



## Acrylamide content and quality characteristics of French fries influenced by different frying methods

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### ABSTRACT

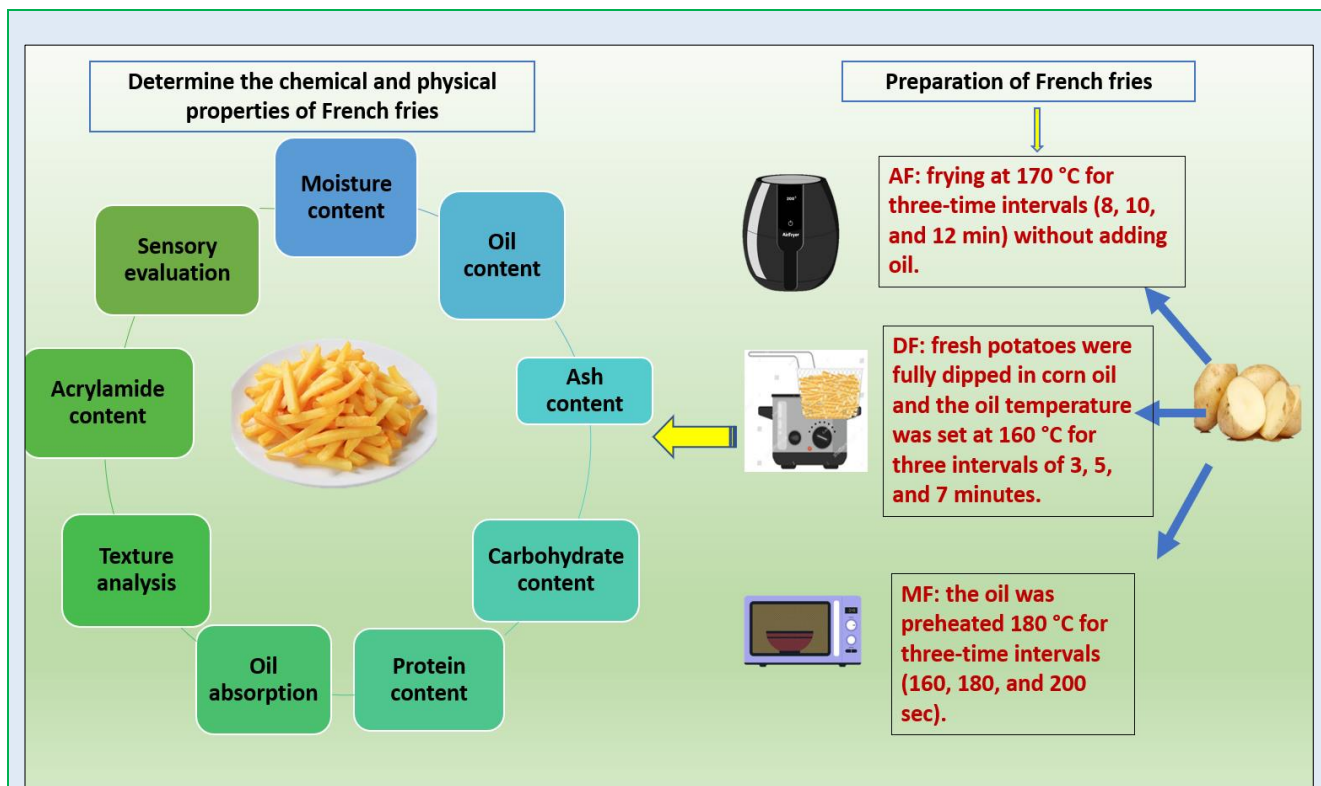
**Background:** This study aimed to compare the effects of three different frying methods, namely air frying (AF), microwave frying (MF), and deep frying (DF) in corn oil, on the moisture and texture, as well as the content and absorption of oil, carbohydrates and acrylamide in French fries.

**Materials and Methods:** For the DF, the fresh potatoes were fully dipped in corn oil and the oil temperature was set at 160 °C for three intervals of 3, 5, and 7 minutes. In the MF, the oil was preheated to 180 °C for three time intervals of 160, 180, and 200 seconds. The AF was set at a temperature of 170 °C for three time intervals of 8, 10, and 12 minutes, without adding oil.

**Results:** The results showed that AF resulted in a lower acrylamide content (21.8 ppm) after 8 minutes at 170°C compared to the other frying methods. However, DF in corn oil was preferred in terms of color, flavor, and overall acceptance in the sensory evaluation of the French fries. MF resulted in the hardest French fry texture due to excessive evaporation of moisture.

**Conclusion:** The findings suggest that AF may be a healthier option with a lower acrylamide content, while DF in corn oil may be preferred for its superior sensory characteristics.

