acrolein intermediate production, and lipid oxidation (Arvanitoyannis *et al.*, 2014; MirzaAlizadeh *et al.*, 2025). Additionally, asparagine and reducing sugars can combine nucleophilically to produce acrylamide, or asparagine can be hydrolyzed and then dehydrated to produce acrylic acid as a precursor (Stadler & Gökmen, 2024). By generating reactive oxygen species and accelerating the production of acrylamide through intermediates like acrolein, thermal processing further

encourages lipid oxidation (Rasool *et al.*, 2025). Fatty acids are oxidatively degraded at high temperatures to produce acrolein, which can then transform into acrylic acid and act as a precursor for acrylamide (Stadler *et al.*, 2004; Gertz and Klostermann, 2002). Furthermore, intermediates produced from asparagine may react with dicarbonyl chemicals, such as hydroxymethylfurfural (HMF), increasing the accumulation of acrylamide (Jin *et al.*, 2013). When taken as a whole, these pathways demonstrate the complex chemistry that underlies the creation of acrylamide and emphasize how crucial it is to take into account a variety of reaction pathways when evaluating food safety.

Figure 2: Fat oxidation pathway of acrylamide formation
Source: Hamzalıoğlu et al. (2019)Figure 3: Acrolein Pathway for acrylamide formation
Source: (Krishnakumar and Visvanathan, 2014)

Factors Affecting Acrylamide Formation in Plantain Chips

A number of variables, such as the ripening stage, sugar composition, amino acid profile, frying temperature, and antioxidant content, have a significant impact on the acrylamide levels in plantain chips. The concentration of reducing sugars like glucose and fructose rises as plantains ripen, increasing the possibility of acrylamide production. According to Udomkun *et al.* (2021), acrylamide levels and ripening stage were significantly positively correlated ($P < 0.05$, $r = 0.57$). According to the same study, the concentrations of glucose and fructose increased significantly

($P < 0.05$) during ripening and were strongly correlated with the synthesis of acrylamide ($r = 0.85$ and 0.96 , respectively). Shamla and Nisha (2017) further verified that as plantain chips ripen, their acrylamide content rises due to increased quantities of reducing sugars and free amino acids, especially asparagine.

Acrylamide production is mostly dependent on reducing carbohydrates. The two main components of plant foods are fructose and glucose (Gertz *et al.*, 2023; Keramat *et al.*, 2011; Mottram *et al.*, 2002). According to Ciesarová *et al.* (2006), glucose needs higher temperatures (over 140°C) to start substantial production, while fructose can produce

acrylamide at comparatively low temperatures. Shamla and Nisha (2014) found that whereas asparagine showed a mild correlation ($p > 0.05$), glucose and fructose levels rose throughout ripening and showed high relationships with acrylamide ($r = 0.95$ and 0.94 , respectively; $p < 0.05$). It's interesting to note that phenolic chemicals dropped throughout ripening and had a negative correlation with the creation of acrylamide, indicating that antioxidants might reduce its development.

Numerous research support the ripening stage's impact. According to Omotosho *et al.* (2017), unripe plantains have lower amounts of acrylamide than ripe ones. According to Omini *et al.* (2019), fried ripe plantains had higher acrylamide concentrations than unripe plantains while having a lower asparagine content. This finding emphasizes the importance of reducing sugars over amino acids in the generation of acrylamide.

Additionally, processing conditions are crucial. According to Abubakari *et al.* (2025), acrylamide levels are greatly impacted by frying temperature, time, and citric acid pretreatment. Citric acid pretreatment decreased acrylamide concentrations, while higher temperatures and longer frying durations increased them. According to Akinosun *et al.* (2021), yam and plantain chips fried at 210 °C showed the greatest quantities of acrylamide (703 ± 27 and 706 ± 13 µg/kg, respectively), while buns baked at 150 °C had the lowest levels (25 ± 8 µg/kg).

