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Heavy metal contamination in Albanian *Origanum vulgare* L. and *Salvia officinalis* L.

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ABSTRACT

Medicinal and aromatic plants are widely used in pharmaceutical, food, and cosmetic products, so their chemical safety and quality are essential to ensure therapeutic efficacy and protect consumer health. This study evaluated the concentration of selected trace and potentially toxic elements in two commonly used medicinal plants, *Origanum vulgare* L. and *Salvia officinalis* L., collected from different regions of Albania. Twelve samples were analysed for cadmium (Cd), nickel (Ni), chromium (Cr), aluminium (Al), lead (Pb) and copper (Cu). Elemental determination was performed using graphite furnace atomic absorption spectrometry (GF-AAS), after microwave-assisted digestion following the USEPA 3052 protocol, with quality assurance procedures in accordance with the internationally accepted guidelines for medicinal plant analysis. The results indicated that most of the analysed samples complied with the permissible limits established by FAO/WHO for heavy metals in medicinal plants. Al was the most abundant element in both species, with concentrations ranging from 43.96 mg/kg to 213.23 mg/kg in *S. officinalis* and from 34.14 mg/kg to 129.14 mg/kg in *O. vulgare*. Although elevated, aluminium levels likely reflect natural geogenic origin, rather than anthropogenic contamination. Cu and Cr were detected at moderate concentrations (Cu: 3.57–4.25 mg/kg and Cr: 1.23–7.85 mg/kg in *S. officinalis*; Cu: 4.32–7.29 mg/kg and Cr: 0.27–1.81 mg/kg in *O. vulgare*), remaining within acceptable limits. Pb and Cd were present only at trace levels in all analysed samples. The Ni levels exceeded the recommended limit in both *S. officinalis* (1.09–7.47 mg/kg), and *O. vulgare* samples (1.73–7.41 mg/kg), suggesting a possible contamination of the plants. The non-carcinogenic risk assessment, based on target hazard quotient (THQ) and hazard index (HI), showed values well below the safety threshold, with a resulting HI of 0.096 for *S. officinalis* and 0.055 for *O. vulgare*. Therefore, from a pharmaceutical safety perspective, these results suggest a low estimated non-carcinogenic risk under the defined exposure conditions.

Keywords: medicinal plants, heavy metals, trace elements, human health risk assessment, *Salvia officinalis, Origanum vulgare.*

INTRODUCTION

Medicinal and aromatic plants are gaining increasing interest due to their extensive use in the food, pharmaceutical, and cosmetic industries. Consequently, the quality and safety of these plants represent a current issue for consumer health. Among the medicinal plant species widely used by the Albanian population, and also exported abroad, are *Origanum vulgare* L. and *Salvia officinalis* L.

Origanum vulgare L. belongs to the Lamiaceae family, is a well-known medicinal and aromatic plant recognized for its traditional therapeutic properties as well as its culinary applications. *O. vulgare* is considered a polymorphic species with several subspecies that differ in morphological characteristics, particularly in the structure of their reproductive organs, the site of essential oil accumulation, and also in their composition [1].

The genomic and cytogenetic analyses of *O. vulgare* across the Balkan region have revealed high levels of genetic variability, combined with a relatively small yet remarkably stable genome among populations. The presence of well-defined population structures highlights the existence of distinct and traceable genetic groups shaped by local evolutionary pressures. This knowledge provides a solid basis for understanding how *O. vulgare* populations adapt to the diverse Albanian ecosystems [2].

In Albania, the *O. vulgare* populations occur naturally in both northern regions (Bulqizë, Dibër, Malësi, Madhe, Shkodër) and southern regions (Pogradec, Sarandë, Tepelenë, Vlorë). These areas share Mediterranean climatic conditions, serpentine and calcareous soils, and varying degrees of anthropogenic pressure [3–5]. These environmental factors, together with underlying genetic variation, contribute to high polymorphism in essential oil composition and to the development of distinct chemotypes [6].

Generally, the essential oil is primarily found in the aerial parts of the plant, particularly in the leaves and flowers. Its biological activity is largely attributed to the presence of phenolic monoterpenes, essentially thymol, carvacrol, and β-caryophyllene, which are responsible for its antimicrobial, antioxidant, and anti-inflammatory activity [7]. The antimicrobial effect is associated with the ability of these compounds to damage the outer microbial cell membrane, increasing its permeability [8,9]. This disruption leads to the damage of essential intracellular components, including ions and adenosine triphosphate (ATP), ultimately resulting in cell death. In addition, carvacrol has been reported to alter bacteria's communication with each other (quorum sensing), reducing their ability to cause infection [10]. In fact, *O. vulgare* is known as a natural antiseptic agent, as its essential oil has shown to be effective against antibiotic-resistant and non-resistant bacterial strains, like *Escherichia coli* and *Staphylococcus aureus* [11].

The antioxidant activity is related to its capacity to neutralize reactive oxygen species (ROS) and to enhance the activity of endogenous antioxidant enzymes, including superoxide dismutase (SOD), catalase (CAT), and glutathione peroxidase (GPx) [12]. These mechanisms contribute to protecting cells from oxidative damage. Furthermore, the anti-inflammatory effect occurs through the inhibition of key inflammatory pathways, including cyclooxygenase-2 (COX-2), the nuclear factor kappa B (NF-κB), and by reducing the production of inflammatory molecules such as interleukin-6 (IL-6), interleukin-1β (IL-1β), and tumor necrosis factor α (TNFα) [13, 14].

Moreover, *O. vulgare* exerts antifungal, insecticidal, and antiviral properties due to the presence of volatile and non-volatile phenolic compounds [15, 16].

A comparable eco-evolutionary scenario is observed in *Salvia officinalis* L. (*S.officinalis*), another aromatic species of considerable economic and phytotherapeutic relevance widely distributed across the Adriatic Basin. *S. officinalis* also belongs to the botanical family of Lamiaceae, which includes more than 230 genera and 7100 species worldwide.

In Albania, this species grows mostly in mountainous areas, but it is also found in southern regions, such as Delvinë, Kolonë, Përmet and Skrapar [4]. *S. officinalis* exhibits substantial genetic variation across natural and cultivated populations, shaped by both historical evolutionary processes and adaptive responses to environmental conditions. Genomic sequencing studies have identified clusters of genes involved in terpenoid and other secondary-metabolite biosynthesis, with single nucleotide polymorphisms contributing to chemitypic diversity [17, 18].