**Keywords:** Acrylamide, Air frying, Deep frying, Microwave, Oil absorption, Sensory evaluation.



**Graphical Abstract:** Acrylamide content and quality characteristics of French fries

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## INTRODUCTION

Potatoes are a staple food in many countries and are consumed in various forms including boiled, baked, roasted, mashed, and fried. In addition, potatoes are a starchy root vegetable that contain a high amount of carbohydrates, primarily in the form of starch. On average, potatoes contain between 70-80% starch by weight, depending on the variety and cooking method. When amino acids and reducing sugars are heated, a chemical reaction known as the Maillard reaction takes place that produces a variety of substances. The high temperatures involved in the frying process of deep-fried foods, such as French fries, can cause the Maillard reaction to occur rapidly [1].

When foods are cooked at high temperatures, the Maillard reaction can produce hazardous compounds like acrylamide. Acrylamide is formed as a result of the

Maillard reaction between the amino acid asparagine and reducing sugars. The International Agency for Research on Cancer (IARC) has classified acrylamide as a probable human carcinogen, and studies have suggested a link between high levels of acrylamide consumption and an increased risk of certain types of cancer in humans [2-3].

Air frying (AF) is an emerging processing technology that has become increasingly popular among consumers in recent years. AF involves cooking food by circulating hot air around it using a specialized appliance called an air fryer. Unlike deep frying (DF), which involves submerging food in hot oil, AF uses little to no oil to achieve a crispy, fried-like texture. However, it is worth noting that AF may not be a suitable replacement for all deep-fried foods, as some foods may not achieve the

same texture or flavor as traditional DF. Additionally, some studies suggest that AF may not completely eliminate the formation of acrylamide, although it can significantly reduce its formation compared to DF [4-6]. Numerous studies have demonstrated that thermal processing alters the physical and chemical structure of food [7-9].

Microwave frying (MF) can facilitate Maillard reactions, which can lead to acrylamide formation in food, similar to conventional heating methods. However, there is currently limited information available about the effects of MF on the formation of acrylamide and its interactions between food ingredients during this process. Some studies have suggested that MF may produce more acrylamide compared to conventional heating methods, possibly due to the rapid temperature increase in the food caused by microwaves. MF can generate heat energy inside the food, which does not require a medium for heat transfer, unlike conventional heating. As a result, products with low thermal conductivity may quickly reach high temperatures during MF, which may provide a favorable medium for the occurrence of acrylamide formation and affect its kinetics [10-12].

Therefore, it is important to understand the effects of different heat treatment methods on food and to carefully manage the thermal processing of food to minimize the formation of hazardous compounds. This can be achieved through the use of appropriate cooking methods, temperature control, and food handling practices. In this study, the effect of different cooking methods (DF, AF, MF) on the formation of acrylamide and changes in the physical and chemical properties of French fries will be discussed. This research contributes to the existing knowledge on heat treatment and food safety. It provides valuable information that can be used to

develop guidelines and recommendations for consumers, food manufacturers, and regulatory authorities to minimize acrylamide formation and ensure the production of safer and higher quality fried foods.

## MATERIALS AND METHODES

**Preparation of French Fries:** Potato samples (*Solanum tuberosum* L.) were collected from the local market in Tikrit City, where they were washed, peeled, cut 1 cm ×1 cm ×6 cm, and fried in three different methods. The first method (DF), used corn oil at a temperature of 160 °C for three different periods of time for frying (3, 5, and 7 minutes, respectively). The second method, (AF with air fryer (Silver crest, Germany)) did not include oil and was set at a temperature of 170 °C for three different periods of time for frying (8, 10, and 12 minutes, respectively). MF is done using a microwave (Gosonic, China) by preheating the oil for 8 minutes. After the oil temperature reached 180 °C, the samples were placed for three periods of time for frying (200, 180, and 160 seconds, respectively). The times and temperatures were chosen in advance according to a preliminary study conducted on samples. The selected frying times and temperatures resulted in a sensually acceptable product with desirable characteristics and a palatable flavor. These optimal frying conditions ensured that the French fries had an appealing appearance, with a golden-brown color and a crispy texture.

**Moisture Content Determination:** Moisture content was measured based on the standard method according to AOAC, 1990 [13], by taking 5 g of fried potato sample, placing it in a petri dish of known weight, and drying it using an electric oven at a temperature of 105 °C for 3 hours. The percentage of moisture was calculated according to the following equation (1):

**Equation 1:**

$$\% \text{ of moisture} = W_b - W_a / W_b \times 100$$

$W_b$  = the weight of the sample before drying

$W_a$  = the weight of the sample after drying

**Oil Content Determination:** The percentage of total oil in fried potato samples was estimated according to AOAC, 1990 [13], using the Soxhlet extractor, where 0.5 g of dried and ground fried potato samples were weighed and placed in the device with 200 mL of hexane added to it. The extraction process continued for 4-6 hours. The samples were then collected from the apparatus and placed in an electric oven for half an hour at a temperature of 80 °C in order to get rid of the remaining solvent. After that, the dried samples were weighed, and the percentage of oil was calculated according to the following equation (2):

**Equation 2:**

$$\% \text{ of oil} = W_b - W_a / W_b \times 100$$

$W_b$  = the weight of the sample before extraction (g)

$W_a$  = the weight of the sample after extraction (g).

