



Assessment of heavy metal content in *Paliurus spina-christi* leaves and soils near an abandoned gold mine: A case study from Erzincan, Türkiye

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Terk edilmiş bir altın madeni yakınlarındaki *Paliurus spina-christi*'nin yaprak ve topraklarında ağır metal içeriğinin değerlendirilmesi: Erzincan-Türkiye örneği

Received : 02.06.2026

Accepted : 15.09.2026

Online : 09.10.2026

Abstract: This study was conducted in an abandoned gold-mining area, located in the İliç district of Erzincan Province, in eastern Türkiye. Three localities were selected from areas close to mining area. The highest Zn, Cu, and Pb concentrations in both soil and leaf tissues were found at locality 3, the nearest site to the mine tailing pond. So, Zn, Cu and Pb concentrations in all soil and leaf samples of *Paliurus spina-christi* were mainly from tailing releases. Statistical analysis showed that the concentrations of Zn, Mn, Cu, and Pb in soil and leaf samples varied depending on both the group factor (soil vs. leaf) and the locality factor (localities 1, 2, and 3). Negative Igeo values in the present study indicate the absence of contamination by the studied heavy metals. For all elements, the concentrations measured in leaf samples were many times higher than those in soil. In particular, Mn concentration in the leaves of *P. spina-christi* collected from locality 3 exceeded the threshold value and reached toxic levels. Very high BAC values for Zn and Mn (BAC>10), and high BAC values for Cu (from 1 to 10) suggest that *P. spina-christi* can be used as a bioindicator species for monitoring pollution by these elements in local mining areas.

Key words: Bioindicator, heavy metal pollution, gold mining, *Paliurus spina-christi*

Özet: Bu çalışma, Türkiye'nin doğusunda, Erzincan ilinin İliç ilçesinde bulunan terk edilmiş bir altın madeni alanında gerçekleştirilmiştir. Maden alanına yakın bölgelerden üç lokasyon seçilmiştir. Hem toprak hem de yaprak dokularında en yüksek Zn, Cu ve Pb konsantrasyonları, maden atık havuzuna en yakın olan 3 numaralı lokasyonda bulunmuştur. Dolayısıyla, *Paliurus spina-christi*'nin tüm toprak ve yaprak örneklerindeki Zn, Cu ve Pb konsantrasyonları esas olarak atık salınımlarından kaynaklandığı sonucuna varılmıştır. İstatistiksel analiz, toprak ve yaprak örneklerindeki Zn, Mn, Cu ve Pb konsantrasyonlarının hem grup faktörüne (toprak ve yaprak) hem de lokasyon faktörüne (1, 2 ve 3 numaralı lokasyonlar) bağlı olarak değiştiğini göstermiştir. Bu çalışmada negatif Igeo değerleri, incelenen ağır metallere kirlenmenin olmadığını göstermektedir. Tüm elementler için, yaprak örneklerinde ölçülen konsantrasyonlar, topraktakilerden birçok kat daha yüksektir. Özellikle, 3 numaralı lokasyondan toplanan *P. spina-christi* yapraklarındaki Mn konsantrasyonu eşik değerini aşmış ve toksik seviyelere ulaşmıştır. Çinko ve manganez için çok yüksek BAC değerleri (BAC>10) ve bakır için yüksek BAC değerleri (1 ila 10 arası), *P. spina-christi*'nin yerel madencilik alanlarında bu elementlerin neden olduğu kirliliği izlemek için biyolojik gösterge türü olarak kullanılabileceğini göstermektedir.

Anahtar Kelimeler: Biyoidikatör, ağır metal kirliliği, altın madenciliği, *Paliurus spina-christi*

Citation: Huseyinova R, Cüce M (2026). Assessment of heavy metal content in *Paliurus spina-christi* leaves and soils near an abandoned gold mine: A case study from Erzincan, Türkiye. Anatolian Journal of Botany 10(2): 229-236.

1. Introduction

Although mining activities play a critical role in meeting the global economy's raw material needs by providing employment opportunities for local communities, large-scale accidents, particularly those involving toxic substances, can cause irreversible environmental damage to ecosystems. Heavy metals (HMs) such as cadmium (Cd), copper (Cu), zinc (Zn), manganese (Mn), lead (Pb), mercury (Hg), and iron (Fe) released into the environment after such events are among the priority pollutants in environmental risk assessments due to their non-biodegradable, persistent, and highly toxic nature. These metals accumulate in soil, plants, and water systems, causing long-term contamination in the biosphere (Nwankwoala et al., 2022; Usman Nurudeena et al., 2025).

