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## **► To cite this version:**

Ramia Al Bakain, Kiril Simitchiev, Asya Hristozova, Lidia Kaynarova, Evelina Varbanova, et al.. Environmental assessment and comparative analysis of toxic metal(oids) contamination: application to herbal plants from Jordan. International Journal of Environmental Analytical Chemistry, In press, <10.1080/03067319.2025.2612573>. <hal-05480138>

**HAL Id: hal-05480138**

**<https://hal.science/hal-05480138v1>**

Submitted on 27 Jan 2026

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**Environmental Assessment and Comparative Analysis of Toxic metal(oids)  
Contamination: Application to Herbal Plants from Jordan**

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## ABSTRACT

This study evaluated 13 metal(loid)s (Al, As, Cd, Co, Cr, Cu, Fe, Hg, Ni, Pb, Pd, Sb, Sr) in 28 medicinal and edible plants from Jordan's Southern Badia using ICP-MS and ICP-OES with certified reference material validation (excluding Pd and Sb). The study revealed that As, Co, Hg, Pb, Pd, and Sb were below their maximum contaminant limits (MCLs), indicating low uptake and minimal anthropogenic influence. Cd, Cr, and Cu were generally below MCLs, with only five species near or slightly exceeding limits. In contrast, Ni exceeded the MCL ( $0.30 \text{ mg}\cdot\text{kg}^{-1}$ ) in all plants, ranging from  $0.320 \pm 0.001 \text{ mg}\cdot\text{kg}^{-1}$  (*Ziziphus spina-christi*) to  $6.32 \pm 0.34 \text{ mg}\cdot\text{kg}^{-1}$  (*Nigella sativa*). Al was consistently high, surpassing the MCL ( $5.00 \text{ mg}\cdot\text{kg}^{-1}$ ) across all samples, from  $22.42 \pm 2.42 \text{ mg}\cdot\text{kg}^{-1}$  (*Coriandrum sativum*) to  $1322.31 \pm 72.26 \text{ mg}\cdot\text{kg}^{-1}$  (*Origanum majorana*), with several species exceeding  $500 \text{ mg}\cdot\text{kg}^{-1}$ . Ten species surpassed the Fe MCL ( $300 \text{ mg}\cdot\text{kg}^{-1}$ ), with *O. majorana* reaching  $\sim 4.4\times$  MCL, while *Artemisia Judaica*, *Teucrium polium*, *Mentha sp.*, and *Ocimum basilicum* had  $2\text{--}3\times$  MCL. Sr varied widely, with 12 species above the MCL ( $50 \text{ mg}\cdot\text{kg}^{-1}$ ); the highest concentrations occurred in *O. majorana* ( $365.14 \pm 27.91 \text{ mg}\cdot\text{kg}^{-1}$ ) and *Z. spina-christi* ( $358.92 \pm 21.44 \text{ mg}\cdot\text{kg}^{-1}$ ). PCA and HCA showed that Al, Fe, and Sr were the dominant contributors to plant clustering. The generally low levels of the remaining metal(loid)s reflect the region's calcareous sandy-loamy soils, alkaline pH, low urbanization, semi-arid climate, and plant exclusion mechanisms, all of which limit metal bioavailability and uptake. These findings provide a crucial baseline for assessing metal contamination in Jordanian herbal plants and offer implications for product safety, environmental policy, public awareness, and the use of native plants as bio-indicators in arid regions.

**KEYWORDS:** Chemometric Analysis; Jordanian Herbal plants; Potentially Toxic Elements; Southern Badia region.

## 1. Introduction

Over recent decades, natural-product research has expanded rapidly due to advances in high-resolution analytical technologies and chemometric methods [1-3]. These tools have improved the characterization of structural and chemical diversity in medicinally relevant natural products [4-8]. Global use of natural products, especially medicinal plants and their bioactive metabolites—has also risen markedly [5, 6, 9, 10]. The World Health Organization (WHO) includes traditional medicine within complementary and alternative medicine, encompassing health practices outside mainstream clinical system [11].

Herbal medicine has long been central to traditional healthcare in the Middle East. Despite the region's arid climate, it hosts more than 13,500 plant species [12]. Jordan, noted for its geographic and climatic diversity, supports particularly rich flora, with over 200 traditional medicinal preparations in use [13, 14]. Herbal remedies are culturally ingrained and widely used for general health in Jordan [7, 9, 15-17]. Most medicinal plants are wild, though some are cultivated and well known locally [18]. Jordan's indigenous medicinal plants are of special scientific interest due to their adaptation to extreme conditions, especially in the Badia—an arid to semi-arid zone receiving less than 200 mm of annual rainfall [19]. Covering about 80% of the country yet inhabited by only around 5% of the population (mainly Bedouins), the Badia continues to supply vital resources, including desert plants of notable medicinal and nutritional value. Approximately, 2,543 vascular plant species in Jordan about 20% of its flora are classified as medicinal, spanning 868 genera and 142 families [20]. Harsh abiotic conditions enhance secondary-metabolite production, making Jordanian plants a rich source of unique phytochemicals with therapeutic potential. Their distinct chemical profiles remain underexplored but offer promise for developing treatments for infectious, inflammatory, and neurological diseases. Although many native species are not yet fully characterized, emerging evidence highlights their bioactive constituents especially antioxidants and anti-inflammatory compounds with potential neuroprotective and systemic health benefits. [7, 9, 13, 16, 17, 19, 21-25].

Alongside beneficial secondary metabolites, plants can accumulate environmental toxins such as metal(loids) [26, 27]. These elements are concerning because they readily build up in edible plant parts and can harm soil health, plant growth, water quality, and agricultural productivity [28, 29]. Excess metal(loids) pose serious risks to humans: when levels exceed maximum contaminant limits, they can damage the liver, kidneys, lungs, blood composition, and the central nervous system [28, 30]. Contamination arises from factors such as soil composition, pollution, climate, anthropogenic activities, and harvesting or handling practices [28, 29].

Accordingly, the WHO advises screening medicinal and dietary plants for metal(loids) and other contaminant [31].

Several analytical techniques are used to measure metal(loid) concentrations in plant tissues. Inductively coupled plasma, such as optical emission spectrometry (ICP-OES) and mass spectrometry (ICP-MS), are the most common, offering highly accurate, multi-element trace detection Atomic absorption spectroscopy (AAS), whether flame or graphite furnace, is cost-effective and suitable for low-level measurements, though limited to single-element analysis and lower throughput [32]. X-ray fluorescence (XRF) provides rapid, non-destructive, in situ analysis for field studies but has lower sensitivity than ICP-MS [33].

Hierarchical Cluster (HCA) and Principal Component Analysis (PCA) are beneficial chemometric tools in analytical chemistry to visualize the structure of the data and carry out data classifications. They were implemented in many analytical studies [1-4, 28, 30, 34-41] for many purposes: to fingerprint the most relevant compounds in recognizing sample varieties, to detect the variation on chemical profiles as a result of different environmental parameters in different areas, and to show the compounds that are responsible for grouping samples between clusters.

In Jordan, data on metal(loid) contamination in herbal plants remain limited. Abu-Darwish et al. reported elevated levels of Ni, Cr, and Cu in several species, including *Achillea santolina*, *Amygdalus communis*, *Artemisia herba-alba*, *Crataegus aronia*, *Viscum cruciatum*, and *Nepeta involucrata* [20]. El-Rjoob et al. found Pb, Zn, Cu, and Cd in various parts of *Rosmarinus officinalis*, with Pb, Ni, and Fe particularly concentrated in the leaves, flowers, and stems [42].

However, comprehensive and systematic data on toxic metal(loid) concentrations in extracts of many locally used medicinal and dietary plants in Jordan remain scarce. This gap is particularly notable given the wide diversity of herbal species consumed on a daily basis for medicinal and nutritional purposes, highlighting the need for more extensive monitoring and assessment to ensure public safety.

Further research is needed to assess toxic metal(loid) levels in locally used medicinal and dietary plants in Jordan. The wide diversity of herbs and their daily consumption pose potential health risks, while soil composition, environmental factors, and plant-specific accumulation traits can influence metal(loid) uptake. Systematic evaluation of multiple species is therefore essential to inform safe consumption practices and support public health. Therefore, the present study, for the first time provided a comprehensive work to evaluate 13 metal(loids); aluminum (Al), antimony (Sb), arsenic (As), cadmium (Cd), chromium (Cr), cobalt (Co), copper (Cu), iron (Fe), lead (Pb), mercury (Hg), nickel

(Ni), palladium (Pd) and strontium (Sr) in 28 different local Jordanian plants: *Artemisia judaica*, *Hibiscus sabdariffa*, *Carthamus tinctorius*, *Trigonella foenum-graecum*, *Matricaria chamomilla* L., *Ziziphus spina-christi*, *Pimpinella anisum*, *Salvia rosmarinus*, *Cinnamomum verum*, *Foeniculum vulgare*, *Artemisia vulgaris*, *Origanum majorana*, *Coriandrum sativum*, *Ceratonia siliqua*, *Nigella sativa*, *Syzygium aromaticum*, *Zingiber officinale*, *Myristica fragrans*, *Capsicum annum*, *Elettaria cardamomum*, *Teucrium polium*, *Mentha* sp., *Salvia officinalis*, *Paronychia argentea*, *Laurus nobilis*, *Thymus vulgaris*, *Cuminum cyminum* and *Ocimum basilicum*. Plasma spectrochemical methods (ICP-MS and ICP-OES) were implemented for the metal(oids) profiling. The method was validated and evaluated for selectivity and precision (*i.e.*, repeatability). PCA and HCA were employed in this study to: (i) identify the metal(oids) most significant in distinguishing plant varieties, (ii) assess the variation in metal(oids) profiles across different plant types, (iii) determine which plants could be grouped together, (iv) identify the metal(oids) responsible for clustering the Jordanian plants.

## **2. Materials and methods**

### **2.1. Plant samples**

Representative samples of 28 herbal plant species were collected in 2024 from the Southern Badia desert and from local folk healers at the same region. Fresh leaves, flowers, and fruits were placed in dry, sealed plastic bags and transported to the laboratory. Upon arrival, the plant materials were rinsed with Milli-Q water and air-dried at room temperature for 3–4 days. After drying, the edible portions were crushed, sieved through a mesh screen, and stored in a cool, dry facility prior to analysis. The 28 selected herbal plants are listed in Table 1.

