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ROYAL SOCIETY OF CHEMISTRY

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Cite this: *RSC Adv.*, 2025, **15**, 34918

Cornflakes as a source of dietary metal exposure in Lebanon: a risk assessment study

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Received 20th July 2025
Accepted 12th September 2025

DOI: 10.1039/d5ra05243b

rsc.li/rsc-advances

This study investigates the occurrence of toxic metals in cornflakes marketed in Lebanon and the associated health risks from their consumption. Following a market screening, 21 stock-keeping units (SKUs) of cornflakes from different manufacturers and countries of origin were identified and collected across two production periods ($n = 42$). The samples were analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS). Arsenic (As), cadmium (Cd), chromium (Cr), mercury (Hg), and lead (Pb) were quantified and compared against both international and Lebanese regulatory standards. All samples exceeded international limits for Cr. Most samples surpassed permissible levels for Pb (73.8%) and Hg (76.2%), while a smaller proportion (19%) exceeded the limits of As. However, the concentrations of all toxic metals remained below the Lebanese national limits. The analysis indicated that the brand of the cornflakes did not exert a significant influence on metal concentrations ($p \geq 0.05$), whereas statistically significant differences ($p \leq 0.05$) were observed in the levels of Cr and Pb when comparing Lebanese to imported products. Estimated Daily Intake (EDI) and Hazard Quotient (HQ) calculations indicated no significant health risk for adults. Nevertheless, the frequent detection of contaminated samples and the increasing consumption of ready-to-eat cereals raise concerns about cumulative exposure, particularly among children. This research underscores the urgent need for updated national food safety regulations, strengthened food surveillance systems, and immediate public health interventions to reduce toxic metal exposure in the Lebanese population.

1 Introduction

Cornflakes, made from processed corn grit, have become a staple food product. Originating from the United States in the late 19th century,[1] cornflakes are now manufactured globally, often fortified with vitamins and minerals. Their nutritional value varies depending on the production method and formulation. Some blends include legumes and tubers to enhance protein and fiber content while others are marketed primarily for convenience. In Lebanon, the breakfast cereal market is expected to grow by nearly 10% from 2025 to 2030, with a projected value exceeding USD 34 million.[2] This growth is largely driven by urbanization and shifting dietary patterns.[3] However, the increasing consumption of such processed foods raises concerns regarding product safety, especially in the absence of local studies on contaminants like toxic metals. Table 1 lists the sources of exposure, along with the health effects of toxic metals.

Toxic metals, such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg), are naturally occurring elements that have been intensified in the environment by human activity.[4,5] Though some metals (like copper or zinc) are essential in trace amounts, the aforementioned toxic metals are non-essential and can cause severe harm even at low exposure levels. These metals are introduced into the food chain through industrial pollution, mining, pesticide use, and improper e-waste disposal.[6,7] Exposure can occur *via* contaminated soil, water, or air, with crops like corn particularly vulnerable to absorbing these substances.[8–10] Once consumed, these metals bioaccumulate in the human body, potentially causing a range of health effects including cancer, kidney and liver damage, neurodevelopmental deficits, and cardiovascular disease.[11] Various analytical techniques are used to detect and quantify metal concentrations in foods. These include Atomic Absorption Spectrometry (AAS) used for high-sensitivity single-element analysis.[12] Additionally, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) and Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) offer rapid, multi-element analysis with low detection limits.[13,14] Furthermore, X-ray Fluorescence (XRF) is a non-destructive method capable of

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Table 1 Sources of exposure and health effects of toxic metals

Element	Source of exposure	Health effects	References
As	Contaminated drinking water, industrial processes, pesticides	Skin lesions, skin cancer, cardiovascular diseases, developmental toxicity, carcinogenic to humans	WHO, 2022
Cd	Occupational exposure (battery production, welding), contaminated food and water	Lung and kidney damage, osteoporosis, increased risk of cancer	WHO, 2019; OSHA, n.d.
Hg	Consumption of contaminated fish, industrial emissions	Neurotoxicity (especially in children), kidney toxicity, cardiovascular effects	WHO, 2024
Cr	Chromite mining, leather tanning, electroplating, industrial discharge	Cr(VI): carcinogenic, respiratory damage; Cr(III): generally less toxic	WHO, 2022
Pb	Lead-based paints, contaminated soil and water, occupational exposure, packaging, pesticide	Neurodevelopmental deficits in children, hypertension, kidney damage, anemia, reduced IQ	WHO, 2024; CDC, n.d.

analyzing a wide range of elements.[15] The choice of method depends on factors such as sample composition, element type, and required sensitivity.

