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Dietary exposure, carcinogenic and neurotoxic risk assessment of acrylamide in breakfast cereals marketed in Lebanon and the UAE

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ABSTRACT

This study assessed acrylamide (AA) content in breakfast cereals marketed in Lebanon and the United Arab Emirates (UAE) and examined the associated dietary, carcinogenic, and neurotoxic risks. Following a comprehensive market screening, a total of 21 stock keeping units (SKUs) from Lebanon and 76 from the UAE were identified, collected, and analyzed for AA using LC-MS/MS. At the same time, a food frequency questionnaire involved 845 participants gathered information on breakfast cereal consumption habits, body weight, and demographic details. AA was found in all samples, with average levels of 525.75 μg/kg in Lebanon and 573.02 μg/kg in the UAE, both exceeding many reported international levels. Estimated dietary exposures were 0.39 μg/kg-bw/day in Lebanon and 0.53 μg/kg-bw/day in the UAE, accounting for about 25% of the WHO's maximum tolerable daily intake. Although neurotoxic risk assessments based on US-EPA reference values suggested low concern for average consumers, carcinogenic risk against NFCA and WHO limits indicated an increased risk for average and high consumers, particularly for products with above-average AA levels. Carcinogenic risk assessment showed that average acrylamide exposure from breakfast cereals reached 0.39 μg/kg-bw/day in Lebanon and 0.53 μg/kg-bw/day in the UAE, exceeding the NFCA and WHO reference values by 2.8–4.9 fold and 3.8–6.6 fold, respectively. Product origin, addition of chocolate or nuts, and processing methods significantly ($p < 0.05$) affected AA concentrations. The findings highlight the urgent need for strategies to reduce AA levels in breakfast cereal products and to improve regulatory control in developing countries to limit long-term health risks.

1. Introduction

Acrylamide (AA) is an odorless crystalline compound, also known as 2-propenamide (Fig. 1) which is primarily used in the production of polyacrylamide, an important industrial material formed through enhanced polymerization (Organization & Safety, 1985). AA is commonly used in wastewater treatment, soil conditioning, and often serves as a waterproofing material used in the construction of tunnels and dams to secure foundations (Xiong et al., 2018). Other applications of AA, although some are prohibited, include dispersion of dye in the textile industry, production of paper, laboratory DNA and RNA separation, and as a multi-functional additive in the cosmetic industry. Despite these industrial applications, dietary exposure resulting from thermally processed foods is now recognized as the dominant source of acrylamide for the general population. Even with several existing theories concerning the formation mechanism of dietary AA, the primary mechanism involves the Maillard reaction (Friedman, 2003). The formation of AA occurs when certain foods are cooked – fried, baked, or roasted – at high temperatures (above 120°C) (Mestdagh et al., 2008). Upon thermal processing, the Maillard reaction (Fig. 1) occurs between amino acids (e.g., asparagine) and reducing sugars (e.g., glucose or fructose), producing the characteristic color and flavor of fried, baked, and roasted foods (Stadler et al., 2002). Additionally, one of the main precursors of AA was identified to be 3-aminopropionamide (3-APA), an amine formed during

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the Maillard reaction (Zyzak et al., 2003).

Although dietary exposure is now recognized as the primary route of acrylamide intake for the general population, prior to the early 2000s, exposure to acrylamide was thought to be associated with drinking water and occupational settings, such as packaging made from polymers (Humans, 1994). In fact, in 2002, researchers at the University of Stockholm, in collaboration with specialists from the Swedish National Food Administration, identified increased acrylamide levels in drinking water that exceeded the limit allowed at the time (Jeong et al., 2020; Koszucka et al., 2020; Rifai & Saleh, 2020). They also reported the unexpected presence of acrylamide in heat-processed, carbohydrate-rich foods, a finding that fundamentally shifted scientific and regulatory focus toward dietary exposure pathways.

On the other hand, dietary acrylamide is found in processed foods subjected to thermal treatment, such as chips, bread, crackers, coffee, rice cakes, cereals, and others (Merhi et al., 2020). Notably, cereal-based foods constitute an important source of dietary acrylamide, although their contribution differs markedly by product type; breakfast cereals contribute variably but remain of particular regulatory interest due to their relatively high acrylamide levels, established benchmark values, and frequent consumption, especially among children and high-consumer groups.

Mitigating and controlling its formation within these products is critical in minimizing human exposure and the associated health risks (Mesias et al., 2022). As a probable human carcinogen, AA poses a serious health concern, especially in heat-processed foodstuff where it is most prevalent (Rifai & Saleh, 2020). Other adverse effects caused of AA exposure in humans and animals can include gait abnormality (unusual walking pattern), weight loss, or even myopathy (skeletal muscle weakness) (Hosamani & Muralidhara, 2013).

Breakfast cereals are among the most popular foods globally, valued for their diverse flavors and convenience (Liyanage et al., 2021; Žilić et al., 2022). However, the European Commission has highlighted these products as having some of the highest average acrylamide levels (European Commission, 2017). Numerous studies have emphasized the significant acrylamide content in breakfast cereals and their contribution to dietary AA exposure (Hariri et al., 2015b; Konings et al., 2003; Mesías et al., 2019; Žilić et al., 2022). This highlights the need for regulatory benchmark levels, mitigation measures during food processing, and ongoing monitoring to reduce dietary acrylamide exposure and limit potential health concerns (Merhi et al., 2020). To face this growing health concern, the food industry has proposed adjustments to food processing parameters while maintaining product quality, such as lowering the pH, reducing cooking temperature, and shortening cooking time. Another recommendation would be to introduce reported inhibitors of AA formation, such as some organic acids including tartaric, citric and formic acids (Schouten et al., 2021).