### **2.2. Chemical and reagents**

All reagents and solvents used for extraction and sample preparation were of HPLC ultra-grade. Nitric acid (HNO<sub>3</sub>, 65%) was purchased from Chem-Lab NV (Zedelgem, Belgium), and hydrogen peroxide (H<sub>2</sub>O<sub>2</sub>, 30%) was obtained from Sigma-Aldrich (St. Louis, MO, USA). Standard solutions used for external calibration and standard additions in both instrumental techniques were prepared by appropriate dilution of a NIST-traceable certified reference material (CRM) containing 33 elements and single-element solutions for Hg, Pt, and Pd were supplied by PAChem (Bogomilovo, Bulgaria). The internal standard Rh used in ICP-MS measurements was provided by CPACChem (Bogomilovo, Bulgaria). For the accuracy tests, the CRM bush branches and leaves (NCS DC 73348 CRM) from the China National Analysis Center for Iron and Steel

(Beijing, China) was applied. Ultrapure water ( $18 \text{ M}\Omega \text{ cm}^{-1}$ ) generated by the Milli-Q Plus water purification system (PURELAB Chorus 2+ ELGA Veolia, France) was used to prepare the aqueous solutions and for dilution purposes.

### **2.3. *Extraction of elements***

The air-dried plants were homogenized as a mixture of only leaf [1], fruit and/or flower particles with no seeds or stem using a ceramic electric grinder. Approximately 250 mg portion of each dried plant sample were digested with concentrated extraction solution of  $\text{HNO}_3\text{:H}_2\text{O}_2$  (10:2, v/v). Samples were allowed to react for 2hr at ambient temperature and then treated in a microwave digestion system (Milestone Ethos One Milestone Technologies Inc., California, USA) to break down the plants and to allow the metal(oids) to be recovered in the solvents.

The microwave digestion system utilized closed, pressurized Teflon-TFM vessels specifically designed to withstand high temperatures and pressures. This rotor configuration enabled multiple samples to be processed simultaneously under sealed, controlled conditions [34]. Digestion followed the program described here: the temperature was raised linearly to  $180^\circ\text{C}$  over 20 minutes, then held at  $180^\circ\text{C}$  for an additional 20 minutes to ensure complete mineralization of the sample matrix. A certified reference material (CRM) of bush branches and leaves served as a positive control, and the acid mixture served as a negative (blank) control; both were prepared using the same procedure as the plant samples. After cooling to room temperature, the final digest was filtered and gravimetrically diluted with Milli-Q water to a final volume of 50 mL prior to analysis. A procedural blank was also prepared following the same protocol. All extractions and ICP-MS injections were performed in triplicate, and the concentration of each element is reported as the mean value with the corresponding combined uncertainty.

**Table 1.** The Jordanian plants implemented in this study.

| Scientific name                    | Local Arabic name | Common name            | Family name   | Medicinal use                                                                                                                                            |
|------------------------------------|-------------------|------------------------|---------------|----------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Artemisia judaica</i>           | Beetheran         | Wormwood               | Asteraceae    | Wound Healing [10]                                                                                                                                       |
| <i>Hibiscus sabdariffa</i>         | Karkadeen         | Roselle                | Malvaceae     | Qntihypertensive, anti-inflammatory and antimicrobial [43]                                                                                               |
| <i>Carthamus tinctorius</i>        | Osfor             | Safflower              | Asteraceae    | Treatment for rheumatism and paralysis, vitiligo and black spots, psoriasis, mouth ulcers, phlegm humor, poisoning, numb limbs and melancholy humor [44] |
| <i>Trigonella foenum - graceum</i> | Helbee            | Fenugreek              | Fabaceae      | Ease childbirth, aid digestion, and tonic to improve metabolism [45]                                                                                     |
| <i>Matricaria chamomilla</i> L     | Babonej           | Chamomile              | Asteraceae    | Interesting antioxidant, antibacterial, antifungal, antidiabetic, anti-inflammatory, anti-depressant, anti-allergic, and analgesic activities [5]        |
| <i>Ziziphus spina-christi</i>      | Warak al seder    | Christ's thorn- jujube | Rhamnaceae    | Treatment of: malaria, digestive issues, typhoid, liver complaints, skin infections, urinary disorders, obesity, diarrhea, and sleeplessness [46]        |
| <i>Pimpinella anisum</i>           | Yansoon           | Anise                  | Rhamnaceae    | Antimicrobial, antifungal, antiviral, antioxidant, muscle relaxant, analgesic and anticonvulsant activity, effects on gastrointestinal system [47]       |
| <i>Salvia rosmarinus</i>           | Ikleel al jabal   | Rosemary               | Lamiaceae     | Treatment of inflammatory diseases [48]                                                                                                                  |
| <i>Cinnamomum verum</i>            | Kerfeh            | Cinnamon               | Lauraceae     | Antifungal activity [49]                                                                                                                                 |
| <i>Foeniculum vulgare</i>          | Shomar            | Fennel                 | Apiaceae      | Antifungal, antibacterial, antioxidant, antithrombotic and hepatoprotective activities [50]                                                              |
| <i>Artemisia vulgaris</i>          | Sheeh             | Mugwort                | Asteraceae    | Antioxidant, hepatoprotective, antispasmodic, antinociceptive, estrogenic, cytotoxic, antibacterial, and antifungal effects [51]                         |
| <i>Origanum majorana</i>           | Markadosh         | Marjoram               | Lamiaceae     | Antimicrobial and antifungal activities [52]                                                                                                             |
| <i>Coriandrum sativum</i>          | Kosbara           | Coriander              | Apiaceae      | Antibacterial, antifungal, anti-oxidative activities [53]                                                                                                |
| <i>Ceratonia siliqua</i>           | Karoob            | Carob                  | Fabaceae      | Anti-cancer, antireflux, anti-diabetic, anti-diarrheal, anti-hyperlipidemia, anti-bacterial, anti-microbial, and anti-fungal [54]                        |
| <i>Nigella sativa</i>              | Habet al araka    | Black seed             | Ranunculaceae | Anti-cancer, antireflux, anti-diabetic, anti-diarrheal, anti-hyperlipidemia, anti-bacterial, anti-microbial, and anti-fungal [55]                        |
| <i>Syzygium aromaticum</i>         | Gronfl            | Clove                  | Myrtaceae     | Anti-microbial and antioxidant activities [56]                                                                                                           |
| <i>Zingiber officinale</i>         | Zanjabeel         | Ginger                 | Zingiberaceae | Therapeutic effects on diarrhea and dysentery [57]                                                                                                       |
| <i>Myristica fragrans</i>          | Joset al teab     | Nutmeg                 | Myristicaceae | Bactericidal potential against three Gram-positive cariogenic bacteria [58]                                                                              |

|                             |               |                 |                 |                                                                                                                                                                                     |
|-----------------------------|---------------|-----------------|-----------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Capsicum annuum</i>      | Felfel        | Sweet pepper    | Solanaceae      | Control of metabolic syndrome and its related disorders such as obesity, disrupted lipid profile, diabetes and its complications [59]                                               |
| <i>Elettaria cardamomum</i> | Heal          | Cardamom        | Zingiberaceae   | Anti-inflammatory, analgesic, antioxidant, and antimicrobial [60]                                                                                                                   |
| <i>Teucrium polium</i>      | Jaadeh        | Felty-germander | Lamiaceae       | Antidiabetic agent [61]                                                                                                                                                             |
| <i>Mentha sp.</i>           | Na'na         | Mentha          | Lamiaceae       | Antibacterial activities against <i>Bacillus subtilis</i> , <i>Streptococcus aureus</i> [62]                                                                                        |
| <i>Salvia officinalis</i>   | Meramieh      | Sage            | Lamiaceae       | Therapeutic effects, especially in neurodegenerative diseases and various carcinomas [63]                                                                                           |
| <i>Paronychia-argentea</i>  | rejel hamameh | Silver nailwort | Caryophyllaceae | Dissolve kidney stones and treat urinary tract infections and diseases [64]                                                                                                         |
| <i>Laurus nobilis</i>       | Warak el ghar | Laurel          | Lauraceae       | Antioxidant and antimicrobial activities [65]                                                                                                                                       |
| <i>Thymus vulgaris</i>      | Zaatar        | Garden thyme    | Lamiaceae       | Antioxidant and antimicrobial activities [66]                                                                                                                                       |
| <i>Cuminum cyminum</i>      | Kammon        | Cumin           | Apiaceae        | Act as antispasmodic, antiseptic, antiparasitic, lactigenic, hypolipidemic, antifatulence, aromatic, carminative, digestive and stimulant [67]                                      |
| <i>Ocimum basilicum</i>     | Rihan         | Basil           | Lamiaceae       | Possesses a potent bioprotective effect against Cd-induced oxidative stress and genotoxicity, acting both through enzymatic activation and the inherent antioxidant properties [68] |

#### 2.4. Inductively Coupled Plasma for Elemental Analysis

The analyzed elements were classified into two groups according to their concentration levels in the sample solutions. The concentrations of Al, Fe and Sr were determined using inductively coupled plasma–optical emission spectrometry (ICP-OES; iCAP 6300 Duo, Thermo Scientific, Waltham, MA, USA). Trace elements, including As, Cd, Co, Cr, Cu, Hg, Ni, Pb, Pd, and Sb, were quantified using inductively coupled plasma–mass spectrometry (ICP-MS; Agilent 7700, Agilent Technologies Inc., Santa Clara, CA, USA). The instrumental operating conditions for both techniques are summarized in Table 2. To evaluate the total extraction procedure and to assess the quality of the results; blanks, multi-elements standard (for calibration purposes) and CRM were analyzed in triplicate as well as the real plant samples.

For ICP-OES measurements, two emission lines were monitored for each element to evaluate potential spectral interferences. The assessment of the non-spectral matrix effect was conducted by monitoring the recovery of the standard additions (0.5 and 1.0 mg.L<sup>-1</sup>).

Regarding ICP-MS analysis, two isotopes per element were monitored to assess potential spectral interferences, except for monoisotopic elements (As and Co). Additionally, measurements were performed in collision gas mode (He, 4.8 mL.min<sup>-1</sup>) to minimize the formation of matrix-induced polyatomic species for As, Co, Cr, Cu, and Ni. An internal standard (Rh) was employed to correct instrumental sensitivity drift and potential matrix suppression. ICP-MS instrument was equipped with collision cells that effectively eliminate or neutralize polyatomic interferences prior to ion transmission to the mass analyzer. These collision cells employed inert gases to dissociate polyatomic species via kinetic energy discrimination. Additionally, isotopes with minimal known interferences have been selected to mitigate the impact of polyatomic ions on analyte quantification. Matrix effects were systematically controlled by employing calibration standards prepared in the same acid matrix and under identical dilution conditions as for the samples [34]. This ensures matrix matching between standards and samples, thereby reducing variability arising from differences in physical properties.