The heap leaching method, widely used in gold mining, involves processing the ore with cyanide solutions,

resulting in the formation of various toxic compounds that create complex structures with HMs (Laitos, 2013; Meneguzzo et al., 2020; Yudiantoro et al., 2026). It is stated that in the İliç Gold Mine, in addition to "gold," ore minerals include sulfide minerals such as pyrite, pyrrhotite, and chalcopyrite, and heavy metals such as copper, zinc, lead, and arsenic, which lead to the formation of acid mine drainage. Acidic waters and heavy metal-rich sediments seeping from tailings washed by rainwater may mix directly into the Karasu River and the dam waters.

The İliç mine accident stands out as one of the most significant environmental disasters to occur in Türkiye in recent years. On February 13, 2024, a heap-leaching landslide occurred at a gold mine in the İliç district of Erzincan province, resulting in the rapid displacement and spread of millions of cubic meters of material over a wide area. This event constituted not only a geotechnical failure but also a critical environmental risk due to the release of

HM_s and chemical waste into the environment (TBB, 2024). The mixing of such pollutants into the soil and water environment triggers the formation of acid mine drainage, increasing the mobility of HMs and facilitating their uptake by plants.

The ecological and toxicological importance of HM accumulation in plants stems from their ability to be transported through nutrition, energy flow, and the food chain (Mohamed et al., 2025). HMs accumulating in plant tissues are transferred to higher trophic levels via herbivorous organisms, and their concentrations can increase through biomagnification processes (Tchounwou et al., 2012; Tang et al., 2022). This situation can lead to serious consequences, especially for human health, such as chronic toxicity, neurological disorders, and various metabolic diseases (Noor-ul and Tauseef, 2015). Therefore, determining HM levels in plants after mining accidents is a critical requirement not only for environmental monitoring but also for food safety and public health risk assessments.

One suitable candidate for this type of study is *Paliurus spina-christi* Mill., a species belonging to the Rhamnaceae family, which has a significant population around the Çöpler Gold Mine. It is described as a shrub species that generally reaches 2–4 m in height, exhibiting xerophytic characteristics that enable it to adapt to this wide distribution area. The plant is characterized by its stiff, spiny structure, alternately arranged leaves, highly photosynthetic leaf tissue, and extensive root system. These morphological and physiological features facilitate the plant's adaptation to various environmental stress conditions and enable it to efficiently absorb soil nutrients (Davis, 1967; Tutin et al., 1968; Zohary, 1973; Savran et al., 2020). Furthermore, the widespread presence of the species in the Turkish flora and its use in traditional medicine support its preference in environmental monitoring studies (Zengin et al., 2023; Çelebi and Duman, 2026). In addition, the interaction of *P. spina-christi* with HMs shows that this plant has a high binding and accumulation capacity for metal ions. In particular, the fact that the plant's biomass is an effective biosorbent for toxic metals such as Pb and Cd, and its capacity to bind these metals with high efficiency, makes the plant's evaluation within the scope of this study important (Özmal et al., 2022).

When the toxic effects of HMs on human health and ecosystems are considered together with the risk of these pollutants spreading into the environment during mining activities, the establishment of effective monitoring systems and the implementation of strong regulatory mechanisms stand out as a critical requirement, especially in areas close to densely populated areas or sensitive ecosystems and in sites where mining accidents occur (Laoye et al., 2025; Usman Nurudeena et al., 2025).

The aim of this study is 1) to quantitatively determine the contents of some HMs (Cu, Zn, Mn, and Pb) in the soil and leaf samples of *P. spina-christi* species growing in the mining area after the Çöpler Gold Mine accident in Iliç district of Erzincan province; 2) to establish risk assessment to ensure sustainable management for this area; 3) to determine whether *P. spina-christi* can be used as a biomonitoring species in a heavy metal accumulation or not.

2. Materials and Method

2.1. Study area and sampling

The study area was situated in the vicinity of the abandoned gold mining area, in the Iliç district of Erzincan Province, in the eastern region of Türkiye. Three localities were selected (upper site-locality 1; medium site-locality 2; lower site-locality 3) in the study area. These localities were chosen from the areas close to the mining area, as access to the mining area was not permitted. The coordinates of these localities are 1) 39° 25' 32.6" N 38° 33' 17.0" E, 1267 m, 2) 39° 26' 06.0" N 38° 33' 38.7" E, 1245 m and 3) 39° 26' 26.8" N 38° 32' 44.5" E, 1053 m. These localities contain scattered, large populations of the *P. spina-christi* tree.

Leaves of *P. spina-christi* individuals were collected from the selected three localities. Leaf samples were collected from trees at a height of 2-3 m, with an effort to include all directions as far as possible, and cutting off at least four branches from all around the crown periphery. About 50 leaves were collected from each locality.