In Lebanon, Hariri et al. (Hariri et al., 2015a); Naous et al. (2018) and Naous et al. (2022) determined the risks of AA from the consumption of potato/corn chips, baked foodstuffs, and caffeinated beverages, respectively. Additionally, Bou-Mitri et al. (2026); El Darra et al. (2025); Hassan et al. (2025), and Hassan et al. (2023) measured glyphosate, pesticide residues, toxic metals, and mycotoxins, respectively, in cornflakes marketed in Lebanon. Furthermore, Hassan et al. (2022) and Akoury et al. (2023) assessed aflatoxin B1 and toxic metals, respectively, in rice consumed in Lebanon. Despite increasing global attention to acrylamide exposure, region-specific data linking breakfast cereal consumption to dietary exposure and associated health risks in Arab populations remain limited, hindering accurate risk characterization and public health assessment in this region. Given the widespread consumption of breakfast cereals and their relatively high acrylamide content, this gap may lead to underestimation of exposure and its potential long-term health effects, particularly among frequent consumers. Addressing this gap also aligns with Sustainable Development Goal 3 (Good Health and Well-Being), which promotes reducing exposure to harmful food contaminants and improving public health . In this context, the present study considers how food composition, processing conditions, and product origin influence acrylamide formation in breakfast cereals, and subsequently links these concentrations to dietary exposure and risk characterization using established toxicological metrics such as MOE, NOAEL, and BMDL10.

However, given the absence of studies in the literature assessing AA exposure from the consumption of breakfast cereals in the Arab region, our study aims to assess the neurotoxic and carcinogenic risks associated with dietary AA in the Lebanese and Emirati populations. It underscores the need for mitigation strategies and regulatory measures during industrial processing to reduce AA in food products.

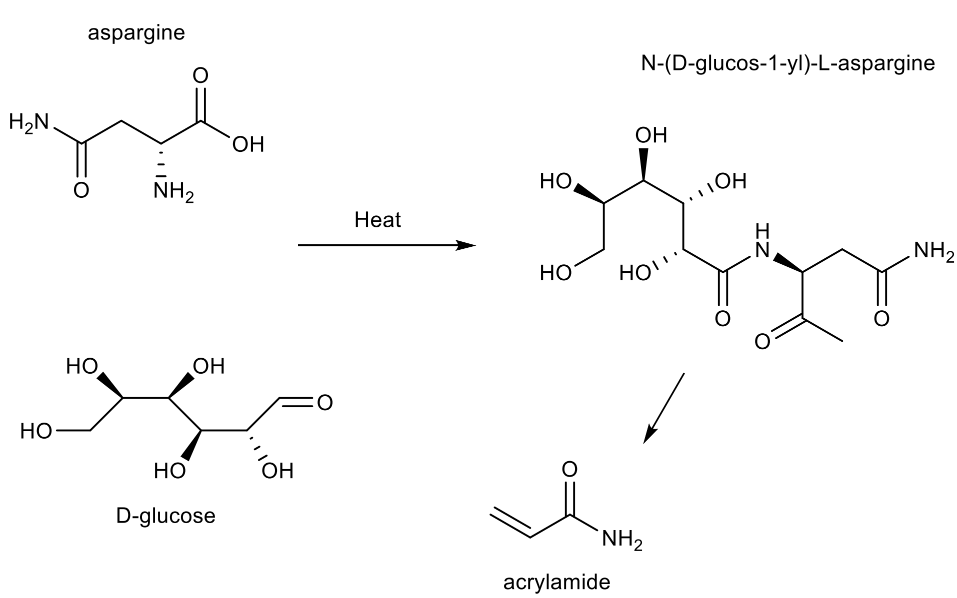

Fig. 1. Mechanism of acrylamide formation from food products: Maillard reaction (Mottram et al., 2002).

2. Methods

2.1. Materials and methods

A market screening of the breakfast cereals stock keeping units (SKUs) involved the largest five retail markets in Lebanon and UAE. A total of 21 and 76 SKUs were identified, respectively. These were collected and analyzed in triplicates using LC-MS/MS.

2.2. Chemicals and reagents

All reagents and chemicals utilized in the analyses of AA were of analytical grade. Acrylamide (≥ 99%) Magnesium sulfate, sodium chloride, activated charcoal and acetonitrile (LC–MS grade) were purchased from Merck, Germany. Distilled water (type II +) was prepared using a Millipore MilliQ system.