This extensive genetic variability underpins both the ecological resilience of natural populations and the biochemical profiles relevant for environmental studies, including trace elements and heavy-metal accumulation.

S. officinalis, commonly known as sage, is rich in flavonoids and phenolic acids that exert strong antioxidant properties. Several *in vitro* and *in vivo* studies have also demonstrated its antibacterial activity [19]. This aromatic perennial herb is further known for its neuroprotective potential showing promising results in improving cognitive function and memory, especially in the patients with Alzheimer's disease [20]. These biological activities are attributed to the presence of several bioactive compounds, including rosmarinic acid, carnosic acid, thujone, flavonoids, and ursolic acid, which together provide brain-protective, antioxidant, anti-inflammatory, antimicrobial, and cholinesterase-inhibiting effects. In particular, rosmarinic and carnosic acids play an important role in reducing oxidative stress, chelating excess metal ions, and activating the nuclear factor erythroid 2-related factor 2 (Nrf2) pathway, leading to higher levels of protective and detoxifying enzymes in the body [21, 22]. In addition, sage extracts inhibit the enzymes acetylcholinesterase (AChE) and butyrylcholinesterase (BChE), which are responsible for the degradation of acetylcholine, allowing more of it to remain active in the brain [23]. They also show anti-inflammatory effects by inhibiting key inflammatory pathways (COX and lipoxygenase (LOX)) and reducing molecules like prostaglandin E_2 (PGE_2), nitric oxide (NO), and pro-inflammatory cytokines [24]. Furthermore, certain sage compounds can interact with γ-aminobutyric acid sub-type A (GABA-A) and nicotinic receptors, which may contribute to anxiolytic effects [25].

However, despite the benefits associated with the use of medicinal and aromatic plants, the environmental pressure and the increase in human activities have raised concerns about the potential accumulation of heavy metals in these widely consumed species.

Heavy metals and metalloids, such as arsenic (As), lead (Pb), mercury (Hg), cadmium (Cd), chromium (Cr), nickel (Ni), aluminium (Al), and copper (Cu), are among the most concerning environmental contaminants due to their non-biodegradability, persistence, and potential for bioaccumulation along the food chain. They represent a risk factor both for plant physiology and for human health.

In plants, the uptake of heavy metals from soil, air, and water, can interfere with different processes including photosynthesis, nutrient uptake, oxidative stress, cellular integrity, and production of metabolites [26]. In particular, *O. vulgare* and *S. officinalis* may alter essential-oil biosynthesis and composition, threatening the quality and safety of plant-derived products [27, 28].

Accumulation and amplification of heavy metals in human tissues through the consumption of contaminated medicinal plants may lead to dangerous health outcomes. In fact, chronic exposure to the plant materials containing heavy metals, even at low concentrations, can lead to bioaccumulation in different tissues, inducing oxidative stress, mitochondrial dysfunction, altered enzymatic activity, and DNA damage [26]. Overall, these impairments may contribute to the development of renal, hepatic, neurological, and cardiovascular disorders, as well as increased risk of mutagenesis and carcinogenesis [29–31].

In the Albanian context, recent geochemical and environmental surveys have documented the presence as well as spatial variability of these metals in soils and water resources. From these studies, it can be deduced how the presence of toxic metals can lead to their accumulation in native plants, which, by entering the food chain, may affect the health of the population.

Heavy metal contamination in Albania shows a complex spatial distribution which is influenced by both natural geological formations and anthropogenic activities. In particular, the geological serpentine formations, mostly located in central and northern Albania, are naturally rich in Cr, Ni, and Co; while elevated Pb, Cu, Cd and Zn concentrations are found in the areas with intensive industrial activities like the metallurgical complex in Elbasan, copper extraction in Rehova, and at waste disposal spots [2].

Agricultural soils and irrigation waters in these areas sometimes show exceeded guideline values of heavy metals, raising potential concerns regarding metal bioaccumulation in plants and subsequent risks to human health [2,5].

Although Albania has established environmental monitoring networks, these findings highlight the importance of assessing heavy metal levels in locally grown plants. In this context, the present study investigated two widely used and commercially important species, *Salvia officinalis* L. and *Origanum vulgare* L., largely consumed by Albanian populations and exported worldwide. The aim of this research was to determine the concentrations of selected trace and potentially toxic elements in these plants in order to evaluate potential human exposure and to provide insights into environmental contamination patterns in Albanian ecosystems. Also, non-carcinogenic risk was assessed to evaluate the potential risk to the consumer's health.

METHODS

In this study, the following toxic metals were quantified: Al, Cd, Pb, Ni, Cu, and Cr in medicinal plants. Specifically, the *Origanum vulgare* L. samples were collected from northern Albania, where it is traditionally used as mountain tea, the *Origanum vulgare* samples were collected from southern Albania. The *Salvia officinalis* samples were collected throughout the country, representing approximately 50% of Albania's medicinal plant exports.

In addition to elemental quantification, environmental contamination was assessed using the pollution index (PI) and the metal index (MI), which provide indicators of soil–plant metal accumulation and overall contamination levels. Furthermore, the potential health risks to consumers were assessed using the target hazard quotient (THQ) and hazard index (HI), which estimate non-carcinogenic risk associated with the consumption of contaminated plant material.

Collection and preparation of medicinal plant samples

The medicinal plant samples were collected from multiple geographical regions of Albania, including Kukës, Elbasan, Pogradec, Korçë, Përmet, Tepelenë, Mallakastër, and Berat, or were obtained directly from local traditional healers (Figure 1). Each sample was placed in a sterilised polyethylene bag, sealed, and transported to the laboratory under appropriate conditions to prevent contamination. Approximately 50 g of each sample was washed thoroughly with deionised water to remove dust and surface impurities. The samples were then dried in an oven at 55 °C until a constant weight was achieved, followed by grinding into a fine powder to ensure homogeneity and uniform distribution of metals.

Sample digestion procedure

The plant samples were digested in Teflon vessels using a nitric acid–hydrogen peroxide mixture, following a modified protocol based on USEPA Method 3052 (microwave-assisted acid digestion of siliceous and organic matrices) and WHO guidelines for the quality control of medicinal plant materials [32, 33].