2.2. Laboratory analysis

Zn, Cu, Mn, and Pb concentrations were determined by a UNICAM 929 atomic absorption spectrophotometer after ashing them in a muffle furnace. The ashed samples were digested on a hotplate at 80–90 °C for three hours in 20 ml of a 1:1 HCl-pure water solution. The limit of detection (LOD) was 0.038, 1.67, 0.034 and 0.125 for Pb, Zn, Mn, and Cu, respectively. IAEA-336 reference material was used for plant samples.

Soil samples were taken from the same three localities around *P. spina-christi* specimens at the 0-30 cm depth in the Çöpler mining area in September 2024, using a random sampling method. A total of 9 soil samples were taken from three localities. Coordinates of all sampling points were determined with a Global Positioning System (GPS). Soil samples were then taken to the laboratory, air dried, and large particles were broken into small pieces with a wooden hammer and passed through a 2 mm sieve. For heavy metal analyses (Pb, Zn, Cu and Mn), samples were passed through a 100 µm sieve and subjected to acid-digestion (HNO₃:HCl mixture, 1:3 ratio) (Barbes et al., 2014; Parlak et al., 2024). Heavy metal concentrations of soil samples were also measured by using a UNICAM 929 atomic absorption spectrophotometer. SQC001 reference material was used for soil samples. LOD values for soil samples were 0.02, 0.50, 0.03 and 0.060 mg/kg for Pb, Zn, Cu and Mn, respectively.

2.3. Risk assessment

Geoaccumulation Index (Igeo) and Biological Absorption Coefficient (BAC) values were calculated in this study to determine the degree of contamination. We used Igeo to investigate soil contamination. Igeo values were calculated according to the formula:

$I_{geo} = \log_2 C_n / 1.5 B_n$, where C_n is the measured concentration (mg/kg) of the metal under investigation and B_n is the geochemical background of the same metal recorded in mg/kg. To account for a modest anthropogenic impact on a specific metal in the environment, a factor of 1.5 was used to account for possible changes in background values. The pollution of the soil can be determined from the Igeo values using Muller classification: " $I_{geo} \leq 0$

(uncontaminated), $0 < I_{geo} < 1$ (uncontaminated to moderately contaminated), $1 < I_{geo} < 2$ (moderately contaminated), $2 < I_{geo} < 3$ (moderately to heavily contaminated), $3 < I_{geo} < 4$ (heavily contaminated), $4 < I_{geo} < 5$ (heavily contaminated to extremely contaminated) and $I_{geo} \geq 5$ (extremely contaminated)" (Lima e Cunha et al., 2014; Wiafe et al., 2022).

Biological Absorption Coefficient (BAC) is determined as a ratio of the element in plant parts to that present in the soil. In this study, leaf tissue concentration was used.

$BAC = [leaf]/[soil]$. A BAC value above 10 indicates a very strong accumulation of the analyzed element. Accordingly, BAC from 1 to 10 indicates strongly accumulated; from 0.1 to 1 indicates moderately accumulated; from 0.01 to 0.1 weakly absorbed, and between 0.001-0.01 values indicates very weak absorption of the element (Jiménez-Ballesta et al., 2022).

2.4. Statistical analysis

Statistical analyses were performed using R (v4.3.0) with the packages multcompView, ggplot2, ggpubr, and dplyr. Two-way ANOVA was conducted to assess how Zn, Mn, Cu, and Pb concentrations in soil and leaf samples varied according to group (soil vs. leaf) and locality (1, 2, and 3), and to determine the statistical significance of these effects and their interaction (R Core, 2025). A one-way ANOVA was also conducted to evaluate differences among localities in I_{geo} and BAC values. A p-value of less than 0.05 was considered statistically significant.

3. Results and Discussion

3.1. Soil heavy metal concentrations

The descriptive statistics of heavy metal concentrations in soils and leaves of *P. spina-christi* were summarized in Tables 1 and 2. All of the studied heavy metals were below

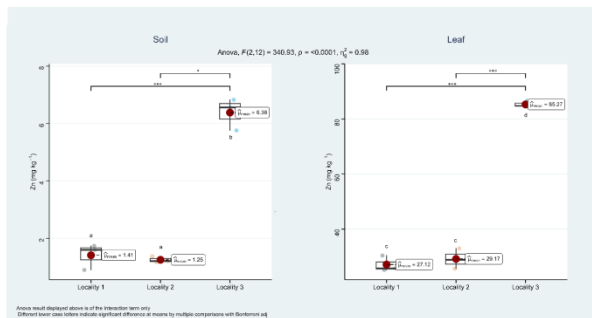


Figure 1. Spatial distribution of Zinc (Zn) concentrations in soil and leaf samples among different localities