2.3. Acrylamide extraction

AA was extracted from breakfast cereals based on modified previously reported methods (Biedermann et al., 2002; Zhao, 2019). A sample of each ground SKU (0.5 g) was mixed with water (5 mL) and vortexed for 3 min. Acetonitrile (5 mL) was then added and the mixture was vortexed for 3 min. Clean-up was achieved by modified QuEChERS prepared by adding the mixture of magnesium sulfate (0.4 g), sodium chloride (0.1 g) and activated charcoal (5 mg) and then the mixture was centrifuged at 5000 rpm at 4°C for 10 min. A volume of 1mL was withdrawn from the upper layer of the centrifuge tube and filtered using PTFE Millipore 0.25 μm filter and analysed via LCMS/MS. The QuEChERS method was selected due to its well-documented advantages, including simplicity, rapid sample preparation, low solvent consumption, cost-effectiveness, and suitability for complex food matrices. The dispersive solid-phase clean-up step efficiently removes matrix interferences such as lipids, proteins, and pigments, thereby improving analytical sensitivity, accuracy, and reproducibility. Previous systematic evaluations have demonstrated that optimized QuEChERS protocols provide reliable recoveries and robust quantification of food contaminants across cereal-based and other processed food products (Sadighara et al., 2024).

2.3.1. Determination and quantification of acrylamide (AA).

Samples (triplicates) were analyzed using Ultra-Performance Liquid 96 Chromatography Mass Spectrometry (UPLC-MS/MS) Dionex Ultimate 3000 - TSQ Endura Triple 97 Quadrupole Mass Spectrometer (Thermo Fisher Scientific, Waltham, MA, USA). A 5 μL injection of each sample was done on a Hypersil Gold column (100×2.1 mm, 1.9 μm) (Thermo 99 Fisher Scientific, USA) maintained at 25°C. The mobile phase consisted of (A) water and (B) methanol, both containing 0.1% formic acid, delivered under isocratic elution (A:B; 5:95) at a flow rate of 0.25 mL/min for a total run time was 8 min. The autosampler temperature was set at 5°C.

Mass spectrometric detection was performed using electrospray ionization in positive mode (ESI+). Acrylamide was monitored in selected reaction monitoring (SRM) mode at a retention time of 1.17 min and CID Gas of 1.5 mTorr whereby the transitions from 72.1→55.0 (CE 10 V); 72.1→44.0 (CE 10 V) and 72.1→27 (CE 16 V) were monitored. The following optimized source parameters, including sheath (50 Arb) and auxiliary gas (10 Arb) flows, and ion transfer tube temperature (325°C), vaporizer temperature (350°C), were applied.

Quantification was performed using external calibration with five concentration levels (1–50 μg/L), yielding linear calibration curves with coefficients of determination ($R^2 \geq 0.997$). A QuEChERS-based extraction and clean-up procedure was employed to reduce matrix interferences. Method accuracy was evaluated by spiking a representative cereal matrix at 30 μg/kg prior to extraction, resulting in a mean recovery of 79.5%. Method repeatability at this fortification level ($n = 3$) showed acceptable precision (SD = 0.15 ppb and %RSD = 0.64%). This value reflects repeatability based on triplicate analyses of the same sample under controlled analytical conditions and does not represent variability across different batches or products.

Method performance was evaluated through recovery experiments using spiked samples, replicate analyses, and procedural blanks, confirming acceptable analytical consistency.

Although an isotopically labeled internal standard was not employed, method performance was evaluated through recovery experiments, replicate analysis, and procedural blanks, demonstrating acceptable accuracy and repeatability. Nevertheless, the absence of isotope dilution may introduce matrix-related variability, and this is acknowledged as a limitation of the present study.

The instrumental limit of detection (LOD) and limit of quantification (LOQ), estimated at signal-to-noise ratios of 3 and 10, were 0.1 μg/L and 1.0 μg/L, respectively.

Considering the sample preparation procedure (0.5 g test portion extracted with 10 mL solvent), the corresponding method LOQ was 20 μg/kg.

(Biedermann et al., 2002).

2.4. Consumption patterns

To determine the national consumption of breakfast cereals across Lebanon and the United Arab Emirates, an online food frequency questionnaire targeting both populations was conducted in 2024 in which a convenient sample of 845 responses were recorded. The target population pertains to national residents from the ages of 3-75 and residing across the entire geographical area of both countries. Participants provided data on their age, gender, body weight, cereal type preferences, reasons for selection, and daily cereal consumption. The survey was pre-approved by the International Review Board at the Lebanese American University (IRB #: LAU.SAS.HH1.5/May/2024). Consent from all participants was acquired through the survey as approved by the IRB committee.

2.5. Dietary exposure assessment

The daily intake of acrylamide and the assessment of neurotoxic and carcinogenic risks were evaluated based on previously published procedures (El-Zakhem Naous et al., 2018; Merhi et al., 2020; Naous et al., 2022). For the daily intake in both Lebanon and the UAE, the average body weight, mass of breakfast cereals consumed, and that of acrylamide content were considered based on the survey results conducted by Hassan et al. (Hassan et al., 2024). The margin of exposure (MOE), no-observed adverse-effect level (NOAEL) and the benchmark dose for a 10% response (BMDL10) were used to assess the neurotoxic and carcinogenic risks (Additives, 2011; Benford et al., 2010). The Food and Agriculture Organization (FAO), and World Health Organization (WHO) Expert Committee on Food Additives (JECFA) set the NAOEL value as 0.2 mg/kg-bw/day to assess neurotoxic risks based on morphological modifications in rat nerves (Additives, 2011). As for the assessment of the carcinogenic risks, 0.31 and 0.18 mg/kg-bw/day were used as recommended by JECFA (Additives, 2011).

