

Elemental Profiling and Chemometric Analysis of Imported Cereals: Occurrence, Variability and Low Dietary Risk

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Abstract

This study evaluates the concentrations, and health risks of heavy metals (Pb, Cu, As, Sn, Cd, Hg) in imported rice and wheat flour in Somalia. Samples were analysed using ICP-MS. Multivariate statistical techniques were applied to examine the influence of crop type and geographic origin. Mean concentrations of toxic elements (Pb, As, Cd, Hg) were substantially below maximum limits established by international regulatory frameworks. Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) values were all below threshold levels. Significant variation in copper concentrations was observed between cereal types ($p < 0.001$), with wheat flour containing twice the levels found in rice. Elemental composition was primarily structured by crop type and secondarily by geographic origin. PCA explained 73.8% of total variance revealing clear separation between cereal matrices. HCA identified distinct clusters corresponding to countries of origin. The geochemical profiling of elements reflected environmental conditions in production regions.

Keywords: Chemometrics; Food Safety; Heavy Metals; ICP-MS; Rice; Somalia; Traceability; Wheat Flour

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INTRODUCTION

The expansion of global food trade has fundamentally altered the structure of food supply systems in low-income and import-dependent countries. In such contexts, the safety and quality of staple foods are most likely determined by environmental and regulatory conditions in exporting regions and less likely by domestic production systems. This shift has increased the importance of cross-border food safety governance and systematic monitoring of imported commodities (Singh et al., 2024; Sarker et al., 2022). In Somalia, staple cereals such as rice (*Oryza sativa*) and wheat (*Triticum aestivum*) are entirely sourced from international markets due to structural constraints including low agricultural productivity, climate variability, and institutional limitations (FAO et al., 2025; Welburn et al., 2016). Under these conditions, the assessment of food safety risks extends beyond local handling practices to encompass production environments, trade routes, and origin-specific factors.

Food safety hazards in cereals are commonly classified into biological, chemical, and physical categories. Biological contaminants, particularly mycotoxins, have received some attention in the Somali context (Wielogorska et al., 2019), unlike chemical hazards such as heavy metals which remain insufficiently characterized. This gap is significant given the persistence, non-biodegradability, and bioaccumulative nature of inorganic contaminants. Heavy metals including lead (Pb), cadmium (Cd), arsenic (As), and mercury (Hg) are of particular concern due to their well-documented toxicity and long-term health impacts. Lead exposure has been associated with neurotoxicity and cardiovascular disease (WHO, 2025; Pan et al., 2024), cadmium with renal dysfunction and bone demineralization (Doccioli et al., 2024; Lei et al., 2024; Ortega-Romero et al., 2025), arsenic with carcinogenicity affecting multiple organ systems (Ganie et al., 2024; EFSA CONTAM Panel, 2024; Islam et al., 2017), and mercury with neurological and immunological impairment (Chamoli and Karn, 2024; de Paula Arrifano et al., 2023). These elements can accumulate in human tissues over time, leading to chronic health effects even at low exposure levels (Järup, 2003; Tchounwou et al., 2012).

The accumulation of trace elements in cereal grains is governed by a multitude of determinants including environmental, agronomic, and biological factors. The bioavailability and uptake of these metals are – in turn – influenced by soil composition, irrigation water quality, the application of fertilizers and pesticides (Mamun et al., 2022; McLaughlin et al., 1999). For instance, arsenic accumulation in rice is strongly associated with anaerobic conditions in flooded paddy systems, which enhance arsenic solubility and plant uptake (Meharg and Rahman, 2003; Meharg and Zhao, 2012). Similarly, cadmium uptake has been linked to soil chemistry and agricultural practices, including phosphate fertilization (Grant et al., 1998; Clemens et al., 2013). These findings are consistent with broader theoretical frameworks in plant physiology that describe metal uptake as a function of both environmental availability and plant-specific transport mechanisms (Clemens, 2001; Zhao et al., 2009). Elemental accumulation is further modulated by crop type due to inherent physiological and anatomical differences. Wheat is known to accumulate higher concentrations of essential micronutrients such as copper and zinc, largely due to storage in the aleurone layer and embryo (Shewry and Hey, 2015; White and Broadley, 2005). In contrast, polished rice typically exhibits lower mineral content because milling removes outer layers where trace elements are concentrated (Clemens and Ma, 2016; Yang et al., 2023). These differences are not only nutritionally relevant but also critical for interpreting contamination data, as they distinguish between biologically inherent mineral content and environmentally derived contamination. The distinction between essential and toxic elements is therefore central to risk assessment frameworks (Mansour, 2014; Jaishankar et al., 2014).

Geographic origin on the other hand constitutes another major determinant of elemental composition. The concept of elemental fingerprinting posits that the chemical profile of agricultural products reflects the geochemical characteristics of the soil, water, and climatic conditions in which they were produced (Kelly et al., 2005). This principle has been widely applied in food authentication and traceability studies, where multi-element and isotopic analyses are used to distinguish products based on origin (Danezis et al., 2017). Multivariate statistical techniques such as principal component analysis (PCA) and hierarchical cluster analysis (HCA) enable the identification of patterns within complex datasets and facilitate the classification of samples according to their chemical signatures. These approaches have been successfully employed to differentiate cereals grown in distinct agro-ecological zones and to detect anomalies associated with contamination or adulteration.