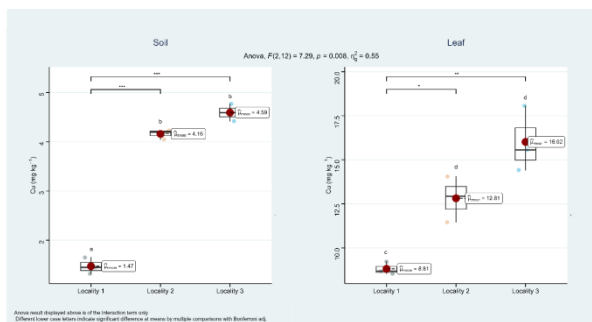


Figure 2. Spatial distribution of copper (Cu) concentrations in soil and leaf samples among different localities

the maximum acceptable limits according to the ranges developed by Kabata-Pendias and Pendias (2001) and Konanc (2021).

The zinc concentration in the soil samples examined ranged from 0.90 to 1.74 mg/kg at locality 1, from 1.17 to 1.38 mg/kg at locality 2, and from 5.76 to 6.83 mg/kg at locality 3 in this study. The highest Zn content was found at locality 3 with an average of 6.38 mg/kg (Table 1). Locality 3 is the closest to the mine tailing pond in the study area. Total Zn content in uncontaminated and natural soils ranges from 10 to 300 mg/kg with a worldwide mean estimated around 54-60 mg/kg (Noulas et al., 2018). Zinc is mainly sourced from sphalerite (ZnS), commonly occurring alongside galena (PbS) in Au-bearing conglomerates. Zinc also comes when separating Au from the Au-CN solution. Tibane and Mamba (2022) reported an average Zn concentration of 72.28 mg/kg in the gold mining region of South Africa. Similarly, in the study conducted by Ali et al. (2017) in the artisanal gold-mining area in Sudan, Zn concentration in the soils has been reported as 77 mg/kg, exceeding by half the concentration of in most soils in the world. The Zn concentrations in the soil samples of *P. spina-christi* obtained in our study are significantly lower than those in most soils worldwide.

Copper-sulfate ($CuSO_4$) is widely used in the recovery of pyrite as a by-product and in the production of sulphuric acid used in uranium extraction from the gold processing plant. The mean Cu concentrations in our study were determined to be 1.47, 4.16, and 4.59 mg/kg for localities 1, 2, and 3, respectively (Table 1). The highest Cu concentrations were also determined at locality 3, the closest area to the mine tailing pond. Total Cu content in uncontaminated soils was estimated between 2 and 100 mg/kg with an average concentration of approximately 30 mg/kg (Poggere et al. 2023; Cai et al. 2025). Poggere et al. (2023) reported a Cu concentration of 684 mg/kg in soils affected by mine tailings in Brazil. According to Cai et al. (2025), Cu concentration in contaminated soils was observed with a mean of 1221.6 mg/kg, exceeding the local background value by 38 times around the tailings reservoir, in China. Our results were slightly lower than the world average values for Cu content in uncontaminated soils.

Cyanide used in the process to obtain gold ore also mobilizes heavy metals. Pyrite from these minerals reacts with oxygen and water to form sulphuric acid. Under acidic conditions, manganese is especially prone to dissolution and can easily leach into the soil. The mean Mn concentrations in the soil samples of *P. spina-christi* ranged from 5.69 to 9.05 mg/kg across the three localities (Table 1). The highest Mn concentrations were observed at locality 2. Tibane and Mamba (2022) reported very high Mn content in soils from the gold-mining area in South Africa, averaging 618.39 mg/kg. Ali et al. (2017) also reported that Mn concentrations ranged from 37.35 to 655 mg/kg in the gold mining area in Sudan. Comparison of our results with the aforementioned studies indicates that manganese concentrations are significantly lower.

The range of concentration of Pb in the samples of locality 1 was from a minimum of 4.17 mg/kg to a maximum of 4.83 mg/kg, with a mean of 4.44 mg/kg, whereas in the samples of locality 2, these values ranged between 5.83 and 7.83 mg/kg, with a mean of 6.69 mg/kg. The highest soil Pb concentrations were again observed at locality 3, ranging

Table 1. Descriptive statistics and Igeo values for studied heavy metals (mg/kg) in the soils samples of the *Paliurus spina-christi*