2.6. Statistical analysis

Acrylamide concentration (ppb) and sample characteristics, including source and country of origin, were entered into SPSS version 29 for analysis. As the distribution of acrylamide concentrations did not meet the assumption of normality, a square-root transformation was applied, resulting in a normally distributed variable. Differences in the mean of the transformed acrylamide values were assessed using the independent samples t-test when comparing two groups, and one-way ANOVA when comparing more than two groups. Statistical significance was set at a p-value < 0.05.

3. Results and discussion

3.1. Acrylamide analysis

Triplicate samples of breakfast cereal products collected from the Lebanese and the UAE markets were extracted and analyzed using LCMS-MS to quantify the AA content. All SKUs scored acrylamide concentration above the LOQ. The average acrylamide content of the cereal products was 573.02 and 525.75 µg/kg and in the UAE and the Lebanese markets, respectively (Table 1). It is evident that the averages are comparable and relatively high exceeding the benchmark (300 µg/kg) set by the EU (Commission, 2017).. In the Lebanese market, acrylamide levels ranged from 160.08 to 1262.06 µg/kg, while in the UAE market, values ranged from 114.78 to 1246.8 µg/kg.

The average acrylamide content for breakfast cereals in Columbia scored 726 µg/kg (Pacetti et al., 2015), which is higher than the average in Lebanon and UAE by 1.35 and 1.27 folds, respectively. The Syrian population reported an average of AA content of 121 µg/kg in cereal products (Alyousef et al., 2016); a level that is less than that of both Lebanese and UAE markets by 4.34 and 4.74 folds, respectively. As for the cereal-based products sold in Japan, an average of 491 µg/kg of acrylamide content was reported which is in turn less than both markets by an average factor of 1.13 (Wong et al., 2014). Furthermore, the Slovenian market reported an average of 288.9 µg/kg for cereals (Mencin et al., 2020).

3.2. Dietary intake of acrylamide from cereals

The present study does not include in vivo or in vitro toxicological experiments, as its objective is to evaluate dietary exposure and associated health risks using established toxicological reference points derived from previous animal and mechanistic studies. Carcinogenic and neurotoxic risks were therefore assessed using margin of exposure and reference dose approaches, in accordance with international food risk assessment frameworks. Evaluation of the dietary exposure to acrylamide form breakfast cereals was evaluated using our previously published procedure (El-Zakhem Naous et al., 2018) by considering the average acrylamide content in cereals, average body weight and the average consumption of cereal products in both the Lebanese and the UAE markets (Table 2). The dietary exposure to acrylamide upon consuming breakfast cereals was found to be 0.39 and 0.53 µg/kg-bw/day in the Lebanese and the UAE markets, respectively. Add to this, the cereals-based products are not the only source of acrylamide as the latter is present in coffee and hot beverages (El-Zakhem Naous et al., 2018), bread (Naous et al., 2022), meat (Lee et al., 2020), rice cakes (Croft et al., 2004), and many other thermally processed food products. Even though acrylamide content from cereals lie in the accepted range (0.3-2 µg/kg-bw/day) set by the WHO (Programme, 2002), it is worth mentioning that the daily consumption of acrylamide contribute in almost 25% of the maximum tolerable exposure to acrylamide. Although cheese is a common component of breakfast in many countries, it is not regarded as a significant dietary source of acrylamide. Dairy products such as cheese contain minimal amounts of reducing sugars and are generally not subjected to processing conditions conducive to acrylamide formation. Consequently, regulatory and scientific assessments consistently report negligible or non-detectable acrylamide levels in cheese and other dairy products (EFSA, 2015) (Food & Drug, 2023).

Table 1
Acrylamide concentration in breakfast cereals marketd in Labanon and UAE.

	Lebanon	UAE
Number of samples	21	76
Maximum Acrylamide (µg/ kg)	1262.1	1246.8 114.8
Minimum Acrylamide (µg/ kg)	160.1	573.0±484.6
Mean± SD(µg/ kg)	525.8±338.5	

Acrylamide concentrations are expressed in µg/kg. Values represent the minimum, maximum, and mean concentrations measured across all analyzed stock keeping units (SKUs) in each market.

Table 2
Estimated dietary intake of acrylamide from breakfast cereals.

	Lebanon	UAE
Maximum Acrylamide (µg/kg-bw/day)	0.93	2.25
Minimum Acrylamide (µg/kg-bw/day)	0.09	0.07
Average Acrylamide (µg/kg-bw/day)	0.39	0.53

Once the data is tailored towards individual samples (Tables S1 and S2), it was found that 29% and 35% of the samples in the Lebanese and UAE market, respectively, consist of acrylamide levels that are above the average (Table 1) with one sample specifically from the UAE market exhibiting acrylamide levels that correlates to an intake of 2.25 µg/kg-bw/day. This yields to a higher acrylamide contribution from breakfast cereals to reach 50%, 75% and 100% of the maximum tolerable levels dependent on the consumed samples.

Dietary intake values (µg/kg-bw/day) were calculated using acrylamide concentrations measured in cereals, average daily cereal consumption, and body weight data obtained from the food frequency questionnaire.

Based on the estimated dietary exposure, subsequent carcinogenic and neurotoxic risk assessments were performed using established toxicological reference points.

To further evaluate the health implications of the estimated dietary exposure, both carcinogenic and neurotoxic risks were assessed.