Given the diversity of import sources in Somali market, including South Asia, the Middle East, and North Africa, variability in elemental composition is highly expected. The maximum allowable concentrations for toxic elements in food products are defined in international regulatory standards, such as those established by the Codex Alimentarius Commission and the European Union (Codex Alimentarius Commission, 2019; European Union, 2006). These standards are based on toxicological risk assessments and are widely used as benchmarks for food safety. However, in low-regulatory-capacity settings, monitoring and enforcement mechanisms are often limited, and rely on the integrity of external supply chains (Grace, 2017). Advances in analytical chemistry have enhanced the ability to detect trace elements in complex food matrices. Inductively coupled plasma–mass spectrometry (ICP-MS) provides high sensitivity, precision, and the capacity for simultaneous multi-element analysis (Skoog et al., 2017; Persson et al., 2012). When hyphenated with chemometric methods, ICP-MS data can provide both contamination assessment and source attribution. This combination of analytical and statistical approaches represents a critical development in modern food safety science, particularly in contexts where conventional regulatory infrastructures are constrained or absent.

This study aims to (i) quantify the concentrations of selected heavy metals in imported rice and wheat flour available in Somali markets, (ii) evaluate the effect of crop type and geographic origin on elemental distribution, and (iii) apply multivariate statistical techniques to investigate patterns relevant to food safety and traceability. The study contributes to a more comprehensive understanding of chemical food safety risks in import-dependent systems and provides an empirical basis for developing origin-based monitoring strategies.

MATERIALS AND METHODS

Sample Collection and Classification

A total of 39 cereal samples, comprising rice (*Oryza sativa*, $n = 23$) and wheat flour (*Triticum aestivum*, $n = 16$), were collected from retail markets in four major commercial centres in Somalia: Boosaaso, Baidabo, Mogadishu, and Kismaayo. Each sample (approximately 0.5 kg) was obtained using a randomised purchasing approach to reflect products available to consumers. Samples were stored in sterile, food-grade polyethylene containers and maintained under ambient conditions prior to analysis. Samples were categorised according to country of origin based on product labelling in an attempt to account for the variability associated with international supply chains. The identified origins included Turkiye, Pakistan, India, Oman, and Egypt. Each sample was assigned a unique alphanumeric code indicating both collection location and declared origin. This classification enabled subsequent evaluation of both geographic and product-based influences on elemental composition, consistent with

traceability frameworks used in food authentication studies (Kelly et al., 2005; Danezis et al., 2017).

Reagents, Standards, and Quality Control

All reagents used were of analytical or supra-pure grade to minimise contamination. Nitric acid (HNO₃, 69–71%) and hydrogen peroxide (H₂O₂, 30%) were used for sample digestion. For all dilutions, ultrapure water was used which was obtained from a Milli-Q purification system. Multi-element certified reference standards (1000 mg/L) for Pb, Cu, As, Sn, Cd, and Hg were used for calibration of the analytical instrument in line with best practices in ICP-MS analysis to ensure accuracy and reproducibility (Skoog et al., 2017; Persson et al., 2012). Quality assurance procedures were followed employing established analytical protocols, including calibration verification, reagent blanks, and instrument performance checks. The analytical method adhered to AOAC Official Method 2015.01, which is widely recognised for trace element determination in food matrices (AOAC, 2016).

Sample Preparation and Digestion

Samples were homogenised prior to analysis to ensure representativeness. Subsamples ranging from 0.25 to 1.0 g were weighed into high-pressure microwave digestion vessels. A mixture of 6–8 mL nitric acid and 2 mL hydrogen peroxide was added to each sample. Pre-digestion was allowed for approximately 10 minutes to reduce vigorous reactions during heating. Microwave-assisted digestion was conducted using a two-stage temperature program: initial ramping to 170 °C followed by holding, and a second stage reaching 175 °C. This approach ensures complete oxidation of organic matter and efficient release of bound trace elements, consistent with established digestion protocols for cereal matrices (Persson et al., 2012). After digestion, samples were cooled, diluted to volume with ultrapure water, and filtered through 0.45 µm membrane filters prior to analysis.

Instrumental Analysis

Elemental quantification was performed using inductively coupled plasma–mass spectrometry (ICP-MS), a technique recognised for its high sensitivity and capability for multi-element detection at trace levels. ICP-MS is widely applied in food safety and environmental studies due to its low detection limits and precision (Skoog et al., 2017). Analytical measurements were conducted in an ISO/IEC 17025:2017 accredited laboratory, ensuring compliance with international standards for testing and calibration. Concentrations of elements were calculated by correcting sample readings against procedural blanks and calibration curves derived from certified standards. Limits of detection (LOD) and quantification (LOQ) were determined based on instrument sensitivity for each element. These parameters are essential for evaluating analytical reliability, particularly when concentrations approach trace levels (Persson et al., 2012).