Locality	Statistics	Zn	Mn	Cu	Pb	Igeo Zn	IgeoMn	IgeoCu	IgeoPb
Locality 1	Mean	1.41	5.69	1.47	4.44	-6.33	-7.31	-4.72	-2.76
	Max	1.74	5.99	1.65	4.83	-5.97	-7.24	-4.51	-2.64
	Min	0.90	5.16	1.32	4.17	-6.97	-7.46	-4.97	-2.85
	SD	0.45	0.46	0.16	0.34	0.55	0.12	0.23	0.10
Locality 2	Mean	1.25	9.05	4.16	6.69	-6.42	-6.64	-3.17	-2.17
	Max	1.38	9.76	4.23	7.83	-6.26	-6.53	-3.15	-1.94
	Min	1.17	8.66	4.05	5.83	-6.51	-6.70	-3.21	-2.37
	SD	0.11	0.61	0.09	1.02	0.14	0.09	0.03	0.21
Locality 3	Mean	6.38	7.06	4.59	13.72	-4.06	-7.00	-3.03	-1.13
	Max	6.83	7.53	4.77	14.83	-3.97	-6.90	-2.98	-1.02
	Min	5.76	6.77	4.42	13.00	-4.21	-7.06	-3.08	-1.21
	SD	0.55	0.41	0.17	0.97	0.12	0.08	0.05	0.10

from 13.00 mg/kg to 14.83 mg/kg with a mean of 13.72 mg/kg (Table 1). Darma et al. (2022) reported Pb concentrations in the gold mining area above 400 mg/kg, whereas the permissible limit for Nigerian soils is 85 mg/kg. On the other hand, Akoto et al. (2023) have reported the highest Pb concentration as 21.65 mg/kg in the area where mining tailings are dumped. In our study, soil Pb concentrations (13.72 mg/kg) were also considerably higher than those at the other two localities. As locality 3 is the closest to the mining tailing pond, our results align with earlier observations that anthropogenic activities contribute to Pb accumulation in soil (Léopold et al., 2016; Akoto et al., 2023).

3.2. Leaf heavy metal concentrations

The mean heavy metal concentrations for *P. spina-christi* in all studied sites ranked as follows: Mn>Zn>Cu>Pb. With respect to localities, the highest heavy metal concentrations in the leaf tissues were found at locality 3, the closest area to the tailing pond of the mining area.

The highest Zn concentration was observed in the leaves of *P. spina-christi* at locality 3, with a mean value of 85.27 mg/kg, whereas the lowest Zn concentration was recorded at locality 1 with a mean value of 27.11 mg/kg. The Zn concentrations in the leaves of *P. spina-christi* exceeded the Zn concentrations in the soils at all sampling sites (Table 2; Fig. 1).

This indicates that the plant can accumulate heavy metals at levels several-fold higher than those in the soil under normal growing conditions. The recommended permissible limit of Zn in plants is 50 mg/kg according to the World Health Organization (WHO) (Nazir et al. 2015). Our results for Zn concentration in leaves at locality 3 are higher than the world-permissible average limit for plants. According to Aliyu et al. (2023), Zn concentrations in different plant species collected from the Bagega mining area, Nigeria, ranged from 4.6 to 90 mg/kg. In general, a high concentrations of Zn in plant tissues may result from habitats highly contaminated with Zn.

Metal transport and distribution in plant tissues are influenced by the available metal levels and plant species. The highest copper (Cu) content in the study area was found at locality 3, with a mean value of 16.01 mg/kg, while the lowest Cu concentration was recorded at locality 1, with a mean value of 8.81 mg/kg (Table 2; Fig. 2).

As Cu is an essential micronutrient for both plants and humans, Cu concentrations of 5-30 mg/kg are generally considered adequate in plant tissues (Kumar et al. 2021). According to these reference values, the Cu concentrations determined in the present study remained below the threshold levels for plant tissues. Cruzado-Tafur et al. (2021) reported that indigenous species in Peru, such as *Achyrocline alata* (Kunth) DC. and *Hypericum laricifolium* Juss., have higher Cu concentrations in their leaves than in their roots. Cu concentrations in the leaves of these species were 16 mg/kg and 11 mg/kg, respectively. On the other hand, Deng et al. (2025) reported that *Salix balfouriana*, due to its remarkable metal adsorption capacity in copper tailings, may be considered a promising candidate for phytoremediation in local mining areas.

Mn concentrations in plant tissues generally range from 30 to 500 mg/kg, with adequate levels often falling between 20 and 100 mg/kg, depending on the species (Shao et al., 2017). Kahangwa et al. (2021) reported Mn concentrations ranging from 125 to 2346 µg/g in the shoots of various plant species collected from a gold mining area in Tanzania. In our study, the highest Mn concentrations were again observed at locality 3, ranging from 662.40 to 726.07 mg/kg, with a mean value of 696.29 mg/kg (Table 2). Although threshold values for Mn vary by species, as shown, the Mn concentration in the leaves of *P. spina-christi* collected from locality 3 exceeded the threshold and reached toxic levels (Fig. 3).

The highest lead (Pb) concentrations in the leaf tissues of *P. spina-christi* ranged from 3.42 to 4.73 mg/kg, with a mean of 4.17 mg/kg at locality 3 (Table 2; Fig. 4).