3.3. Carcinogenic risk assessment

For carcinogenic risk assessment, the NFCA and WHO set the acrylamide dietary intake limits as 0.08 and 0.14 µg/kg-bw/day respectively. For the average consumers, the Lebanese population seems to be at risk with a dietary intake value of 0.39 µg/kg-bw/day that is 4.9 and 2.8 folds higher than the values set by NFCA and WHO respectively (NFCA, 2002; WHO, 1996). As for the UAE population, average consumers are also at risk with a dietary intake of 0.53 µ/kg-bw/day and that is 6.6 and 3.8 folds (Table 3) higher than the values set by NFCA and WHO respectively (NFCA, 2002; WHO, 1996).

On the other hand, to assess the Margin of Exposure for carcinogenic risk assessment (MOE_C), JECFA set the lower limits of 310(180) depending on the $BMDL_{10}$ value JOINT. Based on these limits, the Lebanese (794; 461) and the UAE (585; 340) population appear to pose no carcinogenic concern with MOE_C values for both $BMDL_{10}$ (0.31 mg/kg-bw/day) and $BMDL_{10}$ (0.18 mg/kg-bw/day), respectively (Table 2). Alarmingly however, if we couple the average UAE cereal consumer to the consumption of the above-average-acrylamide cereal products, *ie.* 1246 µg/kg (2.2 folds the average) then these consumers will be subjected to carcinogenic concern. Add to this, the risk will increase if we consider the high consumers with the different probabilities of getting the cereals with high or average acrylamide content. Critically, 6.5% of the samples in the UAE market will subject consumers to carcinogenic concern as values lie in the range of 156 and 81.

Table 3
MOE_C values across the Lebanese and UAE populations.

	Lebanon	UAE	Risk
MOE_C (average consumers-average acrylamide)	794 (461)	585 (340)	Low concern
MOE_C (high consumers-average acrylamide)	–	274 (159)	Potential concern
MOE_C (average consumers-max acrylamide)	333 (193)	138 (80)	Potential concern

3.4. Neurotoxic risk assessment

The average exposure of the Lebanese and the UAE population to acrylamide from breakfast cereals based on results extracted from the food frequency questionnaire was determined as 0.39 and 0.53 μg/kg-bw/day respectively. These values lie in the accepted range as the reference dose (RfD) of 2 μg/kg-bw/day set by the recent US-EPA based on neurotoxic investigations in rats (EPA, 2010).

To assess the Margin of Exposure for neurotoxic risk assessment (MOE_N), JECFA set the limits of 200 and 50 for the mean and high dietary exposure respectively (Additives, 2011). MOE values are presented as reference points for comparative risk characterization and do not represent health-based safety limits.From that perspective, average consumers in both populations (Table 4) appear to pose no neurotoxic risk concern with an MOE_N value of 377 and 513 for the UAE and the Lebanese population, respectively. Notably, consumers purchasing cereals with high acrylamide content among the UAE population also pose a considerable risk concern with an MOE_N value of 177.

3.5. Impact of raw materials, processing variables and origin on AA formation pathways

Acrylamide is not present in most of the raw material used to prepare many of the acrylamide-rich food matrices. Two main mechanistic theories are adapted -among many proposed assumptions- to explain the acrylamide formation. One involves the Maillard reaction between free Asparagine (Asn) and reducing sugars upon heating (Friedman, 2003). Another links the conversion of triglycerides from vegetable oils to acrolein at elevated temperature to the formation of acrylamide (Gertz & Klostermann, 2002; Zhang & Zhang, 2007). In other words, acrylamide formation in any type of food is due to the ingredients used to form the food matrix as well as the processing conditions. In 2022, a detailed study was conducted in our labs evaluating the acrylamide content in the main components of the Lebanese breakfast including kaak, bread, toast, and crackers (Naous et al., 2022). Results showed that the precursors of food matrix and additives dictate the acrylamide formation. The type of flour, fermentation process, baking temperature and time, sugar, salt, and many other flavors made a significant effect in acrylamide content. Different research groups all over the world validated these results. For instance, replacing Rye flour by whole-wheat flour yielded lower acrylamide content (Fredriksson et al., 2004). Furthermore, the milling process of the wheat grain reduced the Asn proving the size effect on acrylamide content during fermentation (Liu et al., 2018). Beyond the composition, temperature and time of baking influence acrylamide content. While some researchers have indicated that higher temperatures lead to increased formation of acrylamide, other studies have shown that heating at high temperatures for extended periods might lead to acrylamide dissociation and hence lower acrylamide content (Amrein et al., 2004; Mottram et al., 2002; Rydberg et al., 2003; Stadler et al., 2002; Taeymans et al., 2004; Tareke et al., 2002). The drawback of the latter could be the organoleptic properties of the desired food matrix. From this point, understanding the factors that affect the acrylamide formation is crucial to optimize the food processing conditions that might reach a minimum level of acrylamide exposure from many food matrices.

Table 4
MOE_N values across the Lebanese and UAE populations.

	Lebanon	UAE	Risk
MOE_N (average consumers-average acrylamide)	513	377	Low concern
MOE_N (high consumers-average acrylamide)	–	177	Potential concern
MOE_N (average consumers-max acrylamide)	220	89	Potential concern

The effect of country of origin, and composition (nuts, bran, chocolate) on acrylamide content will be discussed in this part.