Toxic metal contamination in cereals is a global concern. In Ethiopia, Getu *et al.* (2022) found that Cd and Pb levels in staple grains significantly exceeded global safety thresholds.[16] Similarly, Oduro *et al.* (2023) in Ghana detected dangerously high levels of As, Cd, Cr, and Pb in breakfast cereals.[17] In Morocco, while contamination levels were generally lower, Pb and Cd were still detected in most samples.[18] These studies collectively demonstrate that even packaged, branded products can carry serious contamination risks. Although Lebanon has adopted standards *via* its national body the Lebanese Standards Institution (LIBNOR) and international frameworks (*e.g.* Codex Alimentarius, EU regulations), enforcement remains inconsistent due to weak infrastructure and limited monitoring capacity.[19,20] Research shows frequent violations in food categories such as dairy, spices, and meat, yet cornflakes have not been assessed, until now. Maximum permissible limits (MPLs) vary slightly across agencies but often converge around specific values. For example, the EU allows up to 0.2 mg kg^{-1} Pb in cereals, while the JECFA no longer sets a safe weekly intake, indicating that no level of Pb exposure is considered completely safe.[21,22] In Lebanon, the lack of data leaves a blind spot in risk management, particularly for frequently consumed processed foods like cornflakes.

Cornflakes are a widely consumed processed food in Lebanon, yet no studies have evaluated their contamination with toxic metals such as arsenic (As), cadmium (Cd), chromium (Cr), lead (Pb), and mercury (Hg) while rice and other staples have been analyzed.[23] International research has documented heavy metal contamination in cereals and other staple foods, highlighting potential health risks, but Lebanon lacks local data, creating a significant gap in food safety knowledge.[24–26] Given the increasing consumption of cornflakes, the possibility of dietary exposure to toxic metals, and the limited enforcement of food safety regulations, it is essential to assess both imported and locally manufactured products. This study therefore aims to determine metal concentrations in commercially available cornflakes and evaluate associated health risks, providing critical evidence to inform public health policy, enhance consumer awareness, and strengthen regulatory oversight in Lebanon.

2 Methods

2.1 Sample selection and collection

A comprehensive market screening was carried out in Lebanon across the three major retail outlets (purposive sampling) to identify available cornflake products. Twenty-one stock-keeping units (SKUs) were identified and procured during two collection periods (summer 2022 and December 2023/$n = 42$) The collection was conducted across two periods to account for potential seasonal and batch-to-batch variations in product composition. This ensures that the dataset was representative of different production cycles and market conditions. The SKUs reflected variations in brand, flavor, and product formulation. Upon collection, all samples were stored in their original packs at 4 °C to ensure sample stability until analysis. In this study, the term "brand" refers to the commercial label under which a cornflake or cereal product is marketed, distinguishing products from different manufacturers. We collected 10 brands, 3 of which were local. Out of the 42 SKUs, 18 were made in Lebanon. All the SKUs had a plastic primary packaging and cardboard secondary packaging.

2.2 Chemicals and reagents

For the analysis of toxic metals, the following reagents were used: standard solutions of arsenic, cadmium, mercury, and lead (Merck, Darmstadt, Germany), hydrogen peroxide (Sigma-Aldrich, Germany), nitric acid (BDH Laboratory Supplies, England), and hydrochloric acid (AnalaR Normapur, France). Certified reference materials (CRM BCR-610 for groundwater and IRMM-804 for rice flour) were obtained from the Institute for Reference Materials and Measurements (Geel, Belgium) to ensure the accuracy of the analytical methods. All solutions were prepared with analytical-grade chemicals and ultrapure

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water (18.2 MΩ cm) produced using a Milli-Q water purification system (Millipore, France).

2.3 Sample digestion

Each cornflake sample (~0.5 g) was digested using a Multiwave ECO microwave digestion system (Anton Paar, Austria). The digestion involved adding 8 mL of nitric acid (69%) and 2 mL of hydrogen peroxide (30%) and heating the mixture at 180 °C for 10 minutes at 850 W, followed by rapid cooling at 22 °C. After digestion, 2 mL of 37% hydrochloric acid was added, and the solution was diluted with 3% nitric acid using ultrapure water. Final dilution (5×) was performed to maintain accurate concentrations. The selected isotopes for quantification were ^{52}Cr, ^{59}Co, ^{63}Cu, ^{64}Zn, ^{75}As, ^{98}Mo, ^{114}Cd, ^{200}Hg, and ^{208}Pb due to their stability and low polyatomic interference.

