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Essential and Toxic Element Profiles in Selected Spices from Greater Casablanca, Morocco

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ABSTRACT

In Morocco, spices are an integral part of daily cuisine and serve as a vector of both nutritional and toxicological exposure. Monitoring elemental composition is essential to ensure consumer safety, animal health when used as feed additives, and compliance with international standards. The present study aimed to determine the concentrations of essential (potassium, calcium, magnesium, sodium, and iron) and toxic (lead, cadmium, arsenic, chromium, and nickel) elements in commonly consumed spices in Morocco, including cinnamon, cumin, ginger, black pepper, and turmeric. A total of 162 spice samples were obtained from markets in the Greater Casablanca, Morocco. Five essential elements, including potassium, calcium, magnesium, sodium, and iron, and five toxic trace metals, including lead, cadmium, arsenic, chromium, and nickel, were determined by inductively coupled plasma mass spectrometry (ICP-MS) after microwave-assisted digestion. Cumin indicated the highest levels of magnesium (6.86 ± 1.61 g/kg), sodium (3.98 ± 1.59 g/kg), calcium (11.13 ± 4.53 g/kg), and iron (753.71 ± 446.07 mg/kg). Turmeric had the highest levels of potassium (25.96 ± 13.51 g/kg). Cinnamon had elevated levels of lead (2.05 mg/kg) and cadmium (0.29 mg/kg), exceeding Moroccan and European regulatory limits. Additionally, cumin indicated the highest levels of arsenic (0.45 ± 0.30 mg/kg) and nickel (4.18 ± 2.85 mg/kg) compared to other spices. Principal component analysis (PCA) revealed distinct elemental patterns. The first component (PC1), driven by magnesium and sodium, clearly separated cumin due to its high macronutrient content. The second component (PC2), influenced by cadmium and lead, isolated cinnamon because of its toxic metal burden. The PC1 and PC2 accounted for 64.6% of the total variance. Turmeric and ginger formed a close cluster in the PCA plot, associated with higher levels of potassium, calcium, and nickel. Black pepper was positioned between these groups, reflecting intermediate composition. Pearson correlation analysis supported these findings, with a strong correlation between lead and cadmium, suggesting a shared contamination source. These results emphasized the nutritional and toxicological roles of spices in Moroccan diets. Regular monitoring is essential to protect public health in both animals and humans.

Keywords: Food safety, Inductively coupled plasma mass spectrometry, Spices, Toxic metal

INTRODUCTION

In many cultures, spices represent indispensable components of daily cooking, recognized for their sensory attributes as well as for their nutritional value and therapeutic potential (Peter, 2006; Embuscado, 2019). Spices provide bioactive compounds, dietary fiber, and micronutrients, particularly potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), and iron (Fe), which play key roles in different physiological functions (Otunola et al., 2010). Cumin (*Cuminum cyminum* L.) is recognized for its richness in Fe and Mg (Bouhenni et al., 2019), while turmeric (*Curcuma longa* L.) is an essential source of K and antioxidant polyphenols (Saeed et al., 2021). Likewise, cinnamon provides high levels of Ca, Mg, and Fe (Gul and Safdar, 2009), ginger is rich in Ca and trace minerals such as Fe, copper (Cu), zinc (Zn), and manganese (Mn; Ayoade et al., 2023), and black pepper contains notable amounts of Ca, K, and essential trace elements (Ayoade et al., 2023).

Additionally, spices may be a potential dietary source of toxic metals such as lead (Pb), cadmium (Cd), arsenic (As), chromium (Cr), and nickel (Ni), which can adversely affect human health as shown by widespread contamination of spices with Pb, Cd, and As (Huff et al., 2025), and animal health even at minimal concentrations (Rahman and Singh, 2019). In animals, these elements can disrupt oxidative balance and damage key organs such as the liver, kidneys, and

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brain (Destro et al., 2025). Their presence in spices may result from soil contamination, the use of polluted irrigation water, atmospheric deposition, or inappropriate processing such as drying, grinding, or storage under unhygienic conditions (Osei-Safo et al., 2024). Several international surveys have demonstrated that spices marketed in both local and global markets may exceed the maximum limits of toxic trace metals set by national and international regulations. Moussa et al. (2024) reported that 50% of analyzed cinnamon samples from the Lebanese market exceeded the international safety limit for Pb, which was set at 0.3 mg/kg by Codex Alimentarius. In Pakistan, Olusola et al. (2025) documented elevated As concentrations in cumin, whereas in South Africa, Ezez et al. (2024) reported the occurrence of Cd in several spice varieties. These findings highlighted the need for strict monitoring of toxic trace metal concentrations in spices, particularly in developing countries where regulations may be less rigorously enforced (Akhtar et al., 2020).

Although spices are primarily associated with human nutrition, they are increasingly used in the formulation of natural additives and flavor enhancers in animal feed due to their antioxidant, antimicrobial, and growth-promoting properties (Windisch et al., 2008; Hashemi and Davoodi, 2011). However, their potential contamination with toxic trace elements raises concerns not only for human consumers but also for animal health and food safety within the livestock production chain (Jaishankar et al., 2014). Monitoring the elemental composition of spices is therefore essential to evaluate their safety and suitability for use in animal feed.

In Morocco, although a few studies have investigated the nutritional composition and metal contamination of certain spices (Bouzaid et al., 2024; Najem et al., 2024), data remain limited and do not cover all commonly consumed varieties. The Greater Casablanca region, the country's main urban and commercial center, constitutes a strategic market where spices from diverse geographic origins converge, potentially increasing the variability of elemental profiles and contamination levels (Boularbah et al., 2006). The present study aimed to determine the concentrations of essential (K, Ca, Mg, Na, Fe) and toxic (Pb, Cd, As, Cr, Ni) elements in five widely consumed spices in Morocco, including cinnamon, cumin, ginger, black pepper, and turmeric using inductively coupled plasma mass spectrometry (ICP-MS), and to assess potential risks to human and animal health through multivariate analysis and comparison with established limitations and existing data.

MATERIALS AND METHODS

Ethical approval

The present study was conducted *in vitro* according to the guidelines of the Faculty of Sciences, Ain Chock, Hassan II Casablanca University, Casablanca, Morocco.

Materials

Sample preparation was carried out in triplicate using a microwave digestion system (Milestone, Bergamo, Italy) equipped with temperature and pressure sensors. The system employed polytetrafluoroethylene (PTFE) vessels designed to withstand pressures up to 110 bar. An ICP-MS (Agilent Technologies, Santa Clara, CA, USA) was used for the spices analysis. The instrument was equipped with a standard Fassel-type plasma torch, featuring a 2.5 mm internal diameter. The ICP-MS operating conditions were specified with a forward power of 1.5 kW, a plasma gas flow of 15 L/min, an auxiliary gas flow of 0.8 L/min, a nebulizer gas flow of 1.06 L/min, and a spray chamber temperature maintained at 2°C. The ICP-MS was equipped with an off-axis ion lens, a quadrupole mass filter, and an electron multiplier detector, and it was further complemented by an ASX-520 autosampler (Cetac Technologies Inc., Omaha, NE, USA) and an integrated sample introduction system. High-purity argon (99.9998%) supplied by OXAIR (Morocco) was used. Before each experiment, the instrument was tuned for daily performance using 10 mL of the Elan 6100 DRC sensitivity detection limit solution (Perkin-Elmer Pure, USA).

Reagents

Concentrated analytical reagent grade nitric acid (HNO_3) 70% and hydrogen peroxide (H_2O_2) 30-32% were obtained from Merck (Darmstadt, Germany). Ultrapure deionized water with a resistivity of 18.2 MΩ·cm was obtained from a Milli-Q Plus water purification system (Millipore, Bedford, MA, USA). Stock standard solutions of Cr, Ni, As, Cd, and Pb (10 µg/mL in 2% HNO_3) and standard solutions of K, Ca, Na, Mg, and Fe (10,000 µg/mL in 5% HNO_3) were obtained from Agilent, Santa Clara, USA. Spinach leaves were used as a certified reference material because they were of plant origin, similar to spices. Standard reference material spinach leaves (SRM 1570a) was obtained from the National Institute of Standards and Technology, Gaithersburg, USA. Plastic and glass containers were soaked in 10% v/v HNO_3 for at least 24 hours and then thoroughly rinsed with Milli-Q water before use. All containers, polypropylene vials, pipette tips, and reagents that came into contact with samples or standard solutions were checked for potential contamination by analyzing reagent blanks under the same conditions.

Sample collection

A total of 137 bulk spice samples available on the market were collected from local markets across the greater Casablanca region, Morocco (Table 1). The samples were purchased at different times from February to June 2025. The spice samples were stored in clean, sealed containers at room temperature until further analysis, using the same analytical procedures and ICP-MS settings as for the samples.