A. Country of origin

The country of origin is shown to have significant effect on the AA content in breakfast cereals, with developing countries producing products with higher AA content than the developed countries. This should come as no surprise as developed countries are not only more aware of the AA issue but rather the cereal companies are inflicted with tougher policies that are intended to improve consumer safety. For example, in 2006, Spain reported an average of 207 μg/kg for AA in corn-based cornflakes (Rufián-Henares et al., 2006). It was considered as a high content as the consumption was relatively above average. Hence, measures were taken to assess the factors leading to the AA formation;

Mesías et al. (2019) reported a 3.23-fold reduction in the mean acrylamide content of corn-based cereals to 64 μg/kg following process modifications.

(Mesías et al., 2019). This is a valid example that tells clearly that acrylamide formation could be controlled and limited if efforts are made to control the additives, thermal procedure, and the time needed for the process. Likewise, Belgium has executed a study that followed annually the AA levels in many food products parallel with population exposure for five years (2002-2007). As a consequence, the cereal industry unified and controlled recipes in the food industry with the sole purpose of lowering acrylamide levels. This eventually led to a favorable outcome as SS levels in cereals dropped during the period of 2008-2013 by 20% (Claeys et al., 2016). These methods were applied to similar products such as ginger bread and results showed AA levels reduced from 431 to 225 μg/kg (Claeys et al., 2016). On the contrary, no improvements at this level were made in a number of developing countries such as Lebanon (Merhi et al., 2020), Brazil (Arisseto et al., 2007), and Pakistan (Kaur & Halford, 2023)

The results from our study confirm these findings as SKUs in the UAE market produced in developed countries have an average of 506.40 μg/kg while those originated from developing countries scored an average of 1068.95 μg/kg. Similarly in the Lebanese market, average of acrylamide content varied from 576.15 to 424.92 μg/kg when considering samples' origin from developing to developed countries, respectively. The effect of the country of origin was found significant ($p < 0.05$) in both countries (Table 5).

B. Nuts

The presence of nuts in breakfast cereals have been shown to increase acrylamide levels as roasted nuts are known to contain high acrylamide levels. (Süvari et al., 2017) In addition, acrylamide content in nuts depends on both their nature (pistachio, almonds, peanuts) as well as the time and temperature needed for roasting (raw nuts do not contain acrylamide) (Süvari et al., 2017). **Sü**vari et al. (Süvari et al., 2017) reported that roasted almonds contain the highest acrylamide content (273 ng/mL) followed by sunflower seeds (61.5 ng/mL) and then roasted peanuts (60.5 ng/mL). In the same regard, another study showed that the divergency of acrylamide content of roasted nuts is related to their composition, time and temperature of roasting (Nematollahi et al., 2020). The range of acrylamide level in roasted seeds and nuts varied between 33.36 and 250.90 μg/kg, where highest and lowest acrylamide contents were recorded for roasted almonds (176.88 μg/kg) and roasted hazelnuts (90.61 μg/kg) respectively. As for roasted pistachio, acrylamide content ranged between 57 and 851 μg/kg (Asadi et al., 2020). Sun-dried pistachios and raw pistachios contained acrylamide in the range of 93 and 57 μg/kg respectively. Finally, it is worthwhile noting that the time frame during which the nuts are added to the cereal products while undertaking heat processing also contributes to the variation in acrylamide levels (Boyaci Gunduz, 2023). These factors explain that the type, amount and the degree of roasting of nuts influence their contribution to the acrylamide content. In our study, the presence of nuts was not significant (Table 5). The reason could be due to the factors discussed above.

C. Chocolate

Table 5
Effect of product characteristics and country of origin on acrylamide levels in breakfast cereals.

*: n=1

Variable	Category	Mean ± SD (μg/kg)	p-value
Entire sample	Lebanon	15.44 ± 5.06	0.624
	UAE	16.07 ± 5.36	
Country of origin	France	16.69 ± 4.37	0.04
	UK	13.41 ± 3.69	
	USA	13.95 ± 4.56	
	Lebanon	14.49 ± 4.20	
	Switzerland	15.18 ± 3.07	
	Poland	16.54 ± 4.51	
	India	25.20 ± 10.08	
	Ukraine	21.12 ± 4.45	
	Egypt	16.07 ± 5.18	
	Germany	12.25 ± 3.84	
	Spain	15.40 ± 8.01	
	Canada*	16.89	
	Europe*	19.76	
	Italy/UK*	12.32	
	Malta*	21.49	
	Mexico*	19.98	
	Turkey*	12.57	
Production season	Fall	16.74 ± 5.67	0.846
	Winter	15.63 ± 2.74	
	Spring	15.24 ± 4.95	
	Summer	16.44 ± 6.07	
Months between production & analysis	< 5	16.55 ± 6.64	0.927
	5–10 months	16.13 ± 5.56	
	>10 months	15.63 ± 4.33	
Whole grain	Yes	17.01 ± 4.82	0.081
	No	14.84 ± 5.84	
Shape	Plain	14.01 ± 3.89	0.148
	Shaped	16.45 ± 5.53	
Chocolate	Yes	18.72 ± 4.71	< 0.001
	No	14.24 ± 5.05	
Contains nuts	Yes	17.48 ± 6.59	0.325
	No	15.80 ± 5.12	