2.4 ICP-MS analysis

Quantification of toxic metals was performed using an Inductively Coupled Plasma Mass Spectrometer (ICP-MS) (Thermo Fisher Scientific, Germany) following EPA Method 6020B (EPA, 2014). The system operated with 99.9995% pure argon gas. Calibration was conducted using multi-element standards prepared in 2% HNO_3 + 0.5% HCl. Instrument parameters such as torch position, ion lens settings, and gas flows were optimized to enhance sensitivity. Samples were introduced through a borosilicate glass nebulizer and atomized into a high-temperature plasma (6000–8000 °C). Ionized particles were filtered *via* ion optics and analyzed based on their mass-to-charge (m/z) ratios. Each sample was measured in triplicate, and external calibration curves with $R^2 \geq 0.9999$ ensured high accuracy. Quality control was performed using certified standards and blanks. Key ICP-MS operating parameters included RF power (400–1600 W), nebulizer gas flow (1.03 L min^{-1}), collision cell mode (He 4.0 mL min^{-1}), acquisition mass range (2–290 a.m.u.), dwell time (0.04 s), three replicates per sample.

2.5 Exposure estimation

To assess consumer exposure, Estimated Daily Intake (EDI) was calculated for each toxic metal. Consumption data were sourced from Hassan *et al.* (2023),[3] defining daily intake levels as:

- 57 g per day for daily consumers.
- 1.0 g per day for regular consumers.
- 0.2 g per day for rare consumers.

EDI was computed using the formula:[27]

$$\mathrm{EDI} = \frac{\mathrm{Mean\ concentration}\left(\mathrm{mg\ kg^{-1}}\right) \times \mathrm{Daily\ intake}(\mathrm{kg\ per\ day})}{\mathrm{Body\ weight}(\mathrm{kg})}$$

The average adult body weight used was 76 kg,[3] and the Estimated Weekly Intake (EWI) was derived by multiplying EDI by 7.

2.6 Risk assessment

Health risks were evaluated by calculating the Hazard Quotient (HQ) for each metal:

$$\mathrm{HQ} = \frac{\mathrm{EDI}(\mathrm{mg\ per\ kg\ per\ day})}{\mathrm{Tolerable\ daily\ intake}}$$

Reference TDIs and benchmark dose values were obtained from authoritative sources including the Food and Agriculture Organization (FAO) of the United Nations, the Joint FAO/WHO Expert Committee on Food Additives (JECFA), European Food Safety Authority (EFSA), and World Health Organization (WHO). An HQ greater than 1.0 suggests a potential risk to human health. HQ values below 1.0 indicate that exposure is unlikely to pose adverse health effects.

2.7 Statistical analysis

Data analysis was conducted using SPSS v30. Normality tests indicated that some metal concentration distributions deviated from Gaussian patterns. As a result, ANOVA with Brown–Forsythe correction was employed to compare means, offering robustness against non-normal distributions. Non-parametric sensitivity analyses (not shown) confirmed the consistency of the main results. All statistical tests were two-sided, with a significance threshold of 0.05.

3 Results

3.1 Findings from ICP-MS analysis

A summary of the ICP-MS analysis for toxic metals in cornflake SKUs collected from the Lebanese market ($n = 42$) is presented in Table 2. As and Cd exhibited contamination ranges of 0.0314–0.1824 mg kg^{-1}, and 0.0597–0.0836 mg kg^{-1}, respectively, while the range of Cr levels were between 0.1122 and

Table 2 Mean, standard deviation, minimum and maximum values of toxic metals (mg kg^{-1}) in cornflakes collected from Lebanon ($n = 42$)

Toxic metal	Parameter	mg kg^{-1}
As	Mean	0.0831
	Standard deviation	0.0320
	Minimum	0.0314
	Maximum	0.1824
Cd	Mean	0.0636
	Standard deviation	0.0043
	Minimum	0.0597
	Maximum	0.0836
Cr	Mean	0.1993
	Standard deviation	0.0581
	Minimum	0.1122
	Maximum	0.3790
Hg	Mean	0.0233
	Standard deviation	0.0127
	Minimum	0.0033
	Maximum	0.0596
Pb	Mean	0.0689
	Standard deviation	0.1067
	Minimum	0.0035
	Maximum	0.4745

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Table 3 Number and percentage of SKUs exceeding regulatory limits for each toxic metal (n = 42)[a]

Metal	Regulatory limit (mg kg^{-1})	Regulatory source	m (%) Of SKUs exceeding limit
Cr	0.05	EFSA	42 (100.0%)
		LIBNOR	N/A
As	0.1	EFSA/FDA	8 (19.0%)
	1.0	LIBNOR	0 (0.0%)
Cd	0.04–0.18	EU regulation 2021/1323	0 (0.0%)
		LIBNOR	N/A
Hg	0.01	EU regulation 2018/73	32 (76.2%)
		LIBNOR	N/A
Pb	0.02	EU regulation 2021/1317	31 (73.8%)
	0.5	LIBNOR	0 (0.0%)

[a] n: number; N/A: not applicable.

