

Acrylamide Formation: The Effect of Thawing and Frying Methods in Chicken and Fish Meat

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Abstract Acrylamide (AA) is a potentially harmful compound found especially in foods cooked at high temperatures. The formation of AA has been linked to various health problems, including cancer. This study investigates the effect of different thawing methods (microwave, refrigerator, and water immersion) and cooking methods (air frying and deep fat frying) on AA formation. Fish meat, chicken breast, thigh, and wing samples were used. The samples were air-fried and deep-fat fried after different thawing methods. AA was analyzed by gas chromatography -mass spectrophotometer (GC-MS). The acrylamide levels of the deep-fat-fried chicken meats ranged from n.d. (not detected) to 79.40±9.52µg/kg, whereas those of the air-fried chicken meats ranged from n.d. to 60.00±9.12 µg/kg. The acrylamide levels of the deep-fat-fried fish meats ranged from 60.00±9.98 to 64.40±4.93µg/kg, whereas those of the air-fried fish meats ranged from 50.00±9.12 to 60.75±6.75µg/kg. These results show that AA formation in fish and chicken meat was lower in air frying than in deep fat frying. This suggests that air frying could be a healthier alternative. On the other hand, the effectiveness of thawing methods is not significant, indicating that the use of various thawing methods does not have a significant effect on AA formation. These findings indicate that air frying is a promising method with the potential to produce healthy fried products in terms of AA formation.

Keywords: acrylamide, fish, chicken, thawing, frying, GC-MS

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1. Introduction

Acrylamide (AA) is a potentially neurotoxic and cancer-causing chemical formed when foods high in carbohydrates and protein are exposed to temperatures above 120°C [1]. Studies have shown that AA levels can range from <10ng/g -8000ng/g depending on the product [2]. Even within the same food group, AA levels can vary significantly [3].

Many studies have shown that high consumption of processed meat can increase the risk of cancer in humans (breast, prostate, colorectal, ureter and pancreatic). Because the high cooking temperatures used in their production can cause high levels of carcinogenic compounds such as AA [4,5,6]. Classified as a probable carcinogen (Group 2A) for humans by the International Agency for Research on Cancer (IARC), AA is also formed when frying fish and chicken [5,7].

The Joint FAO/WHO Expert Committee on Food Additives proposed two different BMDL₁₀ (lower limits on the benchmark dose for a 10% response) values for AA:

0.31mg/kg BW/day for the induction of mammary tumors in rats and 0.18mg/kg BW/day for Harderian gland tumors in mice. These values were determined based on scientific evidence and are objective measures of the dose-response relationship [8].

Since the formation of carcinogenic compounds such as AA in fish and chicken meat poses a significant risk to human health, studies are needed to determine alternative cooking methods that produce healthier products without compromising texture, flavor, taste characteristics and appearance [9,10,11]. Some studies have investigated limiting the formation of carcinogenic compounds through the use of pre-cooking methods such as microwave pre-thawing, pre-drying and low-pressure frying [12,13,14]. An additional way to reduce the formation of carcinogenic compounds is to use a different cooking method. For example, air frying can often be used as a substitute for deep-frying. This method allows to produce fried foods using a small amount of oil. This technology allows for a 90% reduction in the fat content of fried products [10].

Despite the abundance of studies to assess the effect and levels of AA formation in fried foods, few studies

have examined the effect of thawing and frying methods on AA formation in foodstuffs. Therefore, we investigated AA formation in fish, chicken breasts, thighs and wings frozen at -20°C , thawed in the microwave, in the refrigerator and by immersion in water, followed by air frying and deep-fat frying.

2. Materials and Methods

2.1. Food Samples

Fish (*Salmo trutta*), skinless chicken breasts as thighs and wings with skin were purchased from a local food market. Sunflower oil for frying were purchased from national markers, used for frying the chicken and fish samples.

2.2. Chemicals

Acrylamide ($\%>99$) and $^{13}\text{C}_3$ labelled acrylamide ($\%>99$) were purchased from Sigma-Aldrich (St. Louis, MO, USA). The solvents and chemicals used in this study were of analytical purity.