## **2.5. Quality control: analyses of certified reference materials (CRM)**

Accuracy of the measurement of the concentrations in plants was verified using NCS DC 73348 CRM (n =3). Mean recoveries results revealed that all known elemental values for this standard fall within the range of 87% - 109% as presented in appendix 1. Quantification of elemental concentrations was performed using an external calibration approach based on six multi-element standards in a range between 0.1–5 mg.L<sup>-1</sup> (0.1, 0.2, 0.5, 1.0, 2.0, and 5.0 mg.L<sup>-1</sup>) and between 0.5–100 µg.L<sup>-1</sup> (0.5, 1.0, 5.0, 20.0, 50.0, and 100.0 µg.L<sup>-1</sup>) for ICP-OES and ICP-MS, respectively. For Hg and Pd, the certified value was **not reported** in the NCS DC 73348 CRM reference sheet, therefore, calibration solutions were prepared from the corresponding single-element standards over the range 0.1–5 µg.L<sup>-1</sup>.

## 2.6. Human Health Risk Assessment

Estimated Daily Intake (EDI) and Target Hazard Quotients (THQ) were used to assess the risk of contamination with heavy metals from herbal plants on human health. These parameters were established for the Al, Fe, Ni and Sr for a person of 70 kg. The daily intake was calculated based on the recommended dose set by the U.S. Environmental Protection Agency (EPA) [69]. To calculate the Estimated Daily Intake (EDI) of Al, Fe, Ni and Sr from plants, the first step is to determine the concentration of the metal in the plants (typically in mg/kg) and the amount of that plants consumed daily (kg/day).

**Table 2.** Instrumental conditions and parameters used in the detection of metal(oids).

| Instrumental parameters                       | ICP-OES (iCAP 6300 Duo)                                                                      | ICP-MS (Agilent 7700)                                                                                                                                                                                                                   |
|-----------------------------------------------|----------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| RF power (kW)                                 | 1.15                                                                                         | 1.5                                                                                                                                                                                                                                     |
| Ar plasma gas flow (L.min <sup>-1</sup> )     | 15                                                                                           | 15                                                                                                                                                                                                                                      |
| Ar auxiliary gas flow (L. min <sup>-1</sup> ) | 0.7                                                                                          | 0.9                                                                                                                                                                                                                                     |
| Ar nebulizer gas flow (L. min <sup>-1</sup> ) | 0.5                                                                                          | 0.95                                                                                                                                                                                                                                    |
| Sample uptake (mL.min <sup>-1</sup> )         | 1.8                                                                                          | 0.34                                                                                                                                                                                                                                    |
| Nebulizer                                     | Concentric                                                                                   | MicroMist (Glass                                                                                                                                                                                                                        |
| Spray chamber                                 | Cyclonic (Tracey Spray Chamber), Glass                                                       | Scott double pass, Peltier cooled 2°C                                                                                                                                                                                                   |
| Observation mode                              | Radial                                                                                       | not applicable                                                                                                                                                                                                                          |
| Replicates                                    | 3                                                                                            | 3                                                                                                                                                                                                                                       |
| Analyte                                       | <b>Wavelength (nm)</b>                                                                       | <b>Isotope</b>                                                                                                                                                                                                                          |
|                                               | Al (309.271)<br>Al (396.152)<br>Fe (259.940)<br>Fe (238.204)<br>Sr (421.552)<br>Sr (215.284) | <sup>52, 53</sup> Cr, <sup>59</sup> Co<br><sup>60, 62</sup> Ni, <sup>63, 65</sup> Cu,<br><sup>75</sup> As, <sup>104, 105</sup> Pd,<br><sup>111, 113</sup> Cd, <sup>121, 123</sup> Sb,<br><sup>201, 202</sup> Hg, <sup>206, 208</sup> Pb |
| Internal standard                             | -                                                                                            | <sup>103</sup> Rh                                                                                                                                                                                                                       |

The EDI is then calculated using the following formula:

$$EDI = \frac{C \times IR}{BW} \quad \text{Eq. 1}$$

where C is the metal concentration in the plant sample in mg/kg, IR is the Ingestion rate in Kg/day (0.003 Kg/day), and BW is the body weight (70 kg).

Based on Equation (1), the Target Hazard Quotient (THQ) was calculated for noncarcinogenic

risk. This parameter was established for each metal according to the following equation, according to the U.S EPA [69]:

$$THQ = \frac{EDI}{RDI} \quad \text{Eq. 2}$$

where EDI is the Estimated Daily Intake, in mg/kg/day, and RfD is the Reference Dose according to the U.S EPA, in mg/kg/day, which represents the tolerable daily intake of the metal via oral exposure. The RfDs of Al, Fe, Ni and Sr are 0.0113, 0.7, 0.2 and 0.6 mg/kg/day, respectively [69].

## **2.7. Data treatment**

The acquisition and processing of data was carried out through the utilization of Qtegra version 22.1465.44 (ICP-OES) and MassHunter 4.4 version C.01.04 (ICP-MS) software.

## **2.8. Statistical software**

The statistical analysis including PCA and HCA was performed using Chemoface 1.61 software which works under Matlab® (Mathworks, 8.6, USA) and XLSTAT software (Excel, Microsoft®).

### **- Multivariate analysis of plants samples**

The complete set of results obtained from the whole analysis was structured into a data matrix  $X_{n \times l}$ , where  $n$  denotes the number of herbal plant samples and  $l$  represents the number of quantified variables (i.e. metal(loids)). In the present study, matrix  $X$  was structured with dimensions of 13 (metal(loids)  $\times$  28 (plant samples)). This matrix was subsequently subjected to PCA and HCA as described in the following sections. Prior to these analyses, mean-centering and normalization of the data were performed to facilitate the interpretation of the underlying data structure. Unsupervised pattern recognition techniques were employed to discern intrinsic data groupings and latent structures without the influence of class labels.

### **- Herbal plants characterization by PCA and HCA**

The aim of the unsupervised methods employed in analytical chemistry is for reducing the complexity of the data and visualizing object grouping or clustering [1, 2, 4, 28, 30, 34, 35, 37]. In this study, HCA and PCA were employed with two main objectives: (i) to determine whether the 28 herbal plant samples collected from Jordan would cluster based on their metal(loid) contents, and (ii) to assess whether the 13-measured metal(loids) would group according to similarities or

differences in their concentration profiles across the various plant species. Determining metal(loid) levels in herbal plants is essential to: i) ensure the safety and quality of herbal products;

ii) provide a critical framework for industrial, medicinal, and food applications;

iii) evaluate environmental and geographical influences on metal(loid) accumulation; and iv) support regulatory compliance and risk assessment for consumer health protection.

### **Quantitative plants classification by PCA and HCA**

The data matrix  $X$  ( $13 \times n$ ) (i.e. 13 metal(loids) from  $n$  plants) is decomposed into two matrices,  $T$  (score matrix) and  $L$  (loading matrix) using a suitable PCA algorithm. The first step in PCA is the computation of loadings. Mathematically, the loadings are the Eigen vectors of the matrix ( $XX^T$ ). The loadings are grouped into a matrix  $L$ . The collected loadings are orthonormal, meaning that they are both orthogonal and normalized. The relationship between the original matrix  $X$ , the loading matrix  $L$  and the score matrix  $T$  is described as [39, 70]:

$$X = TL^T \quad \text{Eq.3}$$

Mathematically, matrix  $X$  is decomposed into the product of two matrices,  $T$  and  $L$ , on the condition that  $L$  is formed by orthonormal columns [39, 70]. The optimum number of factors ( $h$ ) is necessary to create an optimum number of loadings and scores and produce informative discrimination among plants/metal(loids). The analytical scan data were subjected to HCA and PCA analysis. In this study, 13 metal(loids) are the original variables (13 dimensions) in PCA. By calculating the covariance matrix between these 13 dimensions, PCA can generate 13 PCs that are orthogonal to each other and can explain 100% of the total variance of the orthogonal data. Each PC is a linear combination of the original 13 variables. All detected metal(loids) contents were rather necessary for plants clustering. Accordingly, the number of variables used in clustering was 13 (metal(loids))  $\times$  28 (plants).

### **3. Results and Discussion**

In this study, Al, As, Cd, Co, Cr, Cu, Fe, Hg, Ni, Pb, Pd, Sb, Sr were evaluated in 28 local Jordanian plants (Table 3) including: *Artemisia judaica*, *Hibiscus sabdariffa*, *Carthamus tinctorius*, *Trigonella foenum-graecum*, *Matricaria chamomilla* L, *Ziziphus spina-christi*, *Pimpinella anisum*, *Salvia rosmarinus*, *Cinnamomum verum*, *Foeniculum vulgare*, *Artemisia vulgaris*, *Origanum majorana*, *Coriandrum sativum*, *Ceratonia siliqua*, *Nigella sativa*, *Syzygium aromaticum*, *Zingiber officinale*, *Myristica fragrans*, *Capsicum annuum*, *Elettaria cardamomum*, *Teucrium polium*, *Mentha* sp., *Salvia officinalis*, *Paronychia argentea*, *Laurus nobilis*, *Thymus vulgaris*, *Cuminum*

*cyminum* and *Ocimum basilicum*. To the best of our knowledge, this is the first comprehensive study to evaluate the concentrations of 13 metal(oids) in 28 Medicinal and edible plants commonly used in Jordanian traditional practices. Many of these species have been traditionally used in Jordanian folk medicine and are also incorporated into the local food system [71-73]. Such plants are often prepared locally as water infusions or decoctions and are commonly consumed as traditional beverages, used in cooking, and employed to treat various ailments while alleviating associated pain and symptoms [74-76].

The safety of consuming herbs was evaluated by comparing the measured concentrations of metal(oids) with reference to the maximum contaminant levels (MCLs) (i.e. 5.0; 3.0; 0.3; 5.0; 2.0; 20; 300; 0.2; 0.3; 10 and 50 mg kg<sup>-1</sup> for Al, As, Cd, Co, Cr, Cu, Fe, Hg, Ni, Pb and Sr, respectively) reported for each metal(oids) in medicinal and edible herbs [77-79], set by different regulatory authorities along with reported scientific publications, where, Pd and Sb were not indicated. These authorities include the European Commission, specifically Regulation (EC) No. 2073/2005 for leafy vegetables and herbs, The United States Pharmacopoeia USP44-NF39, WHO, the Joint Food and Agriculture Organization (FAO)/WHO Expert Committee Food Additive (JECFA) [77-79].