Table 1. Distribution of spice samples sourced from greater Casablanca, Morocco, by type

Type of spice	Family	Part studied	Number of samples	Percentage (%)
Cumin	Apiaceae	Fruits	25	15.4
Cinnamon	Lauraceae	Bark	37	22.8
Turmeric	Zingiberaceae	Roots	25	15.4
Black pepper	Piperaceae	Fruits	25	15.4
Ginger	Zingiberaceae	Roots	25	15.4

Sample preparation and digestion

Exactly 1 g of each spice sample was weighed into a PTFE digestion vessel, followed by the addition of 5 mL of concentrated HNO_3 70% and 2 mL of H_2O_2 30-32%. The mixture was then digested using a microwave system, following a modified AOAC protocol (AOAC International, 2013). Microwave digestion started at 80°C for five minutes, followed by sequential heating to 120°C and 150°C, each for five minutes, then maintained at 180°C for 20 minutes before cooling to 40°C. Once cooled, the digests were brought to a final volume of 50 mL with ultrapure water, carefully labeled, and subsequently subjected to analysis. Control blanks were prepared in parallel using the identical procedure.

Quality assurance

For determining minor and trace elements in spices, the analytical assessment was validated by examining essential method performance parameters, including sensitivity, linearity, precision, accuracy, and recovery. The calibration process involved constructing curves based on the distinct concentrations of the standard solutions, including Na (0.5 mg/L), Mg (2.5 mg/L), K (5 mg/L), and Ca (50 mg/L), Fe (2, 10, 20, 100, and 200 µg/L), Cr (0.2 µg/L), Ni (1 µg/L), As (2 µg/L), Cd (10 µg/L), and Pb (20 µg/L). In addition, blanks were analyzed for each target element to verify linearity, and correlation coefficients (R^2) were subsequently calculated in accordance with the NF T90-210 standard (AFNOR, 2018).

Instrumental sensitivity was assessed by determining the detection limits for each of the analyzed elements, including Na, Mg, K, Ca, Fe, Cr, Ni, As, Cd, and Pb. The limits of detection (LOD) and limits of quantification (LOQ) were derived by dividing three and ten times the standard deviation of the blank, respectively, by the slope of the calibration curve. The calibration curves were designed to ensure that the concentrations of all analyte elements in the samples remained within the linear range and above the lower limit of linearity established for the method (Voica et al., 2021).

Method precision was verified through the analysis of an appropriate standard reference material (IAEA-407, International Atomic Energy Agency, Environment Laboratories, Monaco) to determine Na, Mg, K, Ca, Aluminium (Al), Mn, Fe, Cu, Zn, Cr, cobalt (Co), Ni, As, selenium (Se), Cd, and Pb. Precision was assessed by comparing the experimentally obtained concentrations of the elements with their certified reference values, and the results were expressed as percentage recovery. To ensure analytical quality control, spiking recovery tests were conducted following the general approach described by Mihaylova et al. (2013).

Statistical analysis

All statistical analyses were performed using R software (version 4.3.2, Posit Team, 2023). The raw multielement concentration data were first examined to detect potential outliers and missing values. The suitability of a factor analysis was initially assessed using the Kaiser-Meyer-Olkin (KMO) index (Kaiser, 1974) to measure sampling adequacy for studying inter-variable correlations. In parallel, Bartlett's test of sphericity (Bartlett, 1950) was applied to verify that the correlation matrix differed significantly from an identity matrix. A principal component analysis (PCA; Jolliffe and Cadima, 2016) was then conducted to reduce dimensionality and visually represent the variance gradients in the dataset. The first two principal components (PC1 and PC2) were used for graphical projection, enabling the potential clustering of samples based on their elemental profiles. To explore bivariate relationships between elements, Pearson correlation coefficients (r) were calculated (Pearson, 1895). Results were synthesized in a correlogram presented as a heatmap

(Friendly, 2002). Finally, a hierarchical cluster analysis (HCA) was performed using Ward's linkage method and Euclidean distance (Ward, 1963) to group samples or elements with similar concentration patterns. Statistical significance was considered at a p-value less than 5% ($p < 0.05$) for Bartlett's test and Pearson correlation coefficients.

RESULTS AND DISCUSSION

Validation of the analytical method

The ICP-MS method demonstrated strong performance in terms of reliability and robustness for the quantification of the target elements (Table 2). Linearity was excellent across all calibration curves, with correlation coefficients ranging from 0.9989 (Ca) to 0.9999 (Mg and Ni), significantly surpassing the standard acceptance limit of 0.995 for elemental quantification. The LOQ obtained was appropriate for trace and macro-elements. For trace elements (Cd, Pb, As, Cr, Ni, Fe), the LOQs were very low, ranging from 0.0030 µg/L (Cd) to 0.198 µg/L (Ni), thus enabling reliable detection at trace levels. In contrast, for macro-elements (K, Ca, Mg, Na), the LOQs were higher, ranging from 0.318 µg/L (Na) to 57.2 µg/L (K), which remains consistent with their naturally higher concentrations in food matrices (ICH, 2005).

The method demonstrated satisfactory precision, with relative standard deviations (RSD) ranging from 1.7% to 3.1%, well below the 5% acceptability criterion generally recommended for ICP-MS. Accuracy, evaluated through recovery rates, varied from 91.43% (K) to 105.12% (Pb), in compliance with international recommendations (80-120%). These results confirmed that the method of Food products-Determination of trace elements-Determination of arsenic, cadmium, mercury and lead by ICP-MS after pressure digestion (IMANOR, 2012) allowed reliable and reproducible quantification of both macro and trace elements, while maintaining a level of sensitivity appropriate for each element category.

Table 2. Linearity and precision of the analyzed elements, and validation through a standard reference material

Elements	R^2	LOQ (µg/L)	RSD	Recovery (%)
K	0.9992	57.2	1.7	91.43
Ca	0.9989	21.4	2.0	100.20
Mg	0.9999	0.350	1.8	98.65
Na	0.9996	0.318	1.8	91.49
Fe	0.9993	0.0793	2.5	99.25
Pb	0.9997	0.0250	3.1	105.12
Cd	0.9996	0.0030	2.5	102.22
As	0.9998	0.0078	2.2	92.65
Cr	0.9996	0.0522	2.0	97.74
Ni	0.9999	0.1980	2.9	99.24

R^2: Correlation coefficient, LOQ (µg/L): Limit of quantification, RSD: Relative standard deviation. Standard reference material: IAEA-407 established by the International Atomic Energy Agency, Environment Laboratories, Monaco.

Presence of multiple elements in spices

Toxic elements

The analysis of spice samples from the Greater Casablanca, Morocco, revealed measurable levels of five toxic elements, including Pb, Cd, As, Cr, and Ni across all spice types (Table 3). These concentrations were highly variable and, in many instances, exceeded international food safety thresholds. Lead was detected in all samples, with cinnamon exhibiting the highest concentration (2.05 ± 0.23 mg/kg), followed by black pepper (0.60 ± 0.24 mg/kg), cumin (0.3 ± 0.15 mg/kg), ginger (0.15 ± 0.09 mg/kg), and turmeric (0.14 ± 0.09 mg/kg). Under European regulation 2021/1317, the allowable limits for Pb depend on the spice category, comprising 2.00 mg/kg in bark-derived spices, 1.50 mg/kg in roots and rhizomes, 0.90 mg/kg in seeds, and 0.60 mg/kg in fruit spices. In the present results, the Pb concentration measured in cinnamon (2.05 ± 0.23 mg/kg), a bark-derived spice, exceeded the maximum level established by the European Union (EU). For black pepper (0.60 ± 0.24 mg/kg) and cumin (0.3 ± 0.15 mg/kg), classified as fruit and seed spices, respectively, the concentrations were within EU thresholds (0.60 mg/kg for fruit and 0.90 mg/kg for seed spices). Ginger (0.15 ± 0.09 mg/kg) and turmeric (0.14 ± 0.09 mg/kg), both considered root and rhizome spices, were well below the EU limit of 1.50 mg/kg.

Lead contamination in animal feed ingredients, including plant-based additives such as spices, is recognized as a major toxicological concern for domestic animals, including cattle, poultry, and pets (Aronson, 1971). Chronic Pb ingestion in livestock results in bioaccumulation in the liver, kidneys, and bones, leading to growth impairment, reproductive disorders, and neurological effects (Aronson, 1971). Analyses of feed materials have reported Pb concentrations as high as 3,600 mg/Kg, suggesting that even minor contamination from plant-derived additives can substantially increase total Pb intake in animals (Fox and Boylen, 1978). Prolonged exposure has been associated with hematological and enzymatic dysfunctions, oxidative stress, and reproductive abnormalities in ruminants and poultry (Tesink, 1994).