**Ash Determination:** The ash percentage was estimated according to the method 940.26 AOAC, 1990 [13], placing 5 g of dried fried potato sample in a weighted ceramic lid and treating them with a temperature of 600 °C for 6 hours. The percentage of ash was calculated according to the following equation (3):

**Equation 3:**

$$\% \text{ of ash} = W_{\text{ash}} / W_s \times 100$$

$W_{\text{ash}}$  = Ash weight (g)

$W_s$  = Sample weight (g).

**Protein Determination:** Protein was measured in fried potato samples using the Kjeldahl apparatus, according to the method mentioned in (AOAC, 2008). Briefly, 0.5 g of fried potato samples were placed in a digestion tube, 15 mL of concentrated sulfuric acid (95%) was added to it with drops of perchloric acid ( $\text{HClO}_4$ ), and the digested

samples were distilled after adding 10 mL of 0.1 N NaOH. The liberated ammonia was collected in a conical flask containing 25 mL of boric acid (2%) with two drops of Bromocresol Green and methyl Red Reagent Guide and flushed with hydrochloric acid 0.05 N. The protein percentage was calculated according to the following equation (4):

**Equation 4:**

$$\% \text{ of protein} = \text{Amount of HCL consumed (ml)} \times \text{standard} (0.05) \times 0.014 \times 6.25 / \text{sample weight (g)} \times 100$$

**Carbohydrate Determination:** The carbohydrate ratio was calculated by subtracting the total ingredients from 100, as provided in AOAC, 2000 [14].

**Texture Analysis:** The texture of the samples was estimated using the Texture analyzer according to the method mentioned by Verma [15].

**Oil Absorption of French Fries:** By calculating the difference between the percentage of oil in the sample before and after frying, the amount of oil absorbed during the frying process was estimated according to Ouchon [16]. The oil absorbency was assessed for the MF and DF methods, but not for the AF samples, since no oil was added in the air fryer during this study.

**Acrylamide Determination by HPLC:** Sample extraction: 1 g mass of the homogenized and finely grinded sample was placed into a 50mL centrifuge tube, and a 20mL of n-hexane was added. The tube was shaken by vortex for 5 minutes. Then, each tube was centrifuged at 6,000 rpm for 15 minutes, followed by filtration under vacuum, and the n-hexane layer was discarded. The de-fatted sediment is dried in the oven at 60 °C for 15 minutes, then extracted by the addition of 5mL lukewarm water and vortexed for 5 minutes. The homogenized mixture was filtered under a vacuum, and the aqueous phase was collected and further cleaned-up by applying each

sample to a preconditioned SPE tube. The SPE dispersive conditions removed most of the remaining fats and other interferences remaining in the aqueous aliquot. SPE cartridges were conditioned with 3mL methanol and equilibrated with 6mL of water. The methanol and water portions used to prepare the cartridge were then discarded. 2mL of the aqueous filtrate was directly loaded on the top of an SPE cartridge at a flow rate of 2mL/min. The extract was allowed to pass through the SPE sorbent bed, followed by 0.5 mL of water. The first 0.5 mL eluted from the SPE tube was discarded, while the next 1mL is collected and filtered by a 0.45µm syringe filter and introduced directly to HPLC analysis.

HPLC analysis: Samples were HPLC model (SYKAM) Germany. The mobile phase was acetonitrile distilled water (D.W) (60: 40 V/V) and the column separation was C18-OSD (25 Cm \* 4.6 mm), at a flow rate = 1 ml / min. The detector was (Florescence) at Ex = 217 nm, Em= 334 nm.

**Sensory Evaluation:** Sensory evaluation was conducted according to Jaggan [17], asking 10 people to rate French fries in terms of color, aroma, flavor, texture, and overall acceptability, using a hedonic scale ranging from 1-9 points. Here is a brief description of each point on a 9-point hedonic scale: 1: Dislike Extremely, 2: Dislike Very Much, 3: Dislike Moderately, 4: Dislike Slightly, 5: Neither Like nor Dislike (Neutral), 6: Like Slightly, 7: Like Moderately, 8: Like Very Much, 9: Like Extremely

**Statistical Analysis:** A one-way ANOVA followed by Duncan's multiple range test (DMRT) was performed using SPSS 11.00 (SPSS Inc., Chicago, IL, USA) to analyze and compare the data. Results were presented as mean  $\pm$  SD and P-values  $\leq$  0.05 were regarded as statistically significant.

## RESULTS AND DISCUSSION

**Moisture Content:** Moisture content is an important parameter in food products, as it has a direct effect on the texture, color and sensory acceptability of the food. Table 1 shows the percentage of moisture in the fried potato samples by different methods (MF, AF, and DF). There were significant differences ( $P > 0.05$ ) for all samples' values obtained by different methods and intervals, with the exception of T1 for DF and MF (results did not vary significantly from each other). The moisture content of fried potatoes decreased significantly with increasing time in all types of frying methods. The highest moisture content was in AF at 8 minutes (68.12%), and the lowest moisture content was in MF for 200 seconds (33.82%). These findings agree with Fang [18] in his research of fried fish skins by different frying method, in addition to Zhou's [19] study on the effect of microwave heating at two frequencies (2.45 and 5.85 GHz) on French fries.