Briefly, approximately 0.5–1.0 g of homogenised plant materials was weighed into each Teflon digestion vessel and treated with 15 mL of nitric acid (HNO_3) (65%, ultrapure) and 2 mL of hydrogen peroxide (H_2O_2) (30%). To ensure analytical repeatability and reproducibility, each sample was digested and analysed in duplicate (two parallel digestions per sample). The samples were allowed to react with the digestion mixture for 24 h and then heated at 150 °C for about 6 h in closed vessels. In the final step, the vessel caps were opened, and heating continued until a moist salt residue was obtained (final volume 2–3 mL).

After cooling, the digests were quantitatively transferred into volumetric flasks, diluted to 50 mL with distilled water, filtered through 0.2 µm nylon membrane filters, and stored at 4 °C until metal analysis.

Chemical analysis of metals

The concentrations of metals in plant samples were determined using atomic absorption spectroscopy with graphite furnace atomisation (AAS/GFAAS). Instrumental parameters, including hollow-cathode lamp current, spectral slit width, and pyrolysis and atomisation temperatures, were optimised individually for each element prior to analysis. Measurements were performed using an Analytik Jena 800 G instrument, and metal concentrations were quantified using the calibration curve method (Table 1).

Figure 1. Map of geographical sites in Albania where the samples were collected

Table 1. Instrumental conditions applied for each element

Element	⌊ (nm)	⊗⌊$_{1/2}$	KS	Pyrolisis Temp. °C	Atomization Temp. °C	LOD ⌠g/L	Working range ⌠g/L
Al	309.3	0.2	No	1100/850	2250/2000	1	1–5
Cd	228.8	0.2	Yes	600/250	2000/1800	0.05	0.1–0.8
Cr	357.9	0.2	No	1100/850	2250/1800	0.1	0.5–10
Cu	324.7	0.2	No	1100/850	2000/1800	0.5	0.2–10
Pb	283.3	0.2	Yes	900/550	2100/1800	0.6	5–100
Ni	232.0	0.2	Yes	750/450	2200/2000	0.5	1–10

RESULTS

Descriptive statistics

According to FAO/WHO guidelines for medicinal and aromatic plants intended for human consumption, the recommended maximum limits for heavy metals are approximately: Pb (10 mg/kg), Cd (0.3 mg/kg), Cu (20–40 mg/kg), Cr (2 mg/kg), and Ni (1.5 mg/kg), with values expressed on a dry weight basis. For Al, no specific maximum limit has been established, as it is generally regarded as a geogenic element rather than a regulated contaminant in plant materials [33,34].

Salvia officinalis

Analysis of *S. officinalis* is shown in Table 2 and revealed that Al was the most abundant metal in all the samples, ranging from 43.96 mg/kg to 213.23 mg/kg, with the highest concentration recorded in the sample collected from Përmet. This finding is consistent with the natural abundance of Al in soils and the absence of a specific maximum limit for this element in medicinal plants according to the EU and WHO regulations. Nevertheless, the reported values are also in line with those reported in the literature. Cu concentrations ranged from 3.57 mg/kg to 4.25 mg/kg remaining well below the recommended limits for medicinal plants (20.00–40.00 mg/kg according to FAO/WHO), confirming that Cu, as an essential trace element, does not pose a toxicological risk in the analysed samples. Cr exhibited site-specific variability, with the highest concentration observed in the samples collected from Përmet soils (7.85 mg/kg) and the lowest from Tepelenë (1.23 mg/kg); however, all the values remained below levels considered potentially toxic for plant materials.

Pb concentrations were very low across all the sampling sites (0.03–0.06 mg/kg), significantly below the maximum allowed limit of 10 mg/kg, established by FAO/WHO and EU Regulation (EC No. 1881/2006). Among all the analysed metals, cadmium was found to be the one with the lowest concentration (0.02–0.04 mg/kg), far below the maximum allowed limit of 0.30 mg/kg for medicinal plants.

Unlike all the other metals tested, Ni was the only one to exceed the recommended limit values. Indeed, Ni concentrations ranged from 1.09 mg/kg to 7.47 mg/kg, with the highest value recorded in the samples collected from Përmet. Several samples exceeded the reference value of 1.5 mg/kg, suggesting that Ni could be a potential toxic contaminant in *S. officinalis* from certain locations (Table 3).

Overall, the results indicate that the *S. officinalis* collected from all the studied locations complies with international safety standards for most metals, posing no significant risk of heavy metal contamination, except for nickel, which requires careful monitoring.

Origanum vulgare and Origanum vulgare L.

The analysis of the *O. vulgare* samples is illustrated in Table 4, and as observed for *S. officinalis,* Al was the most abundant metal, ranging from 34.14 mg/kg to 129.14 mg/kg; with the highest concentration recorded in the samples collected from Berat. However, the absence of a specific FAO/WHO limit for Al in medicinal plants suggests that these values are primarily associated with the natural geochemical background of soil, rather than anthropogenic contamination.

Cu concentrations ranged from 4.32 mg/kg to 7.29 mg/kg, so they are substantially lower than the maximum allowed limit (20.00–40.00 mg/kg), suggesting that Cu is mainly present as an essential trace element, rather than as a contaminant. The highest value concentration was observed in the samples collected from Pogradec,

Table 2. Mean values and Standard deviation of heavy metals in the *S. officinalis* samples based on the area where they were collected

S. officinalis	Al		Cu		Cd		Pb		Cr		Ni	
	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st
Korçë	43.96	0.49	3.68	0.06	0.03	0.001	0.06	0.001	1.86	0.18	2.37	0.06
Berat	88.09	2.41	3.57	0.02	0.04	0.001	0.06	0.002	2.17	1.42	1.09	0.01
Tepelenë	104.91	0.55	3.93	0.22	0.02	0.001	0.03	0.001	1.23	0.59	1.77	0.02
Kukës	64.21	0.87	4.11	0.12	0.02	0.0001	0.03	0.002	1.24	0.04	1.49	0.01
Pogradec	110.17	0.83	4.09	0.02	0.01	0.001	0.04	0.001	2.91	0.28	3.06	0.14
Përmet	213.23	0.34	4.25	0.15	0.02	0.001	0.03	0.002	7.85	0.64	7.47	0.24

Table 3. Descriptive statistics of trace metals in *S. officinalis* (mg/kg, dry weight)