2.3. Freezing and Thawing Processes

In the study, 30 fish, 30 chicken thighs, 30 chicken wings and 30 chicken breast samples of approximately 100g were used. Samples were frozen in polypropylene containers at -20°C for 24 hours. Frozen fish and chicken samples were subjected to thawing in the microwave, in the refrigerator and by immersion in water before frying. The thawing practices used in this study are as follows: Microwave thawing (Arçelik, MD574, Turkey) at 120W for 10 minutes; refrigerator thawing (Vestel NF52101 451 Lt No-Frost Refrigerator, Turkey) at 4°C for 24 hours; and water thawing by immersion in distilled water at 20°C for 1 hour (water was replaced after 30 minutes). These thawing practices are recommended by the United States Department of Agriculture (USDA) as safe defrosting methods. Cooking was performed immediately after thawing to avoid contamination [15].

2.4. Frying Processes

Chicken and fish samples were fried in sunflower oil. Each frying experiment consisted of 5 consecutive sessions. Deep-fat frying was performed in an electric deep fryer (Deep Fryer Electric Double ZH-904) with 5L oil capacity. Temperature changes during oil frying were controlled using a calibrated K-type thermocouple (Fluke 51 II, Wash., U.S.A.) with a stainless steel probe immersed in oil. An air fryer (Philips Airfryer 7000, Turkey) with adjustable temperature up to 200°C , 2.2L capacity and 2200W power was used for air frying. Once the oil temperature reached $180 \pm 5^{\circ}\text{C}$ and stabilized for 10 min, samples were fried in oil 10 min. and air fryer. Fresh oil was used for each frying experiment. After frying, the samples were dried on paper towels, cooled to room temperature, crushed and homogenized using a blender (Arzum AR1108-S Smarty Neo 900W, Turkey). The homogenized samples were immediately analyzed.

2.5. Determination of Acrylamide Content

Weighed 1g of the homogenized sample was placed in 50mL tubes, to which 10mL of water and $^{13}\text{C}_3$ acrylamide (1mL, 100ng/mL) were added. The tube was shaken at 250rpm for 20 min, then centrifuged at 12000rpm for 5 min (Hettich Universal 320 R, Germany) and filtered through a $0.45\mu\text{m}$ polivinidenflorit (PVDF) syringe filter. The filtrate was degreased by adding 5mL n-hexane. The aqueous phase was subjected to bromination (1.5g KBr, 1mL 0.1mol/L HBr + KBrO_3) overnight. Excess bromine was removed with sodium hyposulphite (1mL, 0.1mol). The sample was then extracted 2 times with 5mL ethylacetate and collected. The extract was evaporated to dryness, the dried extract was dissolved in 100 μL ethylacetate and 5 μL of the solution was injected into the GC-MS system [16].

2.6. GC-MS Analysis

The analysis was performed using a GC-MS QP2010 system (Shimadzu, Kyoto, Japan) and a Teknokroma TRB-225 ($0.25\text{mm} \times 0.25\mu\text{m} \times 0.30\text{m}$) column (Barcelona, Spain). The injection port temperature was set to 240°C , the detector temperature to 250°C , the ion source temperature to 210°C , and the oven temperature ranged from 70 – 260°C . Helium was used as the carrier gas with a flow rate of 1mL/min, and the injection volume was 5 μL . The identification mode was SIM, and the target ions were set at m/z 135, 137, 152, and 155. The results were calculated by taking the mean value of three injections for each sample [16].

2.7. Method Quality Control

The calibration curve was generated using six different amounts of the standard solution (50, 70, 90, 110, 130, 150ppb) through injection. The null method was utilized to calculate the limit of detection (LOD) and limit of quantification (LOQ) values. For LOD determination, a signal-to-noise ratio of 3:1 was used, and for LOQ determination, the value of baseline noise in the chromatogram of the blank samples was multiplied by 10.

2.8. Recovery Performance

The method's performance was evaluated through the recovery method. Two different concentrations of AA (50 $\mu\text{g/L}$ and 100 $\mu\text{g/L}$) were added to the samples, and the validated extraction and detection method was applied. The analysis was repeated three times, and the mean recovery (%) and standard deviation (SD) were calculated.

2.9. Data Analysis

The statistical analysis of the data was performed using the IBM SPSS Statistics Version 22.0 package program. Descriptive statistics, such as mean and standard deviation, were used to analyze AA levels. A three-way analysis of variance was conducted to determine the differences in mean values for different thawing and frying methods on the samples. Statistical significance was considered at $p < 0.001$ for all tests.