The faster decrease in humidity observed in DF and MF compared to AF can be attributed to the different times and temperatures to which the samples were exposed, as well as the thermal transfer properties of oil compared to air. In DF, the samples were immersed in hot oil, which has a higher thermal conductivity than air. This allows for faster heat transfer from the oil to the surface of the food, leading to a faster decrease in moisture content. Overall, the differences in humidity reduction rates among the three frying methods (DF, AF, and MF) can be attributed to the specific temperatures, times, and heat transfer mechanisms involved in each method. Thus, MF led to a significantly lower moisture content in fried potatoes compared to other methods, which can be attributed to the unique heating mechanism of microwaves. When high-moisture food is heated in a microwave, the pressure inside the food rises rapidly and reaches higher values than conventional heating methods. Under high pressure, a significant

amount of moisture is pushed toward the surface of the food. However, the surface of the food is unable to retain this moisture effectively and as a result, the water is "pumped" out of the food without undergoing any change in phase, meaning it remains in a liquid state. This phenomenon is commonly referred to as "Liquid Pumping." [20]. The results of this study do not align with

Verma [15], who found that the electromagnetic field, such as in MF, accelerates the heating of the water present in French fries (polar particles) compared to frying oil (non-polar particles). This difference in heating behavior can result in the hardening of the surface crust of the food and subsequently lead to less evaporation of surface moisture.

**Table 1.** Chemical properties of French fries

Processing chemical properties	Time	MF	AF	DF
Moisture content %	T <sub>1</sub>	47.50 ± 1.69 <sup>d</sup>	68.12 ± 0.37 <sup>a</sup>	46.19 ± 0.96 <sup>d</sup>
	T <sub>2</sub>	40.98 ± 0.12 <sup>f</sup>	64.40 ± 0.49 <sup>b</sup>	42.74 ± 0.64 <sup>e</sup>
	T <sub>3</sub>	33.82 ± 1.04 <sup>g</sup>	47.45 ± 0.62 <sup>c</sup>	40.54 ± 0.60 <sup>f</sup>
Oil content %	T <sub>1</sub>	11.10 ± 0.21 <sup>f</sup>	3.01 ± 0.37 <sup>g</sup>	25.80 ± 0.28 <sup>c</sup>
	T <sub>2</sub>	12.15 ± 0.20 <sup>e</sup>	2.10 ± 0.20 <sup>h</sup>	29.10 ± 1.12 <sup>b</sup>
	T <sub>3</sub>	16.10 ± 0.34 <sup>d</sup>	2.11 ± 0.14 <sup>h</sup>	31.16 ± 0.23 <sup>a</sup>
Ash content %	T <sub>1</sub>	2.46 ± 0.40 <sup>cd</sup>	2.91 ± 0.5 <sup>c</sup>	3.70 ± 0.11 <sup>a</sup>
	T <sub>2</sub>	2.51 ± 0.40 <sup>cd</sup>	2.39 ± 0.49 <sup>cd</sup>	3.58 ± 0.29 <sup>a</sup>
	T <sub>3</sub>	1.06 ± 0.23 <sup>e</sup>	1.97 ± 0.29 <sup>d</sup>	3.26 ± 0.13 <sup>ab</sup>
Protein content %	T <sub>1</sub>	1.86 ± 0.05 <sup>d</sup>	1.40 ± 0.02 <sup>g</sup>	2.48 ± 0.02 <sup>a</sup>
	T <sub>2</sub>	1.74 ± 0.04 <sup>e</sup>	1.29 ± 0.01 <sup>h</sup>	2.19 ± 0.05 <sup>b</sup>
	T <sub>3</sub>	1.62 ± 0.03 <sup>f</sup>	1.21 ± 0.01 <sup>i</sup>	1.99 ± 0.02 <sup>c</sup>
Carbohydrate %	T <sub>1</sub>	37.08 ± 1.84 <sup>c</sup>	24.57 ± 1.23 <sup>f</sup>	22.23 ± 1.55 <sup>fg</sup>
	T <sub>2</sub>	42.42 ± 0.34 <sup>b</sup>	28.83 ± 0.32 <sup>e</sup>	22.39 ± 1.26 <sup>g</sup>
	T <sub>3</sub>	45.39 ± 0.24 <sup>a</sup>	33.65 ± 0.52 <sup>d</sup>	22.44 ± 0.84 <sup>g</sup>

Different letters in the same group indicate statistically significance (p < 0.05) by Duncan's test. The data are the mean of three measurements for the sample (Values ± SD).