As no significant matrix-induced suppression or enhancement was observed, the absence of matrix effects was substantiated in this study.

### **3.1. Metal(oids) with Harmless Levels in the Herbs**

Herein, the concentrations of As, Co, Hg, Pb, Pd and Sb detected in the analyzed plants as shown in Table 3 (in term of mg.kg<sup>-1</sup> ± standard deviation SD) were all below the MCLs. The highest concentrations were found to be ranged from 0.19 mg.kg<sup>-1</sup> for As; 1.11 mg kg<sup>-1</sup> for Co; 0.182 mg.kg<sup>-1</sup> for Hg; 1.50 mg.kg<sup>-1</sup> for Pb; 0.20 mg.kg<sup>-1</sup> for Pd and finally 0.065 mg.kg<sup>-1</sup> for Sb. The Co concentrations ranged between 0.019 mg.kg<sup>-1</sup> in karoob (*Ceratonia siliqua*), 0.021 mg.kg<sup>-1</sup> in *jaset al teab* (*Myristica fragrans*) and 1.11 mg.kg<sup>-1</sup> in zanjabeel (*Zingiber officinale*), which remained well below the upper safe limit before human toxicity risk of 1-5 mg.kg<sup>-1</sup> in plants.

Regarding As, Pd and Pb, their contents varied from non-detectable levels to a maximum value of 0.19 ± 0.03 mg.kg<sup>-1</sup>, 0.20±0.04 mg.kg<sup>-1</sup> and 1.5±0.07 mg.kg<sup>-1</sup> in markadosh (*Origanum majorana*) which remains significantly lower than the MCLs. Similarly, Sb was detected only in trace quantity with maximum value of 0.065±0.009 mg.kg<sup>-1</sup> in warak al seder (*Ziziphus spina-christi*). Regarding Hg which is considered as one of the most toxic heavy metals, it was detected in only 9 plants at harmless/negligible concentrations, reaching a maximum value of 0.182±0.002

mg.kg<sup>-1</sup> in beetheran (*Artemisia judaica*) that is even substantially below the MCL safety threshold of 0.20 mg.kg<sup>-1</sup>. The data imply that these metal(loid)s are present at low levels which could be related to the negligible contributions from human or industrial sources at Southern Badia desert and at the traditional shops of the folk healers and to the low soil uptake of these metal(loid)s.

### **3.2. Metals in the Herbs: Predominantly at Safe levels with minor exceptions**

Regarding the metals; Cd, Cr, and Cu, the analyzed plant samples exhibited concentrations below the established maximum contaminant limits with few exceptions that were observed in only five species at concentrations approaching or slightly exceeding the MCLs. Specifically, Cd levels were elevated in kerfeh (*Cinnamomum verum*) and sheeh (*Artemisia vulgaris*) at 0.33±0.04 mg.kg<sup>-1</sup> and 0.43±0.03 mg.kg<sup>-1</sup>, respectively. Cr showed an excess value of 0.76 mg kg<sup>-1</sup> above the MCL in markadosh (*Origanum majorana*). For Cu, heal (*Elettaria cardamomum*) and rihan (*Ocimum basilicum*) exhibited concentrations of 33.90±1.30 mg.kg<sup>-1</sup> and 20.43±1.00 mg.kg<sup>-1</sup>, respectively, approaching or marginally exceeding regulatory MCL (*i.e.* 20.00 mg.kg<sup>-1</sup>).

**Table 3.** Concentrations (mg.kg<sup>-1</sup>±SD) of the measured metal(loid)s in the 28 Jordanian herbal plants presented as a mean (n=3) with corresponding combined uncertainties.  
(\* values given with “<” are below corresponding method limit of quantification MLQ).

| Concentrations of metal(loid)s (mg Kg <sup>-1</sup> ) |                                  |           |             |           |            |             |             |             |             |             |             |               |               |              |
|-------------------------------------------------------|----------------------------------|-----------|-------------|-----------|------------|-------------|-------------|-------------|-------------|-------------|-------------|---------------|---------------|--------------|
| Local Arabic name                                     | Scientific name                  | Cr        | Co          | Ni        | Cu         | As          | Pd          | Cd          | Sb          | Hg          | Pb          | Fe            | Al            | Sr           |
| Beetheran                                             | <i>Artemisia judaica</i>         | 1.18±0.12 | 0.36±0.02   | 1.25±0.03 | 9.07±0.35  | 0.09±0.01   | 0.02±0.01   | 0.06±0.01   | 0.012±0.002 | 0.182±0.002 | 0.94±0.05   | 667.86±25.55  | 602.80±22.06  | 101.76±6.44  |
| karkadeen                                             | <i>Hibiscus sabdariffa</i>       | 0.28±0.03 | 0.26±0.01   | 2.17±0.02 | 4.37±0.37  | 0.03±0.01   | 0.043±0.004 | 0.08±0.01   | <0.01*      | <0.01*      | 0.18±0.01   | 170.66±4.39   | 387.39±16.41  | 90.65±5.98   |
| Osfor                                                 | <i>Carthamus tinctorius</i>      | 1.17±0.14 | 0.23±0.02   | 2.56±0.10 | 15.62±0.70 | 0.060±0.013 | 0.017±0.002 | 0.22±0.03   | 0.021±0.003 | 0.049±0.001 | 0.74±0.04   | 330.10±9.22   | 355.26±17.81  | 16.32±1.00   |
| Helbee                                                | <i>Trigoneila foenum-graceum</i> | 0.97±0.13 | 0.25±0.02   | 2.00±0.02 | 11.01±0.80 | 0.080±0.012 | 0.13±0.02   | 0.038±0.005 | <0.01       | 0.044±0.002 | 0.17±0.01   | 329.51±9.54   | 314.11±12.42  | 219.69±13.78 |
| Babonej                                               | <i>Matricaria chamomilla</i> L   | 0.76±0.09 | 0.48±0.02   | 3.54±0.01 | 18.24±0.64 | 0.054±0.013 | 0.056±0.012 | 0.09±0.01   | <0.01       | 0.025±0.002 | 0.22±0.02   | 380.10±11.48  | 321.60±11.34  | 78.45±4.72   |
| Warak al seder                                        | <i>Ziziphus spina-christi</i>    | 0.43±0.05 | 0.080±0.004 | 0.32±0.01 | 4.43±0.40  | 0.038±0.008 | 0.18±0.03   | 0.015±0.002 | 0.065±0.009 | <0.01       | 0.43±0.02   | 222.36±7.83   | 169.82±12.03  | 358.92±21.44 |
| Yansoon                                               | <i>Pimpinella anisum</i>         | 0.20±0.05 | 0.25±0.03   | 1.13±0.05 | 12.28±0.90 | 0.023±0.006 | 0.016±0.003 | 0.077±0.009 | <0.01       | 0.014±0.001 | 0.040±0.002 | 117.76±4.42   | 81.13±4.70    | 25.66±1.80   |
| Ikeel al jabal                                        | <i>Salvia rosmarinus</i>         | 1.02±0.07 | 0.16±0.01   | 0.49±0.05 | 5.00±0.60  | 0.10±0.02   | 0.027±0.005 | 0.006±0.001 | <0.01       | <0.01       | 0.44±0.03   | 470.56±14.21  | 595.97±34.86  | 47.81±3.50   |
| Kerfeh                                                | <i>Cinnamomum verum</i>          | 0.15±0.02 | 0.14±0.01   | 0.38±0.01 | 5.10±0.61  | 0.03±0.01   | 0.024±0.005 | 0.33±0.04   | <0.01       | 0.021±0.001 | 1.06±0.04   | 69.97±3.51    | 118.64±7.37   | 33.49±2.06   |
| Shomar                                                | <i>Foeniculum vulgare</i>        | 0.17±0.02 | 0.10±0.01   | 0.86±0.06 | 15.14±1.0  | 0.026±0.006 | 0.05±0.01   | 0.006±0.001 | <0.01       | <0.01       | 0.06±0.01   | 108.95±7.04   | 77.56±4.68    | 99.81±6.26   |
| Sheeh                                                 | <i>Artemisia vulgaris</i>        | 0.45±0.05 | 0.12±0.02   | 2.36±0.17 | 9.88±0.95  | 0.05±0.01   | 0.018±0.003 | 0.43±0.03   | <0.01       | 0.021±0.001 | 0.17±0.01   | 173.55±7.94   | 192.15±9.74   | 21.70±1.38   |
| Markadosh                                             | <i>Origanum majorana</i>         | 2.76±0.16 | 0.69±0.03   | 1.80±0.10 | 10.71±1.00 | 0.19±0.03   | 0.20±0.04   | 0.028±0.003 | <0.01       | 0.020±0.003 | 1.50±0.07   | 1334.20±35.14 | 1322.31±72.26 | 565.14±27.91 |
| Kshara                                                | <i>Coriaria sativum</i>          | 0.05±0.01 | 0.072±0.005 | 0.48±0.02 | 11.53±1.00 | <0.01       | 0.012±0.003 | 0.018±0.002 | <0.01       | <0.01       | 0.018±0.002 | 47.85±2.99    | 22.42±2.42    | 14.60±1.20   |
| Karob                                                 | <i>Ceratonia siligra</i>         | 0.03±0.01 | 0.019±0.001 | 0.43±0.03 | 2.36±0.30  | <0.01       | <0.01       | <0.005      | <0.01       | <0.01       | 0.012±0.002 | 20.63±1.96    | 23.98±2.60    | 11.59±1.08   |
| Habet al baraka                                       | <i>Nigella saliva</i>            | 0.04±0.01 | 0.071±.004  | 6.32±0.34 | 14.17±0.50 | 0.031±0.007 | <0.01       | 0.016±0.003 | <0.01       | <0.01       | 0.010±0.001 | 66.15±4.8     | 25.91±1.63    | 11.57±0.90   |
| Gronfi                                                | <i>Syzygium aromaticum</i>       | 0.10±0.02 | 0.03±0.002  | 0.34±0.01 | 3.91±0.20  | <0.01       | 0.033±0.008 | <0.005      | <0.01       | <0.01       | 0.053±0.001 | 47.51±3.10    | 70.64±5.04    | 64.21±3.94   |
| Zanjabeel                                             | <i>Zingiber officinale</i>       | 0.36±0.06 | 1.11±0.07   | 1.02±0.05 | 3.41±0.20  | 0.017±0.004 | <0.01       | 0.022±0.001 | <0.01       | <0.01       | 0.068±0.003 | 144.02±5.39   | 177.19±6.91   | 4.71±0.49    |
| Josef al teab                                         | <i>Myrsitica fragrans</i>        | <0.01     | 0.021±0.002 | 0.48±0.04 | 8.39±0.50  | <0.01       | 0.018±0.004 | 0.005±0.001 | <0.01       | <0.01       | <0.005      | 15.10±1.55    | 54.22±3.54    | 22.16±1.39   |
| Fefel                                                 | <i>Capsicum annuum</i>           | 0.14±0.03 | 0.058±0.004 | 3.22±0.15 | 12.30±0.60 | <0.01       | 0.019±0.005 | <0.005      | 0.040±0.005 | <0.01       | 0.015±0.001 | 62.87±4.60    | 50.22±3.75    | 40.71±2.16   |
| Heal                                                  | <i>Elettaria cardamomum</i>      | 0.05±0.01 | 0.30±0.03   | 0.56±0.04 | 33.90±1.30 | <0.01       | 0.030±0.009 | 0.068±0.008 | <0.01       | <0.01       | 0.35±0.02   | 47.87±4.02    | 44.58±3.13    | 58.94±3.91   |
| Jaadeh                                                | <i>Teucrium polium</i>           | 1.94±0.10 | 0.35±0.02   | 4.34±0.16 | 8.09±0.40  | 0.135±0.025 | 0.052±0.013 | 0.041±0.007 | 0.022±0.003 | <0.01       | 0.58±0.04   | 632.58±16.25  | 673.93±31.22  | 92.31±5.91   |
| Mente                                                 | <i>Mentha sp.</i>                | 1.29±0.06 | 0.43±0.04   | 1.42±0.07 | 12.48±0.50 | 0.078±0.016 | 0.072±0.016 | 0.015±0.002 | 0.031±0.004 | <0.01       | 0.65±0.05   | 754.95±19.21  | 684.08±29.50  | 132.95±7.95  |
| Merameih                                              | <i>Salvia officinalis</i>        | 0.49±0.07 | 0.10±0.01   | 0.48±0.03 | 5.61±0.60  | 0.039±0.009 | 0.011±0.003 | <0.005      | 0.015±0.003 | <0.01       | 0.37±0.03   | 208.68±8.48   | 211.66±15.51  | 17.89±1.45   |
| Rejlel hamameh                                        | <i>Paronychia argentea</i>       | 1.11±0.07 | 0.14±0.01   | 1.18±0.04 | 3.93±0.40  | 0.054±0.011 | 0.023±0.006 | 0.072±0.009 | 0.011±0.002 | <0.01       | 0.28±0.02   | 273.56±10.43  | 331.68±15.16  | 37.51±2.28   |
| Ghapaper                                              | <i>Laurus nobilis</i>            | 0.22±0.03 | 0.03±0.01   | 0.86±0.01 | 3.49±0.30  | 0.016±0.004 | <0.01       | 0.034±0.004 | <0.01       | <0.01       | 0.23±0.01   | 72.36±6.58    | 69.45±2.95    | 4.90±0.60    |
| Zaatar                                                | <i>Thymus vulgaris</i>           | 1.13±0.04 | 0.23±0.01   | 2.62±0.14 | 9.14±0.60  | 0.087±0.018 | 0.020±0.006 | 0.019±0.003 | <0.01       | <0.01       | 0.36±0.02   | 483.83±20.63  | 561.35±31.29  | 34.77±2.63   |
| Kammon                                                | <i>Cuminum cyminum</i>           | 0.30±0.04 | 0.11±0.01   | 1.18±0.04 | 7.63±0.70  | 0.026±0.005 | 0.022±0.005 | 0.026±0.003 | <0.01       | <0.01       | 0.070±0.007 | 127.95±7.32   | 126.74±7.35   | 36.27±2.23   |
| Rihan                                                 | <i>Ocimum basilicum</i>          | 1.80±0.13 | 0.71±0.03   | 1.33±0.07 | 20.43±1.00 | 0.096±0.017 | 0.15±0.03   | 0.026±0.004 | <0.01       | 0.089±0.014 | 0.94±0.06   | 836.54±25.68  | 757.12±41.18  | 241.44±18.09 |