Table 3. Minimum, maximum, mean, and standard deviation concentrations of trace elements in different spices

Element		Cr (mg/kg)	Ni (mg/kg)	Pb (mg/kg)	Cd (mg/kg)	As (mg/kg)
Cinnamon	Range	0.178-1.86	0.171-2.437	1.228-2.4	0.157-0.394	0.024-0.176
	Mean ± SD	0.96 ± 0.52	1.34 ± 0.73	2.05 ± 0.23	0.29 ± 0.07	0.09 ± 0.04
Cumin	Range	0.912-4.98	0.469-8.979	0.048-0.56	0.027-0.1	0.026-0.986
	Mean ± SD	2.64 ± 1.14	4.18 ± 2.85	0.30 ± 0.15	0.06 ± 0.02	0.45 ± 0.30
Ginger	Range	0.428-2.78	0.105-1.379	0.013-0.285	0.014-0.089	0.019-0.098
	Mean ± SD	1.79 ± 0.77	0.76 ± 0.39	0.15 ± 0.09	0.04 ± 0.02	0.06 ± 0.02
Black pepper	Range	0.899-6.583	0.648-0.952	0.818-0.96	0.006-0.049	0.401-0.493
	Mean ± SD	3.62 ± 2.13	0.45 ± 0.26	0.60 ± 0.24	0.03 ± 0.01	0.27 ± 0.14
Turmeric	Range	0.279-1.618	0.117-1.281	0.017-0.299	0.004-0.038	0.004-0.07
	Mean ± SD	0.81 ± 0.36	0.70 ± 0.37	0.14 ± 0.09	0.02 ± 0.01	0.04 ± 0.02

Cr: Chromium, Ni: Nickel, Pb: Lead, Cd: Cadmium, As: Arsenic, SD: Standard Deviation

The Pb level in cinnamon (2.05 mg/kg) approached or slightly exceeded the EU maximum permissible limit for bark spices (2.00 mg/kg; EU Commission, 2023) but remains within the Codex Alimentarius proposed limit (2.50 mg/kg). The Pb value in cinnamon was comparable to levels reported in Ecuador, where cinnamon samples averaged 0.36-0.80 mg/kg, with some exceeding the EU threshold (Yánez-Jácome et al., 2024), and to those detected in India, where Pb contamination has been documented in cinnamon and other common spices. Experimental studies using a catfish (*Clarias gariepinus*) model further highlighted that cinnamon exposed to Pb can accumulate the metal, with measurable toxicological consequences (Yousaf et al., 2025). In a Lebanese market survey, cinnamon exhibited the greatest mean Pb level (0.972 ± 0.893 mg/kg), remaining within the EU permissible range (Moussa et al., 2024). In the United States, a recent outbreak linked to cinnamon-containing applesauce resulted in widespread pediatric Pb poisoning, demonstrating that contaminated cinnamon can represent a significant public health risk (Troeschel, 2025).

In black pepper, the Pb content was 0.60 ± 0.24 mg/kg, matching exactly the EU regulatory limit for fruit spices. Beyond its contamination risk, black pepper has also been shown to improve growth performance, feed efficiency, blood parameters, and gut morphology in broiler chickens (El-Gogary et al., 2024). The Pb value in black pepper was consistent with concentrations reported in Libya, where black pepper and other spices contained Pb close to 0.60 mg/kg (Ziyaina et al., 2014). The Pb value in black pepper in the present study was comparable to Algeria, where remarkable mycological contamination and aflatoxin B_1 levels in common spices have been documented, although not specifically in black pepper (Azzoune et al., 2015). Similar ranges were reported in Europe, where Pb in black pepper was measured between 0.10 and 0.79 mg/kg (Blagojević et al., 2016), underscoring regional variability.

The Pb level in cumin (0.30 ± 0.15 mg/kg) falls well within the EU maximum (0.90 mg/kg for seed spices). Comparable results were found in Egypt, where cumin and other spices were reported to contain measurable concentrations of heavy metals such as Pb, Cd, and Cr (Abou-Arab and Abou Donia, 2000). In Iran, fungal contamination and related mycotoxins were detected in cumin samples, raising concerns about potential co-occurrence with heavy metals (Al-Harthi, 2024). The present findings highlighted how Pb levels in cumin and black pepper vary geographically, reflecting differences in soil composition, agricultural practices, and post-harvest handling.

Ginger in the present study exhibited a Pb concentration of 0.15 ± 0.09 mg/kg, well below the EU limit of 1.50 mg/kg for root and rhizome spices. Higher values have been found, with ginger samples containing up to 0.79 mg/kg Pb in European markets (Blagojević et al., 2016), while Moroccan spice surveys confirmed variability in composition and contamination profiles depending on geographic origin (Bouzaid et al., 2024). Comparable levels have been reported in India and European markets, where Pb contamination in ginger and other common spices was observed, with concentrations in some cases exceeding international safety thresholds (Blagojević et al., 2016).

Turmeric recorded the lowest Pb concentration at 0.14 ± 0.09 mg/kg, which was considerably lower than the Pb concentrations of 1.7 to 5.0 mg/kg reported in the study conducted by Vostrikova et al. (2021). In South Asia, although contamination levels are generally low to moderate, several market surveys have identified the use of Pb chromate as an adulterant in certain spice products (Forsyth et al., 2024). Studies from Bangladesh further highlighted turmeric as a potential source of chronic Pb exposure, especially for children (Gleason et al., 2014). The measured values were well below both EU and Codex limits, reflecting turmeric's relatively low natural uptake of Pb. However, the measured values highlighted potential risks from anthropogenic sources, including adulteration and inadequate post-harvest practices

Cadmium levels followed a similar trend, highest in cinnamon (0.29 ± 0.07 mg/kg), and notably present in cumin (0.06 ± 0.02 mg/kg), ginger (0.04 ± 0.02 mg/kg), black pepper (0.03 ± 0.01 mg/kg), and turmeric (0.02 ± 0.01 mg/kg). In cinnamon, the cadmium concentration was 0.29 mg/kg, which was similar to levels previously reported in South Asian spice markets (Baig et al., 2019). Similar studies have reported the presence of toxic trace elements such as Pb and Cd in spices and aromatic herbs collected in Tunisia and Italy (Potortì et al., 2020). Regulatory limits for Cd in spices are currently under development, with existing guidelines varying among different authorities. For example, the EU set a maximum level of 0.20 mg/kg for fresh herbs (Regulation EU 2021/1323), and this value might be adjusted for dried spices using a dehydration factor as recommended by the European spice association (EU Commission, 2021). Additionally, regulatory authorities such as the European Commission have set a maximum Cd level of 1.0 mg/kg for food supplements, a category that may include certain dried plant materials such as spices (EU Commission, 2021). However, the Alimentarius (1995) and Mayne (2023) have not yet established specific Cd limits for spices. In Lebanon, Cd was detected in over 8% of spice samples, with some exceeding the regulatory thresholds (Moussa et al., 2024). According to EU No 1275/2013 of 6 December 2013, amending Annex I to Directive 2002/32/EC on undesirable substances in animal feed, the maximum permissible level of Cd in complete animal feed was set at 0.5 mg/kg (at 12% moisture), with higher limits applying to certain categories, including 1 mg/kg for complete feed for cattle (except calves), sheep (except lambs), goats (except kids) and fish, and 2 mg/kg for complete feed for pet animals (Official Journal of the European Communities, 2002).

For ginger, the concentration of Cd, 0.04 mg/kg, was lower than the values reported in North African markets, where ginger and mixed spice samples contained Cd levels up to 0.36 mg/kg (Ziyaina et al., 2014). However, the level of Cd remained lower than that reported in Ethiopian ginger, where cadmium was detected in specific samples (Belay, 2014). The present results suggested that ginger contamination varies across regions but generally remains moderate.

The Cd concentration in the black pepper sample (0.03 mg/kg) was also lower than the range found in Indian markets, where heavy metal surveys reported Cd values between 0.12 and 0.20 mg/kg (Sharda et al., 2017), and was also lower than the Cd concentrations reported in black pepper samples, which ranged from 0.008 to 0.067 mg/kg (mean = 0.026 mg/kg; Tinggi, 2025). In the Cumin samples, the present value of 0.06 mg/kg was lower than the 0.16 mg/kg reported in Tunisian and well below the 0.21 mg/kg measured in Pakistan (Baig et al., 2019), suggesting comparatively reduced Cd contamination in cumin from the Casablanca region, Morocco.

The level of Cd in turmeric (0.02 mg/kg) was lower than that reported in Iranian markets, where turmeric and other spices indicated Cd values up to 0.13 mg/kg (Varmazyar and Sobhan, 2017). This level remains below that reported in North Africa, where turmeric sold in Libya was found to contain 0.36 mg/kg of Cd (Ziyaina et al., 2014). The EU Commission has set the maximum allowed Cd level in most spices at 0.20 mg/kg. In comparison, the average Cd concentration found in cinnamon samples (0.29 ± 0.07 mg/kg) in the present study was higher, which raised concern. No scientific data are currently available regarding the Cd content of turmeric when used in animal feed formulations. The nephrotoxic potential of Cd at low exposure levels was well documented, and chronic ingestion from dietary sources, including spices, has been highlighted in biomonitoring and exposure studies from Turkey (Sekeroglu et al., 2006), France (Arnich et al., 2012), and Morocco, where Cherkani-Hassani et al. (2020) reported Cd detection in breast milk, highlighting dietary exposure in humans. The present findings reinforced the importance of monitoring turmeric and other spices, even when average Cd levels appear relatively low.