0.3790 mg kg^{-1}. On the other hand, Hg and Pb contamination ranges were 0.0033–0.0596 mg kg^{-1}, and 0.0035–0.4745 mg kg^{-1}, respectively.

The levels of toxic metals in our samples were compared against internationally recognized regulatory limits (Table 3). Cr posed the most significant concern; 100% of the samples (n = 42) exceeded the EFSA limit of 0.05 mg kg^{-1}. Cr is not yet regulated under Lebanese standards. As levels exceeded the EFSA/FDA limit of 0.1 mg kg^{-1},[28] in 8 out of 42 samples (19%). However, when assessed against the Lebanese limit of 1.0 mg kg^{-1}, none of the samples exceeded the national threshold. Cd, although present in all samples, remained within acceptable safety margins, with none of the samples exceeding the EU Regulation 2021/1323 limits (EU, 2021) (0.04–0.18 mg kg^{-1} depending on product type). Hg levels were of more concern, with 76.2% of the samples (n = 32) exceeding the EU limit of 0.01 mg kg^{-1}. No limit of Hg concentration are set by LIBNOR in cornflakes. EU guidelines are thus the most suitable comparators. Pb was also of specific concern. Although the average level was 0.0689 mg kg^{-1}, 31 out of 42 samples (73.8%) exceeded the EU Regulation 2021/1317 limit (EU, 2021) of 0.02 mg kg^{-1}. Nonetheless, no sample exceeded the Lebanese permissible limit of 0.5 mg kg^{-1}, underscoring a gap between international risk perception and national regulatory enforcement. The effect of brand and country of origin on toxic metals contamination levels are presented in Table 4. Among the analyzed brands, Brand 1 (28.6%) and Brand 2 (19%) represented the majority of SKUs, while Brand 3 and Brand 4 each comprised 4.8%. No statistically significant differences in Cr, As, Pb, Cd, or Hg were observed across brands (p > 0.05). On the other hand, SKUs manufactured in Lebanon (42.9% of samples) had significantly lower Cr levels (0.1798 ± 0.0304 mg kg^{-1}; $p = 0.041$) than those imported (0.2139 ± 0.0704 mg kg^{-1}). However, Pb was significantly higher in Lebanese products (0.1114 ± 0.1438 mg kg^{-1}; p = 0.049), potentially reflecting environmental contamination. No significant differences were found in As, Cd, or Hg by country of origin.

To provide a clearer assessment of contamination severity, the contamination factor (CF) was calculated for each metal by comparing the mean concentrations with internationally recognized permissible limits (EFSA/EU/FDA). The results indicated that Cr (CF = 3.99) and Pb (CF = 3.45) exhibited considerable contamination, while Hg (CF = 2.33) and Cd (CF = 1.59) fell within the moderate contamination range. Arsenic showed a low level of contamination (CF = 0.83). These findings highlight that, although certain metals frequently exceeded international regulatory limits, the overall contamination profile can be quantified to prioritize risk management. To further evaluate potential health risks, Estimated Daily Intake (EDI) and Hazard Quotient (HQ) values were calculated based on the mean metal concentrations and internationally accepted reference doses (BMDL, TDI, PTWI, or EPA guidelines). As shown in Table 5, all estimated daily intakes for the metals were below their safety thresholds. As had a mean concentration of 0.0831 mg kg^{-1}, corresponding to an EDI of 0.000062 mg kg^{-1} body weight per day and an EWI of 0.000436 mg kg^{-1} body weight per week. This intake is below the $BMDL_{0.5}$ value of 0.003 mg per kg per day established by JECFA for inorganic As, resulting in a HQ of 0.021 and thus no considerable health risk. For Cd, the mean concentration was 0.0636 mg kg^{-1}, which gives an EDI of 0.000048 mg per kg per day and an EWI of 0.000334 mg per kg per week. When compared to the derived daily limit of 0.000357 mg per kg per day (based on EFSA's TWI of 0.0025 mg kg^{-1}), the calculated HQ was 0.134, suggesting no health risk for regular consumers. Cr averaged 0.1993 which led to an EDI estimate of 0.000149 mg per kg per day and an EWI of 0.001046 mg per kg per week. Using the EFSA TDI for Cr(III) of 0.3 mg per kg per day, the resulting HQ was 0.0005, which is far