Statistical Analysis

Data analysis was conducted using established statistical and chemometric methods to evaluate variability and identify patterns in elemental composition. Descriptive statistics were first computed to summarise concentration levels across sample groups. Given the unbalanced nature of the dataset (unequal number of samples per city and country), a Type II ANOVA was applied to assess the effects of three independent variables: crop type, country of origin, and city of collection, on metal concentrations. Both one-way and multi-way ANOVA models

were used, with statistical significance evaluated at $p < 0.05$. This approach is consistent with standard methodologies for comparing group means in environmental and food chemistry studies (Tukey, 1949). To further investigate group differences, post-hoc comparisons were performed using Tukey's Honestly Significant Difference (HSD) test. This method controls for family-wise error rates and is appropriate for identifying pairwise differences following significant ANOVA results.

Multivariate statistical techniques were employed to analyse complex relationships among variables. Principal Component Analysis (PCA) was used to reduce data dimensionality and to visualise clustering patterns based on elemental composition. PCA is widely applied in food authentication and environmental chemistry for identifying latent structures within datasets (Danezis et al., 2017). Hierarchical Cluster Analysis (HCA), using Ward's linkage method and Euclidean distance, was conducted to group samples according to similarity in their chemical profiles to minimise within-cluster variance and is commonly used in geochemical fingerprinting studies (Kelly et al., 2005).

All statistical analyses were performed using Python-based scientific libraries, including Pandas, SciPy, Scikit-learn, and Statsmodels. The integration of these computational tools allows reproducible and robust analysis of complex datasets, supporting the application of chemometric approaches in food safety assessment.

Dietary Exposure and Risk Assessment

A screening-level dietary risk assessment was conducted to evaluate potential health risks associated with heavy metal exposure through cereal consumption. The Estimated Daily Intake (EDI) for each element was calculated based on mean concentration, daily intake rate, and body weight, following established frameworks (WHO & FAO, 2022; Järup, 2003). Non-carcinogenic risk was assessed using the Hazard Quotient (HQ), defined as the ratio of EDI to the reference dose (RfD). An HQ value below 1 indicates that exposure is unlikely to result in adverse health effects. The combined risk from multiple elements was evaluated using the Hazard Index (HI), calculated as the sum of individual HQ values. These metrics are widely used in environmental health risk assessment and provide a standardised approach for interpreting exposure data (Mansour, 2014; Tchounwou et al., 2012). The use of conservative assumptions, including a high consumption rate (0.3 kg/day) and average body weight (60 kg), ensures that the risk assessment reflects a worst-case exposure scenario. While this approach provides a useful screening tool, it does not account for variability in dietary patterns or cumulative exposure from multiple sources, which are recognised limitations in risk assessment studies (WHO & FAO, 2022).

RESULTS AND DISCUSSION

The measured concentrations of heavy metals in rice and wheat flour are summarised in Table 1. Across all samples, toxic elements (Pb, As, Cd, Hg) were consistently detected at very low levels, frequently approaching the limits of detection (LOD) and quantification (LOQ). Mean lead concentrations in both rice and wheat flour (0.002 mg/kg) are approximately two orders of magnitude lower than the maximum level of 0.2 mg/kg established by the Codex Alimentarius Commission and the European Union (Codex Alimentarius Commission, 2019; European Union, 2006). Similarly, cadmium and arsenic concentrations remain far below their respective limits (0.15–0.2 mg/kg), while mercury levels are negligible. The uniformity of these results across all sampling locations and origins (Table 2) indicates that imported cereals

available in Somali markets are sourced from production systems with low environmental contamination. This observation aligns with global monitoring studies showing that cereals entering regulated international trade typically comply with safety standards (Sarker et al., 2022; Singh et al., 2024). In contrast, studies conducted in contaminated agricultural regions, such as parts of South Asia, have reported substantially higher concentrations, particularly for cadmium and arsenic (Zeeshan et al., 2023; Meharg & Rahman, 2003). The absence of such elevated values in the present dataset - though with limited sample size due to financial and logistical constraints - may suggest that the sampled imports originate from relatively low-risk agro-ecological zones. However, the low absolute concentrations should not be interpreted as an absence of risk. Heavy metals are cumulative toxicants, and chronic exposure, even at low levels, may contribute to long-term health effects (Järup, 2003; Tchounwou et al., 2012). Therefore, compliance with regulatory limits reflects short-term safety but does not eliminate the need for continuous surveillance.