Reported Acrylamide Concentrations of Plantain Chips/Other Plantain Products

Due to the health risks linked with this pollutant, acrylamide production in snacks made from bananas and plantains has been extensively studied. Daniali *et al.* (2013), found acrylamide levels in Malaysian fried and baked banana snacks ranged from 74.0 to 7468.8 µg/kg for banana fritters (Pisang goreng), from 28.9 to 243.7 µg/kg for banana chips (kerepek pisang), from 160.7 to 500.4 µg/kg for sweet banana

chips (kerepek pisang manis), and from 31.7 to 609.1 µg/kg for banana balls (cekodok pisang). Acrylamide concentrations of 100–430 µg/kg were found in green banana chips, 180 µg/kg in mature banana chips, and 1090 µg/kg in banana fritters by Bent *et al.* (2012).

Products made from plantains also exhibit a great deal of variation. Plantain slices had 240 µg/kg of acrylamide, while tostones had 440 µg/kg, according to Bassama *et al.* (2012). 894.40 ± 56.35 µg/kg was found in fried ripe plantains (Díaz-Ávila *et al.*, 2024). Acrylamide levels in plantain chips (*Musa paradisiaca*) ranged from 49.8 to 2062 µg/kg when evaluated by Shamla and Nisha (2017). In particular, ripe plantain snacks had an average of 894.40 ± 56.35 µg/kg. Barón-Cortés *et al.* (2021) observed a significantly lower average of 26.6 µg/kg in ripe plantains, while Pertuz-Cruz *et al.* (2022) reported values ranging from undetectable to 1542 µg/kg. Abubakari *et al.* (2025), revealed the concentrations of acrylamide in fried plantains ranged from 9.13×10^1 to 1.17×10^3 µg/g; Shamla *et al.* (2019) reported that deep-fried plantain chips contained between 4.9×10^1 and 2.06×10^3 µg/kg; Akinosun *et al.* (2021) found that plantain chips fried at 210 °C reached 706 ± 13 µg/kg, whereas yam chips under the same conditions contained 703 ± 27 µg/kg.

Acrylamide levels vary greatly when compared to other fried foods. Sweet potato fries (20 minutes) had the highest results, surpassing the European Union criterion of 500 µg/kg, according to Ajani *et al.* (2019), who measured concentrations ranging from < 3 to 720 µg/kg across fried items. French fries that were cooked for 20 minutes similarly above this limit, however those that were fried for 10 minutes had 360 µg/kg, which was less than the standard. Fried plantains, yams, and beef, on the other hand, typically stayed within the EU limit. Buns baked at 150 °C contained only 25 ± 8 µg/kg, according to Akinosun *et al.* (2021), highlighting the impact of temperature and cooking technique on acrylamide formation.

Table 2: Comparison of Acrylamide Concentration in Plantain and Other Food Commodities

Commodity	Acrylamide Concentration (µg/kg)	Reference
Banana fritter (Pisang goreng)	74.0 – 7468.8	Daniali <i>et al.</i> (2013)
Banana chips (kerepek pisang)	28.9 – 243.7	Daniali <i>et al.</i> (2013)
Sweet banana chips (kerepek pisang manis)	160.7 – 500.4	Daniali <i>et al.</i> (2013)
Banana balls (cekodok pisang)	31.7 – 609.1	Daniali <i>et al.</i> (2013)
Banana chips (green)	100 – 430	Bent <i>et al.</i> (2012)
Banana chips (ripe)	180	Bent <i>et al.</i> (2012)
Banana fritters (ripe)	1090	Bent <i>et al.</i> (2012)
Plantain slices	240	Bassama <i>et al.</i> (2012)
Plantain tostones	440	Bassama <i>et al.</i> (2012)
Fried ripe plantain	894.40 ± 56.35	Díaz-Ávila <i>et al.</i> (2024)
Plantain chips (different ripening levels)	49.8 – 2062	Shamla & Nisha (2017)
Ripe plantain snacks	894.40 ± 56.35	Shamla & Nisha (2017)
Ripe plantain (average)	26.6	Barón-Cortés <i>et al.</i> (2021)
Plantain (various samples)	Undetectable – 1542	Pertuz-Cruz <i>et al.</i> (2022)
Fried plantain	$9.13 \times 10^1 - 1.17 \times 10^3$ ($\approx 91.3 - 1170$)	Abubakari <i>et al.</i> (2025)
Deep-fried plantain chips	$4.9 \times 10^1 - 2.06 \times 10^3$ ($\approx 49 - 2060$)	Shamla <i>et al.</i> (2019)
Plantain chips (fried at 210 °C)	706 ± 13	Akinosun <i>et al.</i> (2021)
Yam chips (fried at 210 °C)	703 ± 27	Akinosun <i>et al.</i> (2021)
Sweet potato fries (20 min)	> 500 (exceeded EU benchmark)	Ajani <i>et al.</i> (2019)
French fries (20 min)	> 500 (exceeded EU benchmark)	Ajani <i>et al.</i> (2019)
French fries (10 min)	360 (below benchmark)	Ajani <i>et al.</i> (2019)
Fried meat	$\leq 3 - 720$ (lowest among fried foods)	Ajani <i>et al.</i> (2019)
Buns (baked at 150 °C)	25 ± 8	Akinosun <i>et al.</i> (2021)