Parameter	Cr	Cu	Pb	Cd	Ni	Al
Mean	**2.88**	**3.94**	**0.04**	**0.02**	**2.88**	**104**
Median	2.01	4.01	0.03	0.02	2.07	96.5
Standard deviation	2.52	0.26	0.02	0.01	2.35	59.0
Range	6.62	0.68	0.04	0.02	6.38	169
Minimum	1.23	3.57	0.03	0.01	1.09	44.0
Maximum	7.85	4.25	0.06	0.04	7.47	213
Count	6	6	6	6	6	6
Confidence level (95.0%)	2.64	0.28	0.02	0.01	2.47	61.9

Table 4. Mean values and Standard deviation of heavy metals in *O. vulgare* samples based on the area where they were collected

O. vulgare	Al		Cu		Cd		Pb		Cr		Ni	
	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st	Avarage (mg/kg)	Dev. st
Berat	129.14	0.31	6.65	0.21	0.03	0.001	0.06	0.002	1.81	0.11	4.75	0.10
Pogradec	113.47	0.75	7.29	0.58	0.02	0.001	0.04	0.001	0.72	0.22	1.73	0.02
Pogradec L	90.01	0.94	5.96	0.05	0.004	0.0001	0.04	0.001	0.53	0.05	5.33	0.13
Kukës L	34.14	1.67	5.19	0.12	0.01	0.008	0.04	0.001	0.27	0.04	3.79	0.17
Ballsh	60.43	0.29	6.99	0.59	0.03	0.002	0.07	0.0001	0.91	0.13	4.72	0.08
Elbasan L	48.38	0.57	4.32	0.06	0.01	0.0001	0.05	0.001	0.74	0.02	7.41	0.20

while the lowest one from the sample collected from Elbasan. Cr exhibited concentrations between 0.27 mg/kg and 1.81 mg/kg, remaining within the permissible limit of 2.00 mg/kg. Only the sample collected from Berat approached this threshold, but without exceeding it. Pb concentrations ranged from 0.04 mg/kg to 0.07 mg/kg, which are significantly lower than the maximum allowed limit of 10 mg/kg. Similarly, Cd showed very low concentrations (0.01–0.04 mg/kg), far below the FAO/WHO recommended limit of 0.30 mg/kg, indicating no apparent risk associated with this toxic metal.

Ni, however, exceeded the recommended limit in several samples, with concentrations ranging from 1.73 mg/kg to 7.41 mg/kg, confirming the need for further investigations regarding the potential health risks associated with Ni accumulation (Table 5). Especially in the samples collected from Elbasan, the concentrations of Ni were particularly high.

In this study, the samples of *Origanum vulgare* and *Origanum vulgare* L. were evaluated and *Origanum vulgare* exhibits higher metal concentrations compared to *Origanum vulgare* L., particularly for aluminium, nickel and chromium.

Table 5. Descriptive statistics of trace metals in *O. vulgare* (mg/kg, dry weight)

Parameter	Cr	Cu	Pb	Cd	Ni	Al
Mean	**0.83**	**6.07**	**0.05**	**0.02**	**4.62**	**79.26**
Median	0.73	6.31	0.05	0.01	4.74	75.22
Standard deviation	0.53	1.14	0.01	0.01	1.87	37.73
Range	1.54	2.97	0.03	0.03	5.69	95.00
Minimum	0.27	4.32	0.04	0.01	1.73	34.14
Maximum	1.81	7.29	0.07	0.03	7.41	129.14
Count	6	6	6	6	6	6
Confidence level (95.0%)	0.55	1.20	0.01	0.01	1.96	39.59

Boxplot for *Salvia officinalis, Origanum vulgare*, and *Origanum vulgare* L.

The boxplots for Cr, Cu, and Ni illustrate the distribution of these metals across the analysed samples of *O. vulgare* and *S. officinalis*. Cu concentrations are well below the maximum permissible limit (30.00 mg/kg) in all the samples, indicating that this element is present primarily as an essential micronutrient rather than as a contaminant. Cr concentrations appear close to, and in some cases slightly above, the reference limit of 2.30 mg/kg, particularly in *S. officinalis*. This trend may suggest a possible geogenic influence related to the natural composition of the soils in the sampling areas. Regarding Ni, when compared with the recommended limit of 1.50 mg/kg, several samples, especially those of *O. vulgare* and *O. vulgare* L., show higher concentrations and greater variability. This pattern indicates a more pronounced tendency for Ni accumulation (Figure 2). Such variability may be associated with differences in soil properties, geological background, and nickel bioavailability among the sampling sites.

The boxplot analysis of Pb, Cd and Al, indicates that the concentrations of these metals in the *S. officinalis*, *O. vulgare* and *O. vulgare* L. samples are well below the maximum allowed limits (Pb = 10.00 mg/kg; Cd = 0.30 mg/kg; Al = 2000.00 mg/kg), confirming the overall safety of these medicinal plants with respect to heavy metals contamination (Figure 3).

Pb and Al show greater variability among samples, especially in *Origanum*, suggesting the influence of local pedological conditions, soil mineral composition, and metal bioavailability. In contrast, Cd exhibits lower concentrations and a more homogeneous distribution across the analysed samples, indicating limited accumulation and a reduced impact of site-specific environmental factors.