Table 4 p-values for the effect of independent variables on toxic metal levels in cornflakes

Independ ent variable	Cr	As	Cd	Hg	Pb
Brand	0.376	0.540	0.500	0.951	0.144
Country of origin (Lebanon *vs.* imported)	0.041	0.989	0.598	0.350	0.049

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Table 5 Estimated Daily Intake (EDI), Estimated Weekly Intake (EWI), and Hazard Quotient (HQ) for daily consumers in Lebanon

Metal	Mean conc. (mg kg^{-1})	EDI (mg per kg bw per day)	EWI (mg per kg bw per week)	Reference TDI/RfD (mg per kg per day)	HQ	Interpretation
As	0.0831	0.000062	0.000436	0.003 (BMDL$_{0.5}$, JECFA)	0.021	No risk
Cd	0.0636	0.000048	0.000334	0.000357 (EFSA TWI/7)	0.134	No risk
Cr	0.1993	0.000149	0.001046	0.3 (EFSA for Cr(III))	0.0005	No risk
Hg	0.0233	0.000017	0.000122	0.000571 (JECFA PTWI/7)	0.029	No risk
Pb	0.0689	0.000052	0.000362	0.0005 (BMDL$_{01}$)	0.104	No risk

below the threshold of concern. Hg averaged 0.0233 mg kg^{-1} with an EDI of 0.000017 mg per kg per day and an EWI of 0.000122 mg per kg per week. Compared to the JECFA PTWI calculated daily dose equivalent of 0.000571 mg per kg per day, HQ was 0.029, again indicating no substantial health risk from dietary exposure. Lastly, Pb was found at a mean value of 0.0689 mg kg^{-1}, which resulted in an EDI of 0.000052 mg per kg per day and an EWI of 0.000362 mg per kg per week. Using the U.S. EPA reference value of 0.0005 mg per kg per day, the HQ was found to be 0.104 that is less than the threshold for risk, suggesting no toxicological concern.

4 Discussion

To date, no peer-reviewed studies have directly analyzed toxic metals in cornflakes sold in Lebanon. However, related research on cereals and grains offers relevant context.

4.1 Arsenic (As)

Our cornflake SKUs had As at a mean 0.083 mg kg^{-1} (range 0.031–0.182 mg kg^{-1}). Akoury *et al.* (2023)[23] analyzed 236 rice samples from Lebanon and the UAE and found that 25% of samples from Lebanon exceeded Codex limits for As with a mean of 0.24 mg kg^{-1}, while 73% exceeded the European Commission's limit for Cd, with a mean of 0.29 mg kg^{-1}. Another study in Ghana, also found elevated As levels in cereals, with mean concentrations of 0.050 mg kg^{-1} in maize, 0.150 mg kg^{-1} in rice, 0.059 mg kg^{-1} in millet, and 0.068 mg kg^{-1} in sorghum, all exceeding the WHO limit (0.015 mg kg^{-1}).[29] However, when comparing these results to ours, which used stricter regulatory thresholds, the tamale samples remained below these limits. Similarly, in Bangladesh, the authors found elevated As levels in cereals, with a mean concentration of 0.97 mg kg^{-1}, nearly double the maximum permissible limit (0.5 mg kg^{-1}).[30] Rice had the highest As content (1.48 mg kg^{-1}), followed by maize (0.98 mg kg^{-1}) and wheat (0.46 mg kg^{-1}).[30] This highlights severe As contamination in staple foods, likely due to industrial pollution and irrigation water, posing long-term health risks despite non-carcinogenic (HQ < 1). In short, our As results are broadly consistent with other reports of cereals.