### 3.3. Metals Exhibiting Substantial Levels in all Herbs

Herein, Ni levels exceeded MCL (i.e. 0.30 ppm) [77] in all plant samples, ranging from  $0.320 \pm 0.001 \text{ mg.kg}^{-1}$  in warak al seder (*Ziziphus spina-christi*) to  $6.32 \pm 0.34 \text{ mg.kg}^{-1}$  in habet al baraka (*Nigella sativa*). Ni is an essential micronutrient required in trace amounts for plant growth and metabolism; however, excessive Ni can disrupt the uptake of other plant's nutrients such as Fe, Mg, Ca, and Zn causing metabolic imbalances and reduced productivity [80].

Aluminum concentrations varied widely among the analyzed plants, while its level was notably higher than MCL (i.e.  $5.00 \text{ mg.kg}^{-1}$ ) [77] in all plants ranging from  $22.42 \pm 2.42 \text{ mg.kg}^{-1}$  in ksbara (*Coriandrum sativum*) to an exceptionally high  $1322.31 \pm 72.26 \text{ mg.kg}^{-1}$  in markadosh (*Origanum majorana*). Rihan (*Ocimum basilicum*), mente (*Mentha sp*), jaadeh (*Teucrium polium*), beetheran (*Artemisia judaica*), ikleel al jabal (*Salvia rosmarinus*) and zaatar (*Thymus vulgaris*) exhibited elevated Al levels, exceeding several hundred  $\text{mg.kg}^{-1}$  at ( $757.12 \pm 41.18$ ), ( $684.04 \pm 29.50$ ), ( $673.93 \pm 31.22$ ), ( $602.8 \pm 22.06$ ), ( $595.97 \pm 34.86$ ) and ( $561.35 \pm 31.29$ )  $\text{mg.kg}^{-1}$ , respectively. Other plants recorded concentrations of Al between 200-400  $\text{mg.kg}^{-1}$ , such as karkadeen (*Hibiscus sabdariffa*), osfor (*Carthamus tinctorius*), helbee (*Trigonella foenum-graceum*), babonej (*Matricaria chamomilla*), meramieh (*Salvia officinalis*) and rejel hamameh (*Paronychia argentea*). The remaining 15 plants showed low Al concentrations (i.e. below  $200 \text{ mg.kg}^{-1}$ ) in comparison to the other plants, yet still exceeding the MCL of  $5 \text{ mg.kg}^{-1}$ .

Ten plant species among the 28 revealed a high Fe content exceeding the MCL (i.e.  $300 \text{ mg.kg}^{-1}$ ). Markadosh (*Origanum majorana*) exhibited the highest Fe level among all plants with  $\approx 4.4 \times \text{MCL}$ , while beetheran (*Artemisia judaica*), jaadeh (*Teucrium polium*), mente (*Mentha sp.*), and rihan (*Ocimum basilicum*) had levels of  $2\text{--}3 \times \text{MCL}$ . For osfor (*Carthamus tinctorius*), helbee (*Trigonella foenum-graecum*), babonej (*Matricaria chamomilla*), ikleel al jabal (*Salvia rosmarinus*), and zaatar (*Thymus vulgaris*), their levels were near or slightly above the MCL. Iron is an essential micronutrient, critical for photosynthesis, respiration, chlorophyll synthesis, and enzyme activation, acting as a cofactor in redox reactions. Plants acquire Fe from soil minerals (i.e. iron oxides and sulfides) where Fe uptake in plants from the soil occurs via Strategy I (reduction-based, dicots and non-grass monocots) or Strategy II (chelation-based, grasses) mechanisms [81]. The current outcomes are consistent with the results reported by Abu-Darwish, who found that Fe had the highest levels ( $128.27\text{--}979.64 \text{ mg/kg}$ ), where, the maximum level observed in the present study was  $1334.20 \text{ mg/Kg}$  which is higher than the one reported in the previous study [82].

Regarding Sr, its content in the examined plants showed considerable variations, with 12 species exceeding the MCL (i.e. 50 mg.kg<sup>-1</sup>). Among all plants, those with the highest Sr level; markadosh (*Origanum majorana*) and warak al seder (*Ziziphus spina-christi*) have concentration of 365.14±27.91 and 358.92±21.44 mg.kg<sup>-1</sup>, respectively, followed by rihan (*Ocimum basilicum*), helbee (*Trigonella foenum-graceum*), mente (*Mentha sp.*), beetheran (*Artemisia judaica*), shomar (*Foeniculum vulgare*), jaadeh (*Teucrium polium*), karkadeen (*Hibiscus sabdariffa*), babonej (*Matricaria chamomilla L*), gronfl (*Syzygium aromaticum*) and heal (*Elettaria cardamomum*) with concentrations between 58.94±3.91 and 241.44±18.09 mg.kg<sup>-1</sup>. Conversely, 16 plants of the species exhibited concentrations below the MCL. This variation in Sr content likely reflects differences in: the metal(loid)s soil uptake mechanisms, soil bioavailability among the species, human or industrial sources at Southern Badia desert and in the traditional shops of the folk healers.

#### **3.4. Environmental and Plant-Specific Factors Governing Metal(loid) Levels**

Regarding As, Co, Hg, Pb, Pd and Sb, these metal(oids) occur naturally in the environment but are also significantly influenced by anthropogenic activities. Arsenic is released naturally through the weathering of arsenic-bearing minerals such as arsenopyrite and realgar, as well as via volcanic emissions, geothermal activities, and leaching from soils and rocks into groundwater [83]. Human activities, including the use of arsenic-based pesticides, mining, smelting, fossil fuel combustion, and improper disposal of industrial effluents into the soil, further enhance its environmental presence [84]. These results are consistent with the findings of Abu-Darwish et al., who reported that As, Hg, and Pb levels were below the maximum contaminant limits (MCLs) in several herbal plants in Jordan [20].

According to cobalt, it is naturally occurring in minerals such as cobaltite and erythrite and in soils derived from mafic and ultramafic rocks, in addition to human-induced contributions that include mining, refining, alloy production, pigments, battery manufacturing, and waste disposal [85].

Mercury is mobilized naturally through volcanic eruptions, forest fires, geothermal activity, and weathering of cinnabar (HgS) [86]. In contrast, anthropogenic emissions primarily originate from coal combustion, gold and silver mining, chlor-alkali production, cement and paint manufacturing, and the improper disposal of mercury-containing products [86].