3. Results

3.1. Method Validation

Figure 1 depicts the retention times of the acrylamide standard and internal standard in the GC-MS chromatograms of a typical chicken meat sample. In chicken and fish meat LOD, LOQ and recovery values in Table 1 and Table 2. The methods coefficient of determination (R^2) was 0.996.

3.2. Thawing and Frying Methods on the Contents of Acrylamide in Chicken Meat

The AA content of the air-fried and deep-fat-fried chicken breast, thigh, and wing samples was determined following thawing in a microwave, in a refrigerator, and by immersion in water. The effects of the frying method on acrylamide formation were examined using the same thawing methods and the same chicken meat part (Table 3).

The acrylamide (AA) levels of the deep-fat-fried chicken meats ranged from below the limit of detection (not detected) to $79.40 \pm 9.52 \mu\text{g/kg}$, whereas those of the air-fried chicken meats ranged from below the limit of detection to $60.00 \pm 9.12 \mu\text{g/kg}$. Overall, the deep-fat-fried samples exhibited significantly higher acrylamide levels than the air-fried samples, with the exception of the thigh and wing parts thawed in a refrigerator ($p < 0.001$). For this study, deep-fat frying was conducted using sunflower oil for 10 minutes, whereas air frying was performed without an oil spray for 10 minutes, the air-fried chicken meat samples exhibited lower acrylamide levels.

The impact of various thawing methods (microwave, refrigerator, water immersion) on the formation of acrylamide was evaluated using the same frying method and the same chicken meat part. No significant differences

were observed ($p > 0.001$), except for the deep-fat-fried thigh meat thawed using a microwave.

The formation of acrylamide in chicken breasts, thighs, and wings thawed and fried using identical methods was investigated. In general, regardless of the frying method employed, the chicken wings exhibited the highest acrylamide contents, followed by the chicken thighs and the breast meat. No significant differences were observed among the air-fried chicken meat parts. However, the deep-fat-fried chicken wings exhibited significantly higher acrylamide contents than the breast and thigh samples. These findings may be attributed to the varying fat content of the chicken meat samples.

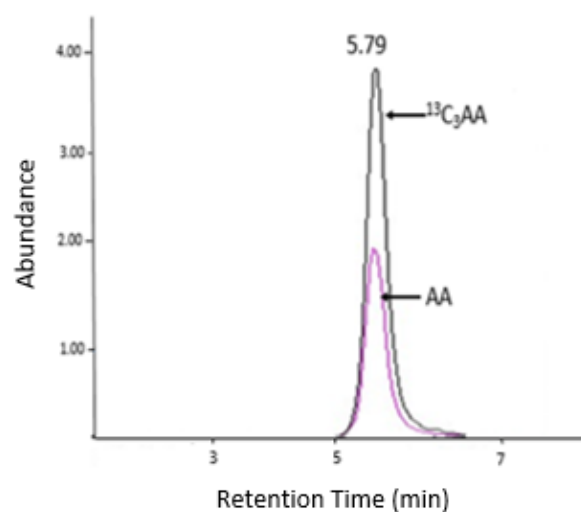


Figure 1. Typical gas chromatography–mass spectrometry (GC-MS) chromatograms for the acrylamide standard ($100 \mu\text{g/kg}$) and the internal standard ($50 \mu\text{g/kg}$) in deep-fat-fried chicken wing samples after thawing by water immersion

Table 1. LOD, LOQ and recovery values of analyzed chicken samples

Frying Method	Thawing Method	Chicken Part	Number of samples	LOD ($\mu\text{g/kg}$)	LOQ ($\mu\text{g/kg}$)	% recovery ($50 \mu\text{g/kg}$)	% recovery ($100 \mu\text{g/kg}$)
Air Frying	Microwave	Breasts	5	10	30	78 ± 35	90 ± 8
		Thighs	5	10	31	79 ± 45	89 ± 7
		Wings	5	11	32	77 ± 65	90 ± 9
	Refrigerator	Breasts	5	10	32	80 ± 55	87 ± 65
		Thighs	5	10	30	77 ± 36	89 ± 95
		Wings	5	10	32	79 ± 15	90 ± 45
	Water immersion	Breasts	5	11	30	78 ± 25	88 ± 75
		Thighs	5	10	32	80 ± 65	89 ± 85
		Wings	5	10	31	79 ± 15	89 ± 3
Deep-fat Frying	Microwave	Breasts	5	10	30	80 ± 95	90 ± 15
		Thighs	5	10	31	78 ± 45	89 ± 25
		Wings	5	11	30	79 ± 15	88 ± 55
	Refrigerator	Breasts	5	10	33	78 ± 4	89 ± 7
		Thighs	5	10	32	79 ± 3	90 ± 95
		Wings	5	11	30	77 ± 85	91 ± 75
	Water immersion	Breasts	5	10	31	779 ± 6	87 ± 7
		Thighs	5	10	32	80 ± 75	89 ± 4
		Wings	5	11	30	81 ± 45	88 ± 45