Toxicological Implications of Acrylamide Exposure in Humans and Animals

Acrylamide is a hazardous compound associated with a wide spectrum of toxic effects, including neurotoxicity, cytotoxicity, hepatotoxicity, immunotoxicity, genotoxicity, mutagenicity, and potential carcinogenicity in humans (Gülcan *et al.*, 2020; Zhang *et al.*, 2023). Specific studies have highlighted its carcinogenic potential (Areej *et al.*, 2020), neurotoxic effects (Jong-Su *et al.*, 2021), genotoxicity (De Conti *et al.*, 2019), and reproductive toxicity (Rifai *et al.*, 2020).

The neurotoxic effects of acrylamide have been strongly demonstrated by occupational exposure. Neurological impairment has been reported among coal preparation plant workers who use acrylamide polymers for water clarity (Ubaaji & Orji, 2016). Peripheral neuropathy, which is characterized by sensory loss in a stocking-and-glove distribution, excessive sweating, muscle weakness, and occasionally ataxia, is a common sign of intoxication. After repeated low-level exposure, these effects could manifest weeks to months later, or even years later in cases of chronic exposure. According to research on animals, older rodents experience more severe neuropathy and recover more slowly than younger ones (Food and Agriculture Organization/World Health, FAO/WHO, 2011).

The International Agency for Research on Cancer (IARC) has classified acrylamide as a potential human carcinogen (Group 2A) (International Agency for Research on Cancer, 2024; Augustine & Bent, 2022; Mottram *et al.*, 2002). Animal trials frequently demonstrate the development of tumors in a variety of organs, including the thyroid, testes, mammary glands, lungs, and brain (Das & Srivastav, 2012). Human epidemiological studies are still unclear, although some evidence suggests that smokers are more likely to get lymphatic cancers, and obese individuals are more likely to develop esophageal cancer (Huang *et al.*, 2021; Friedman & Levin, 2018; Zhao *et al.*, 2015).

In a genotoxicity research, it indicates that acrylamide does not alter bacterial genes, its metabolite glycidamide does (FAO/WHO, 2002). In mammalian cells, acrylamide results in polyploidy, chromosomal abnormalities, sister chromatid exchanges, micronuclei, and mitotic disturbances (European Commission, 2003). According to Lee *et al.* (2014), oxidative stress-induced apoptosis is the main source of acrylamide neurotoxicity.

Concerns regarding maternal exposure are raised by the fact that acrylamide can pass thru the placenta and is eliminated in breast milk. Low birth weight, decreased head circumference, and restricted intrauterine growth have all been associated with prenatal consumption (Nagata *et al.*, 2018). Infertility, irritability, and eye infections are other health consequences (Saraji & Javadian, 2019). Acrylamide easily reacts with nucleophilic groups in biological molecules, including DNA, such as thiols, carboxylates, and amines, since it is electrophilic (Mogol *et al.*, 2020).