**Oil Content:** Frying involves the transfer of heat from cooking oil to the food, causing moisture to evaporate from the food and escape into the surrounding air. Meanwhile, the hot oil is absorbed into the food, creating a crust and adding flavor. Table 1 show that the highest percentage of oil was 31.16% at 7 minutes in DF, while the lowest rate of oil was 2.10% in AF. The explanation for this is attributed to the length of frying time, which can affect the amount of oil absorbed by the potatoes. Generally, when food is fried for an extended period, it tends to absorb more oil. This is because longer oil

exposure allows more time for oil penetration into the food's structure. The results obtained match with the previous study by Verma [15] on French fries. In order to obtain a product with low oil content, no oil was used for AF in this study. Regarding the comparison between DF and MF, there were significant differences in the oil content of fried potatoes between these methods. The results indicated that potatoes fried using the MF method contained a lower percentage of oil compared to those fried using the DF method. This finding is consistent with the research conducted by Sansano [21] on the

effect of microwave frying on French fries. One possible explanation for the lower oil content in MF-fried potatoes is the limited spread of oil within the product. MF involves the use of microwaves to heat the food rapidly, leading to a high rate of water evaporation. This rapid evaporation of water may limit the absorption and spread of oil within the potatoes, resulting in lower oil content compared to DF. Additionally, the shorter frying time associated with MF may also contribute to the lower oil content [22].

**Ash Content:** Ash content refers to the inorganic residue left behind after the complete combustion of organic matter and is primarily composed of minerals present in food. The range of ash content in Table 1, from 1.06% to 3.70%, indicates the variability in mineral content among the potato samples. The decrease in ash content after frying is consistent with the findings of Tian [23], and can be attributed to the leaching of water-soluble minerals. Additionally, during frying, some minerals can dissolve in the cooking oil, further contributing to the decrease in ash content. This finding aligns with the Kourouma [24] study on the effects of different frying methods on sweet potatoes, suggesting that the leaching of water-soluble minerals during blanching and frying is a common phenomenon in various types of potatoes. Thus, different factors such as potato variety, blanching and frying conditions, and the specific cooking method used, can influence the changes in ash content.

**Protein Content:** Table 1 indicates a slight decrease in the percentage of protein with an increase in frying times for all different frying methods (DF, AF, and MF). The protein content in the fried potatoes ranged from 1.99% to 2.48% in DF, 1.21% to 1.40% in AF, and 1.62% to 1.86% in MF. The study findings align with Kourouma [24] in his research on the effects of cooking processes on sweet potatoes. During frying, high temperatures can cause the

proteins in potatoes to denature and undergo structural changes. This denaturation and structural modification can lead to protein breakdown and a potential loss of protein content. Additionally, the heat and dehydration during frying can cause water loss, leading to a higher concentration of other components such as carbohydrates and lipids, which can further contribute to the decrease in the percentage of protein [25].

**Carbohydrate Content:** Table 1 shows that the percentage of carbohydrates in the fried potato samples varied depending on the frying method. In DF method, the carbohydrate content ranged from 22.14% to 22.83%. In AF method, the carbohydrate content ranged from 24.57% to 33.65%. In MF method, the carbohydrate content ranged from 37.08% to 45.39%. The increase in carbohydrate content observed in the AF, MF, and DF methods are consistent with the findings of Yaseen [26], which explain the reason for this increase to higher frying temperatures, lower humidity, and higher oil content. These factors can lead to greater starch gelatinization and dehydration during frying, resulting in a higher concentration of carbohydrates in the final product. Studies indicated the effect of frying methods on carbohydrate content of French fries can vary depending on several factors, including the frying temperature, duration, and specific frying technique used. During DF, the high temperature can cause the starch in the potatoes to undergo gelatinization, resulting in a crispy exterior. While some oil may be absorbed during deep frying, the carbohydrate content of the French fries may not significantly change compared to the raw potatoes. In the AF method, the carbohydrate content of the French fries may remain relatively similar to that of the raw potatoes, as the absence or minimal use of oil reduces the potential for significant changes. MF utilizes microwave energy to rapidly heat the food. This method

typically requires less cooking time compared to DF or AF. The carbohydrate content of French fries in the MF method may undergo some changes due to the heating process, including potential starch gelatinization and dehydration. However, the specific impact on carbohydrate content can vary based on the MF conditions and the potato variety used [27, 28].

**Texture Analyzing:** The texture of French fries is a vital aspect that must be thoroughly examined to ensure maximum satisfaction for consumers. To analyze the texture of French fries in this study, we used hardness as a parameter, defined as the maximum force (N) required to penetrate the probe into the sample. The analysis of hardness for fried potatoes involved comparing different methods, and the findings are shown in Table 2. The degree of hardness increased with an increase in frying time for all methods. In particular, fried potatoes cooked using MF exhibited more hardness, which can be attributed to excessive evaporation of moisture during the frying process. On the other hand, no significant differences were found in the hardness of fries between AF and DF. These findings align with a study conducted by Sansano [21], which reported that microwaved French fries had lower water content compared to other frying

methods. The lower water content in microwaved fries can contribute to a surface texture that is more similar to potato chips rather than traditional French fries. However, the results differ from those reported by Verma [15]. Their research suggested that vacuum frying and AF resulted in potatoes with higher hardness compared to MF and DF. These contrasting results may arise from variations in frying conditions, such as temperature, duration, and specific potato varieties used in the studies. Furthermore, it was observed that the textural properties of fried potato tubers of high specific gravity were deemed most desirable.