* : n=1

In 2020, Merhi et al. (2020) investigated the effect of different flavors on the AA content in cereal products in the Lebanese market. Natural flavored cereal products were analyzed and compared to the chocolate and honey flavored products of the same brand. Results showed that AA content of the non-flavored products is less than that of honey and chocolate flavored by 1.5 folds. This observation could be justified by the fact that sugar content in flavored samples (honey and chocolate) is higher than that of the non-flavored (natural). This theory has been proved earlier in 2008 by Hamlet et al in the United Kingdom (Hamlet et al., 2008) whereby experiments on cereal products with different sugar content showed a positive relationship between the sugar and acrylamide content. In particular, when one-fold of maltose and sucrose were added, acrylamide content increased by five and 20 folds respectively (Hamlet et al., 2008). In addition, chocolate is known to contain acrylamide and a study carried in 2016 showed that acrylamide content ranged from 54.2 to 168.0 μg/kgfor cocoa powder and from 25.5 to 256.1 μg /kgfor chocolate (Surma et al., 2016). Furthermore, the type of chocolate influenced the acrylamide content whereby three types of chocolate, dark, milk and white, were investigated. The level of contamination with acrylamide ranged from 91.1 to 256.3 μg /kg, from 30.5 to 193.0 μg /kg and from 25.7 to 83.4 μg/ kgfor dark, milk and white ones, respectively (Surma et al., 2016). It is safe to thereof conclude that chocolate flavored cereals would have higher AA content because of the chocolate itself (type, quantity) and because of the sugar content of this added chocolate.

D. Bran/Whole wheat

Although the presence of bran or whole grains did not have a significant (p>0.05) effect on acrylamide content in cereals in the selected tested samples (Table 5), it is worth understanding their effect as explained by different research groups in this aspect. For instance, despite of the wholewheat and rye products' health benefits, their presence in toasted bread led to higher acrylamide levels compared to white toast. This result is most likely due to the higher content of amino acids and proteins in the wholewheat grains when compared to the white bread (Ahn et al., 2002; Capuano et al., 2010).

The relation between acrylamide content and fiber is still not consistent as the literature showed contradicting results. In 2003, Rydberg showed that acrylamide content was lowered upon the addition of dietary fiber to heated model systems (Rydberg et al., 2003). This was explained due to relating the fiber-water binding to the formation of acrylamide. On the contrary, two years later, a study showed that no-acrylamide lowering effect is observed upon the addition of different amounts of oat bran in the process of preparing crispbread (Mustafa et al., 2005). This would suggest that there are other factors that are contributing to the formation of acrylamide aside from the type of grain used. More studies should be implemented whereby all conditions are the same and the bran and wholewheat are the only variable factor in the experiment for a better understanding of their effect on the acrylamide formation. The product design for cereals includes the use of grains or grain parts that affect the free asparagine content, the choice of rising agent as ammonium bicarbonate or any other alternative, in addition of co-ingredients, and type of sugar added. The processing procedure includes the temperature, time of baking, fermentation time, achieving the lightest color of the final product avoiding burnt additives (Boyaci Gunduz, 2023). Extant literature confirms the effect of these factors on acrylamide content. Processing conditions such as temperature and baking time significantly influence acrylamide formation, as reported in recent studies (Lemos et al., 2023). Ingredient composition, including whole-grain content, has also been shown to affect acrylamide levels in cereal-based products (de Borba et al., 2023).

In the current study, data have shown that the presence of ingredients such as chocolate and nuts, as well as the country of origin (developed versus developing countries) significantly influenced acrylamide levels. Conversely, the presence of bran or whole grains showed no significant effect on acrylamide levels in the cereal samples. In addition to studying the effect of the country of origin as well as the main ingredient classification, we have coupled data from the literature on various food products to extrapolate optimal conditions through which acrylamide formation could be reduced.

3.6. Literature review on optimal industrial processes for lowering Acrylamide levels

Additives and processing parameters exert a clear impact on acrylamide formation in bakery products. Incorporating amino acids or proteins under slightly acidic conditions can effectively suppress acrylamide in bread as these components favor alternative reaction pathways that dominate over acrylamide synthesis (Rydberg et al., 2003). On the other hand, the addition of ammonium hydrogen carbonate enhances both browning and acrylamide formation. This was proved by Rufian-Henares et al.(Rufian-Henares et al., 2007) showing that breads prepared with this leavening agent contain up to 6.7-fold higher acrylamide levels than those prepared without it. As for the effect of sugars and their alternatives, replacing honey with sucrose reduced acrylamide levels by nearly 20-fold (Biedermann & Grob, 2003). Moreover, the pairing between amino acid and sugar played a role. For example, asparagine and fructose produce the highest acrylamide levels, while ribose and glycine minimize its formation (Shen et al., 2019). Similarly, the addition of glycine during blanching has been reported to lower acrylamide by 30–50 %(Braathen et al., 2005). Process parameters play a crucial role in the acrylamide content. Applying a starch coating, for example, shortens baking time and reduces crust temperature, resulting in up to a 77 % decrease in acrylamide (Liu et al., 2018). Agronomic conditions such as high growing temperatures, excessive nitrogen fertilization, or grain sprouting significantly elevate precursor asparagine and consequently acrylamide levels (Claus et al., 2006). Likewise, the type of flour, grain variety, and fermentation method affect the final outcome; rye and low-fiber flours display distinct formation patterns (Ngoita et al., 2014; Przygodzka et al., 2015). Yeast fermentation also plays a beneficial role, as it lowers the levels of precursors, leading to a reduction in acrylamide formation (Sadd et al., 2008).