In reference to lead, it is found naturally in galena (PbS) and other lead-containing minerals and soils, with volcanic activity contributing to its baseline levels, while anthropogenic sources include historical use of leaded gasoline, battery production, smelting, paints, fertilizers, and plumbing materials could also produce Pb [85].

Palladium is a platinum-group element, naturally originates from the weathering of ultramafic rocks and Platinum Group Elements (PGEs)-containing ores, while anthropogenic is also considered as sources of Pd, primarily include automobile catalytic converters, electronic waste, dental materials, jewelry, and industrial catalysts [87].

Antimony occurs naturally in minerals such as stibnite ( $\text{Sb}_2\text{S}_3$ ) and is released via volcanic activity and rock weathering; in addition to the anthropogenic contributions that arise from mining, smelting, flame retardants, batteries, pigments, glass production, and combustion of coal and waste [88].

Concerning copper, it originates from both **natural and anthropogenic sources**. Cu is released into the soil through the **weathering of parent rock material**, including sulfide, oxide, and carbonate minerals and depends on the plant physiology. Certain plant such as basil (*Ocimum basilicum*) exhibits an efficient ability to absorb and regulate essential micronutrients, particularly Cu. Studies indicate that basil selectively accumulates Cu in roots and leaves, where phenolic compounds and essential oils chelate Cu ions to enhance stability [89]. It is important to mention here that Cu presence at a safe level supports the biosynthesis of essential oil and the enzymatic activity in plants, contributing to enhance the plant's medicinal and aromatic properties [89]. In the same context, cardamom (*Elettaria cardamomum*) accumulates Cu due to its high micronutrient uptake efficiency and chelation by flavonoids and tannins [90], this explains the results of the study, which showed that cardamom (*Elettaria cardamomum*) exhibited the highest Cu concentration. Herein, the result agreed with Abu-Darwish et al., who confirmed that some plants such as *herba-alba* contained high Cu level due to its ability to accumulate Cu. The aerial tissues of some herbs can accumulate Cd and Cr through atmospheric deposition of dust and particulate matter during growth, drying, or processing, thereby contributing to the overall Cr and Cd load. Additionally, the natural geochemical background, including the bedrock and soils, may contain Cd as a trace element, which can become more bioavailable under specific conditions such as erosion or wind-mediated redistribution, as reported in studies from central Jordan [91, 92]. Cd accumulation in kerfeh (*Cinnamomum verum*) and in sheeh (*Artemisia vulgaris*) likely results from non-specific plant uptake from the soil via transporters for essential cations such as

$\text{Zn}^{2+}$  and  $\text{Fe}^{2+}$  [93]. These species exhibit tolerances to low concentrations of Cd primarily through root-level chelation and sequestration mechanisms mediated by phenolic and flavonoid compounds and stabilize them within some plant tissues. Additionally, species-specific physiological and metabolic traits in certain *Lamiaceae* plants rather than other plants may promote the uptake or retention of trace metals, contributing to Cr accumulation in *Origanum majorana* [94] as revealed in our study.

Overall, the consistently undetectable or low concentrations of As, Cd, Co, Cr, Cu Hg, Pb, Pd, and Sb observed in the Southern Badia region can be attributed to the combined influence of geological background, minimal anthropogenic inputs, low plant ingestion level from the soil and the arid-soil conditions characteristic of this area [95-98] due to the following reasons as proved by previous published articles: first, the Badia's soils are derived from calcareous, sandy to loamy parent materials with naturally low heavy-metals and meta(loids) content and weak metal enrichment, and the relatively alkaline pH typical of such soils promotes some metal precipitation or sorption, thereby reducing bioavailability in or uptake by plants. Second, the region lacks large urban centers, which in other regions drive elevated soil and plant metal burdens through emissions, waste disposal or vehicle catalyst leaching [78, 97]. Third, the semi-arid climate, low rainfall and high evaporation rates reduce metal mobility, leaching and redistribution, thereby limiting plant uptake of trace elements [95-98]. Finally, vegetation in rangeland or species may possess metal exclusion mechanisms, further constraining accumulation of non-essential toxic elements such as Hg, Pb or Pd. Together, these factors explain why the analyzed plants from studied areas show metal concentrations far below MCLs contamination thresholds and international standards.

Elevated nickel concentrations in plants are determined by soil composition, environmental factors, atmospheric dust deposition, and species-specific accumulation traits. Soils in the Badia are typically arid, calcareous, and derived from ultramafic or serpentine lithologies, which inherently contain high nickel levels, thereby enhancing its bioavailability in the soil solution [79]. Arid conditions, characterized by low rainfall and high evaporation such as Southern Badia in Jordan, further concentrate soluble Ni, enhancing plant uptake from the soil. Additionally, certain species with bioaccumulation or hyperaccumulation tendencies efficiently absorb and store Ni through metal transporters that normally facilitate essential micronutrient uptake.

High Fe concentrations in plants likely reflect the influence of the geological and environmental characteristics of the Southern Badia, including calcareous semi-arid soils, Fe-rich substrates, low

rainfall, localized soluble Fe, anthropogenic inputs, and high evaporation. Plant physiology, secondary metabolism, atmospheric dust, and Strategy I-mediated Fe uptake—facilitated by phenolics, flavonoids, and organic acids—also contribute. Efficient Fe transporters and ferritin storage enable accumulation, supporting metabolic processes and the synthesis of secondary metabolites [99].

For Al, it originates from both natural (geogenic) and anthropogenic sources. Geogenic sources primarily include the parent rocks of local soils such as basalts, limestone, and shales which contain Al within aluminosilicates and clay minerals including kaolinite, illite, and montmorillonite. Weathering of these minerals under arid and semi-arid conditions releases Al into the soil solution, although the process is generally slow in alkaline soils. Although soils in the Badia region are typically alkaline (pH ~7.5–8.5), localized micro-sites with lower pH, organic matter accumulation, or root exudates can lead to acidification, which increases Al solubility and bioavailability [79, 100].

Soil redox conditions, particularly in areas with fluctuating moisture, may also affect Al mobilization by altering the solubility of Al hydroxides.

Plant-specific factors further influence Al uptake. Many plants exude organic acids such as citrate, malate, and oxalate from their roots, which chelate Al and increase its mobility from otherwise insoluble mineral pools. Additionally, Al can be absorbed foliar from deposited dust, particularly in regions exposed to windblown soil particles rich in Al-containing minerals. Certain plant species exhibit physiological adaptations that allow sequestration of Al in vacuoles or binding with organic ligands, reducing its toxicity while allowing accumulation in tissues. Anthropogenic contributions, though minor compared to geogenic sources in the Badia, may include atmospheric deposition from industrial emissions, fertilizers, and irrigation water containing Al residues. Collectively, these factors explain the variable but often elevated Al concentrations observed in local medicinal and edible plants.

Jordan's Badia region, elevated Sr levels in 12 plants are linked to calcareous, arid soils derived from Sr-rich carbonate and gypsum formations [85]. Limited rainfall and high evaporation rates enhance Sr solubility in the soil, while deep-rooted desert plants access Sr-enriched layers. Due to its chemical similarity to Ca, Sr is absorbed via Ca transport pathways, especially in plants with high Ca demand [85].

In addition to the above sources, the Southern Jordanian Badia region has extensive industrial activities including phosphate mining and processing facilities (e.g., Al-Hisa, Al-Shidiya, and Al-Abyad) and cement manufacturing plants (e.g., Rashadiya and Al-Qadisiya) which substantially may increase the concentrations of certain metal(loid)s, particularly Al, Fe, Ni, and Sr, in soils and native vegetation. These increases occur through direct atmospheric deposition, surface runoff from adjacent areas, and wind-borne dust from the mining and processing facilities or through the transportation of phosphate and cement, which also facilitates long-range transport of contaminated particles, thereby impacting air quality and elevating plant exposure to pollutants [101].

Phosphate extraction and processing involve crushing and grinding ore rich in trace metals, producing large amounts of dust containing fine metal particles that can disperse through the atmosphere and settle on nearby soils and plant surfaces. Liquid and solid wastes from phosphate facilities often contain elevated levels of Al and Ni, increasing the risk of leaching into soils and groundwater. Cement production also contributes to metal enrichment through dust emissions generated during the calcination of limestone and clay, the use of additives containing iron and aluminum oxides, and the combustion of fossil fuels in kilns, which can further elevate Ni contamination. Particulate matter from these industrial activities can be transported over long distances and deposited onto agricultural soils, increasing concentrations of Al, Fe, Ni, and Sr in both soils and plant tissues. Such metal enrichment alters soil chemistry and enhances plant uptake of these metal(oids), particularly under the arid to semi-arid, alkaline soil conditions characteristic of the region [85].

In fact, Al, Ni, Fe and Sr can impact human health depending on exposure levels [32]. Chronic Al exposure is linked to neurotoxicity, bone disorders, and renal complications, particularly in individuals with impaired kidney function. For, Ni it can cause allergic reactions, respiratory irritation, organ accumulation, and certain compounds are carcinogenic. While Fe is essential for oxygen transport and metabolism, excessive accumulation leads to oxidative stress, organ damage, and impaired immune function. According to Sr, it generally exhibits low toxicity, but excess can interfere with bone mineralization, particularly in juveniles, whereas radioactive isotopes pose significant skeletal risks.

### 3.5. Comparative Statistical analysis

This section presents a comparative analysis of metal(loid) concentrations in Jordanian medicinal and edible plants. Figures 1 and 2 display the PCA and HCA outcomes derived from the metal(loid) levels presented in Table 3. PCA revealed that two principal components explained 99.16% of the total variance, indicating strong intercorrelations among the 13 measured variables and demonstrating the suitability of PCA for distinguishing the plants based on their metal(loid) accumulation patterns.

The PCA score and loading plots (Figure 1A–B) clearly indicate that Al, Fe, and Sr are the principal drivers of sample separation. Correspondingly, HCA (Figure 2) classified the 28 species into four major clusters. Clusters I and III each contain only a single species, cluster II includes six species, and cluster IV encompasses the remaining twenty species. This distribution highlights the presence of distinct metal(loid) accumulation behaviors among certain plants, while the majority exhibit broadly similar profiles.

The most prominent outcome is that *Origanum majorana* (markadosh) forms a unique cluster (Cluster I). This species exhibited exceptionally high concentrations of Al ( $1322.31 \pm 72.26 \text{ mg}\cdot\text{kg}^{-1}$ ;  $\approx 264\times$  MCL), Fe ( $1334.20 \pm 35.14 \text{ mg}\cdot\text{kg}^{-1}$ ;  $\approx 4.4\times$  MCL), and Sr ( $365.14 \pm 27.91 \text{ mg}\cdot\text{kg}^{-1}$ ;  $\approx 7\times$  MCL). Although Al and Sr were also elevated, the loading plot suggests that Fe contributed most strongly to its distinct separation. The extremely high metal(loid) accumulation in this species may relate to its specific root physiology, greater rhizosphere adsorption capacity, or its natural bioaccumulation tendency, which has been reported in some aromatic and essential-oil-producing plants. Its unique clustering underscores its potential as a bio-indicator species for Fe- and Al-rich soils.