Table 2. LOD, LOQ and recovery values of analyzed fish samples

Frying Method	Thawing Method	Number of samples	LOD ($\mu\text{g/kg}$)	LOQ ($\mu\text{g/kg}$)	% recovery (50 $\mu\text{g/kg}$)	% recovery (100 $\mu\text{g/kg}$)
Air Frying	Microwave	5	10	30	78 $\pm$ 45	89 $\pm$ 75
	Refrigerator	5	11	31	79 $\pm$ 55	90 $\pm$ 35
	Water immersion	5	10	30	80 $\pm$ 5	87 $\pm$ 75
Deep-fat Frying	Microwave	5	10	30	80 $\pm$ 25	90 $\pm$ 1
	Refrigerator	5	11	32	78 $\pm$ 65	90 $\pm$ 8
	Water immersion	5	10	30	79 $\pm$ 8	89 $\pm$ 7

Table 3. Acrylamide levels of air-fried and deep-fat-fried chicken meats thawed using a microwave, a refrigerator, and water immersion

Frying method	Thawing method	Chicken part	Number of samples	Level $\mu\text{g/kg}$	Frying method için p değeri	Thawing method için p değeri	Chicken part için p değeri
Air frying	Microwave	Breasts	5	n.d.	<0.001	0.905	<0.001 ^{ab}
		Thighs	5	n.d.			
		Wings	5	60.00 $\pm$ 9.12			
	Refrigerator	Breasts	5	n.d.			
		Thighs	5	50.00 $\pm$ 9.12			
		Wings	5	53.75 $\pm$ 6.07			
	Water immersion	Breasts	5	n.d.			
		Thighs	5	46.5 $\pm$ 5.44			
		Wings	5	50.25 $\pm$ 4.11			
Deep-fat frying	Microwave	Breasts	5	n.d.	<0.001	0.905	<0.001 ^{ab}
		Thighs	5	55.20 $\pm$ 7.49			
		Wings	5	74.80 $\pm$ 9.36			
	Refrigerator	Breasts	5	59.80 $\pm$ 8.84			
		Thighs	5	54.40 $\pm$ 8.11			
		Wings	5	72.20 $\pm$ 6.49			
	Water immersion	Breasts	5	55.80 $\pm$ 7.46			
		Thighs	5	69.80 $\pm$ 7.46			
		Wings	5	79.40 $\pm$ 9.52			

a: wings difference according to breast region, b: wings difference according to thighs region

For frying method*chicken part $p=0.029$

For frying method*thawing method $p=0.005$

Thawing method* chicken part $p=0.045$

Frying method*chicken part* thawing method $p=0.335$

Table 4. Acrylamide levels of air-fried and deep-fat-fried fish meats thawed using a microwave, a refrigerator, and water immersion

Frying method	Thawing method	Number of samples	level $\mu\text{g/kg}$	Frying method için p değerleri	Thawing method için p değeri
Air frying	Microwave	5	50.00 $\pm$ 9.12	0.041	0.078
	Refrigerator	5	60.50 $\pm$ 10.84		
	Water immersion	5	60.75 $\pm$ 6.75		
Deep-fat frying	Microwave	5	60.50 $\pm$ 9.98		
	Refrigerator	5	64.40 $\pm$ 4.93		
	Water immersion	5	62.50 $\pm$ 6.45		

Frying method*thawing method $p=0.404$

3.3. Thawing and Frying Methods on the Contents of Acrylamide in Fish

The AA contents of air-fried and deep-fried fish samples, which were thawed in the microwave, refrigerator and by immersion in water after are presented in Table 4.

The AA levels of the deep-fat-fried fish meats ranged from 60.00 $\pm$ 9.98 to 64.40 $\pm$ 4.93 $\mu\text{g/kg}$, whereas those of the air-fried fish meats ranged from 50.00 $\pm$ 9.12 to 60.75 $\pm$ 6.75 $\mu\text{g/kg}$. Overall, the deep-fat-fried samples exhibited significantly higher AA levels than the air-fried samples. For this study, deep-fat frying was conducted using sunflower oil for 10 min, whereas air frying was performed without an oil spray for 10 min and the air-fried

fish meat samples exhibited lower AA levels.