Table 1: Concentrations of heavy metals in imported rice (*Oryza sativa*, n = 23) and wheat flour (*Triticum aestivum*, n = 16) samples collected from Somali markets

Parameter	Lead (Pb)	Copper (Cu)	Arsenic (As)	Tin (Sn)	Cadmium (Cd)	Mercury (Hg)
Rice (Mean ± SD), mg/kg	0.002±0.001	1.18±0.28	0.001±0.001	0.001±0.001	0.001±0.001	0.001±0.001
Wheat Flour (Mean ± SD), mg/kg	0.002±0.002	2.6±0.13	0.003±0.002	0.005±0.007	0.003±0.002	0.003±0.002
LOD (ppb)	0.003	0.0003	0.002	0.0001	0.001	0.001
LOQ (ppb)	0.009	0.05	0.006	0.0003	0.003	0.002
EU Max Level (ML), mg/kg	0.2	NS	0.15	NS	0.15	ns
Codex Max Level (ML), mg/kg	0.2	NS	0.2	250 ^a	0.2	0.1

Table 1: Concentrations of heavy metals in imported rice (*Oryza sativa*, n = 23) and wheat flour (*Triticum aestivum*, n = 16) samples collected from Somali markets. Values are presented as mean ± standard deviation (mg/kg, fresh weight basis). Elemental analysis was performed using inductively coupled plasma–mass spectrometry (ICP-MS). Limits of detection (LOD) and limits of quantification (LOQ) are provided for each element. Maximum levels (ML) are based on European Union Regulation (EC) No. 1881/2006 and Codex Alimentarius (CXS 193-1995). “NS” indicates that no maximum level is specified for the given element–matrix combination. The Codex limit for tin applies to canned foods and is included for reference only.

The most prominent pattern in the dataset is the significant difference in copper concentrations between rice and wheat flour. As shown in Table 1, wheat flour exhibits a mean copper concentration of 2.6 ± 0.13 mg/kg, compared to 1.18 ± 0.28 mg/kg in rice. This difference is statistically confirmed by the multi-way ANOVA results (Table 2), where crop type shows a highly significant effect on copper ($F = 133.033$, $p < 0.001$); no significant effects were

observed for other metals. This pattern is further illustrated in Figure 1a and Figure 1b, where the distribution of copper concentrations clearly separates rice and wheat samples across both sample collection locations and country of origin comparisons. Wheat samples consistently occupy higher concentration ranges (approximately 2.39–2.82 mg/kg), whereas rice samples remain within a narrower and lower interval (0.86–2.23 mg/kg). The absence of overlap between these distributions reinforces the statistical significance observed in Table 2.

Table 2: Multi-way analysis of variance (ANOVA) evaluating the effects of crop type, country of origin, and city of collection on heavy metal concentrations.

Metal	Factor	F-value	p-value	Significance
Pb (Lead)	Product	0	0.998	ns
	City	0.9	0.454	ns
	Country	0.946	0.453	ns
Cu (Copper)	Product	133.033	< 0.001	***
	City	5.06	0.007	**
	Country	2.644	0.056	ns
As (Arsenic)	Product	0.785	0.384	ns
	City	0.2	0.896	ns
	Country	0.493	0.741	ns
Sn (Tin)	Product	0.035	0.854	ns
	City	0.182	0.908	ns
	Country	1.196	0.336	ns
Cd (Cadmium)	Product	0.406	0.53	ns
	City	0.602	0.62	ns
	Country	0.887	0.485	ns
Hg (Mercury)	Product	1.602	0.217	ns
	City	1.113	0.362	ns
	Country	0.967	0.442	ns

Table 2: Multi-way analysis of variance (ANOVA) evaluating the effects of crop type, country of origin, and city of collection on heavy metal concentrations. F-values and corresponding p-values are reported for each factor. Statistical significance was assessed at $\alpha = 0.05$. Significance levels are indicated as follows: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; ns, not significant. Analysis was conducted using Type II sums of squares.

The Tukey HSD post-hoc analysis (Table 3) confirms that this difference is robust, with a mean difference of +1.424 mg/kg ($p < 0.001$). This finding is consistent with established plant physiological models, where wheat accumulates higher levels of micronutrients in the aleurone layer and embryo (Shewry & Hey, 2015), while polished rice loses mineral-rich outer layers during milling (Clemens & Ma, 2016). The visual separation observed in Figure 1 therefore reflects intrinsic biological differences rather than environmental contamination. The lack of significant variation for toxic elements across crop types (Table 2) further supports this interpretation. If environmental contamination were a dominant factor, similar differences

would be expected across multiple elements. Instead, the specificity of copper variation indicates a physiological origin.

Table 3: Post-hoc comparison of copper concentrations between cereal types using Tukey’s Honestly Significant Difference (HSD) test.

Group 1	Group 2	Mean Difference	p-adj	95% Confidence Interval	Result
Rice	Wheat Flour	+1.424 mg/kg	<0.001	[1.270,1.580]	Significant

Table 3: Post-hoc comparison of copper concentrations between cereal types using Tukey’s Honestly Significant Difference (HSD) test. Mean differences (mg/kg), adjusted p-values, and 95% confidence intervals are reported. Statistical significance is evaluated at $\alpha = 0.05$.