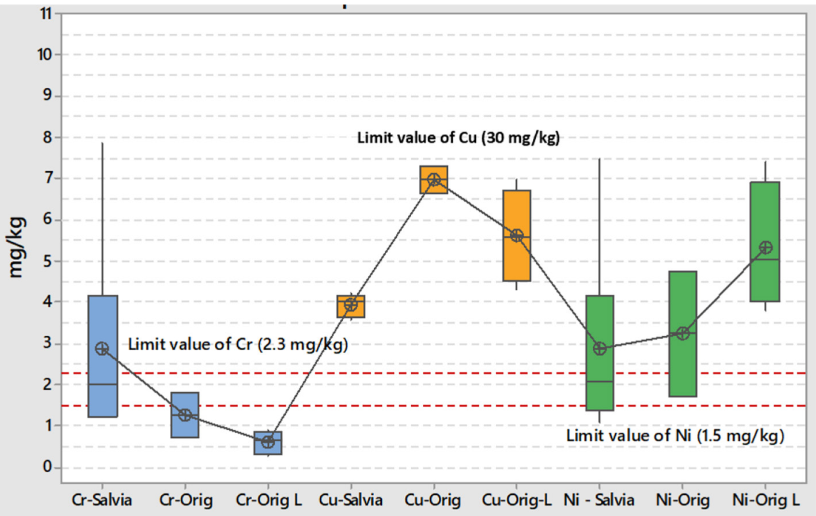
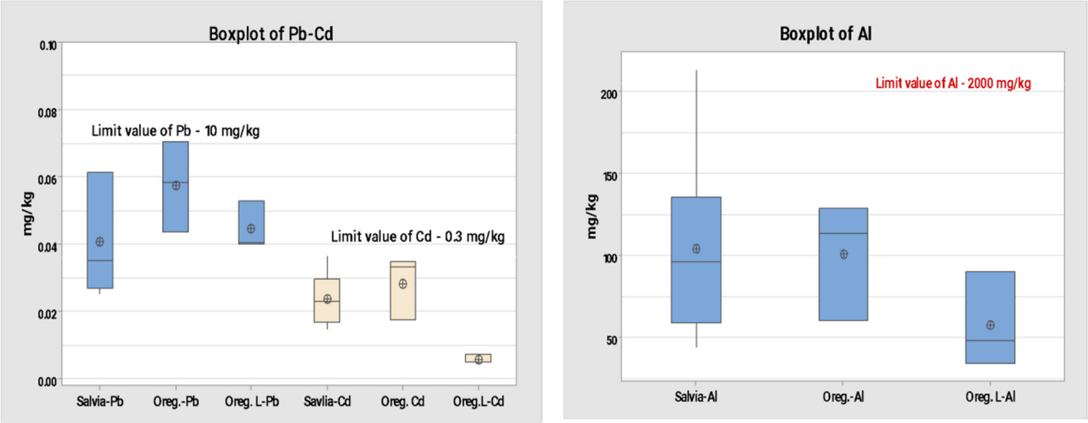


Figure 2. Boxplot of Cr, Cu, and Ni concentrations (mg/kg) in *O. vulgare*, *O. vulgare* L. and *S. officinalis* samples



a) **b)**

Figure 3. Boxplot distribution of Pb, Cd (a) and Al (b) concentrations (mg/kg) in *S. officinalis*, *O. vulgare* and *O. vulgare* L. samples

Analysis of variance (ANOVA)

The analysis of variance (ANOVA), used to assess the variability between groups, showed that *S. officinalis* exhibits higher mean concentrations of Cr (2.88 mg/kg) and Al (104.10 mg/kg) compared with *O. vulgare* (0.83 mg/kg and 79.26 mg/kg, respectively), suggesting a greater accumulation tendency for these elements.

In contrast, *Origanum* shows higher average levels of Cu (6.07 mg/kg compared with 3.94 mg/kg in *S. officinalis*) and Ni (4.62 mg/kg compared with 2.88 mg/kg), indicating a relatively higher uptake of these metals.

Mean Pb concentrations are low and comparable in both species (0.04–0.05 mg/kg), while Cd shows identical mean values (0.02 mg/kg), reflecting the limited accumulation of these potentially toxic metals in the analysed samples (Figure 4).

The results of the two-way ANOVA indicate that the sampling site factor did not have a statistically significant effect on metal concentrations in either *S. officinalis* (F = 1.2; p = 0.30) or *O. vulgare* (F = 1.02; p = 0.42), as the calculated F-values were lower than the critical value (Fcrit = 2.5) and the p-values exceeded the significance threshold ($p > 0.05$).

In contrast, the metal type factor showed statistically significant differences for both species, with high F-values (*S. officinalis*: F = 18.5; $p < 0.001$; *O. vulgare*: F = 25.3; $p = 1.75 \times 10^{-10}$) exceeding the critical value (Fcrit = 2.4) (Table 6).

These findings demonstrate that the observed variations in metal concentrations are primarily influenced by the type of metal, rather than by the sampling location.

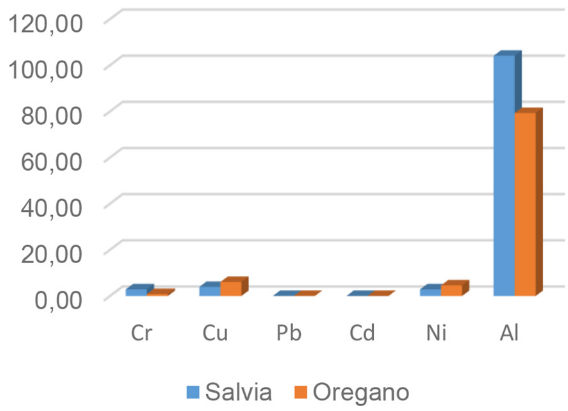


Figure 4. Comparison of mean values of Cr, Cu, Pb, Cd, Ni, and Al (mg/kg) in *S. officinalis* and *O. vulgare*

Principal component analysis (PCA)

A variance study was performed using principal component analysis (PCA). The PCA of *S. officinalis* showed that the first two principal components (F1 = 67.02% and F2 = 25.58%) accounted for 92.60% of the total variance, indicating a strong dataset representation.

The PCA biplot revealed a clear separation of samples according to their metal accumulation signatures. Pb and Cd were negatively loaded on F1 and positively on F2, indicating a coupled behaviour and suggesting a potential common contamination source affecting the samples collected in Berat and Korçë.

Table 6. Two-way ANOVA evaluating the effects of sampling sites and metal type on elemental concentrations

Source of variation	*F-Salvia*	*P-value*	*F-Orig*	*P-value*	*F crit*
Sites	**1.2**	0.3	**1.02**	0.42	**2.5**
Metals	**18.5**	0.0	**25.3**	1.75E-10	**2.4**

In contrast, Cr, Ni, and Al showed strong positive loadings on F1 and clustered closely, reflecting a shared accumulation trend and likely geogenic control, particularly influencing the sample collected in Përmet. Cu was positioned in the positive F1 and negative F2 quadrant, indicating a distinct behaviour compared with Pb and Cd, as well as suggesting different environmental drivers.

Overall, PCA distinguished two major patterns among *S. officinalis* samples: a potential anthropogenic Pb–Cd signature and a geogenic Cr–Ni–Al signature (Figure 5).

Regarding the PCA analysis of *O. vulgare*, it revealed that the first two principal components (F1= 55.09% and F2= 29.16%) explained 84.26% of the total variance, indicating a robust representation of the dataset.