Following the pattern of markadosh but at lower magnitudes, *Ocimum basilicum* (rihan) also displayed elevated Al ( $757.12 \pm 41.18 \text{ mg}\cdot\text{kg}^{-1}$ ) and Fe ( $836.54 \pm 25.68 \text{ mg}\cdot\text{kg}^{-1}$ ). Although rihan shares high concentrations of these metals, its relatively lower levels compared to *O. majorana* allow it to cluster with other moderately enriched plants. For Sr, the highest level was observed in *Ziziphus spina-christi* (warak al seder) at  $358.92 \pm 21.44 \text{ mg}\cdot\text{kg}^{-1}$ , similar to *O. majorana* ( $365.14 \pm 27.91 \text{ mg}\cdot\text{kg}^{-1}$ ).

Cluster II comprises six species, *O. basilicum*, *Mentha* sp., *Teucrium polium*, *Artemisia judaica*, *Salvia rosmarinus*, and *Thymus vulgaris*. All of these exhibit elevated Al and Fe levels, but Al,

often exceeding several hundred  $\text{mg}\cdot\text{kg}^{-1}$ , showed a stronger loading contribution than Fe. This indicates that Al was the dominant element influencing the grouping of these species. Many of these plants are perennial herbs with known capacities for accumulating minerals from calcareous soils, which aligns with the observed clustering pattern.

Cluster III consists solely of *Z. spina-christi*, which exhibited high concentrations of both Al and Sr, the latter being the second-highest among all plants. It formed its own cluster primarily due to its distinctive Sr enrichment, although its proximity to Cluster IV in the dendrogram suggests that its overall metal(loid) profile remains partially similar to the group of plants with moderate-to-low concentrations.

Cluster IV contains the remaining twenty species, all of which showed broadly similar and comparatively lower concentrations of the studied metal(loid)s. For these plants, As, Co, Hg, Pb, Pd, and Sb were either not detected or consistently below their respective MCLs. Cd, Cr, and Cu were also below MCLs in most species, except for a few instances where five species had concentrations near or slightly above the permissible limits. Ni, however, exceeded the MCL in all species, indicating widespread accumulation likely influenced by soil geochemistry or atmospheric deposition.

The clustering pattern observed in the multivariate analysis emphasizes that Al, Fe, and Sr were the main discriminating elements across the dataset. These elements demonstrated the widest concentration ranges and the strongest contributions to both PCA and HCA separation. Their influence reflects underlying environmental factors—such as soil mineralogy, particularly in the calcareous and semi-arid soils of the region—as well as plant-specific uptake mechanisms.

Overall, the statistical outcomes confirm that metal(loid) accumulation in these Jordanian plants is not random but structured into recognizable patterns driven primarily by Al, Fe, and Sr availability and uptake. These findings provide critical insight into plant–soil interactions in arid ecosystems and highlight the potential of certain species, particularly *O. majorana*, *O. basilicum*, and *Z. spina-christi*, to serve as bio-indicators for metal-rich environments.

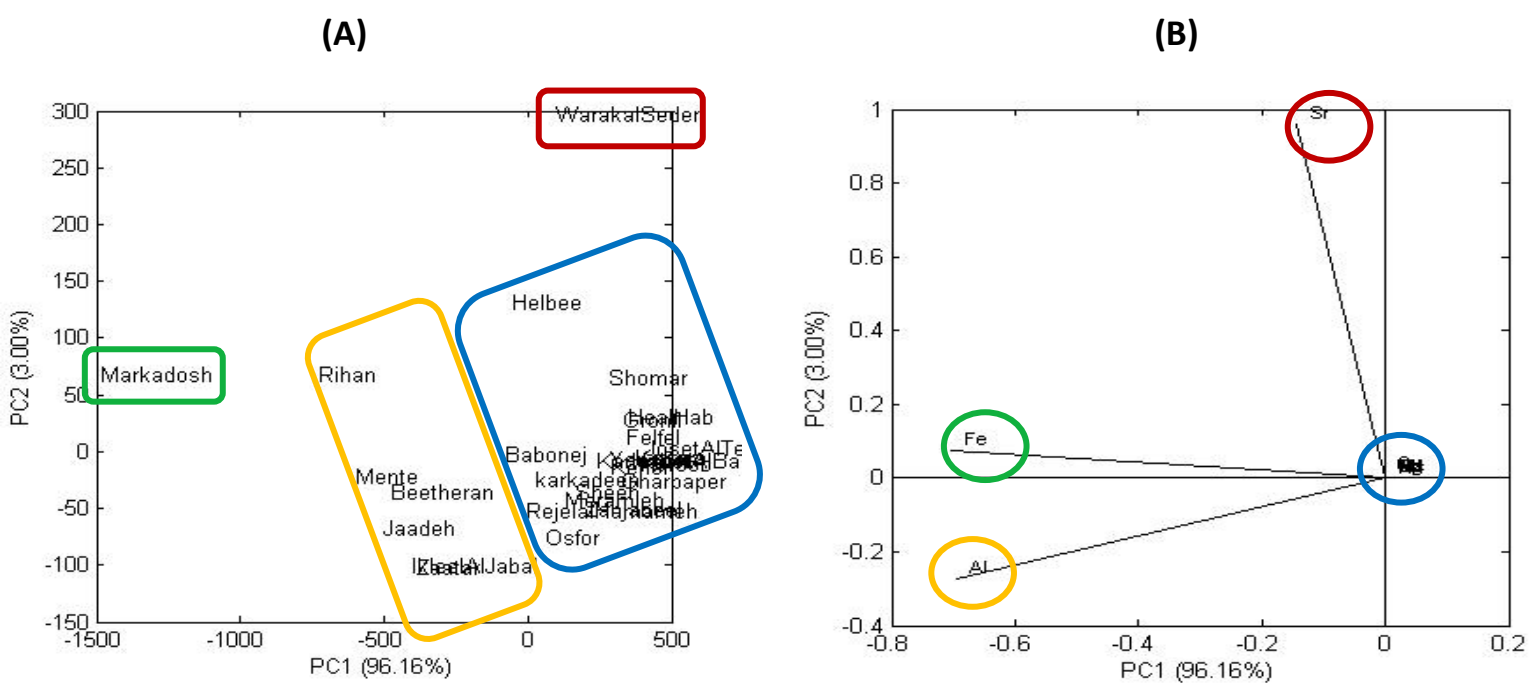


**Figure 1.** Principal component analysis (PCA) outcomes: A) score and B) loading plots of the 28 Jordanian plants.

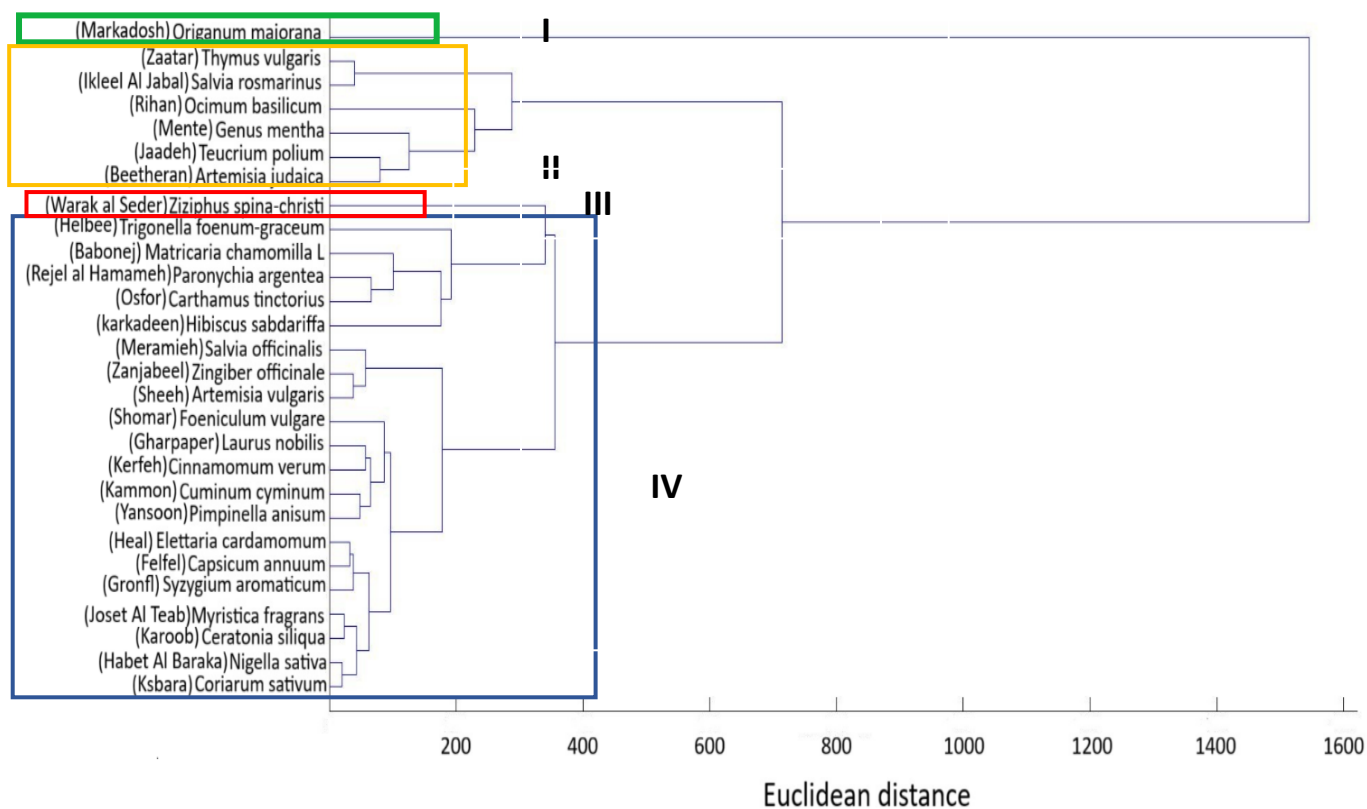


**Figure 2.** Dendrogram based on average linkage clustering identified four distinct clusters among the 28 Jordanian plants: clusters I and III each contained a single plant, cluster II comprised six plants, and cluster IV included the remaining twenty plants.