One of the primary constituents contributing to the texture of processed potatoes is starch, which undergoes gelatinization during heating. As a result of this process, the starch granules swell and become more soluble in water, leading to changes in potato texture [29, 30]. Moreover, the chemical changes that occur during frying and physical modifications contribute significantly to crust formation. For instance, when the potato pieces are submerged in hot oil, the water within the potato is rapidly converted to steam and expands due to the heat. This expansion causes the surface of the potato to rupture and form a series of small bubbles that merge, resulting in a porous crust [31].

**Table 2.** Texture of French fries by different frying process

Texture	Time	MF	AF	DF
Texture (N)	T <sub>1</sub>	8.70 ± 0.7 <sup>b</sup>	8.24 ± 0.6 <sup>c</sup>	8.19 ± 0.2 <sup>c</sup>
	T <sub>2</sub>	9.11 ± 0.3 <sup>a</sup>	8.32 ± 0.2 <sup>c</sup>	8.25 ± 0.7 <sup>c</sup>
	T <sub>3</sub>	9.91 ± 0.1 <sup>a</sup>	8.70 ± 0.2 <sup>b</sup>	8.74 ± 0.4 <sup>b</sup>

Different letters within groups indicate statistically significance ( $p < 0.05$ ) by Duncan's test. The data are the mean of three measurements for the sample ((Values ± SD)

**Oil Absorption of French Fries:** Figure 1 demonstrates the oil absorbency in potato samples during frying, indicating that the moisture was evaporated and replaced by oil in all methods except AF. In AF, no additional oil was added during frying, resulting in no change beyond the original fat content. The oil absorbance percentages in DF

samples were 24.75 ± 0.28, 28.04 ± 0.12, and 30.11 ± 0.23 for frying times of 3, 5, and 7 minutes, respectively. In MF samples, the oil absorbance percentages were 10.05 ± 0.21, 11.1 ± 0.20, and 15.05 ± 0.34 for frying times of 160, 180, and 200 seconds. A significant increase in the oil absorbency rate was observed with the longer frying times for all samples in both DF and MF. This finding

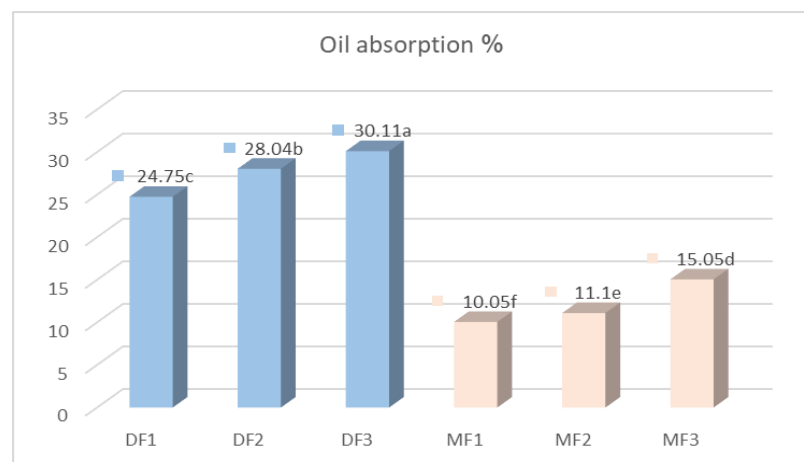


aligns with the results obtained by Su [32] in his study on the reduction of oil uptake in microwave-assisted vacuum fried potato chips. In the current study, the highest oil absorption percentage was achieved in DF ( $30.11 \pm 0.23$ ), while the lowest absorption percentage was observed in MF ( $10.05 \pm 0.21$ ).

The rapid evaporation of moisture in MF samples led to a less cohesive crust and a denser interior with smaller pore diameters. These changes resulted in a decrease in oil absorbency after microwave frying, as reported by Parikh and Takhar [33] and Zhang [34]. In the case of MF, the dielectric properties of the food, particularly water content, greatly influence the heating process.

Water molecules are polar and have high

dielectric properties, meaning they can absorb microwave energy effectively. As microwaves interact with water molecules, they cause rapid oscillation and generate heat, which is transferred throughout the food, leading to evaporation of moisture. As moisture evaporates, it creates porous structures within the food, including the formation of small air pockets and changes in texture, affecting oil absorption. The presence of pores and altered surface characteristics can limit the penetration and absorption of oil into the food during MF [21, 35]. Therefore, the oil absorbency in French fries is primarily affected by the porous structures formed because of moisture evaporation and crust formation, which vary depending on the frying method employed.



**Figure 1.** Oil absorbance of the samples by the DF and MF methods

Different letters indicate statistical significance ( $p < 0.05$ ) by Duncan's test. The data are the mean of three measurements for the samples.