The influence of geographic origin seems less pronounced though it becomes evident when combining ANOVA results (Table 2), post-hoc comparisons (Table 4), and visual patterns in Figure 1b. In contrast to ANOVA indicating that country effects are not statistically significant for most elements ($p > 0.05$), Tukey HSD analysis identifies several significant pairwise differences for copper between exporting countries. For instance, Table 4 shows significant differences between India and Turkiye (+1.325 mg/kg, $p < 0.001$) and between Pakistan and Turkiye (+1.116 mg/kg, $p < 0.001$).

Table 4: Post-hoc comparison of copper concentrations among countries of origin using Tukey’s Honestly Significant Difference (HSD) test.

Group 1	Group 2	Mean Difference	p-adj	Result
India	Oman	+1.550	<0.001	Significant
India	Turkiye	+1.325	<0.001	Significant
Pakistan	Turkiye	+1.116	<0.001	Significant
Egypt	Turkiye	+0.862	0.035	Significant
Egypt	Oman	+1.087	0.021	Significant

Table 4: Post-hoc comparison of copper concentrations among countries of origin using Tukey’s Honestly Significant Difference (HSD) test. Mean differences (mg/kg) and adjusted p-values are reported for pairwise comparisons. Statistical significance is evaluated at $\alpha = 0.05$.

However, these differences largely mirror the separation between rice-exporting countries (India, Pakistan) and wheat-exporting ones (Turkiye, Oman). This indicates that the apparent “country effect” is largely a proxy for crop type instead of a direct consequence of geographic contamination. Nevertheless, Figure 1b reveals subtle intra-group variability, particularly among rice samples from South Asia, which display a wider spread of copper values compared to wheat. This variability is consistent with literature studied heterogeneous agro-ecological conditions in South Asian rice production, including variations in irrigation water quality and soil geochemistry (Meharg and Zhao, 2012; Norton et al., 2009). In contrast, wheat samples from Turkiye exhibit tighter clustering, suggesting more standardised production and processing systems, as also reported in regional studies (Badawy et al., 2020).

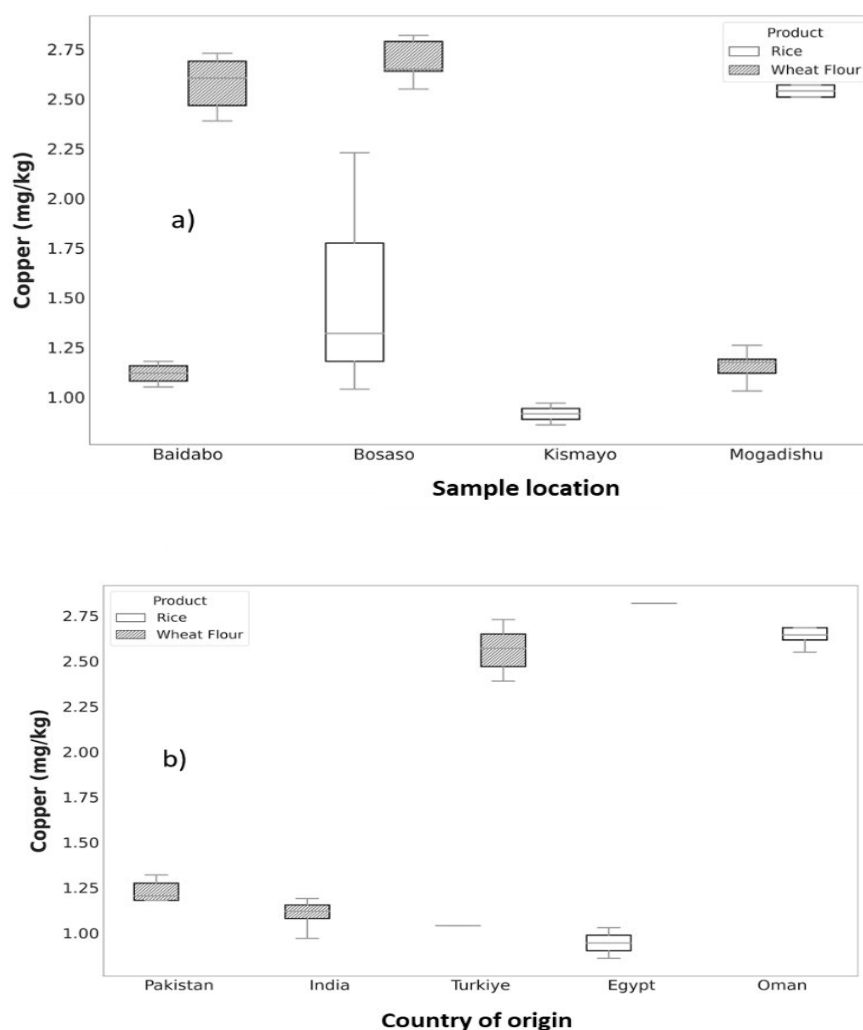


Figure 1: Distribution of copper concentrations (mg/kg) in rice and wheat flour samples by (a) sample location and (b) country of origin.