In general, the deep-fat-fried samples exhibited significantly higher AA levels than the air-fried samples. In this study, deep-fat frying was conducted using sunflower oil for 10 min, whereas air frying was performed without an oil spray for 10 min. and the air-fried fish meat samples exhibited lower AA levels.

4. Discussion

High temperature (>120°C) processing of foods containing lipids and free amino acids, especially carbohydrates, leads to the formation of AA. Numerous

studies in different countries have proven the presence of AA in processed ready-to-pack products (such as potato chips, corn chips, biscuits, baby biscuits, bagels, bread, cake, chickpeas, roasted peanuts, roasted nuts, pretzels etc.) [17,18]. Particularly high levels were found in potato products such as potato chips, French fries, fresh or pre-cooked, ready-to-eat French fries (average levels 239-368mg/kg) [19]. In addition, it was reported that the AA content of pre-prepared or heat-treated products increased after cooking [20,21]. AA formation occurs not only in ready-made products but also in foods heat-treated at home. High temperatures during cooking and long-term cooking increase AA formation [22]. AA plays a role in the pathogenesis of cancer and neurological diseases [1,23]. Constant and high exposure to AA-containing foods increases the risk of associated diseases. For this reason, in recent years, many studies have been conducted on reducing AA levels in foods [20,24,25,32].

The levels of AA formed by high heat are affected by the cooking method of the food product. To investigate this effect, Michalak et al. (2016) subjected heat-treated croquettes filled with meat to baking, deep-frying, pan-frying and microwave cooking. The results showed that baking, deep-frying, pan-frying, and microwave cooking produced 360µg/kg, 298µg/kg, 285µg/kg, and 420µg/kg of AA, respectively. The high levels of AA in products produced by the oven method were explained by the fact that AA is mainly formed in the outer layer exposed to heat and heat transfer is more efficient during convection heating (oven) than during contact heating (pan and deep frying). Increasing the temperature of the product surface increases the formation of AA, which occurs mainly on and near the surface [20]. This is because the conditions in those parts of the product become favourable for AA formation as a result of simultaneous drying [26]. In addition, the fact that cooking in the oven produces higher AA than frying is due to the high temperature and long cooking time [20,27,28,29]. Among these compared cooking methods, microwave ovens are one of the most widely used methods as a means of rapid food heating in daily life. Some studies on the effect of cooking methods on AA formation have shown that microwave heating method has a higher AA formation potential than other cooking methods such as frying and roasting [20,28,29]. Microwaves provide a rapid temperature increase in foods thanks to their capacity to generate heat energy inside the food and because they operate under high pressure to meet high heating temperature requirements [20,29]. However, reducing the microwave power reduces the formation of AA. But, AA formation still remains high compared to other cooking methods [28].

In this study in which airfry fried and deep-fat fried cooking methods were compared, it was found that airfry fried cooking method produced lower AA than deep-fat fried. Although the same temperature and cooking time ($180\pm5^{\circ}\text{C}$ 10 min) were used in both cooking methods, the reason for this difference in AA formation is that the Maillard reaction is much faster in deep-fat fried than in airfry fried. Because although the temperature is the same, the two technologies are different from each other in terms of mass and heat transport kinetics [30]. Previous studies have found that deep-frying produces less AA compared

to microwave and oven-frying [20,28,29]. In this study, it was concluded that airfry fried is healthier in terms of AA than deep-fat fried.

Besides the cooking method, temperature and time, there are also different factors that affect AA formation. For example, in a study investigating the effect of frying cycle and oil type on AA formation in beef nuggets, it was shown that the oil type significantly affected AA formation. Among the different oils examined, the lowest AA concentration was found in palm oil [24]. Oils with high unsaturation are more sensitive to heat treatment, which contributes to AA formation [25]. In fact, using a water-oil mixture in the frying process results in less oxidation reaction in the frying oil and lower AA levels in the product [25]. Soncu and Kolsarici (2017) were found that marinating chicken meat in green tea extract reduced AA formation in the samples during pan-frying and steam baking heat treatments. And also in a study investigating the effect of different thawing processes on AA formation, it was determined that AA was not affected by thawing methods [32]. The findings of the current study also confirm that different thawing methods in chicken and fish meat do not affect AA levels after cooking. In the same study, no significant difference was found between chicken meat pieces in terms of AA content [32]. Similar to the findings of Lee et al. (2020) our results show that the AA content in chicken wings is higher than that in thighs and breasts in the deep-fat frying method, which may be due to the fat content of the chicken pieces.