Human exposure occurs through ingestion, inhalation, and skin absorption, and it quickly spreads to organs including the liver, kidneys, brain, heart, and thymus (Wu *et al.*, 2021; Khorshidian *et al.*, 2020; Matoso *et al.*, 2019; Sarion *et al.*, 2021). After being absorbed, cytochrome P450 converts acrylamide into glycidamide, a more potent metabolite that causes cancer (Kacar *et al.*, 2019). According to Pan *et al.* (2020) and Saraji & Javadian (2019), the acceptable daily intake amounts are 40 µg/kg body weight for neurotoxicity and 2.6 µg/kg for carcinogenicity.

Analytical Techniques for Acrylamide Detection in Food Products

Accurate detection of acrylamide (AA) in food is still crucial due to its toxicological significance. Capillary electrophoresis, immunoenzymatic assays, and electrochemical biosensors are examples of novel analytical techniques that have gradually replaced conventional procedures because they provide sensitive and cost-effective alternatives (Oracz *et al.*, 2011). The most reliable instrumental method is still chromatography. High-Performance Liquid Chromatography (HPLC) and Ultra-Performance Liquid Chromatography (UPLC) offer rapid, reliable results, but they require meticulous sample preparation and specialized procedures (Arisseto *et al.*, 2008). Gas chromatography (GC) and mass spectrometry (GC-MS) are commonly employed in acrylamide analysis, often using derivatization methods such as bromination or silylation to increase detectability and precision (Lee *et al.*, 2007).

Innovative methods for detecting acrylamide include biosensors and immunochemical methods. Even with complicated food matrices, these systems achieve excellent sensitivity and selectivity by using bioreceptors, enzymes, antibodies, or microbial cells. Amperometric and potentiometric electrochemical biosensors are simple, quick to analyze, and small enough to be used for online monitoring. Detection at trace levels has been made possible by methods such as ion-selective electrodes and cyclic voltammetry (Lee *et al.*, 2007; Silva *et al.*, 2011).

Liquid chromatography–tandem mass spectrometry (LC–MS/MS) is one of the most precise methods for measuring acrylamide. This technique makes it possible to identify water-soluble, non-volatile compounds at trace levels (≤ 10 µg/kg). For example, Basaran *et al.* (2020) discovered that acrylamide concentrations in instant coffee from Turkish coffee brands ranged from 16.5 to 79.5 ng/mL. Similarly, Mesías *et al.* (2019) found that acrylamide levels varied from 197 to 639 µg/kg when breakfast cereals, particularly those composed of wheat, were cooked at 200 °C for 35 minutes. LC-MS/MS offers an advantage over GC-MS in that it can directly analyze aqueous samples without the requirement for organic solvents, which is consistent with acrylamide's high water solubility (Shibamoto, 2003).

Gas chromatography–mass spectrometry (GC–MS) is still a viable method for detecting volatile acrylamide. Schouten *et al.* (2021) demonstrated its application in cereal products with a detection limit of 0.6 ng/g. Nematollahi *et al.* (2019) found that acrylamide levels in wafers over 100 ng/g were influenced by baking temperature and duration. Acrylamide concentrations in roasted seeds and nuts ranged from 33.36 to 250.90 µg/kg, depending on the roasting methods (Nematollahi *et al.*, 2020). LC-MS/MS is still regarded as the most versatile and widely used method for examining dietary acrylamide in spite of these advancements (Zhang *et al.*, 2005).

HPLC is widely used for regular food analysis, despite the fact that careful sample preparation is often required to eliminate matrix interferences (Csapó *et al.*, 2008). Sivasakthi *et al.* (2019) found that pretreating potato chips with amino acids such as glycine and cysteine significantly reduced acrylamide levels after frying. For instance, chips treated with 1.0% cysteine and fried for seven minutes at 160 °C showed the most reduction. HPLC-MS/MS and UPLC-MS/MS are now the recommended methods for identifying acrylamide in food products (European Food Safety Authority, 2015). Fourier Transform Infrared Spectroscopy (FT-IR) provides useful information by identifying chemical bonds and generating molecular "fingerprints." Keramat *et al.* (2011)

demonstrated the utility of IR spectrum analysis by identifying decarboxylated asparagine products in glucose–asparagine model reactions.