Chronic ingestion of Cd-contaminated feed leads to its bioaccumulation in the liver and kidneys, resulting in nephrotoxicity, oxidative stress, and impaired reproductive and growth performance in livestock (Darmono, 1999; Hoogenboom et al., 2015). Studies have shown that even low Cd concentrations in feed (1-10 mg/kg) can exceed EU safety thresholds after prolonged exposure, particularly in pigs and ruminants (EFSA, 2004; Hoogenboom et al., 2015). The Cd exposure also interferes with the absorption of essential trace elements such as Zn and Cu, promoting metabolic disorders (Phillips and Prankel, 2011). Moreover, Cd residues in feed can accumulate in sheep tissues, particularly in the liver and kidneys, and may be transferred to animal-derived products such as meat and milk, posing an indirect risk to human health (Penkov and Hristev, 2019; Prankel et al., 2004).

Arsenic was highest in cumin (0.45 ± 0.30 mg/kg), followed by black pepper (0.27 ± 0.14 mg/kg), cinnamon (0.09 ± 0.04 mg/kg), ginger (0.06 ± 0.02 mg/kg), and turmeric (0.04 ± 0.02 mg/kg). The highest As level in cumin (0.45 mg/kg) substantially exceeded the values reported by Yücel et al. (2022), who found an average As concentration of 0.06 mg/kg in cumin samples from Turkey and Egypt, where spice blends including cumin indicated As levels up to 4.8 mg/kg (Abd El-Rahman, 2019). This concentration of As was also higher than that recorded in India, where cumin and black pepper samples contained As at levels of up to 0.17 mg/kg (Sharda et al., 2017), and in Pakistan, where As contamination of common spices reached 0.29 mg/kg (Baig et al., 2019). However, the EU and Codex Alimentarius do not presently establish maximum permissible levels for As in spices; As concentrations exceeding 0.2 mg/kg are often emphasized in risk assessments, based on benchmark levels derived from cereals and vegetables (EU Commission, 2021). In black pepper, the

As level of 0.27 ± 0.14 mg/kg aligned with published data, where concentrations up to 0.51 mg/kg were detected in pepper samples from European and North African markets (Blagojević et al., 2016).

The concentration of As in cinnamon was 0.09 ± 0.04 mg/kg, which was lower than the values recorded in Moroccan markets, where multi-element analysis confirmed the presence of measurable As and other toxic metals in cinnamon samples (El Youssfi et al., 2025). Ginger indicated an As concentration of 0.06 ± 0.02 mg/kg, which was lower than values reported in ginger powders, where As reached up to 0.51 mg/kg (Blagojević et al., 2016) and was also lower than findings from experimental studies in rats showing that ginger consumption can mitigate As toxicity (Adetutu et al., 2024). Lastly, turmeric presented the lowest As level at 0.04 ± 0.02 mg/kg, below average values reported in India, where As reached 0.14-0.18 mg/kg in turmeric and other spices (Sharda et al., 2017), and less than the levels detected in Egyptian spice samples, where As reached up to 4.8 mg/kg (Abd El-Rahman, 2019). According to the European Directive 2002/32/EC on undesirable substances in animal feed, the maximum permissible concentration of As is 2 mg/kg in complete feed and 4 mg/kg in complementary feed for all animal species (Official Journal of the European Communities, 2002). Later, Regulation EU No 744/2012 revised these limits for specific compound feeds, increasing the threshold to 10 mg/kg for particular categories of feed materials intended for bovine animals, sheep, goats, and horses (EU Commission, 2012).

Chromium content was highest in black pepper (3.62 ± 2.13 mg/kg), followed by cumin (2.64 ± 1.14 mg/kg), ginger (1.79 ± 0.77 mg/kg), cinnamon (0.96 ± 0.52 mg/kg), and turmeric (0.81 ± 0.36 mg/kg). The highest level of Cr was observed in black pepper (3.62 mg/kg), which was above the average range reported in Mediterranean markets, where Cr was detected in 95% of spice samples with values up to 1.42 mg/kg (Garcia et al., 2000), and higher than Egyptian values, where Cr concentrations in spices such as coriander reached 11.6 mg/kg (Abd El-Rahman, 2019). Comparable levels have been reported in Nigerian markets, where Cr in common spices such as ginger, turmeric, and black pepper varied widely, reflecting similar variability to Indian and Pakistani datasets (Olusola et al., 2025). Likewise, Ethiopian studies confirmed the occurrence of Cr in rhizomatous and seed spices, with measurable levels in ginger and cumin ranging from 0.013 to 0.034 mg/kg (Belay, 2014). There are currently no EU or Codex standards defining permissible levels of Cr in spices. However, dietary intake assessments rely on adequate intake (AI) references for trivalent chromium (Cr^{3+}), set at 35 µg/day for men and 25 µg/day for women, based on estimated average daily consumption (NASEM, 2022). Cumin contained 2.64 ± 1.14 mg/kg of Cr, which was comparable to levels reported in Moroccan markets, where multi-element ICP-MS analysis confirmed the presence of Cr in cumin samples (El Youssfi et al., 2025) and consistent with multi-country data confirming detectable Cr levels in cumin and other spices (Mir et al., 2024). Turmeric exhibited a concentration of Cr at 0.81 ± 0.36 mg/kg, lower than the international range where Cr was detected in 95% of spice samples from Mediterranean markets (Garcia et al., 2000) and below Egyptian data, where values reached up to 11.6 mg/kg in spice samples (Abd El-Rahman, 2019). The ginger sample contained 1.79 ± 0.77 mg/kg of Cr, which was within the range reported in Ethiopian ginger and cumin (0.013-0.034 mg/kg; Belay, 2014) and consistent with multi-country data from Saudi Arabia confirming detectable Cr in ginger, turmeric, cumin, and cinnamon (Seddigi et al., 2013). Finally, cinnamon indicated Cr concentration at 0.96 ± 0.52 mg/kg, which was within the range of values recorded for Moroccan and Saudi Arabian markets (Seddigi et al., 2013; El Youssfi et al., 2025), suggesting comparatively moderate Cr uptake in bark-based spices.

According to the National Research Council, the maximum tolerable concentration of Cr^{3+} in livestock feed is 3,000 mg/kg when supplied as chromium oxide (Cr_2O_3) and 1,000 mg/kg when supplied as chromium chloride ($CrCl_3$; NRC, 2001). At low doses, Cr improves metabolism, growth, and immune function in animals (Moreira et al., 2020). However, when exposure exceeds safe limits, Cr becomes toxic and can cause severe cellular damage, as demonstrated in studies using the mongoose as an environmental model (Andleeb et al., 2020).

Nickel levels were highest in cumin (4.18 ± 2.85 mg/kg), followed by cinnamon (1.34 ± 0.73 mg/kg), ginger (0.76 ± 0.39 mg/kg), turmeric (0.70 ± 0.37 mg/kg), and black pepper (0.45 ± 0.26 mg/kg). In cumin, the Ni concentration reached 4.18 mg/kg, which was lower than the levels previously reported in Algerian samples (7.61 mg/kg; Kachbi et al., 2022). Nickel contamination has also been reported in cumin and black pepper samples from Moroccan markets (El Youssfi et al., 2025).

Additionally, the concentration of Ni fell within the broader international range of 1.3 to 5.5 mg/kg reported in Iraqi samples and Nigerian markets, where Ni in spices was confirmed in multiple spice varieties (Gaya and Ikechukwu, 2016). Although there are currently no established EU or Codex limits for Ni in spices, dietary exposure assessments consider tolerable daily intake levels ranging from 2.8 to 12 µg/kg body weight/day, depending on population subgroup and risk model. No official or internationally recognized limit for Ni in animal feed has been established so far. In cinnamon, the Ni concentration was 1.34 ± 0.73 mg/kg, which was lower than values reported in Moroccan markets, where ICP-MS analysis detected Ni among several toxic elements in cinnamon (El Youssfi et al., 2025) and Saudi Arabian samples, where Ni levels reached up to 2.6 µg/g (Seddigi et al., 2013). Black pepper presented 0.45 ± 0.26 mg/kg of Ni, lower than Moroccan data from the Rabat-Salé-Témara region, Morocco (El Youssfi et al., 2025) and Nigerian results, where Ni reached 2.33 mg/kg in pepper blends (Iwegbue et al., 2013). Turmeric contained 0.70 ± 0.37 mg/kg of Ni, higher than the levels reported in

Iranian markets, where Ni was detected at 0.033 mg/kg in both packaged and unpackaged turmeric samples (Taghizadeh et al., 2024) and also lower than Saudi Arabian findings, where Ni was consistently present in turmeric (Seddigi et al., 2013). Finally, ginger indicated 0.76 ± 0.39 mg/kg of Ni, which was lower than Moroccan values, where ginger samples contained detectable Ni (El Youssfi et al., 2025), and Saudi Arabian results, where ginger was confirmed as a Ni-accumulating spice (Seddigi et al., 2013).

Macro-elements

The five spices analysed, cinnamon, cumin, ginger, black pepper, and turmeric, revealed remarkably diverse profiles for five key nutritionally relevant elements, including K, Ca, Mg, Na, and Fe (Table 4). These differences indicated distinct physiological uptake behaviors, soil conditions, and regional cultivation practices.