4.2 Cadmium (Cd)

Cd was found at low, consistent levels (mean ∼0.064 mg kg^{-1}, range 0.059–0.084). This narrow range indicates little variation among brands. These values are similar to many reported cereal products. By contrast, in Ethiopia, Cd levels in four cereal samples (barley, teff, wheat, maize) were alarmingly high: 2.01 mg kg^{-1} in barley, 1.84 mg kg^{-1} in teff, 1.95 mg kg^{-1} in wheat, and 1.93 mg kg^{-1} in maize, all far exceeding the FAO/WHO safety limit (0.1–0.2 mg kg^{-1}).[31] Similarly, Ghanati *et al.* (2019) found Cd contamination across all analyzed Iranian food samples, with the highest levels in wheat flour (0.62 mg kg^{-1}) and bread (0.57 mg kg^{-1}), exceeding the FAO/WHO safety limit (0.1 mg kg^{-1}). Though individual HQ for Cd were <1, its presence in processed foods like flour and bread, staples in the Iranian diet, raises concerns about cumulative exposure, particularly in rural areas (HI = 2.28).[32] In parallel, corn (maize) in China had Cd levels averaging 0.10 mg kg^{-1}, with 32% of samples exceeding safety limits (threshold: 0.1 mg kg^{-1}) (Zheng *et al.*, 2020). While soil Cd was relatively low (mean: 0.27 mg kg^{-1}), corn showed a significant correlation with soil Cd (r = 0.31), suggesting uptake from contaminated soils.[33]

4.3 Chromium (Cr)

Cr was the highest metal in our samples (mean ∼0.20 mg kg^{-1}) and a clear outlier in terms of regulation; 100% of samples exceeded the EFSA limit (0.05 mg kg^{-1}). For instance, an Ethiopian survey of staple cereals found Cr as high as 1.57 mg kg^{-1} for wheat and 1.87 mg kg^{-1} for maize, close to our findings, though those remained below the 2011 FAO/WHO limit (2.3 mg kg^{-1}).[31] The discrepancy in regulatory thresholds (EFSA's 0.05 mg kg^{-1} *vs.* FAO/WHO's 2.3 mg kg^{-1}) highlights the need for harmonization. Both datasets indicate widespread Cr presence in cereals, raising concerns about long-term exposure risks, even when adhering to less stringent standards.[31] In Ghana, a study found that Cr levels ranged from 4.66 to 9.85 mg kg^{-1} across cereal types, surpassing the Chinese limit of 1 mg kg^{-1}, with potential links to kidney and gastrointestinal diseases.[17]

4.4 Mercury (Hg)

The mean Hg in our cornflakes was 0.023 mg kg^{-1} (range 0.003–0.060) with 76% of our samples exceeding the EU limit of 0.01 mg kg^{-1}. Comparable findings were reported, a U.S. – China study analyzing 119 infant cereal product, where rice-based cereals had significantly higher levels of THg and MeHg (0.0022 mg kg^{-1} with notably high levels found in samples from Miami, some reaching up to 0.0139 mg kg^{-1}) compared to non-rice varieties (0.0001 mg kg^{-1}), likely due to contaminated rice

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sources used in production.[34] In a study from Portugal, Hg was only detected in cereals from Madeira, with a mean concentration of 0.001 mg kg^{-1}, mainly in rice (0.0013 mg kg^{-1}) and wheat (0.001 mg kg^{-1}), while samples from the Azores showed Hg levels below detection limits.[35] Notably, none of the Madeira samples exceeded EU limits, and dietary exposure assessments showed Hg intake from these cereals contributed to less than 1% of the TWI, indicating minimal risk.[35] This contrast highlights how regional variations in agricultural practices, environmental exposure, and raw material sourcing may significantly influence Hg contamination levels, even within geographically and climatically similar areas.

4.5 Lead (Pb)

Lead averaged 0.069 mg kg^{-1} (0.003–0.475) in our samples. About 74% exceeded the EU limit (0.02 mg kg^{-1}), though none exceeded Lebanon's LIBNOR limit of 0.5 mg kg^{-1}. Comparable patterns have been observed in neighboring countries. In Iran, Amarloei *et al.* reported Pb concentrations in rice as high as 0.88 mg kg^{-1}, above local standards, with HQs exceeding 1 for Pb in rice and As and Hg in wheat.[36] Conversely, the U.S. FDA's Total Diet Study (2018–2020) found very low levels of Pb in breakfast cereals (0.0015 mg kg^{-1}) with no significant health concern noted.[37] In Madeira, rye had the highest Pb levels (mean 0.347 mg kg^{-1}), with 50% of rye and 25% of corn flour samples exceeding the EU limit (0.20 mg kg^{-1}), with possible nephrotic risk (Rubio *et al.*, 2023). In the Azores, Pb levels were even higher in corn flour (mean 0.719 mg kg^{-1}), with 85.7% of samples exceeding the EU limit.[35] These findings highlight regional discrepancies likely due to differences in raw material sources, agricultural practices, and food processing methods.[38]

Across brands and origins, our study found that Lebanese made cornflakes had significantly lower Cr and Mn than imported counterparts, but higher Pb. Brand-wise, Brand 5 products contained the highest Cr levels, Brand 4 products the highest Ni, and Brand 2 the highest Fe. Our study reported non-significant brand-to-brand variation. Different manufacturers use different raw ingredients, agricultural sources, and processing methods.[39] A review found that processing methods can further modify toxic levels, washing often reduces surface contaminants, while cooking may increase or decrease concentrations depending on water quality.