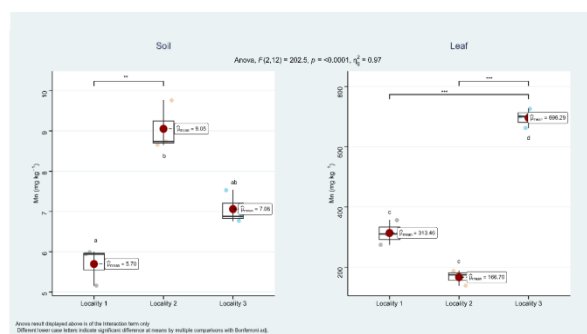
**Figure 3.** Spatial distribution of manganese (Mn) concentrations in soil and leaf samples among different localities

Table 2. Descriptive statistics and BAC values for heavy metals (mg/kg) of the *Paliurus spina-christi* leaves analyzed in the study areas

Locality	Statistics	Zn	Mn	Cu	Pb	BACZn	BACMn	BACCu	BACPb
Locality 1	Mean	27.11	313.45	8.81	2.69	21.45	55.27	6.01	0.61
	Max	30.40	356.07	9.22	2.94	33.78	60.08	6.46	0.68
	Min	25.16	274.28	8.53	2.55	14.46	45.79	5.59	0.54
	SD	2.86	41.00	0.36	0.21	10.70	8.21	0.43	0.07
Locality 2	Mean	29.17	166.79	12.81	2.21	23.36	18.58	3.41	0.33
	Max	33.03	187.00	14.05	2.49	27.29	21.39	3.70	0.41
	Min	25.64	138.64	11.46	1.77	20.89	14.20	3.06	0.27
	SD	3.70	25.09	1.29	0.39	3.43	3.84	0.32	0.07
Locality 3	Mean	85.27	696.29	16.01	4.17	13.42	98.84	3.49	0.30
	Max	86.65	726.07	18.07	4.73	14.72	107.25	3.94	0.34
	Min	84.40	662.40	14.42	3.42	12.69	93.01	3.02	0.26
	SD	1.20	32.03	1.86	0.67	1.12	7.45	0.46	0.04

Cruzado-Tafur et al. (2021) reported the highest Pb content in the leaves of *Arenaria digyna*, with a mean value of 288 mg/kg. Again, in the study carried out by Du et al. (2024) involving two indigenous and dominant plant species in China, Pb concentrations in the aboveground parts of *Artemisia* L. varied from 4.67 to 1261.68 mg/kg, whereas those in the aboveground parts of *Amaranthus* L. varied from 2.24 to 109.18 mg/kg. Pb concentration in the leaves of *P. spina-christi* at locality 3 was higher than the permissible limit of Pb in plants, 2 mg/kg according to WHO (Ogundele et al., 2015). However, the Pb content of leaves in this study was lower than some of the values reported by Cruzado-Tafur et al. (2021) and Du et al. (2024) from the Peruvian Andes and China, respectively.

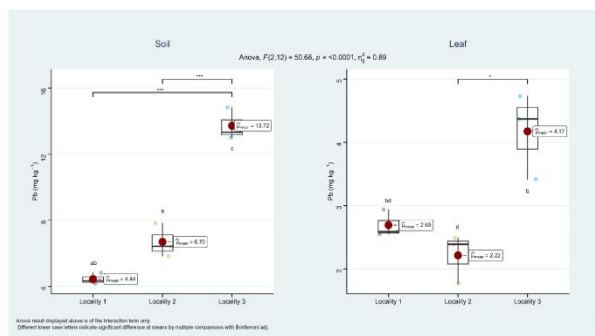
Statistical analysis showed that the concentrations of Zn, Mn, Cu, and Pb in soil and leaf samples varied depending on both the group factor (soil vs. leaf) and the locality factor (localities 1, 2, and 3), as evaluated by two-way ANOVA (Figs. 1-4). For all elements, the concentrations measured in leaf samples were many times higher than those in soil. This difference was not only visually apparent but also highly statistically significant. The group effect was highly significant for all heavy metals studied ($p < 0.001$) with very large effect sizes, indicating that the plant does not act as a passive receiver of these elements but rather as an active accumulator that concentrates them within its tissues.