Table 4. Minimum, maximum, mean concentrations, and standard deviations of major elements in different spices

Element		K (g/kg)	Ca (g/kg)	Mg (g/kg)	Na (g/kg)	Fe (mg/kg)
Cinnamon	Range	0.676-6.151	1.798-8.894	0.327-2.358	0.102-0.647	81.013-398.146
	Mean ± SD	3.62 ± 1.75	5.01 ± 2.18	1.41 ± 0.64	0.41 ± 0.17	269.44 ± 95.61
Cumin	Range	20.034-22.985	2.45-18.972	3.672-9.897	1.512-6.06	100.801-1440.245
	Mean ± SD	21.64 ± 1.01	11.13 ± 4.53	6.86 ± 1.61	3.98 ± 1.59	753.71 ± 446.07
Ginger	Range	4.119-23.665	0.302-3.859	1.105-3.898	0.105-0.492	93.112-893.354
	Mean ± SD	13.97 ± 6.68	2.13 ± 1.13	2.64 ± 0.85	0.31 ± 0.14	423.11 ± 237.84
Black pepper	Range	16.754-17.893	3.802-6.952	1.895-2.97	0.269-0.269	39.002-488.474
	Mean ± SD	14.24 ± 2.06	4.81 ± 1.61	1.89 ± 0.61	0.17 ± 0.06	258.80 ± 164.07
Turmeric	Range	1.742-49.78	0.525-1.486	0.828-3.322	0.084-0.445	92.969-597.859
	Mean ± SD	25.96 ± 13.51	1.00 ± 0.32	1.90 ± 0.70	0.28 ± 0.11	335.18 ± 156.58

K: Potassium, Ca: Calcium, Mg: Magnesium, Na: Sodium, Fe: Iron, SD: Standard deviation.

Turmeric demonstrated a notably high K content, with a study conducted by Maghrabi (2014) reporting levels reaching 24.1 g/kg. Cumin maintained elevated values of K (~20 g/kg), reinforcing its nutritional potential as a dietary source of K. Cinnamon consistently recorded the lowest K, suggesting species-specific uptake limitations or cultivation on K-poor substrates. Potassium content of spices differed by species and region. In the present study, turmeric demonstrated exceptionally high K levels, often exceeding 25 g/kg and reaching nearly 50 g/kg. In the present study, the concentrations of K aligned closely with findings from Morocco, where turmeric recorded some of the highest K values among spices, with concentrations approaching 40 g/kg (El Youssfi et al., 2025). Similar high K levels for turmeric were reported in Uzbekistan, typically ranging from 30 to 45 g/kg, depending on the soil and region (Jabborova et al., 2021). The present results on cumin indicated K levels of around 20 g/kg, consistent with concentrations reported for Moroccan cumin samples, which ranged from 18 to 24 g/kg (El Youssfi et al., 2025). Additionally, Indian sources confirmed similar K concentrations in cumin, typically 16-22 g/kg. This was consistent with the value reported in Moroccan samples (16.72 g/kg; El Youssfi et al., 2025) and lower than that observed in Indonesian samples (33.84 mg/g; Ayustaningwarno et al., 2024), likely reflecting differences in soil characteristics and altitude. In contrast, cinnamon consistently exhibited the lowest K content in the present study (<1 g/kg), consistent with El Youssfi et al. (2025), who reported that Moroccan cinnamon contains less than 2 g/kg. Additionally, studies from India and New Zealand reported concentrations of K ranging from 0.5 to 1.5 g/kg (Cicero et al., 2022). These comparisons clearly indicated that turmeric consistently has the highest K concentration, followed by cumin and ginger, while cinnamon ranks lowest across all studies. Potassium levels in animal feed vary by species and source. In cats, commercial foods containing 0.32-0.34% dry matter are below the recommended minimum of 0.6% (Phillips, 1998). In dogs, K levels ranged from 0.44 to 1.03 g/MJ, aligning with recommended intakes of around 0.7-1 g/MJ (Bijsmans et al., 2021) and in ruminants, while typical needs are covered at 0.5% dry matter, local forages in North Africa can raise K content to 3.1% dry matter, far exceeding basic nutritional requirements (Ward, 1966; Bhanugopan et al., 2015).

In the present study, cumin displayed the highest Ca concentrations, ranging from 11.13 ± 4.53 g/kg, which was substantially higher than values reported for Jordanian sweet cumin in Jordan (~2.22 g/kg; 221.5 mg/100 g; Ereifej et al., 2015). Cinnamon ranked second (5.01 ± 2.18 g/kg), exceeding the 2.99 g/kg reported for Middle Eastern samples (Ereifej et al., 2015) and consistent with other reports of elevated Ca in cinnamon. Black pepper contained an average of 4.81 ± 1.61 g/kg of Ca, consistent with Indian data of 4.39 g/kg (Ayoade et al., 2023). Ginger contained 2.13 ± 1.13 g/kg, higher than the 0.67 g/kg reported in Jordanian samples. In contrast, turmeric recorded the lowest concentrations at 1.00

± 0.32 g/kg, well below the 0.13 g/kg observed in Jordan (Ereifej et al., 2015). These differences underlined the remarkable geographical variability in mineral composition, likely driven by soil properties, agronomic practices, and post-harvest handling.

In the present study, cumin recorded the highest Mg levels (6.86 ± 1.61 g/kg), which fall within the range previously reported for cumin seeds (0.81-36.6 g/kg; Mohammed et al., 2024). Ginger displayed moderate Mg concentrations (2.64 ± 0.85 g/kg), which aligns with literature values of 2-3 g/kg for ginger across African and Asian origins (Ajayi et al., 2013). Black pepper had Mg content of 1.89 ± 0.61 g/kg, comparable to 1.8-2.0 g/kg values reported in Indian and Indonesian samples (Cicero et al., 2022). Turmeric presented slightly lower values (1.90 ± 0.70 g/kg), overlapping with the 1.5-2.5 g/kg range reported in Indian studies (Jabborova et al., 2021). The lowest Mg concentrations was observed in cinnamon (1.41 ± 0.64 g/kg), in agreement with published data showing consistently low Mg levels in cinnamon, with reported levels around 1.40g/kg (Ereifej et al., 2015). The present results confirmed that cumin was the major dietary source of Mg among the tested spices, while cinnamon consistently ranked the lowest, reflecting similar trends reported in global datasets. Natural Mg concentrations measured in compound feeds vary by species. The level of 0.21% in poultry feed (Zang et al., 2014), compared to only 7-8 mg/kg in diets formulated for horses (Harrington, 1974).

Sodium content of spices in the present study indicated a wide variation between species, with cumin exhibiting the highest Na concentrations (3.98 ± 1.59 g/kg). Cinnamon presented intermediate values (0.41 ± 0.17 g/kg), consistent with 0.12 g/kg reported for cinnamon in Jordan (Ereifej et al., 2015). Ginger had low Na content (0.31 ± 0.14 g/kg). Although specific comparative studies are limited, broader mineral surveys have reported similar Na levels in ginger, with values of approximately 0.312 g/kg in Pakistan (Hussain et al., 2020) and 0.234 g/kg in Nigeria (Ayoade et al., 2023). Black pepper had Na content of 0.17 ± 0.06 g/kg, which was consistent with the value reported by El Youssfi et al. (2025) at 0.175 ± 0.006 g/kg in Rabat, Morocco. Turmeric contained 0.28 ± 0.11 g/kg of Na, in line with low Na content for spices found in nutrition references. For example, Zeiner et al. (2022) found Na concentrations in turmeric samples ranging from 0.05 to 0.50 g/kg. The present results confirmed that cumin was the primary dietary source of Na among the spices analyzed, while black pepper consistently indicated the lowest Na content across the present study. Commercial dry pet foods in Europe typically contain between 3,000 and 7,000 mg of Na per kilogram of dry matter, which remains within the EFSA's safe intake threshold of up to 9,000 mg/kg dry matter (Chandler, 2008). For dairy cows in tropical regions, Na-deficient rations may contain only 400 mg/kg, while the minimum recommended intake for lactating cows is approximately 1,200 mg/kg, requiring dietary supplementation (Thiangtum et al., 2011).

Iron content of the analyzed spices indicated noticeable variation among species. Cumin presented the highest concentrations, ranging from 753.71 ± 446.07 mg/kg, which was consistent with previous studies reporting Fe levels between 700 and 1500 mg/kg in cumin seeds from India and North Africa (Meena et al., 2024; El Youssfi et al., 2025). Turmeric exhibited a moderate level of Fe content (335.18 ± 156.58 mg/kg), aligning with reports conducted by Madhusankha et al. (2019), who indicated Fe levels between 320 and 380 mg/kg in Indian turmeric varieties. Ginger contained elevated levels of Fe (423.11 ± 237.84 mg/kg), comparable to levels reported in African samples, such as 578.2 mg/kg in Ethiopian ginger (Firisa et al., 2023) and in traditional leafy vegetables from South Africa (Odhav et al., 2007). Black pepper recorded Fe level of 258.80 ± 164.07 mg/kg, which falls within the 250-550 mg/kg range reported in previous studies conducted in India and Turkey (Yücel and Atasoy, 2019; Ayoade et al., 2023). Cinnamon indicated Fe values ranging from 269.44 ± 95.61 mg/kg, similar to the 250-350 mg/kg reported for Moroccan cinnamon (El Youssfi et al., 2025). The current findings confirmed that cumin was the main dietary source of Fe among the studied spices, while black pepper exhibited relatively low Fe concentrations. Commercial feeds for ruminants typically contain approximately 77 mg/kg of Fe, prior to any supplementation (Standish et al., 1969). In pigs, basal diets typically provide about 100 mg/kg of Fe, without added sources (Ullrey et al., 1960). To ensure safety, the EFSA recommended maximum Fe levels in complete feeds of 450 mg/kg for cattle and poultry, 500 mg/kg for sheep, and 600 mg/kg for pets, which generally aligns with the levels found in commercial products (EFSA Feedap Panel, 2016).