On the other hand, geographic origin was a major factor. Lebanese cornflakes had significantly lower Cr, Mn and Cu than imported ones, but higher Pb. Supporting this, an Iranian studied cereals and found that "rural" areas had higher total toxic metals than those from urban markets, implying local farming conditions (soil, fertilizers, water) affect uptake.[32] Also, in developing countries like Bangladesh, mainly due to poor industrial waste management and lack of safety guidelines.[40] The Rapid Alert System for Food and Feed (RASFF) in Europe monitors and reports such contaminations, with Italy the top notifying country (47%), followed by Spain, Germany, and France, especially products largely originating from China (25%) and other Asian nations.[41] To address this issue, countries implement diverse control measures, including exposure assessments, monitoring programs, and public awareness campaigns.[42]

All our EDIs for As, Cd, Cr, Hg and Pb from cornflakes were far below relevant safety thresholds (BDML, TDI, PTWI, *etc.*), yielding HQ < 1 for each metal. This indicates no significant health risk from these cereals. The Iranian cereal survey revealed that although the individual HQ values for all analyzed toxic metals in wheat products were below 1, the combined hazard index (HI) exceeded the safe threshold of 1 in both urban (HI = 1.83) and rural (HI = 2.28) populations, pointing a possible non-carcinogenic health risk due to repeated exposure.[32] This underscores the importance of considering combined metal exposure, when assessing public health risk.[32] In Spain, a continued reduction in EDI of metals has been observed, due to change in diet and decreased levels of these metals in food, with fish and seafood being the primary sources.[43] Lastly, a study combining dietary recall and analytical methods revealed that cereals and vegetables were major contributors to Cd and Hg intake, while water and beverages were primary sources of Pb.[44]

Taken together, the analysis of toxic metal contamination in the samples revealed that while the estimated daily and weekly intakes As, Cd, Cr, Hg, and Pb were all below international reference doses, indicating no immediate health risk (HQ < 1). The concentrations of several metals frequently exceeded international regulatory limits. Specifically, all samples exceeded the EFSA limit for Cr, while 76% and 74% of samples exceeded EU limits for Hg and Pb, respectively. About 19% of samples exceeded the EFSA/FDA limit for As, whereas Cd remained within acceptable limits across all samples. No samples violated the more lenient Lebanese standards. The contamination levels did not significantly differ by brand, but country of origin showed significant differences for Cr and Pb levels, suggesting imported and local products may vary in quality. Although acute exposure appears safe, the high prevalence of samples exceeding international limits for Cr, Hg, and Pb raises concerns about potential long-term, cumulative health effects, particularly among vulnerable populations, and highlights the need for aligning local regulations with international standards, stricter monitoring, and public education on the risks of toxic metal exposure from food.

Notably, our ICP-MS analysis of 42 cornflake samples from the Lebanese market revealed detectable levels of As, Cd, Cr, Hg, and Pb, with Cr, Hg, and Pb frequently exceeding international limits, while all samples remained below Lebanese thresholds. Cr was the most concerning, with 100% of samples surpassing EFSA limits, likely reflecting widespread environmental contamination and differences in raw material sourcing. Hg and Pb levels were also elevated in a majority of samples, potentially influenced by imported ingredients, agricultural practices, and industrial pollution. In contrast, Cd and As remained largely within safety margins, though cumulative exposure remains a concern. No significant variation was observed across brands, suggesting that processing methods were consistent, whereas country of origin influenced Cr and Pb levels, highlighting the impact of local *versus* imported raw materials and regional soil and water quality. Comparisons with international studies indicate that metal

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contamination in cereals is a global issue, with regional differences driven by environmental factors, agricultural practices, and production methods. Estimated daily intakes and hazard quotients for adults were below safety thresholds, suggesting no immediate health risk; however, the frequent exceedance of international limits, the potential for chronic exposure, and the vulnerability of children emphasize the need for vigilance. Limitations include the exclusive focus on packaged cornflakes, adult-based exposure estimates, and the lack of assessment of cumulative or synergistic effects from multiple metals, which may underestimate actual risk. Overall, the findings underscore the importance of aligning Lebanese regulations with international standards, improving monitoring, and raising public awareness about dietary metal exposure.