In both groups (soil and leaf), the values measured at locality 3 were markedly higher than those at the other sites. Especially in the leaf samples, the concentrations of the studied elements showed a clear trend across localities as follows: Zn: 27 → 29 → 85; Mn: 313 → 166 → 696; Cu:

8.8 → 12.8 → 16; Pb: 2.6 → 2.2 → 4.17. The effect of locality was highly significant for all elements ($p < 0.001$) with very large effect sizes (η^2), indicating that environmental contamination was not homogeneous and that locality 3 was clearly more polluted than the others. Furthermore, the interaction between group and locality was significant for all elements, particularly strong for Zn and Mn. As the level of locality increased, the observed increases in soil were reflected in the leaf samples to a disproportionately greater extent. For example, while Zn concentrations in soil increased approximately fivefold from locality 1 to locality 3, this increase was much more pronounced in the leaf samples. This finding indicates that under more polluted environmental conditions, the plant accumulates these elements more intensively in its tissues (Figs. 1-4).

It is well known that the pollution index (Igeo) serves as a useful tool for evaluating potential environmental contamination. Considering current Igeo values, all Igeo values fall within Class 0, indicating the absence of contamination (Table 1). Although the soils are classified as unpolluted according to the Igeo values, the one-way ANOVA results reveal very strong and statistically significant differences among the localities for all heavy metals studied at $p < 0.001$ level, with very large effect sizes ($\eta^2=0.91-0.98$, Fig. 5). The highest Igeo value was obtained at locality 3 for all elements, indicating that the metal contamination is linked to the release of pollutants from the tailing pond. Overall, the relatively low soil heavy metal concentrations reported in the present study, compared with previous studies, can be explained by the sampling strategy, as samples were collected from the vicinity of the mining area rather than from the ore-processing localities.

BAC values for Zn and Mn were very high ($BAC > 10$) in the study area. Also, BAC values for Cu were high (from 1 to 10), whereas values for Pb indicated moderate accumulation (from 0.1 to 1) of this element in the leaf tissues (Table 2). It can be seen that higher Pb content in the soils is associated with higher concentrations of the same element in the leaves. Our results regarding the soil/leaf ratio of Pb concentrations are consistent with those reported by Jiménez-Ballesta et al. (2022), who conducted their study in vineyards. A similar trend was observed for Cu concentrations, but to a lesser extent. However, the opposite trend was observed for Zn and Mn concentrations. Despite low Zn and Mn concentrations in soil samples, a

**Figure 4.** Spatial distribution of lead (Pb) concentrations in soil and leaf samples among different localities

high level of bioaccumulation was observed in the leaf samples of *P. spina-christi*.

The high BACs for Zn and Cu obtained from granite and volcanic soils suggest the presence of sulfide mineralization, despite these elements are being micronutrients and regularly absorbed by plant tissues (Lima e Cunha et al., 2014). On the other hand, because Pb is the element with lower mobility in the soil than Mn or Zn, BAC values for Pb indicate moderate accumulation of

this element in all three study areas. Pb is not a microelement absorbed by plants and can be toxic for them, which also indicates the presence of sulfide mineralization, commonly enriched in these chalcophile elements. In particular, high BAC values for Zn, Mn, and Cu concentrations reached their peak at locality 3. There were also significant differences with respect to BAC values among localities, except for Zn concentrations at $p < 0.001$ level (Fig. 6). There were no significant differences among localities with respect to BAC values for zinc.