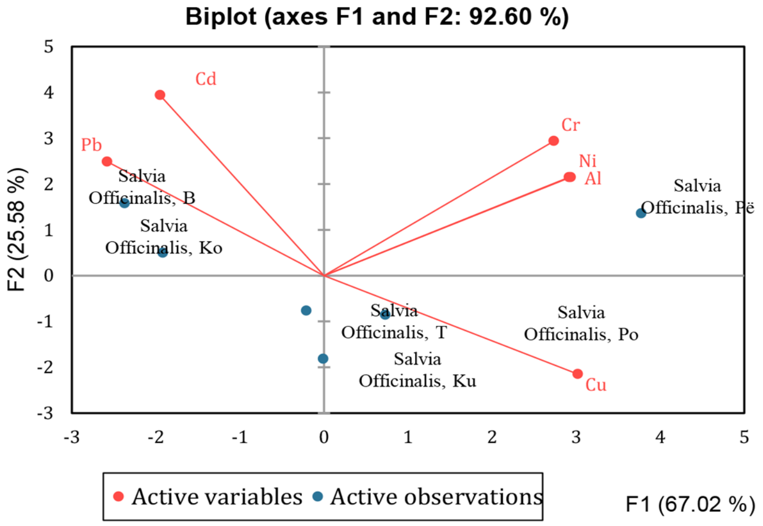


Figure 5. Principal component analysis (PCA) biplot illustrating the relationship between metal variables and *S. officinalis* samples. B – Berat, Ko – Korce, Ku – Kukes, Pe – Permet, Po – Pogradec, T – Tepelene

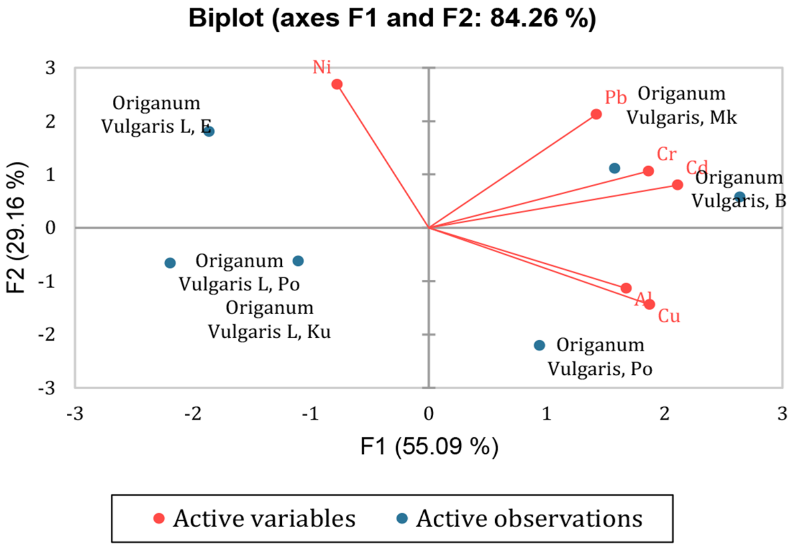


Figure 6. Principal component analysis (PCA) biplot illustrating the relationships between metal variables and *O. vulgare* samples. B – Berat, E – Elbasan, K – Kukes, Mk – Mallakaster, Po – Pogradec

The PCA biplot clearly separated the *O. vulgare* samples into distinct groups according to their metal accumulation patterns. The first component (F1) was mainly associated with Pb, Cd and Cr, suggesting a common accumulation trend and a potentially likely shared contamination source. In contrast, the second component (F2) differentiated samples enriched in Al and Cu from those dominated by Ni.

The close angular relationship between Cu and Al vectors indicates a strong positive correlation between these elements, whereas Ni showed an opposite trend compared to Al and Cu, suggesting different geochemical or environmental controls.

The samples located in the positive region of F1 were associated with elevated Pb–Cd–Cr levels, and they were found especially in the samples collected in Mallakastër and Berat. While a distinct sample group located in the negative F2 region showed a preferential association with Al and Cu, like the samples collected in Pogradec (Figure 6).

Pollution index

The pollution index (PI) was used to evaluate the contamination level of individual metals by comparing their measured concentrations with the corresponding reference values. PI is defined as the ratio between the concentration of a given metal in the sample and its allowed or reference limit [36].
Formula:

$$PI_i = \frac{C_i}{S_i} \tag{1}$$

where: C_i is the measured concentration of metal i in the sample (mg/kg), S_i is the reference or allowed limit for metal i (mg/kg), PI_i is the pollution index of metal i.

As shown in Table 7, the calculated PI values for *S. officinalis* indicate that Cu, Pb, Cd, and Al are well below the reference threshold (PI < 1), suggesting the absence of contamination by these elements. In contrast, Cr (PI = 1.25) and Ni (PI = 1.92) show PI values slightly above 1, indicating low to moderate contamination levels. These values are most likely related to natural geogenic contributions rather than anthropogenic inputs.

Table 7. Pollution index of *S. officinalis*

Metal	Mean (mg/kg)	Reference (mg/kg)	PI
Cr	2.88	2.30	1.25
Cu	3.94	340.00	0.012
Pb	0.04	10.0	0.004
Cd	0.02	0.30	0.067
Ni	2.88	1.50	1.92
Al	104.10	2000.00	0.052

Table 8. Pollution index of *O. vulgare*

Metal	Mean (mg/kg)	Reference (mg/kg)	PI
Cr	0.83	2.30	0.36
Cu	6.07	340	0.02
Pb	0.05	10.0	0.01
Cd	0.02	0.30	0.07
Ni	4.62	1.50	3.08
Al	79.26	2000	0.04

Overall, the PI assessment confirms that the *S. officinalis* samples present a generally low level of heavy metal contamination and can be considered safe with respect to the analysed metals.

The pollution index values for *O. vulgare* indicate that Cr, Cu, Pb, Cd, and Al are well below the reference threshold (PI < 1), indicating no contamination by these elements. In contrast, Ni exhibits a PI value greater than 3 (PI = 3.08), suggesting moderate to high contamination, possibly due to enhanced nickel uptake by the plant or with local geogenic influences in the sampling areas (Table 8).

Overall, *O. vulgare* shows low contamination levels for most analysed metals, with Ni representing the only potential concern.

Metal index

The metal index (MI) was used to assess the overall heavy metal contamination in the analysed plant samples. This index provides an integrated evaluation of metal pollution by comparing the measured concentrations of individual metals with their corresponding maximum allowable concentrations [36, 37].