Correlation analysis between trace and macro-elements

As demonstrated in Figure 1, Strong inter-element correlations emerged from the Pearson matrix, notably between Pb and Cd (r = 0.87), indicating a high degree of association. While explicit r‑values were not widely reported, the co-occurrence of Pb and Cd has been frequently noted in contaminated food matrices. Several studies have demonstrated a consistent co-occurrence of Pb and Cd in contaminated food matrices, such as Lebanese herbs and spices (Moussa et al., 2024), dark chocolate from the United States (Hands et al., 2024), and Turkish herbs and spices (Özden, 2021).

Other strong positive correlations were observed, particularly between Na and Mg (r = 0.76), Ca and As (r = 0.60), as well as Mg and Ca (r = 0.60). These associations may reflect shared geochemical origins linked to soil mineralogy or agricultural amendments. Similar patterns have been discussed in broader studies of heavy-metal contamination in soils and plants (Bouida et al., 2022) and confirmed in South African spice surveys (Oladeji et al., 2023).

Nickel exhibited a moderate correlation with Ca (r = 0.51) and a strong correlation with Na (r = 0.63), suggesting that these three elements may share a common geogenic origin. Similar association patterns were observed in groundwater studies, where Ni indicated a remarkable correlation with Mn (r = 0.766), likely reflecting geological inputs (Islam et al., 2025). Moderate positive correlations between Fe and other elements, specifically Fe and Ni (r = 0.38), Fe and Mg (r = 0.48), and Fe and Na (r = 0.47), implied shared soil-origin or organic matter inputs, consistent with crustal elemental co-distributions (Moore et al., 2022). By contrast, Cr exhibited only weak correlations with other elements, likely indicating distinct contamination sources or mechanisms, as environmental heavy-metal studies have noted differential behavior of Cr in geochemical and pollution contexts (Briffa et al., 2020). Notable negative correlations were found between Cd and K (r = -0.57) and between Pb and K (r = -0.62), suggesting that higher K levels were associated with lower accumulation of heavy metals in the samples. Although the present correlation data were specific to the selected spice samples, similar antagonistic dynamics between K and Cd uptake have been observed in controlled studies, particularly where K fertilization modulates Cd accumulation in crops (Wang et al., 2019).

Moderate inverse relationships were detected between Pb and Mg (r = -0.35) and between Cd and Mg (r = -0.30), indicating that higher Mg levels were associated with lower concentrations of these heavy metals. This inverse trend was consistent with observations in crops grown on calcareous soils, where elevated Mg and Ca contents contribute to reduced heavy-metal mobility and bioavailability (Zaragüeta et al., 2021). Negative but weak correlations between Pb and As (r = -0.15) and Cd and As (r = -0.16) confirmed the absence of strong relationships, although previous multivariate analyses of metals in spices reported a high positive correlation between Pb and As and moderate associations among other metals such as Cd and Zn (Shim et al., 2021).

Overall, the present study highlighted two main groups of elements. On one hand, Pb and Cd are strongly co-detected in spices, indicative of anthropogenic pollution reinforced by data from Lebanese spice markets (Moussa et al., 2024) and Turkish herb analyses (Özden, 2021). On the other hand, naturally interrelated elements such as Na, Mg, Ca, As, and Ni appeared largely of geological or agronomic origin, consistent with metal distribution studies in Moroccan soils (Barakat et al., 2022) and South African spice surveys (Oladeji et al., 2023). The inverse association between K and heavy metal concentrations, suggesting its potential role as an indirect indicator of less-contaminated areas, is supported by regional soil-metal interaction patterns observed in studies conducted on the Moroccan phosphate plateau (Barakat et al., 2022).

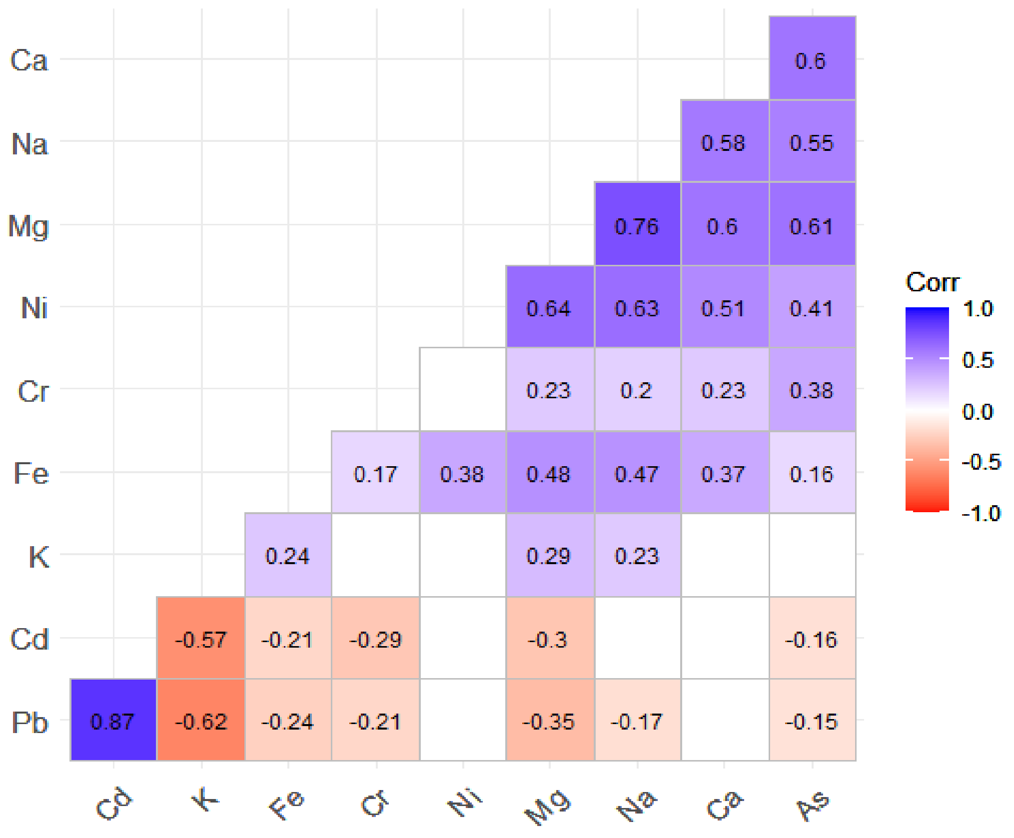

Figure 1. The linear relationships between major and trace elements analysed in the spice samples. K: Potassium, Ca: Calcium, Mg: Magnesium, Na: Sodium, Fe: Iron. Trace elements include Cr: Chromium, Ni: Nickel, Pb: Lead, Cd: Cadmium, and As: Arsenic.

Verification of data factorability

The factorability of the inter-correlation matrix was assessed using two statistical tests (Table 5), including the KMO measure of sampling adequacy and Bartlett's test of sphericity. The overall KMO value was 0.80, indicating a very adequate suitability of the dataset for factor analysis (Kaiser, 1974). Individual KMO values ranged from 0.67 (Pb) to 0.89 (Ni), corresponding to adequacies ranging from acceptable to excellent. Bartlett's test of sphericity confirmed that the correlation matrix was significantly different from an identity matrix ($\chi^2 = 153.42$, df = 45, $p < 0.001$), demonstrating that the observed correlations were sufficient to justify the application of PCA (Bartlett, 1950).

Table 5. Kaiser-Meyer-OLKIN and Bartlett test

KMO and Bartlett test		
Kaiser-Meyer-Olkin (KMO) test: Measure of sampling adequacy		0.797
Bartlett's Test of Sphericity	χ^2	153.42
	df	45
	p-value	0.001

KMO: Kaiser-Meyer-Olki, χ^2: Chi-square value, df: Degrees of freedom, p-value: Probability value

Factor structure and projection of variables

Figures 2 and 3 present the results of a PCA applied to the spice samples to visualize and compare their analytical profiles. The first two factorial axes, Dim 1 (41.2% of the explained variance) and Dim 2 (23.4%), together accounted for 64.6% of the total information, providing a synthetic yet faithful representation of the multivariate relationships among samples (Figure 2).