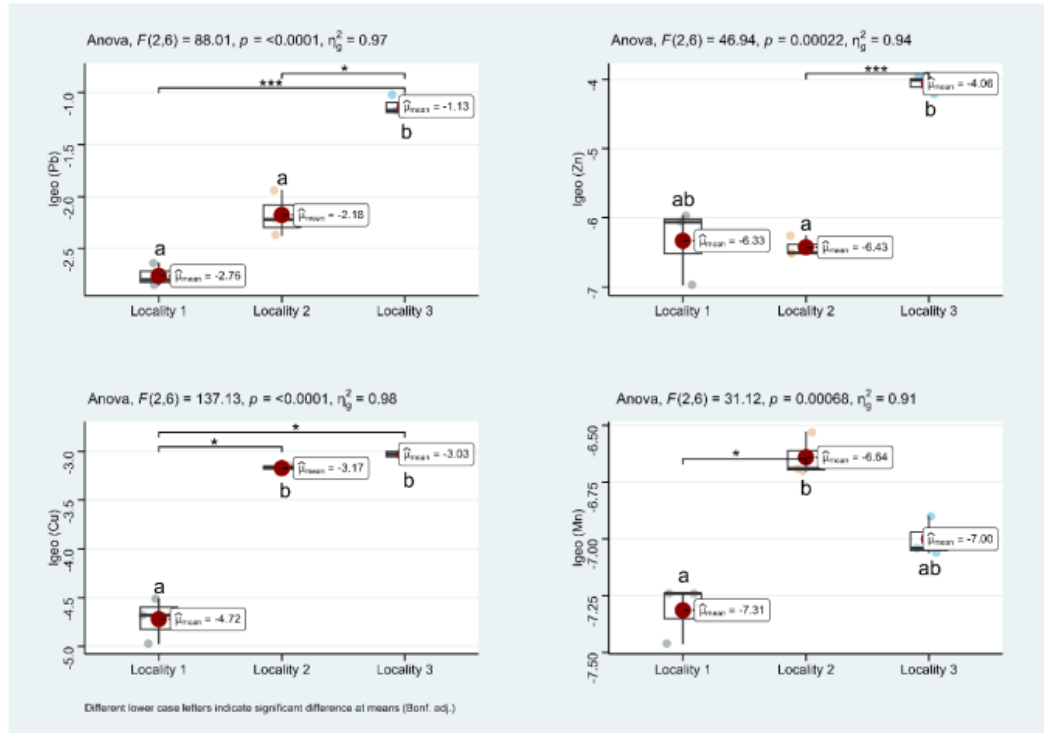


Figure 5. Spatial variability of geoaccumulation index (Igeo) values for Pb, Zn, Cu, and Mn among different localities

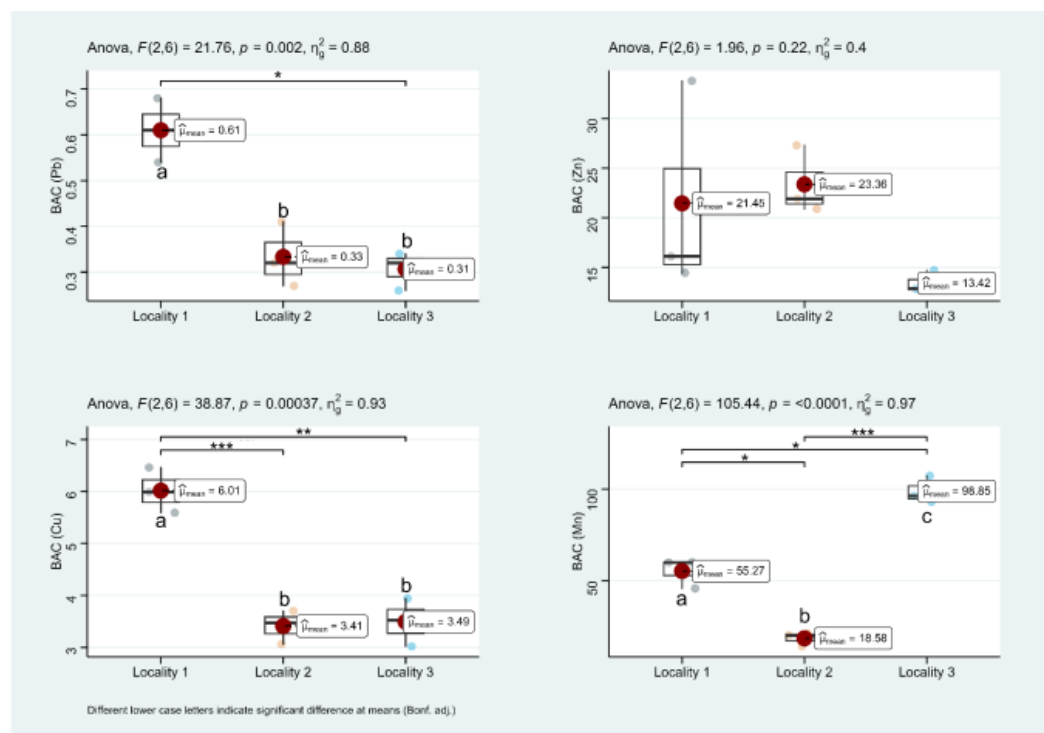


Figure 6. Comparison of bioaccumulation coefficients (BAC) of Pb, Zn, Cu, and Mn among different localities

5. Conclusions

In the present study, the heavy metal concentrations detected in both soil and leaf samples of *P. spina-christi* fell within previously reported ranges. The highest Zn, Cu, and Pb contents in all samples were found at locality 3, which was the closest to the mine tailing pond. So, the Zn, Cu and Pb concentrations in all soil and leaf samples of *P. spina-christi* were mainly from tailing releases. However, despite the highest Mn concentration being detected in the leaf samples at locality 3, the highest Mn concentration in soil samples of *P. spina-christi* was recorded at locality 2. Igeo values in the present study indicate the absence of contamination by the studied heavy metals. There were

significant differences among localities in heavy metal concentrations and Igeo values at the $p < 0.001$ level. Very high BAC values for Zn and Mn ($BAC > 10$), and high BAC values for Cu (from 1 to 10) suggest that *P. spina-christi* can be used as a bioindicator species for monitoring pollution by these elements in local mining areas.

Conflict of Interest

Authors have declared no conflict of interest.

Authors' Contribution

Authors contributed equally.

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