The metal index was calculated using the following equation:

$$MI = \sum_{i=1}^{n} \frac{C_i}{MAC_i} \quad (2)$$

where: C_i is the concentration of the i-th metal in the sample (mg/kg), MAC_i is the maximum concentration allowed for the same metal according to international guidelines (FAO/WHO or European Union standards), n is the total number of analysed metals.

The MI values calculated for *S. officinalis* (4.903) and *O. vulgare* (4.845) were clearly higher than the reference threshold of 1 (Table 9). This means that the total amount of metals measured in the samples is above the maximum allowable concentrations (MACs) considered in this study. However, a closer examination of the individual Ci/MACi ratios reveals that not all metals contribute equally to the overall increase of MI.

Ni is the main contributor to the elevated MI values. It shows the highest relative exceedance in both species (1.920 in *S. officinalis* and 3.080 in *O. vulgare*). In particular, in *O. vulgare*, Ni accounts for the largest part of the total index, suggesting a species-specific tendency for Ni accumulation, potentially related to the natural geochemical characteristics of soil or to local human activities in the cultivation area.

Cr and Al also contribute to the MI, especially in *S. officinalis*, where their Ci/MACi ratios are above 1. These elements increase the overall metal burden, even if lesser than Ni. On the other hand, Pb has a very low influence on the MI after applying the WHO limit of 10 mg/kg for medicinal plants. The Ci/MACi values for Pb are below 0.01 in both species, indicating that lead does not significantly raise the index. Cd and Cu also show relatively low or moderate contributions.

Taken together, the elevated MI values are mainly the result of elevated nickel concentrations, with smaller contributions from Cr and Al, rather than indicating a uniform contamination by all analysed metals. These findings highlight that future monitoring and control efforts should focus especially on nickel, instead of treating all metals as equally responsible for the increased metal index.

Target hazard quotient

The target hazard quotient (THQ) is a risk assessment indicator used to evaluate the potential non-carcinogenic health risk associated with long-term exposure to a single metal through food or medicinal plant consumption. THQ does not represent a probability of risk, but provides a comparative index to estimate risk relative to established reference doses [38,39].

Formula used according to US EPA guidelines:

$$THQ = \frac{EFr \times ED \times IR \times C}{RfD \times BW \times AT} \quad (3)$$

where: EFr is the exposure frequency (days/year, typically 365), ED is the exposure duration (years), IR is the ingestion rate of the food or plant material (kg/day), C is the metal concentration in the food or plant material (mg/kg), RfD is the oral reference dose for the metal (mg/kg/day), BW is the body weight (kg), AT is the averaging time (days; $AT = ED \times 365$ for non-carcinogenic risk).

Because EFr = 365 and AT = ED × 365, the equation is commonly simplified as:

Table 9. Metal index for *S. officinalis* and *O. vulgare*

Metal	MAC (mg/kg, dw)	(Ci / MACi) *Salvia officinalis*	(Ci / MACi) *Origanum vulgare*
Cr	2.0	1.440	0.415
Cu	40	0.099	0.152
Pb	10.0	0.004	0.005
Cd*	0.05	0.400	0.400
Ni	1.5	1.920	3.080
Al	100	1.040	0.793
MI		**4.903**	**4.845**

Note: * For cadmium, the EU maximum allowable concentration of 0.05 mg/kg (dry weight) was adopted, as it represents a more conservative and health-protective limit compared to FAO/WHO guidelines.

Table 10. Target hazard quotient and hazard index for *S.officinalis* and *O. vulgare*

Metal	RfD (mg/kg/day)	THQ – *Salvia officinalis*	THQ – *Origanum vulgare*
Cr	0.003	0.069	0.020
Cu	0.04	0.007	0.011
Pb	0.0035	0.009	0.001
Cd	0.001	0.001	0.001
Ni	0.02	0.010	0.016
Al	1.0	0.007	0.006
Hazard index (HI)	—	0.096	0.055

$$THQ = \frac{IR \times C}{RfD \times BW} \tag{4}$$

The hazard index (HI) represents the cumulative of the target hazard quotients (THQs) of individual contaminants. It provides an integrated assessment of the overall non-carcinogenic risk posed by simultaneous exposure to several metals.

For multiple metals, HI is calculated as:

$$HI = \sum THQ_i$$

Average adult body weight (BW) = 70 kg (adult); daily ingestion rate (IR) = 0.005 kg/day (5 g/day of dried plant material).

The comparative assessment of the THQ values shows that all analysed metals in *S. officinalis* and *O. vulgare* exhibit THQ values below the safety threshold of 1, indicating no significant non-carcinogenic health risk under the assumed daily intake scenario. This finding is further supported by low HI values (0.0956 for *S. officinalis* and 0.0552 for *O. vulgare*) (Table 10). Among the metals, Cr and Ni represented the main contributors to the HI in *S. officinalis* and *O. vulgaris*, respectively; however, their individual contributions remained well within acceptable limits.

Overall, these results indicate that the consumption of these medicinal plants poses minimal health risk with respect to the analysed heavy metals.

DISCUSSION

This study aimed to provide the evaluation of heavy metal contamination in *S. officinalis* and *O. vulgare* collected from different regions of Albania, from North to South, highlighting both environmental and species-specific factors influencing metal accumulation.

Among the analysed metals, Al was the most abundant in both species, ranging from 43.96 mg/kg to 213.23 mg/kg in *S. officinalis* and 34.14 mg/kg to 129.14 mg/kg *in O. vulgare*. These values are in line with the natural geogenic aluminium enrichment of Albanian soils, particularly in the areas with serpentine and calcareous geological formations.

Ni presented the highest concern, particularly in *O. vulgare*, where concentrations ranged from 1.73 to 7.41 mg/kg, exceeding the FAO/WHO guideline of 1.5 mg/kg in several samples, and indicating a species-specific tendency for bioaccumulation.

Pb, Cd, and Cu were detected at low concentrations across all sites, with values far below international limits, indicating minimal anthropogenic contamination for these metals and suggesting that these elements do not pose a significant threat to plant quality and safety for human health. In particular, Cu concentrations were low and uniform, ranging from 3.57 to 4.25 mg/kg in *S. officinalis* and 4.32 to 7.29 mg/kg in *O. vulgare*, remaining well below the limit of 20–40 mg/kg. Pb and Cd were detected at very low levels in both species (Pb: 0.03–0.07 mg/kg; Cd: 0.005–0.037 mg/kg), far below the respective maximum limits of 10 mg/kg and 0.3 mg/kg.