**Acrylamide Content:** The formation of acrylamide in fried potatoes is a concern due to its potential carcinogenic properties. Acrylamide is formed when carbohydrates, such as those present in potatoes, are heated to high temperatures in the presence of certain amino acids, such as asparagine. The results in Figure 2. Indicate variations in acrylamide content among the different frying methods and frying times. Higher temperatures

and longer frying times generally led to increased acrylamide formation in French fries, which is consistent with previous studies [1, 36-37].

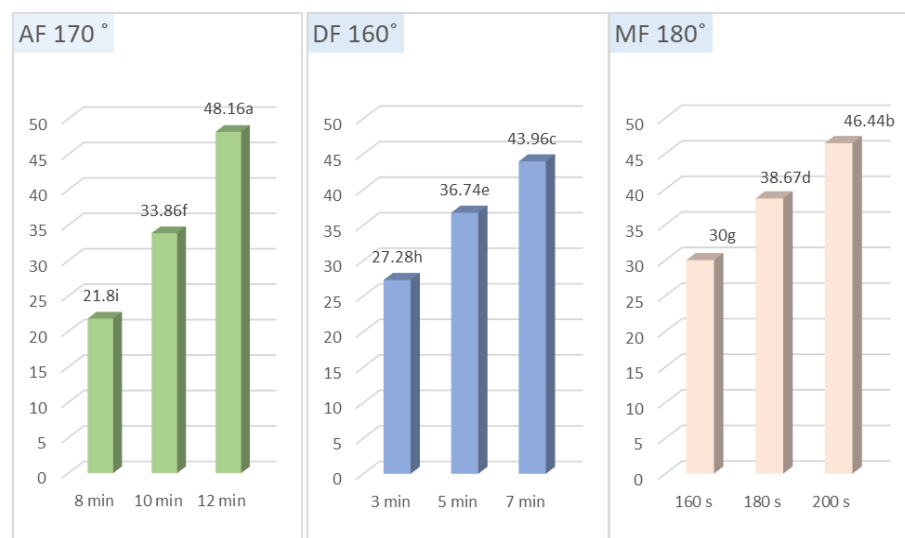
Specifically, in the current study, AF for 12 minutes at a temperature of  $170\text{ }^{\circ}\text{C}$  resulted in the highest acrylamide content. This finding aligns with the research by Verma [15], who reported that AF at lower temperatures for a longer duration resulted in lower acrylamide formation compared to frying at higher

temperatures for a shorter duration. However, it should be noted that AF at lower temperatures for longer durations may still result in a relatively higher acrylamide content compared to other frying methods. On the other hand, MF for 160 seconds at a temperature of 180 °C showed lower acrylamide content. This finding is consistent with the research by Elfaitouri [38], who observed that frying potato chips in corn oil at lower temperatures and shorter times resulted in lower acrylamide formation. It's important to consider that acrylamide content in fried potatoes depends on various factors, including frying processes (temperature, time, pH), the surface-to-volume ratio, the pretreatment of potatoes before frying, and the potato variety. Therefore, it is necessary to optimize frying conditions to minimize acrylamide formation while considering other quality parameters and food safety regulations.

Color formation in French fries occurs as the Maillard reactions progress. The initial pale color of the raw potato transforms into a golden-brown color due to the production of melanoidins, which are brown-colored polymers formed through complex chemical processes during the Maillard reactions [39]. At the same time, acrylamide can also be formed as a byproduct of the Maillard reactions. The exact pathway for acrylamide

formation is still not fully understood, but it involves the reaction between the asparagine and carbonyl compounds derived from reducing sugars. This reaction leads to the formation of acrylamide, which is a heat-induced chemical with potential health concerns. The formation of acrylamide is favored under specific conditions, including high temperatures (typically above 120°C/248°F) and low moisture levels. Longer cooking times can also contribute to increased acrylamide formation. Therefore, controlling these parameters, such as adjusting frying temperature and time, can help mitigate acrylamide formation in French fries [21, 40–42].

It's worth noting that the Maillard reactions are complex and can produce various compounds, including both desirable flavor and color compounds as well as potentially harmful substances, like acrylamide. Ongoing research aims to better understand the mechanisms behind these reactions and develop strategies to reduce acrylamide formation while preserving the desired sensory characteristics of fried foods. Based on the results of this study, AF for 8 minutes at a temperature of 170 °C is suggested as the best option to achieve a product with a low acrylamide content that meets the standards set by the EU Commission.