Boxplots represent median (central line), interquartile range (IQR; box), and $1.5 \times \text{IQR}$ (whiskers). Individual data points are overlaid to illustrate sample distribution. Rice samples ($n = 23$) and wheat flour samples ($n = 16$) are distinguished by fill pattern. Differences between cereal types are statistically significant ($p < 0.05$).

The multivariate relationships among samples are illustrated in Figure 2 (PCA biplot) and Figure 3 (HCA dendrogram). The PCA results show that the first two principal components explain approximately 73.8% of the total variance, indicating that the dataset can be effectively represented in two dimensions.

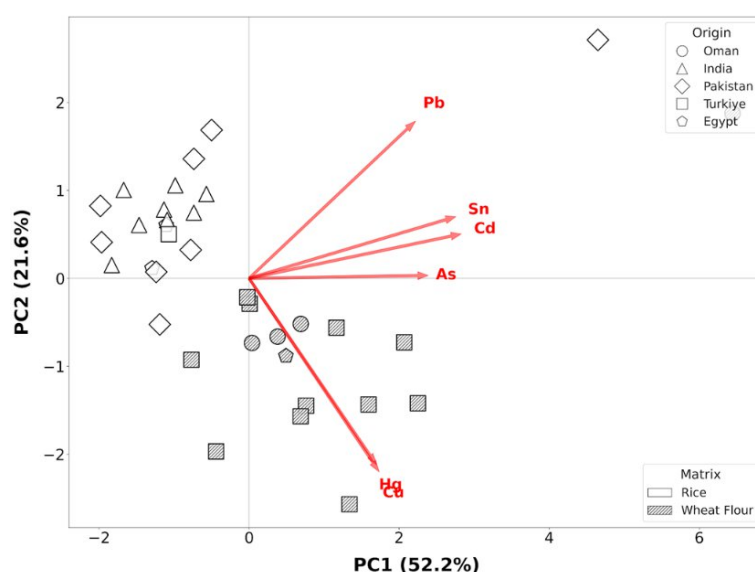


Figure 2: Principal component analysis (PCA) biplot of heavy metal concentrations in rice and wheat flour samples.

Scores represent individual samples, coloured by country of origin and differentiated by cereal type. Loadings (vectors) indicate the contribution of each element to the principal components. The first two principal components (PC1 and PC2) explain 73.8% of the total variance.

In Figure 2, a clear separation between rice and wheat samples is observed along PC1. This separation corresponds to the strong loading of copper, confirming its role as the primary discriminating variable. Toxic elements such as arsenic and mercury are located near the origin, indicating limited contribution to variance. This pattern supports the univariate findings in Table 2 and demonstrates that toxic metals do not drive differentiation within the dataset. Geographic sub-clustering is observed along PC2, where wheat samples from Egypt and Turkiye exhibit slight separation. This is consistent with literature linking trace element variability to soil characteristics and agricultural practices (Alloway, 2013). However, the relatively small magnitude of this separation indicates that geographic effects are secondary to crop-type effects. The HCA dendrogram (Figure 3) reinforces these findings by grouping samples into three clusters: a distinct wheat cluster and two rice sub-clusters. The short branch lengths within the wheat cluster indicate high homogeneity, particularly among Turkish samples, while the longer branches within rice clusters reflect greater variability. This structure supports the concept of elemental fingerprinting, where chemical signatures reflect both plant physiology and environmental conditions (Kelly et al., 2005; Danezis et al., 2017).

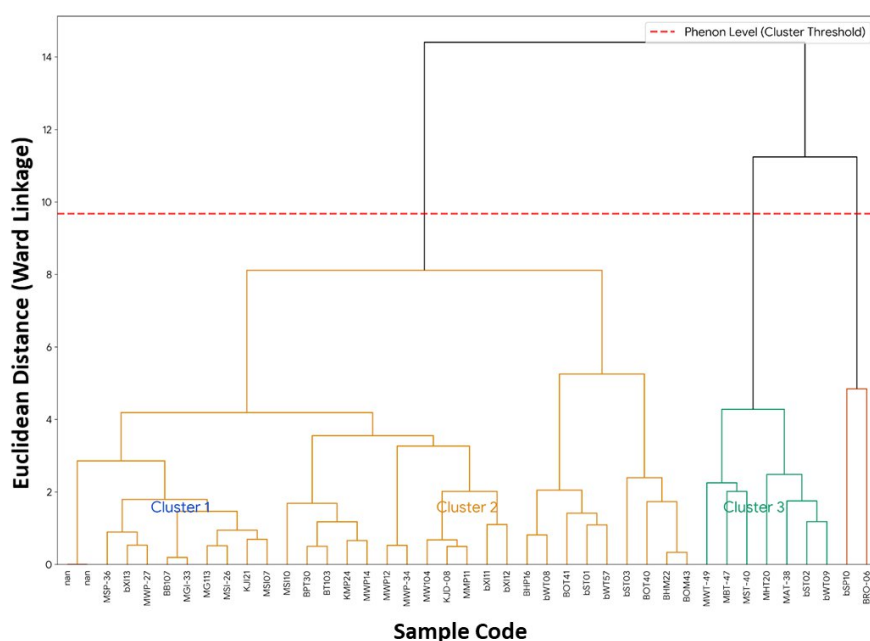


Figure 3: Hierarchical cluster analysis (HCA) dendrogram of cereal samples based on standardised heavy metal concentrations.