Mitigation Strategies to Acrylamide Formation in Fried Plantain Products

Numerous methods for lowering the production of acrylamide in plantain-based products are highlighted by recent developments in food science. When it comes to the development of acrylamide in plantain-based dishes, frying conditions are crucial. Higher temperatures and longer frying periods dramatically increase acrylamide levels, which can reach 951 µg/g at 190 °C after nine minutes, according to Abubakari *et al.* (2025). On the other hand, acrylamide concentrations were significantly decreased by citric acid pretreatment, reaching as low as 65 µg/g. Response surface optimization also showed that pretreating with 20 g/L citric acid and frying at 150 °C for three minutes decreased acrylamide to about 89.6 µg/g, which is significantly lower than the average concentration found in local frying methods (210 µg/g)..

According to Bassama *et al.* (2012), non-isothermal heat treatment can lower acrylamide levels by as much as 50% in addition to thermal control. However, controlling the asparagine content of raw plantains either by immersion pre-treatments or maturity stage selection offers a more straightforward and successful mitigating approach. Other approaches have also been successful. Omini *et al.* (2019), suggested lower pH and higher sodium chloride levels resulted in a significant ($p < 0.05$) decrease in acrylamide concentrations. Acrylamide synthesis decreased by 98.9% in ripe plantains and 35.4% in unripe ones at 10% NaCl, highlighting the potential of salt pre-treatment in acrylamide reduction. Ripe plantains treated with sodium chloride showed a 98.9% reduction in acrylamide.

Additional promise is offered by alternative frying technologies. As a healthier alternative to traditional deep-fat frying, Omotosho *et al.* (2017) showed that infrared (IR) frying preserved nutrient quality and decreased acrylamide generation. Both air and vacuum frying have the potential to lower acrylamide levels without sacrificing flavor. Safer cooking methods can be established with the aid of predictive modeling of frying parameters such as temperature, time, and oil type (Abubakari *et al.*, 2025).

Breeding plantain variants with lower asparagine and sugar content thru genetic and agronomic methods could significantly minimize the production of acrylamide. To find cultivars with advantageous genetic features that reduce precursor chemicals, region-specific research in Africa and Latin America is required (Udomkun *et al.*, 2021; Shamla & Nisha, 2017).

Future Directions

Innovative technologies like electrochemical detection and biosensors are being investigated more and more as supplemental instruments to conventional techniques like HPLC and LC-MS/MS. These developments improve quality control by providing quicker, more economical monitoring and possibly enabling real-time detection while frying (Oracz *et al.*, 2011; Silva *et al.*, 2011).

Epidemiological and toxicological research despite acrylamide's classification as a possible human carcinogen (IARC, 2024), there is still a dearth of epidemiological information about plantain chip use in tropical areas. To evaluate neurotoxicity and cancer risk in populations with high plantain use, long-term research is required (Zamani *et al.*, 2017; Huang *et al.*, 2021).

Plantain chips are not expressly covered by the current EU criteria (≤ 750 µg/kg for fried snacks). To promote safer consumption without damaging traditional dietary traditions, it is crucial to develop region-specific regulatory requirements and increase public awareness about acrylamide dangers (FDA, 2023; European Food Safety Authority (EFSA, 2012)

CONCLUSION

Acrylamide formation in plantain chips is strongly influenced by frying conditions, raw material composition, and pre-treatment strategies. Elevated temperatures and prolonged frying times consistently increase acrylamide levels, while interventions such as citric acid soaking, sodium chloride treatment, and infrared frying significantly reduce concentrations. Advanced analytical techniques (HPLC, LCMS/MS, GC–MS, biosensors) have enabled precise monitoring, while genetic and agronomic approaches offer long-term solutions by lowering precursor compounds in plantain cultivars. Household-level practices, alongside innovative processing methods like vacuum and air frying, provide practical mitigation strategies. Overall, a multifaceted approach combining analytical monitoring, agronomic improvements, optimized processing, and consumer awareness is essential to reduce acrylamide exposure from plantain chips, ensuring both food safety and cultural dietary preservation.

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