5. Conclusion

In this study, we examined the effects of various thawing and frying methods on AA formation in chicken and fish meats. In chicken meat, we found that thawing methods had no effect on AA formation, but air frying contained less AA compared to deep frying. In fish meat, we found that different thawing and frying methods had no effect on AA formation. The results of our research show that air-frying leads to lower AA formation compared to deep frying. These findings indicate that air frying is a promising method with the potential to produce healthy fried products in terms of AA formation.

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Conflict of Interests

Authors declare no conflict of interests.

Authors Contributions

ZKA investigated and wrote the MS. FAK carried out the experiments. ID reviewed and edited the MS, SMK visualized, supervised and edited the manuscript, AD visualized and supervised the work.

References

- [1] Ahn, J.S., Castle, L., Clarke, D.B., Lloyd, A.S., Philo, M.R. and Speck, D.R. Verification of the findings of acrylamide in heated foods. *Food Addit Contam.* 2002; 19(12): 1116-24.
- [2] Sawicka B, Muhammed A, Umachandran K. Food safety of potato processed in the aspect of acrylamide risk. *MOJ Food Process Technol.* 2018; 6(1): 96-102.
- [3] Kim CT, Hwang E S, Lee H J. Reducing acrylamide in fried snack products by adding amino acids. *J Food. Sci.* 2005; 70 (5): C354-C358.
- [4] Rose M, Holland J, Dowding A, Petch SR, White S, Fernandes A, Mortimer D. Investigation into the formation of PAHs in foods prepared in the home to determine the effects of frying, grilling, barbecuing, toasting and roasting. *Food Chem. Toxicol.* 2015; 78: 1–9.
- [5] Demirok E, Kolsarıcı N. Effect of green tea extract and microwave pre-cooking on the formation of acrylamide in fried chicken drumsticks and chicken wings. *Food Res Int.* 2014; 63: 290–8.
- [6] Carrabs G, Marrone R, Mercogliano R, Carosielli L, Vollano L, Anastasio A. Polycyclic aromatic hydrocarbons residues in Gentile di maiale, a smoked meat product typical of some mountain areas in Latina province (Central Italy). *Ital J Food Saf.* 2014; 3(2): 1681.
- [7] International Agency for Research on Cancer (IARC). Some industrial chemicals. In *IARC Monographs on the Evaluation of Carcinogenesis Risks to Humans*. Lyon, France. 1994; 60: 435–53.
- [8] FAO. WHO. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) Evaluation of Certain Contaminants in Food: Seventy-Second Report of the Joint FAO/WHO Expert Committee on Food Additives. World Health Organization; 2011; Geneva, Switzerland.
- [9] Basuny AM, Arafat SM, Ahmed AA. Vacuum frying: An alternative to obtain high quality potato chips and fried oil. *Banats J Biotechnol.* 2012; 3: 22–30.
- [10] Andrés A, Argüelles Á, Castelló M.L, Heredia A. (2013). Mass transfer and volume changes in French fries during air frying. *Food Bioproc Technol.* 6: 1917–1924.
- [11] Andrés-Bello A, García-Segovia P, Martínez-Monzó J. Vacuum frying: An alternative to obtain high-quality dried products. *Food Eng Rev.* 2011; 3: 63–78.
- [12] Şimşek ST, Palazoğlu TK, Gökmen V. Effect of microwave pre-thawing of frozen potato strips on acrylamide level and quality of French fries. *J. Food Eng.* 2010; 97(2): 261–66.
- [13] Dueik V, Moreno MC, Bouchon P. Microstructural approach to understand oil absorption during vacuum and atmospheric frying. *J Food Eng.* 2012; 111: 528–36.
- [14] Cruz G, Cruz-Tirado JP, Delgado K, Guzman Y, Castro F, Rojas ML, Linares G. Impact of pre-drying and frying time on physical properties and sensorial acceptability of fried potato chips. *J Food Sci. Technol.* 2018; 55(1): 138–44.