Clustering was performed using Euclidean distance and Ward's linkage method. The dendrogram illustrates similarity relationships among samples, with shorter branch lengths indicating higher similarity. The horizontal threshold line denotes the level at which clusters were defined. Sample labels correspond to collection locations: Boosaaso (B), Mogadishu (M), Kismaayo (K), and Baidabo (b).

The correlation matrix (Figure 4) provides insight into relationships between elements. Strong positive correlations are observed between Pb–Sn ($r = 0.70$) and Pb–Cd ($r = 0.67$), suggesting shared environmental or geochemical sources. Such co-occurrence is commonly reported in soils influenced by similar parent materials or agricultural inputs (Alloway, 2013; McLaughlin et al., 1999). In contrast, copper shows weak correlation with toxic metals (e.g., Pb–Cu: $r = 0.17$), indicating that it behaves independently as an essential nutrient. This distinction aligns with plant physiological theory, where essential elements are actively regulated, whereas non-essential metals are passively accumulated (Clemens, 2001; Zhao et al., 2009).

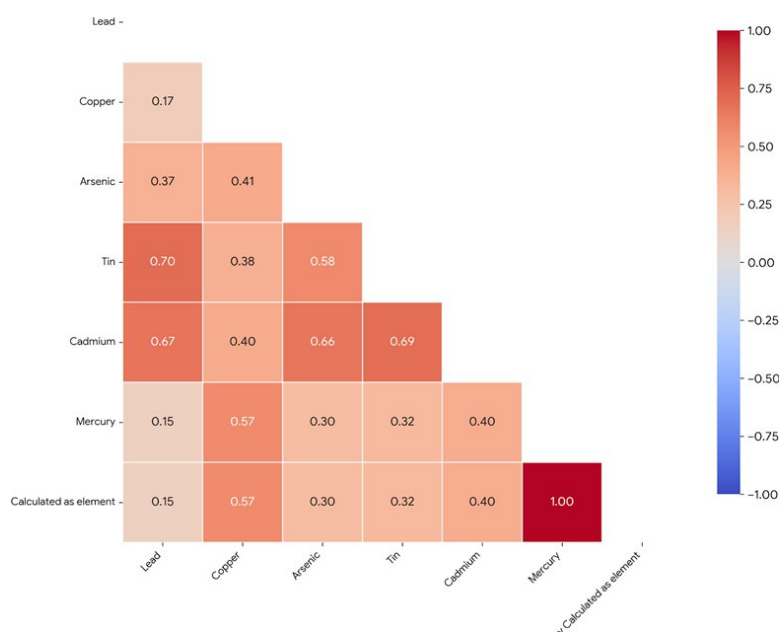


Figure 4: Pearson correlation matrix of heavy metal concentrations in cereal samples. Correlation coefficients (r) are displayed for all element pairs.

Positive correlations are indicated by increasing intensity, with values ranging from -1 to $+1$. Strong positive associations suggest potential co-occurrence or shared geochemical sources, whereas weak correlations indicate independent behaviour.

Dietary Exposure and Risk Assessment

The health risk assessment was conducted using the Estimated Daily Intake (EDI), Hazard Quotient (HQ), and Hazard Index (HI) frameworks. Using the formula:

$$EDI = (C \times IR) / BW$$

where C is concentration (mg/kg), $IR = 0.3$ kg/day, and $BW = 60$ kg adapted from Wielogorska et al., (2019).

For arsenic (highest mean value in wheat flour, Table 1: 0.003 mg/kg):

$$EDI_{As} = (0.003 \times 0.3) / 60$$

$$EDI_{As} = 0.0009 / 60$$

$$EDI_{As} = 1.5 \times 10^{-5} \text{ mg/kg body weight/day}$$

Using the reference dose (RfD) for arsenic (0.0003 mg/kg/day) (WHO & FAO, 2022):

$$HQ_{As} = EDI / RfD$$

$$HQ_{As} = (1.5 \times 10^{-5}) / (3 \times 10^{-4})$$

$$HQ_{As} \approx 0.05$$

Similarly, for lead (mean concentration 0.002 mg/kg):

$$EDI_{Pb} = (0.002 \times 0.3) / 60 = 1.0 \times 10^{-5} \text{ mg/kg/day}$$

$$RfD_{Pb} = 0.0035 \text{ mg/kg/day}$$

$$HQ_{Pb} \approx 0.0029$$

For cadmium (0.003 mg/kg in wheat):

$$EDI_{Cd} = (0.003 \times 0.3) / 60 = 1.5 \times 10^{-5}$$

$$RfD_{Cd} = 0.001$$

$$HQ_{Cd} \approx 0.015$$

All HQ values are significantly below 1, indicating negligible non-carcinogenic risk. The cumulative Hazard Index:

$$HI = \sum HQ_i$$

$$HI = HQ_{As} + HQ_{Pb} + HQ_{Cd} + HQ_{Hg}$$

remains well below unity, confirming that combined exposure does not pose a health concern under the assumed consumption scenario.