This study has multiple strengths. Firstly, it employed ICP-MS, a highly sensitive and widely recognized method for detecting trace levels of toxic metals. Secondly, the selected samples accurately reflected the variety of cornflakes available in Lebanese markets. Thirdly, the procedures for sample preparation and analysis were rigorously verified through repeated testing to ensure reliability. Additionally, the findings were thoroughly compared against the latest international safety standards, an approach often overlooked in similar research. This study has also several limitations that must be acknowledged. First, only packed cornflakes were assessed. However, unpacked, often sold in bulk or loosely packaged, may be more prone to environmental contamination due to direct exposure to air, dust, and handling, potentially leading to even higher levels of toxic metals. Second, while several samples had concentrations below established regulatory thresholds, this does not equate to zero risk. Chronic, cumulative exposure to even low levels of toxic metals can still result in adverse long-term health effects (WHO, 2021). For instance, Pb is especially concerning; according to the WHO, no safe level of intake has been identified for Pb (WHO, 2021). Likewise, Cd accumulates in the body, particularly in the kidneys, with a biological half-life estimated at approximately 15 years. This means that regular consumption of low-level Cd-contaminated foods over time may still lead to toxic accumulation (WHO, 2021). Third, the dietary exposure assessment and HQ calculations were based on average adult consumption patterns, as estimated from FFQ data. This does not account for vulnerable populations such as children, who consume more food per kilogram of body weight and may therefore be disproportionately affected by the same levels of exposure. Fourth, the study focused exclusively on cornflakes, while consumers often consume a variety of cereals and grain-based products. As a result, aggregate exposure to toxic metals from multiple dietary sources may exceed our estimates. Fifth, HQs were calculated individually for each metal, assuming isolated toxicity. However, in real-world scenarios, co-exposure to multiple metals (*e.g.*, Pb, Hg, As) may result in additive or even synergistic effects, particularly regarding neurotoxicity. Our current analysis does not account for these mixture effects, which could underestimate actual health risks. Lastly, due to the cross-sectional nature of the study, causal relationships between toxic metal exposure and health outcomes cannot be inferred.

5 Conclusion

This study is the very first to perform a holistic examination of toxic metal contamination in cornflakes on the Lebanese market. Alarmingly, most cornflake samples exceeded the international safety levels set by bodies like EFSA and the European Commission, particularly for Cr, Hg, and Pb. However, all samples were within the more lenient permissible limits of Lebanese standards, which noted a disconnect between local and international standards. The exposure study showed that the EDI and EWI of the metals *via* consumption of cornflakes were not beyond the internationally accepted safety levels for human adult consumption. This, in turn, suggests that one may not risk suffering from any immediate health problem upon occasional or moderate consumption. However, the high percentage of samples that exceeded international maximum permissible levels, in combination with the growing popularity of cornflakes, especially among children, should be of public health concern. The findings emphasize the urgent requirement for novel national guidelines for food safety that comply with prevailing international standards, along with stricter enforcement and ongoing monitoring of processed cereal products. Public health officials must also consider the additive effects of consuming toxic metals from various food sources. More research is needed to explore more typical diet patterns and perform biomonitoring studies in order to assess internal levels of exposure among vulnerable populations. As a result of the increased consumption of ready-to-eat cereals and their possible contribution to long-term cumulative metal exposure, the importance of evidence-based food policy and consumer education to protect health in Lebanon is highlighted by this study.

Future research should expand to include a wider variety of cereal-based products, including unpackaged or bulk cereals, to capture potential sources of contamination not addressed in this study. Longitudinal monitoring of metal levels across multiple production cycles and seasons would provide insight into temporal variations and cumulative exposure. Additionally, studies should assess vulnerable populations, particularly children, who may be disproportionately affected due to higher intake per body weight. Investigating the combined or synergistic effects of multiple toxic metals is also essential to better estimate real-world health risks. Finally, integrating dietary exposure assessments with biomonitoring studies could provide a more comprehensive evaluation of internal exposure, supporting the development of evidence-based regulations and public health interventions aimed at reducing toxic metal intake in Lebanon.

Conflicts of interest

There are no conflicts to declare.

Data availability

Data is provided within the manuscript or will be made available on request by the corresponding author.

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