Examination of variable contributions to the first two principal components revealed marked associations between specific chemical elements and the differentiation of spices. For Dim 1 (41.2% of variance), the highest contributions were from Mg and Na, followed by As, Ni, and Ca. These variables were essential in distinguishing cumin, which was strongly positioned along the direction of these elements. For Dim 2 (23.4% of variance), the structure was dominated by Cd and Pb, each accounting for nearly one-third of the contribution, followed by K and Ca. These variables were particularly associated with cinnamon, which exhibited elevated Cd and Pb levels, and, to a lesser extent, with certain variations observed for turmeric and ginger. When both axes were considered (accounting for 64.6% of the total variance), Pb and Cd, along with Mg, Na, and Ca, emerged as the most discriminating elements (Figure 3). This pattern accounted for the distinct separation between cumin, marked by elevated concentrations of macro-elements (Mg, Na, Ca), and cinnamon, which was instead associated with higher levels of toxic trace metals (Cd, Pb). Other spices, such as turmeric and ginger, displayed intermediate profiles, influenced primarily by K, Ca, and Ni. This finding is consistent with studies from Morocco and Kenya, where cumin was also reported to have high levels of Mg, Na, Zn, and Fe (Chore et al., 2024; El Youssfi et al., 2025). In contrast, cinnamon exhibited concerning concentrations of heavy metals, particularly Pb and Cd, often exceeding regulatory limits. Multivariate analysis placed it as a distinct group, with a strong correlation between Pb and Cd (Mir et al., 2024; El Youssfi et al., 2025). Turmeric and ginger presented intermediate elemental profiles. Ginger, in particular, was rich in K and Mg, whereas turmeric, though slightly lower in concentration, remained a valuable source of nutrients (Savić et al., 2019; Chore et al., 2024).

The cumulative variance explained by the first two components in the present PCA (Dim 1 = 41.2%, Dim 2 = 23.4%, total = 64.6%) falls within the range generally observed for spice matrices profiled by ICP-MS or coupled plasma-optical emission spectroscopy (ICP-OES). For instance, in a multi-food dataset including spices analyzed by ICP-MS, PCA explained 56.85% of the variance on the first two axes (Voica et al., 2021). Similarly, for green, black, and white pepper as well as cayenne, multi-element profiling combined with PCA yielded a clear separation of groups along PC1-PC2. More recently, a comprehensive multi-analytical strategy combining stable isotope analysis, multi-element profiling, and Fourier transform infrared spectroscopy (FTIR) demonstrated clear discrimination among cinnamon samples, with excellent chemometric performance observed along the first principal components (Primožič et al., 2025). Reviews on food authentication using ICP-MS further highlighted that PC1-PC2 typically capture 40-60% of the total inertia, depending on the number of elements and batch diversity (Mazarakioti et al., 2022).

Overall, this PCA of the present study highlighted a clear structuring of the dataset. Some spices, such as cumin and cinnamon, displayed a well-defined and homogeneous analytical identity, while others, such as ginger and turmeric, presented broadly similar profiles. These similarities could reasonably be attributed to either convergent chemical compositions or common external influences, such as geographical origin, cultivation conditions, and processing practices. The ellipses reinforced these trends by depicting both the extent of internal variability and the potential overlaps between groups, which were key factors for interpreting sample variability and discriminability within analytical and traceability contexts.

The current PCA results revealed a clear structuring of the dataset with cumin and cinnamon displaying distinct and homogeneous elemental signatures, whereas ginger and turmeric demonstrated largely similar profiles along PC1-PC2. This pattern was consistent with multi-element ICP-MS/ICP-OES studies on spices and herbs, where PCA has been shown to clearly separate botanical families, with variance explained on the first two axes typically ranging between 40% and 60% (Tokalıoğlu et al., 2018; PavloviĆ et al., 2020). Comparable outcomes of the present study have been reported, including datasets from Sicily and Tunisia involving spices and aromatic herbs (Potortì et al., 2020), as well as in commercial foodstuffs containing spices (Voica et al., 2021).

Specifically, cumin in the present study formed a very compact cluster and was clearly distinguished from the other categories (Figure 4). Similar separations for seed spices have been observed in PCA analyses based on both major and trace elements, with seeds separating from bark or leaf spices already along PC1-PC2 (Potortì et al., 2020). Cinnamon, a bark spice, showed a stable and well-defined cluster in the present dataset. Similar, consistent, and distinctive mineral profiles for cinnamon have been described in multi-element analyses using chemometric tools (Voica et al., 2021) and further highlighted in broader reviews on elemental authentication (Mazarakioti et al., 2022).

For black pepper, the current results indicated partial overlap of ellipses. This proximity was anticipated, as multi-element profiles of typified pepper samples show that green and black pepper cluster closely together, whereas white pepper, due to its different processing, diverges more markedly along PC1-PC2 (Zeiner et al., 2023).

In Figure 4, each symbol and color correspond to a distinct spice, while ellipses drawn around the points represent 95% confidence intervals, illustrating intra-group dispersion and homogeneity. Examination of the relative positions highlighted several distinct configurations. Cumin (green squares) was strongly shifted towards positive Dim 1 values, standing out clearly from the other spices. Its tight distribution and small ellipse indicated a high degree of homogeneity in its measured characteristics. Cinnamon (yellow triangles), positioned in the upper left quadrant with positive Dim 2 and slightly negative Dim 1, also formed a compact cluster, reflecting a specific and stable chemical signature. Black pepper (red circles) was located in the central-left area of the factorial plane. The ellipse illustrated moderate dispersion, suggesting a characteristic but more variable chemical profile along PC1-PC2. Ginger (blur crosses) and turmeric (purple squares), positioned in the lower part of the plot, displayed substantial overlap of their point clouds. This overlap indicated that the two spices possess closely aligned analytical characteristics along the first two axes, implying that their effective discrimination would require the use of additional dimensions or discriminant variables.

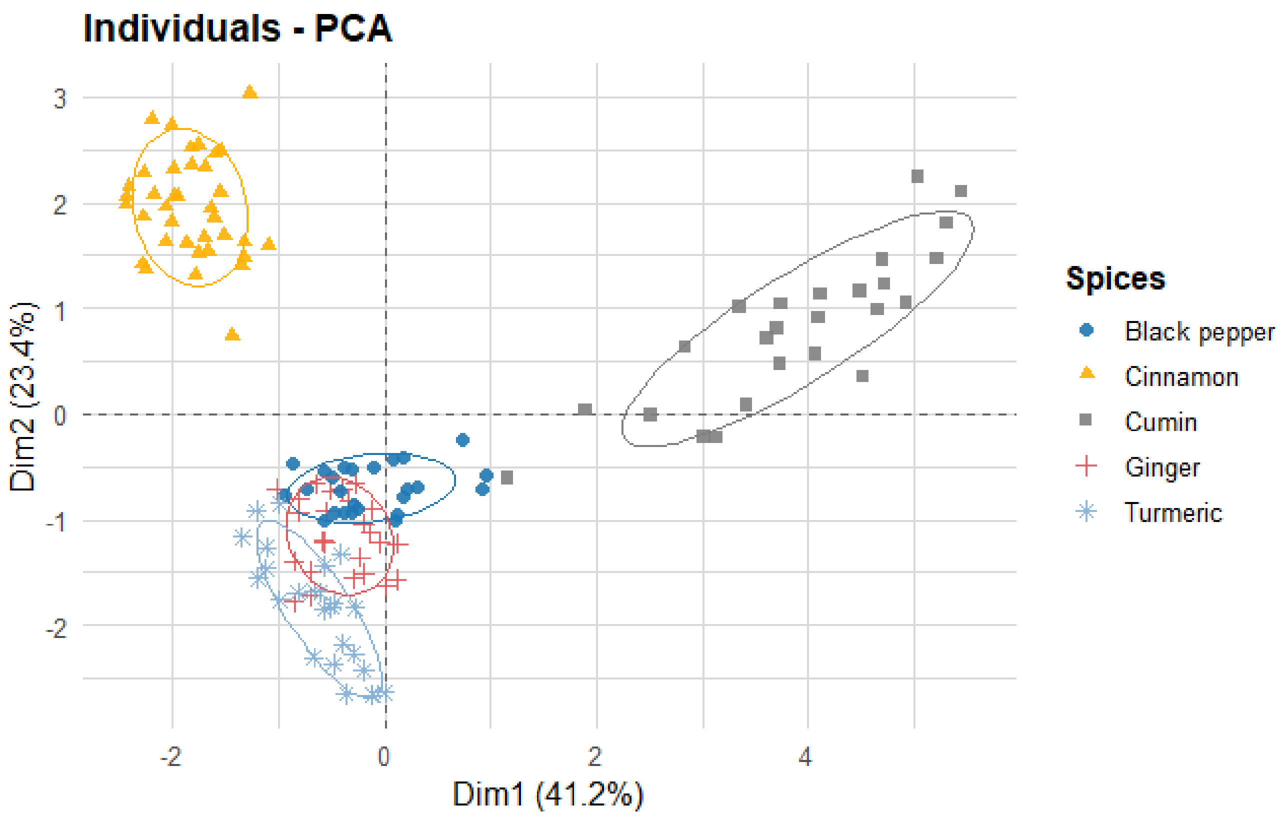

Figure 2. Multivariate separation of analytical spice profiles by principal component analysis. PCA: Principal component analysis, Dim 1: First principal component, Dim 2: Second principal component.