These results are consistent with international assessments showing that cereal-based exposure to heavy metals is generally within safe limits when concentrations are low (WHO & FAO, 2022; Mansour, 2014). However, it must be noted that this assessment is conservative and does not account for cumulative exposure from other dietary sources or arsenic speciation, which can significantly influence toxicity (EFSA CONTAM Panel, 2024).

By linking the quantitative results (Table 1), statistical analyses (Tables 2–4), and multivariate visualisations (Figures 1–4), a consistent pattern emerges. The dataset is characterised by low toxic metal concentrations, strong crop-type differentiation driven by copper, and secondary geographic influences reflected in multivariate clustering. This integrated interpretation confirms that the Somali cereal supply is currently safe with respect to heavy metal contamination, while also demonstrating that elemental composition is primarily determined by biological and environmental factors at the point of origin. The agreement between univariate statistics, multivariate analysis, and visual representations strengthens the robustness of these conclusions and aligns closely with established findings in the literature.

CONCLUSION

This study provides an analytical assessment of heavy metal contamination, elemental variability, and associated health risks in imported rice (*Oryza sativa*) and wheat flour (*Triticum aestivum*) available in Somali markets. The results demonstrate that concentrations of toxic elements, including lead (Pb), arsenic (As), cadmium (Cd), and mercury (Hg), are consistently low and well below maximum limits established by international regulatory frameworks. These findings are supported by dietary exposure estimates, where calculated Hazard Quotients (HQ) and the cumulative Hazard Index (HI) remain below threshold levels, evidencing that current consumption of these cereals is unlikely to pose significant non-

carcinogenic health risks. A key outcome of the study is the identification of crop type as the dominant factor influencing elemental composition. The significantly higher copper concentrations observed in wheat relative to rice are consistent with established physiological differences in micronutrient uptake and storage between cereal species. This finding reinforces the importance of distinguishing between biologically inherent mineral content and environmentally derived contamination when interpreting food safety data. Conversely, toxic elements exhibited minimal variability across both crop types and geographic origins, which may suggest that the cereals analysed originate from production environments with low levels of anthropogenic contamination. This pattern aligns with global observations that regulated agricultural systems and international trade standards contribute to the overall safety of commercially distributed staple foods.

As demonstrated by multivariate analyses, the variation of elemental composition of cereals is associated with crop type and, to a lesser extent, geographic origin. The clear separation between rice and wheat in principal component space, together with clustering patterns observed in hierarchical analysis, supports the application of elemental fingerprinting for food traceability. The greater variability observed in South Asian rice compared to the relative homogeneity of wheat from Türkiye and other regions is consistent with differences in agro-ecological conditions, irrigation practices, and soil geochemistry reported in the literature. These results underscore that the chemical identity of imported cereals is largely established at the point of production and remains stable throughout the supply chain. Despite the absence of immediate health risks, several considerations limit the interpretation of the findings. Heavy metals are cumulative and persistent, and long-term exposure, even at low concentrations, may contribute to chronic health effects. In addition, the risk assessment is based on total metal concentrations and does not account for chemical speciation, particularly for arsenic, where toxicity depends on the proportion of inorganic forms. The analysis also considers a single dietary pathway and does not incorporate cumulative exposure from other food sources, water, or environmental media.

From a policy and regulatory perspective, the findings highlight a structural characteristic of food safety in import-dependent systems where the quality and safety of staple foods are determined primarily by external production environments rather than domestic handling conditions. This has direct implications for food safety governance in Somalia and similar contexts. Conventional approaches based on end-product testing within domestic markets are insufficient on their own and should be complemented by origin-based risk assessment strategies. Such approaches include targeted monitoring of high-variability import sources, routine surveillance at ports of entry, and the integration of chemometric tools for source identification and verification. These strategies are consistent with emerging frameworks in global food safety that emphasise traceability, risk-based monitoring, and international cooperation. In short, the study confirms that imported cereals in Somali markets are currently compliant with international safety standards for heavy metal contamination and do not pose an immediate public health risk. At the same time, it demonstrates that elemental composition is governed by a combination of plant physiology and environmental conditions in exporting regions, which can be effectively characterised using multivariate analytical approaches. The findings support a shift toward proactive, origin-informed food safety systems that prioritise continuous monitoring and supply chain transparency in order to manage long-term risks associated with cumulative exposure.

Use of AI Declaration

During the preparation of this manuscript, ChatGPT (GPT-5.5, OpenAI) was utilised solely for language editing, grammar correction and improvement for readability. The author reviewed and verified all content and takes full responsibility for the final version of the manuscript.

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