Cr and Ni exhibited notable variability among species and sampling locations. Cr showed moderate variability, ranging from 1.23 to 7.85 mg/kg in *S. officinalis* and from 0.27 to 1.81 mg/kg in *O. vulgare*. Some samples exceeded the recommended limit of 2 mg/kg, suggesting the influence of both geogenic soil composition and localized anthropogenic inputs.

In particular, Ni represents the main element of concern, especially in *O. vulgare*, where concentrations frequently exceeded the reference limit of 1.5 mg/kg, reaching a maximum value of 7.41 mg/kg. This species-specific pattern suggests a tendency of *O. vulgare* to bioaccumulate nickel, likely influenced by root uptake efficiency, soil pH, and metal bioavailability.

The high relative contribution of Ni to both the PI and MI confirms its dominant role in the overall metal burden, whereas Cr and Al contributed to a lesser extent. Conversely, Pb, Cd, and Cu had minimal influence on MI, demonstrating that cumulative metal uptake is not equally distributed among elements.

The concentrations observed in the present study are comparable with those reported in other regions of Southeastern Europe, where most metals such as Cu and Cr are generally found within acceptable limits, while Cd and Pb typically occur at low concentrations [44, 45]. Similarly, studies conducted on medicinal plants in Serbia and surrounding regions reported that Ni and Cr may show elevated levels depending on soil composition and environmental conditions, consistent with the findings obtained in this paper [45,46]. Comparable trends have also been observed in Turkey, where metal accumulation in medicinal plants is strongly influenced by soil characteristics and anthropogenic factors [47]. These findings indicate that the contamination profile observed in Albanian medicinal plants reflects a broader regional pattern influenced by both geogenic and environmental factors.

PCA revealed two distinct accumulation patterns: a geogenic Cr–Ni–Al signature and an anthropogenic Pb–Cd signature. The samples enriched in Cr, Ni, and Al were closely associated with regions characterized by serpentine soils and naturally high metal content, whereas Pb and Cd clustered together, suggesting localised anthropogenic sources, such as industrial activities, metal extraction, and waste disposal. These findings highlight the interplay of natural geochemistry and human activity in shaping metal contamination profiles in Albanian medicinal plants.

Despite elevated MI values, particularly due to Ni, health risk assessment using THQ and HI demonstrated no significant non-carcinogenic risk for either species under the assumed daily consumption scenario (5 g/day). HI values were 0.0956 for S. officinalis and 0.0552 for *O. vulgare*, well below the threshold of 1, with Cr and Ni identified as the main contributors. These results demonstrate that, although Ni accumulation requires further investigation, the overall consumption of these plants suggests a low non-carcinogenic risk. However, although THQ and HI values well below 1 indicate that adverse non-carcinogenic effects are unlikely under the defined exposure conditions, they do not indicate absolute safety, particularly in the context of long-term consumption. In fact, these indicators are based on standard assumptions and do not fully account for cumulative exposure, inter-individual variability, or potential effects in vulnerable population groups. Therefore, while the present results suggest a low level of risk for average consumers, continued monitoring, taking into account long-term exposure scenarios remain necessary.

The assumed daily intake of 5 g/day was selected as a realistic and conservative exposure scenario for adult consumers of herbal infusions. However, it should be noted that consumption may vary depending on age, body weight, and consumption habits, and therefore this assumption represents a simplified exposure model which corresponds to typical preparation practices of herbal infusions (approximately 1–2 teaspoons per day), as commonly reported in the literature. Under real-life conditions, the exposure to heavy metals may occur from multiple dietary and environmental sources, including water, vegetables, cereals, and other herbal products. Therefore, the present assessment reflects only the contribution of the investigated plants and does not represent total exposure. Cumulative intake may increase the overall health risk, particularly for metals such as Cd, Pb, and Ni.

Overall, these results suggest the need for species-specific monitoring of medicinal plants, with particular emphasis on nickel in *O. vulgare*, while also considering site-specific geochemical conditions.

These findings contribute to understanding how Albanian medicinal plants interact with environmental metals and provide important insights for policymakers, producers, and consumers. From a practical perspective, the results highlight the importance of regular monitoring of medicinal plant materials and careful selection of cultivation and harvesting areas to minimize contamination and to ensure compliance with international safety standards. For consumers, the findings suggest a low estimated risk under the studied conditions; however, caution is recommended in cases of frequent long-term consumption, combined use of multiple herbal products, or intake by vulnerable population groups.

The importance of this study is not locally limited, but extends to a global scale. Indeed, Albania represents one of the main exporters of dried wild medicinal and aromatic plants worldwide, which are generally treated and re-packaged and used in food industry, home consumption and essential-oil extraction [48]. Albania exports approximately 95% of its production and species such as Origanum vulgare and Salvia officinalis are widely traded, with major export destinations including the United States and Germany, each accounting for about 30–32% of total exports, followed by France and Turkey with about 10% each [49]. Notably, Albania is reported to supply up to 70% of the sage imported by the United States, highlighting its critical role in global supply chains [50]. In this context, systematic quantification of heavy metals in these widely exported species is essential not only to protect the Albanian population, but also to ensure compliance with international safety standards, preserve export/import relationship, and guarantee public health on a global scale.

CONCLUSIONS

This study demonstrated that the *S. officinalis* and *O. vulgare* collected across Albania are associated with a low estimated non-carcinogenic risk under the studied conditions with respect to heavy metal contamination. Aluminium was the most abundant element, reflecting natural soil geochemistry, while Pb, Cd, Cr and Cu remained below international safety limits. Ni showed relatively higher levels, posing as the main element of concern, particularly in *O. vulgare*. These findings highlighted species-specific accumulation patterns and showed that Ni contributes significantly to the PI and MI values. Nevertheless, the risk assessment based on THQ and HI demonstrated that the consumption of these medicinal plants does not pose significant non-carcinogenic health risks under the assumed intake scenario, as all THQ and HI values remained below the safety threshold of 1.

In conclusion, this paper elucidates the importance of continued monitoring of medicinal plants, with a particular attention to nickel, to ensure consumer safety and maintain the quality of Albanian medicinal plant products for local use and international export. Future research should expand the monitoring of medicinal plants to include other potentially toxic elements, particularly arsenic and mercury, in order to provide a more comprehensive assessment of environmental contamination and potential health risks.

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