- [15] United States Department of Agriculture. The Big Thaw—Safe Defrosting Methods. 2024. Online: <https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/food-safety-basics/big-thaw-safe-defrosting-methods>.
- [16] Hasan GMMA, Das AK, Satter MA. Detection of acrylamide traces in some commonly consumed heat-treated carbohydrate-rich foods by GC-MS/MS in Bangladesh. *Heliyon.* 2022; 8 (10): 11092.
- [17] Dağoğlu I, Keskin Alkaç Z, Korkak FA, Kazdal SM, Dağ A. Acrylamide in heat-treated carbohydrate-rich foods in Turkey. *Food Addit Contam Part B Surveill.* 2024; 1-7.
- [18] Nematollahi A, Kamankesh M, Hosseini H, Ghasemi J, Hosseini-Esfahani F, Mohammadi A, Mousavi Khaneghah A. Acrylamide content of collected food products from Tehran's market: a risk assessment study. *Environ Sci Pollut Res Int.* 2020; 27(24): 30558-30570.
- [19] Mustăţea G, & Popa ME. Acrylamide in food—EU versus FDA approaches. *Bulletin UASVM Food Sci Technol.* 2015; 72, 2.
- [20] Michalak J, Gujska E, Czarowska M, Nowak F. Effect of different home-cooking methods on acrylamide formation in pre-prepared croquettes. *J Food Compos Anal.* 2016; 56(10). 134-139.
- [21] Pedreschi F, Kaack K, Granby K. The effect of asparaginase on acrylamide formation in French fries. *Food Chem.* 2008; 109(2): 386-92.
- [22] Perera DN, Hewavitharana GG, Navaratne SB. Comprehensive Study on the Acrylamide Content of High Thermally Processed Foods. *Biomed Res Int.* 2021; 6258508.
- [23] Bin-Jumah M, Abdel-Fattah AM, Saied EM, El-Seedi HR, Abdel-Daim MM. Acrylamide-induced peripheral neuropathy: manifestations, mechanisms, and potential treatment modalities. *Environ Sci Pollut Res Int.* 2021; 28(11): 13031-46.
- [24] Ahmad SNS, Tarmizi AHA, Razak RAA, Jinap S, Norliza S, Sulaiman R, Sanny M. Selection of Vegetable Oils and Frying Cycles Influencing Acrylamide Formation in the Intermittently Fried Beef Nuggets. *Foods.* 2021; 10(2):257.
- [25] Ma R, Gao T, Song L, Zhang L, Jiang Y, Li J, Zhang X, Gao F, Zhou GH. Effects of oil-water mixed frying and pure-oil frying on the quality characteristics of soybean oil and chicken chop. *Food Sci Technol (Campinas).* 2016; 36(2): 329-36.
- [26] Anese M, Bortolomeazzi R, Manzocco L, Manzano M, Giusto C, Nicoli MC. Effect of chemical and biological dipping on acrylamide formation and sensory properties in deep-fried potatoes. *Food Res Int.* 2009; 42(1): 142-47.
- [27] Gökmen V, Palazoğlu TK. Acrylamide Formation in Foods during Thermal Processing with a Focus on Frying. *Food Bioprocess Technol.* 2008; 1: 35-42.
- [28] Yuan Y, Chen F, Zhao GH, Liu J, Zhang HX, Hu XS. A comparative study of acrylamide formation induced by microwave and conventional heating methods. *J Food Sci.* 2007; 72(4), C212-C216.
- [29] Zhang Y, Fang H, Zhang Y. Study on formation of acrylamide in asparagine-sugar microwave heating systems using UPLC-MS/MS analytical method. *Food Chem.* 2008; 108(2): 542-50.
- [30] Sansano M, Juan-Borrás M, Escriche I, Andrés A, Heredia A. Effect of pretreatments and air-frying, a novel technology, on acrylamide generation in fried potatoes. *J Food Sci.* 2015; 80(5): T1120-8.
- [31] Soncu ED, Kolsarıcı N. Microwave thawing and green tea extract efficiency for the formation of acrylamide throughout the production process of chicken burgers and chicken nuggets. *J Sci Food Agric.* 2017; 97: 1790-97.
- [32] Lee JS, Han JW, Jung M, Lee KW, Chung MS. (2020). Effects of thawing and frying methods on the formation of acrylamide and polycyclic aromatic hydrocarbons in chicken meat. *Foods.* 9(5): 573.