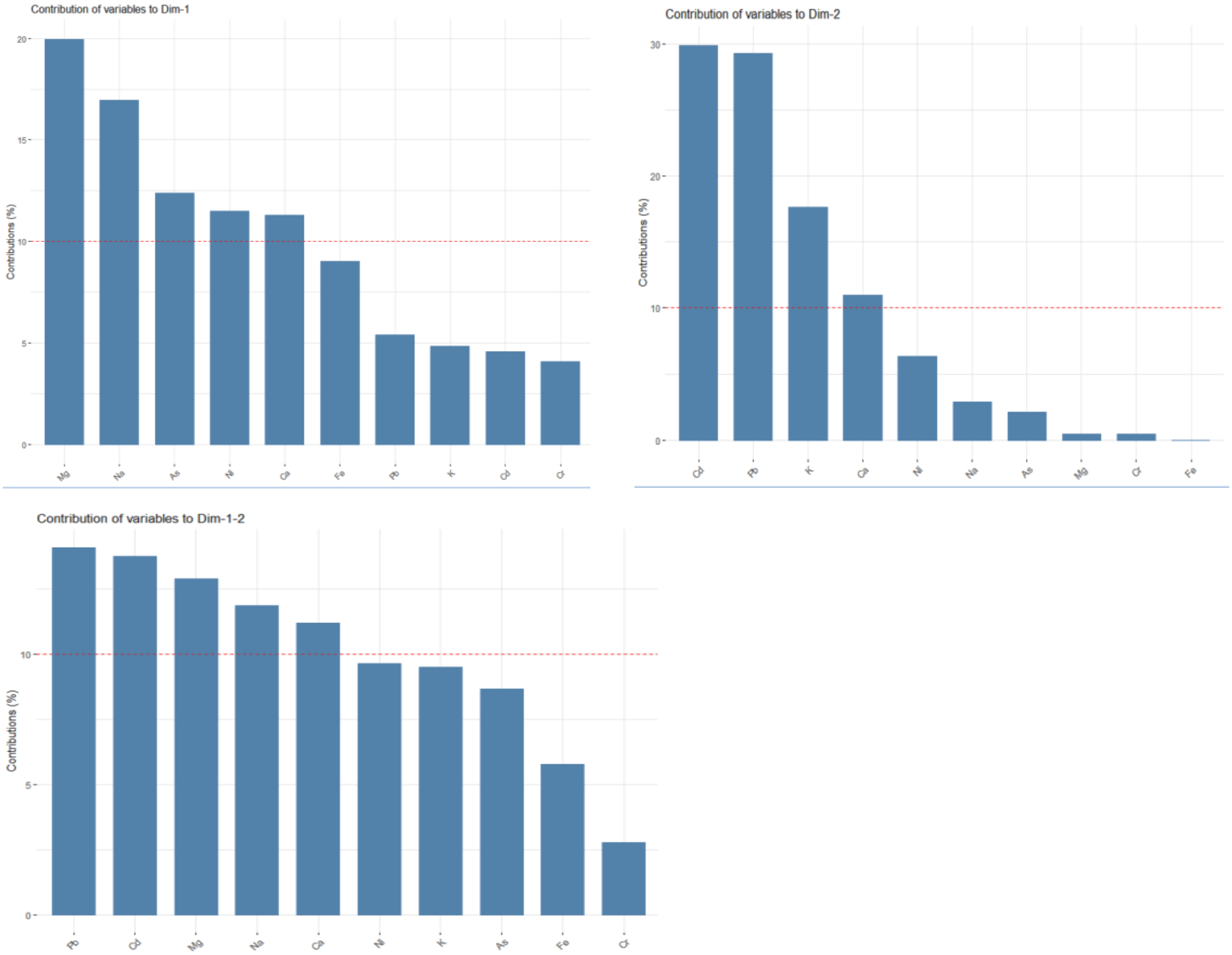

Figure 3. Contribution of macro-elements and trace metals to the differentiation of species in the first two main components of the principal component analysis. Dim 1/Dim 2: First and second principal components.

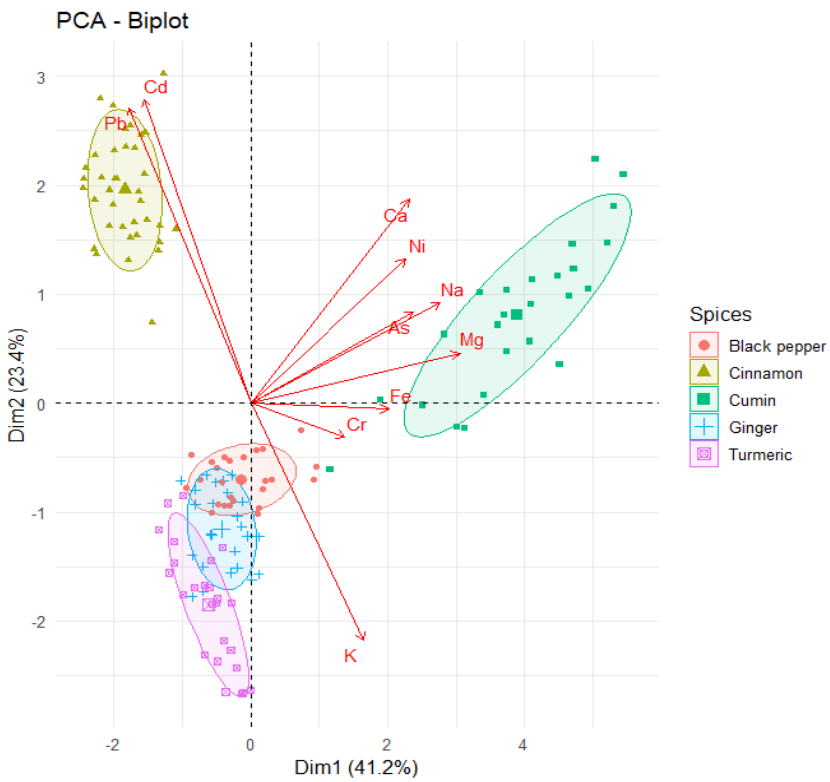

Figure 4. Principal component analysis biplot showing the separation of spice samples and correlation with chemical element contents. PCA: Principal component analysis, Dim 1/Dim 2: Principal components with explained variance (%).

CONCLUSION

The present study represented the first comprehensive multi-element analysis of spices marketed in the Greater Casablanca, Morocco, combining ICP-MS quantification with multivariate statistical approaches. The current results indicated that while some spices, such as turmeric and cumin, are distinguished by their high levels of essential elements such as K, Mg, Na, and Fe, notably cinnamon, display concerning concentrations of toxic metals, particularly Pb (2.05 ± 0.23 mg/kg) and Cd (0.29 ± 0.07 mg/kg), which frequently exceed regulatory limits. The PCA enabled the clear discrimination of spices based on their elemental profiles, revealing two main clusters with one dominated by macro-elements (Cumin, turmeric, ginger) and another characterized by elevated heavy metals (Cinnamon). Strong correlations between Pb and Cd suggested a common source of contamination, potentially linked to agricultural practices or processing methods. The present findings underscored the urgent need for strengthened quality control of spices on the Moroccan market, including systematic monitoring of toxic metals and the implementation of targeted corrective measures. Additionally, the results of the present study highlighted the value of integrated analytical approaches for differentiating products, tracing their origin, and assessing their safety, thereby contributing both to public health protection and to the valorization of local production. Future studies should investigate a larger set of spices across different Moroccan regions, exploring additional contaminants such as pesticides and mycotoxins, and examining the influence of agricultural practices, soil composition, and irrigation water on metal accumulation in spices.

DECLARATIONS

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Author’s contributions

Safaa Sabri was responsible for the conceptualization of the study, initial drafting, collection of samples, scientific interpretations, data analysis, and coordination of the experimental process. Chaima Sabri supervised the study, the critical review of data, and the manuscript. Mohamed Rida Salam contributed to the interpretation of results, contributed to the literature review, and the scientific discussion. Fatiha El Mellouli contributed to the literature review and assisted in the statistical analysis of the data. Asmaa Lafram participated in laboratory experiments. Hanane Khallouki contributed to the statistical analysis and interpretation of results. Yayé Abdou Hassane contributed to the literature review and assisted in data organization. Mostafa Kabine provided general supervision, scientific guidance, and final approval of the manuscript. All authors checked and approved the findings of this study and the last edition of the submitted manuscript.

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Competing interests

The authors declared that they have no competing interests.

Availability of data and materials

All data generated or analyzed during the present study are included in this published article.

Ethical considerations

Ethical issues, including plagiarism, consent to publish, misconduct, data fabrication and/or falsification, double publication and submission, and redundancy, have been checked by all authors. No artificial intelligence (AI) tools were used to assist in conducting, analyzing, or interpreting the present study.

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