**Figure 2.** Acrylamide content (ppm) of the samples by the AF, DF and MF methods

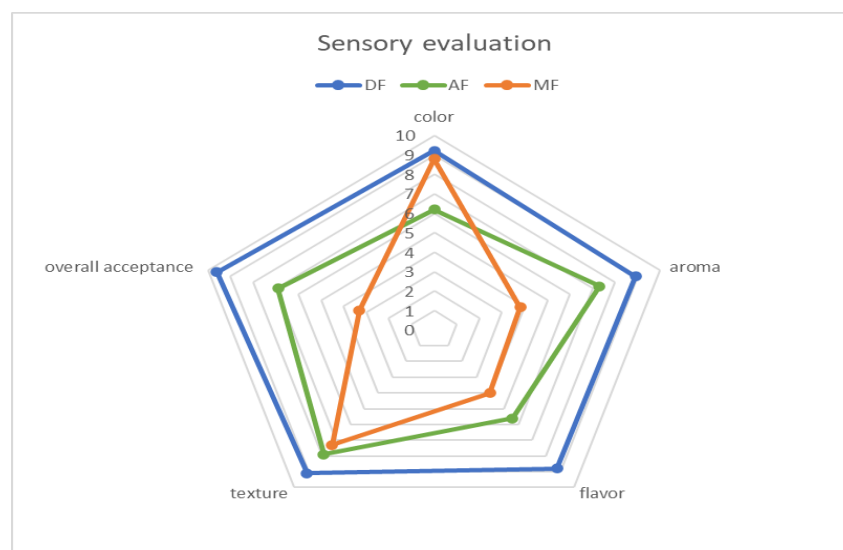
Different letters indicate statistically significance ( $p < 0.05$ ) by Duncan's test. The data are the mean of three measurements for the samples.

**Sensory Evaluation:** Figure 3 presents the sensory properties of the fried potatoes obtained through DF, AF, and MF methods, showcasing variations in sensory acceptance. DF in oil demonstrated higher sensory acceptance in terms of color, aroma, flavor, and texture. On the other hand, the sensory properties of French fries by AF and MF differed significantly, which can be attributed to several factors, including frying temperature, oil absorption rate, thermodynamics, water transfer, and the microstructure of the crust. These factors influence the formation of desirable sensory attributes during the frying process [44–46].

DF tends to produce French fries with a golden-brown, visually appealing color. AF can also yield fries with a desirable color, although it may be slightly lighter. MF may result in French fries with uneven browning, which are less visually appealing. Moreover, DF French fries are often associated with an appetizing and savory aroma. AF fries may have a milder aroma compared to deep-fried ones. Microwave-fried fries may not develop as much aroma due to the limited Maillard reaction occurring at lower temperatures. As for the texture of French fries, deep-fried French fries typically exhibit a crispy exterior and a tender interior. Air-fried fries can also achieve a crispy texture, although it may not be as pronounced as in deep-fried ones. The texture of French fries prepared in the microwave can differ from those

prepared using other frying methods. MF involves a different mechanism of heat transfer compared to DF or AF, which can affect the texture of the final product. When French fries are cooked using the MF method, the heat is generated directly within the food through the absorption of microwave energy. This leads to rapid heating and the evaporation of moisture within the fries. The moisture loss can result in a drier texture and less crispness compared to DF or AF. Additionally, MF may not provide the same level of surface browning and crust formation as traditional frying methods. The Maillard reactions, which are responsible for the desirable browning and flavor development in fried foods, occur less efficiently in MF due to the lower temperatures reached during cooking. As a result, the surface of French fries may be less crispy and have a softer texture.

Some people may enjoy the softer texture of microwave-fried French fries, while others may prefer the crispy and crunchy texture of deep fried or air-fried French fries. The choice of frying method should consider personal preferences and desired texture outcomes. Lastly, the overall acceptability of deep-fried French fries is generally well-accepted by consumers due to their desirable sensory attributes. Air-fried and microwave-fried French fries may have slightly different sensory profiles, and their acceptability can vary among individuals based on personal preferences.



**Figure 3.** Sensory evaluation of French fries

## CONCLUSION

AF is an emerging processing technology that has become increasingly popular among consumers in recent years. However, there is currently limited information available on the effects of MF on the formation of acrylamide, as well as the interactions between food ingredients during microwave processing. In this study, sensory evaluation of French fries prepared using different frying methods, namely deep frying with oil (DF), air frying (AF), and microwave frying (MF), was conducted in the current study. The acrylamide content of fried potatoes was analyzed by high performance liquid chromatography (HPLC). The results indicated that potatoes fried using the AF method contained less acrylamide compared to those fried with the DF method.

Moreover, the highest oil absorption percentage was achieved in DF ( $30.11 \pm 0.23$ ) and the lowest absorption rate was observed in MF ( $10.05 \pm 0.21$ ). However, DF emerged as the preferred method based on sensory evaluation, with superior color, flavor, and overall acceptance of the French fries. On the other hand, MF led to a higher hardness in the texture of the French fries due to excessive moisture evaporation. These findings contribute to the understanding of the trade-offs between health considerations and sensory appeal when selecting a frying method for French fries. However, it is important to note that further research may be needed to confirm these findings and explore potential health effects of each frying method.

**Abbreviations:** AF: Air frying, DF: Deep frying, MF: Microwave frying

**Conflicts of Interest:** The authors declare that the study was conducted without a potential conflict of interest.

**Authors' Contributions:** Zahraa Adil Ahmed: Conceptualization, Resources, Writing – original draft. Nameer K. Mohammed: Conceptualization,

Investigation, Project administration, Data curation, Validation, Writing – review and editing. All authors read and approved the final manuscript.

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