Effective control strategies therefore depend on optimizing both recipe and processing conditions. Moderate salt concentrations (around 2 %) and minimal cysteine levels (approximately 0.005 %) were shown to lower acrylamide while maintaining desirable sensory characteristics (Claus et al., 2008). Natural antioxidants such as bamboo-leaf and green-tea extracts can also reduce acrylamide formation (Zhang & Zhang, 2007) while enzymatic and thermal approaches targeting asparagine depletion provide further mitigation (Matouri & Alemzadeh, 2018). Overall, adjusting the combination of ingredients, fermentation parameters, and baking profiles remains central to minimizing acrylamide levels without compromising the sensory quality of bakery products (Boyaci Gunduz, 2023; Hamlet et al., 2008; Suman et al., 2019).

3.7. Optimizing ingredient and processing combinations for minimizing AA levels in cereal products

Based on the above literature review, acrylamide content in cereals is strongly influenced by the type of ingredients, flavoring, country of origin, and processing conditions. The lowest acrylamide levels are consistently found in cereal products manufactured in developed countries, where stricter regulations and unified recipes are applied. For example, Spain successfully reduced acrylamide in cornflakes from ~207 μg/kg (2006) to ~64 μg/kg (2019) by modifying recipes and processing methods, while Belgian monitoring from 2002–2013 showed similar decreases. Ingredient choice also plays a critical role: cereals without chocolate or nuts contain significantly less acrylamide than flavored products. Non-flavored cereals typically show acrylamide levels about 1.5-fold lower than honey- or chocolate-based products, which can range from 90-250 μg/kg depending on sugar and cocoa content. Nut additions (especially roasted almonds or pistachios) further elevate AA, with levels often between 90-850 μg/kg depending on roasting conditions. Conversely, cereals prepared without such additives consistently fall in the lower range of 60-120 μg/kg. Processing variables are equally important: extended fermentation, optimized baking time (~35 min) and moderate temperature (~180-200°C), along with the use of low-asparagine flours, can reduce acrylamide by 30-50%.

For instance, Spain successfully lowered acrylamide in cornflakes from about 207 μg/kg in 2006 to around 64 μg/kg in 2019 by changing recipes and processing techniques. Belgian monitoring from 2002 to 2013 showed similar reductions. The choice of ingredients also matters: cereals without chocolate or nuts have significantly less acrylamide than flavored products. Non-flavored cereals usually contain acrylamide levels about 1.5 folds lower than those based on honey or chocolate, which can range from 90 to 250 μg/kg depending on sugar and cocoa amounts. Adding nuts, especially roasted almonds or pistachios, increases acrylamide levels to between 90 and 850 μg/kg, depending on how they are roasted. On the other hand, cereals made without such additives generally have lower levels, ranging from 60 to 120 μg/kg. Using sucrose instead of reducing sugars, avoiding ammonium bicarbonate, and applying starch coatings can lower levels by up to 70%. Overall, the best approach to minimize acrylamide in cereals is to produce them in developed countries under regulated conditions, avoid using chocolate or roasted nuts, use low-asparagine flour with longer fermentation, bake at moderate temperatures (180-200°C for 35 minutes), and control sugar content. Under these optimal conditions, expected acrylamide levels would fall between 60 and 120 μg/kg. This is much lower than the average levels of over 500 μg/kg currently seen in the Lebanese and UAE markets.

4. Conclusion

The results of this study shows that the average of acrylamide content of cereals in both the Lebanese and the UAE markets is comparable. The presence of chocolate and nuts increased the acrylamide formation. In addition, the country (developed/developing) is of significant effect on setting limits and controlling the food processing recipes to reduce acrylamide formation in many food matrices. The exposure to acrylamide from cereals for both populations lie in the acceptable range set by WHO. On the other hand, both populations are at carcinogenic risks based on limits set by NFCA and WHO. In addition, no neurotoxic risk was observed for both populations taking recent US-EPA recommendation. Based on values set by JECFA, both populations pose neither carcinogenic nor neurotoxic risks. It is worth mentioning that these calculations are made based on average consumers based on the average of acrylamide content in each market. No doubt that the risk becomes more serious when high consumers are assessed or when even average consumers purchase cereals with acrylamide content higher than that of the average by a factor of 2 or more. Although breakfast cereals may also present additional nutritional concerns, such as high sugar content and targeted marketing toward children, these aspects fall outside the scope of the present study, which focuses specifically on acrylamide occurrence and dietary risk assessment.

Ethical approval

Not applicable.

CRediT authorship contribution statement

Areej Merhi: Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation. **Hussein F. Hassan:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Ghada El-Zakhem Naous:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Clara Al Akoury:** Writing – review & editing, Writing – original draft, Investigation, Data curation. **Hani Dimassi:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Mireille Serhan:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Nisreen Alwan:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Robin I. Taleb:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.afres.2026.102063.

Data availability

Data will be made available on request.

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