### 3.6. Human Health Risk Assessment outcomes

Table 4. presents the **EDI** and **THQ** for selected metals (Al, Fe, Ni and Sr) across 28 commonly consumed medicinal and culinary plants. The EDI values provide a measure of daily exposure to these metals per kilogram of body weight, while THQ indicates potential non-carcinogenic health risks, with values above 1 suggesting possible concern [102, 103].

From the data, **Sr** exhibits the highest THQ in several species, notably *Origanum majorana* (THQ = 5.018), *Mentha sp.* (THQ = 2.593), and *Teucrium polium* (THQ = 2.558), indicating that chronic consumption of these plants could pose a potential health risk regarding strontium intake. Conversely, plants such as *Coriaria sativum* and *Ceratonia siliqua* show very low Sr EDIs and THQs (<0.1), suggesting negligible risk.

**For Al**, EDIs range widely, with *Origanum majorana* again showing the highest THQ (0.082), though all THQ values for Al remain below 1, indicating low non-carcinogenic risk. **Iron (Fe)**, an essential nutrient, exhibits moderate EDI levels across most species, with THQs consistently below 0.1, confirming that dietary intake from these plants is unlikely to cause toxicity. **Nickel** presents very low EDIs and THQs (<0.02) across all species, suggesting minimal risk from oral consumption of these plants. Overall, the data suggest that **strontium is the primary metal of concern**, particularly in *Origanum majorana*, *Mentha sp.*, and *Teucrium polium*, whereas Al, Fe, and Ni do not pose significant non-carcinogenic risks based on THQ values. These findings emphasize the importance of monitoring metal content in medicinal and culinary plants, particularly for metals like strontium that can accumulate and potentially exceed safe intake levels in frequent consumers.

**Table 4.** Estimated Daily Intake (EDI) and Target Hazard Quotients (THQ) for Aluminum, Iron, Nickel and Strontium from plants consumed by adults according to the reference dose RfD with EPA.

| Plant name                       | EDI <sub>Sr</sub>                         | EDI <sub>Al</sub>                         | EDI <sub>Fe</sub>                         | EDI <sub>Ni</sub>                         | THQ <sub>Sr</sub> | THQ <sub>Al</sub> | THQ <sub>Fe</sub> | THQ <sub>Ni</sub> |
|----------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------------------------------|-------------------|-------------------|-------------------|-------------------|
|                                  | (mg.kg <sup>-1</sup> .day <sup>-1</sup> ) | (mg.kg <sup>-1</sup> .day <sup>-1</sup> ) | (mg.kg <sup>-1</sup> .day <sup>-1</sup> ) | (mg.kg <sup>-1</sup> .day <sup>-1</sup> ) |                   |                   |                   |                   |
| <i>Artemisia judaica</i>         | 0.004                                     | 0.026                                     | 0.029                                     | 0.00005                                   | 0.007             | 2.283             | 0.041             | 0.0200            |
| <i>Hibiscus sabdariffa</i>       | 0.004                                     | 0.017                                     | 0.007                                     | 0.00009                                   | 0.006             | 1.469             | 0.010             | 0.0047            |
| <i>Carthamus tinctorius</i>      | 0.001                                     | 0.015                                     | 0.014                                     | 0.00011                                   | 0.001             | 1.345             | 0.020             | 0.0055            |
| <i>Trigonella foenum-graceum</i> | 0.009                                     | 0.014                                     | 0.014                                     | 0.00009                                   | 0.016             | 1.195             | 0.020             | 0.0043            |
| <i>Matricaria chamomilla L</i>   | 0.003                                     | 0.014                                     | 0.016                                     | 0.00015                                   | 0.006             | 1.221             | 0.023             | 0.0076            |
| <i>Ziziphus spina-christi</i>    | 0.015                                     | 0.007                                     | 0.010                                     | 0.00001                                   | 0.026             | 0.644             | 0.014             | 0.0007            |
| <i>Pimpinella anisum</i>         | 0.001                                     | 0.003                                     | 0.005                                     | 0.00005                                   | 0.002             | 0.308             | 0.007             | 0.0024            |
| <i>Salvia rosmarinus</i>         | 0.002                                     | 0.026                                     | 0.020                                     | 0.00002                                   | 0.003             | 2.265             | 0.029             | 0.0011            |
| <i>Cinnamomum verum</i>          | 0.001                                     | 0.005                                     | 0.003                                     | 0.00002                                   | 0.002             | 0.450             | 0.004             | 0.0008            |
| <i>Foeniculum vulgare</i>        | 0.004                                     | 0.003                                     | 0.005                                     | 0.00004                                   | 0.007             | 0.295             | 0.007             | 0.0018            |
| <i>Artemisia vulgaris</i>        | 0.001                                     | 0.008                                     | 0.007                                     | 0.00010                                   | 0.002             | 0.729             | 0.011             | 0.0051            |
| <i>Origanum majorana</i>         | 0.002                                     | 0.057                                     | 0.057                                     | 0.00008                                   | 0.003             | 5.018             | 0.082             | 0.0039            |
| <i>Coriaria sativum</i>          | 0.001                                     | 0.001                                     | 0.002                                     | 0.00002                                   | 0.001             | 0.085             | 0.003             | 0.0010            |
| <i>Ceratonia siliqua</i>         | 0.000                                     | 0.001                                     | 0.001                                     | 0.00002                                   | 0.001             | 0.091             | 0.001             | 0.0009            |
| <i>Nigella sativa</i>            | 0.000                                     | 0.001                                     | 0.003                                     | 0.00027                                   | 0.001             | 0.098             | 0.004             | 0.0136            |
| <i>Syzygium aromaticum</i>       | 0.003                                     | 0.003                                     | 0.002                                     | 0.00001                                   | 0.005             | 0.268             | 0.003             | 0.0007            |
| <i>Zingiber officinale</i>       | 0.000                                     | 0.008                                     | 0.006                                     | 0.00004                                   | 0.000             | 0.672             | 0.009             | 0.0022            |
| <i>Myristica fragrans</i>        | 0.001                                     | 0.002                                     | 0.001                                     | 0.00002                                   | 0.002             | 0.206             | 0.001             | 0.0010            |
| <i>Capsicum annum</i>            | 0.002                                     | 0.002                                     | 0.003                                     | 0.00014                                   | 0.003             | 0.191             | 0.004             | 0.0070            |
| <i>Elettaria cardamomum</i>      | 0.003                                     | 0.002                                     | 0.002                                     | 0.00002                                   | 0.004             | 0.169             | 0.003             | 0.0012            |
| <i>Teucrium polium</i>           | 0.004                                     | 0.029                                     | 0.027                                     | 0.00019                                   | 0.007             | 2.558             | 0.039             | 0.0094            |
| <i>Mentha sp.</i>                | 0.006                                     | 0.029                                     | 0.032                                     | 0.00006                                   | 0.010             | 2.593             | 0.046             | 0.0031            |
| <i>Salvia officinalis</i>        | 0.001                                     | 0.009                                     | 0.009                                     | 0.00002                                   | 0.001             | 0.803             | 0.013             | 0.0010            |
| <i>Paronychia argentea</i>       | 0.002                                     | 0.014                                     | 0.017                                     | 0.00005                                   | 0.003             | 1.257             | 0.024             | 0.0025            |
| <i>Laurus nobilis</i>            | 0.000                                     | 0.003                                     | 0.003                                     | 0.00004                                   | 0.000             | 0.264             | 0.004             | 0.0018            |
| <i>Thymus vulgaris</i>           | 0.001                                     | 0.024                                     | 0.021                                     | 0.00011                                   | 0.002             | 2.133             | 0.030             | 0.0057            |
| <i>Cuminum cyminum</i>           | 0.002                                     | 0.005                                     | 0.005                                     | 0.00005                                   | 0.003             | 0.481             | 0.008             | 0.0025            |
| <i>Ocimum basilicum</i>          | 0.000                                     | 0.033                                     | 0.036                                     | 0.00006                                   | 0.000             | 2.876             | 0.051             | 0.0029            |

#### 4. Conclusion

This study provides a comprehensive assessment of 13 metal(oids) in 28 medicinal and edible plants from Jordan, revealing species-specific accumulation patterns influenced by environmental and physiological factors. Toxic elements such as As, Co, Hg, Pb, Pd, and Sb were negligible, indicating minimal contamination, while Cd, Cr, and Cu were generally within safe levels, while

Ni, Al, Fe, and Sr frequently exceeded regulatory limits due to natural soil composition, arid climate, plant-specific uptake, and potentially local industrial activities. Multivariate analysis identified Al, Fe, and Sr as key drivers of plant clustering. The results provide a detailed understanding of metal(loids) accumulation patterns, identifying species with relatively lower toxic metal(loids) levels and greater suitability for safe consumption. This study also represents an important step toward promoting the safe use of medicinal and culinary herbs, supporting public health, and guiding strategies to minimize human exposure to potentially harmful metal(loids). Moreover, understanding the sources, mobility, and bioaccumulation patterns of metal(loids) in plants is crucial for assessing environmental contamination and ensuring the safety of herbal products intended for human use. Finally, certain plant species identified in this study as exhibiting high accumulation of metal(loid)s could be explored in future research as bioindicators to monitor environmental contamination, providing a practical tool for assessing soil quality and pollution levels in arid regions. The current study focused on total metal(loid) concentrations without evaluating their bioavailability or speciation, which are critical for assessing actual health risks. Future research should include larger-scale and multi-season sampling to capture temporal and spatial variability. Investigating the bioavailability and chemical speciation of metal(loids) in plants could provide a more accurate risk assessment for human consumption. Moreover, controlled experimental studies could help disentangle environmental versus physiological drivers of metal(loid) uptake. Certain plant species identified as high accumulators could be further explored as bioindicators to monitor environmental contamination, offering practical tools for assessing soil quality and pollution levels in arid regions. Expanding research to include potential remediation strategies or soil amendments could also support safer cultivation of medicinal and edible plants.

## **Acknowledgements**

This project was implemented thanks to the financial support provided by (1) L'Agence Universitaire de la Francophonie-Moyen Orient (AUF - Moyen Orient), 2) 25% funding by European Union-Next Generation EU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.004-0001-C01, 3) The University of Jordan, 4) Elsevier Foundation and 5) Schlumberger Foundation.

## **Disclosure statement**

The authors declare that there are no conflicts of interest regarding the publication of this paper.

## Data availability statement

All data generated or analyzed during this study are included in this published manuscript.

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