

Old Mining Waste Affecting Plant Distribution and the Health of Residents in Tehuilotepic Municipality of Taxco Guerrero

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Tables 1 to 7 are available in the Supplementary Files section.

1 **OLD MINING WASTE AFFECTING PLANT DISTRIBUTION AND THE HEALTH OF**
2 **RESIDENTS IN TEHUILOTEPEC MUNICIPALITY OF TAXCO GUERRERO**

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17
18 **Abstract:** The environmental impact of mining waste is associated with factors such as the beneficiation
19 methods used and the climatic conditions of the site. Their presence can affect various environments,
20 including vegetation. Plants possess a range of physiological mechanisms that can contribute to their tolerance
21 to contaminants. This study evaluates the richness and distribution of plant species growing in the mining
22 wastes ("jales") "La Hacienda" and "Los Remedios" in the mining district of Taxco in Tehuilotepec, Guerrero,
23 Mexico, using quadrants. It correlates the presence of vegetation with the content of potentially toxic elements
24 (PTEs) in the mining waste, aiming to identify tolerant plant species. The concentrations of PTE were
25 evaluated in accordance with the corresponding Mexican regulation: NOM-147-SEMARNAT/SSA1-2004.
26 The results indicated that Cd exceeded the limits for most points; Pb, As, and Hg exceeded them in all points,
27 with the highest levels found in the ant mound substrate (HH). Ni is below the norm, and Ag only exceeded
28 the limits in two points (HH and RAF2H). A total of 25 plant species were collected in the mining waste, of

which six are of ecological importance. The comparison with the Shannon index showed low species diversity in the "La Hacienda" and "Remedios" mining waste. Likewise, the Simpson index demonstrated low dominance of one species due to the high diversity of vegetation present around the "La Hacienda" and "Remedios" mining waste sites. The Hazard quotient and hazard index show the risk for As (89-100% total risk) and Pb (6-11% total risk).

Keywords: ancient mining tailings, mining impacts, vegetation succession, plant diversity

Introduction

The mining industry has produced and will continuously produce large quantities of waste. It is projected that 1,150 million tons of potentially toxic elements (PTEs) (As, Cu, Cd, Cr, Fe, Pb, Zn, among others) have been extracted worldwide, with real estimates of mining waste production ranging from 5 to 7 billion tons per year. In Mexico, mining is one of the oldest economic activities, contributing to the country's development from pre-Hispanic times to the present day [1–3]. The mining activity is prominent in Mexico; however, it generates thousands of tons of waste containing high concentrations of PTEs [4]. The physicochemical properties of mine tailings vary greatly depending on the mineral source, but in general, they all contain high concentrations of Cd, Cu, Mn, Ni, Pb, Zn, among others metals, and low concentrations of essential nutrients (P, K, and N), as well as organic matter [5]. Disposal sites for active or inactive mining tailings are common in open areas in Mexico. The contaminants can easily spread through wind and water, impacting large areas, which can be estimated to be tens of hectares in size [6,7]. Furthermore, the excess of PTEs often suppresses root growth in plants, causing leaf chlorosis and reducing biomass.

The accumulation of PTEs in terrestrial environments has become a global issue. Acute effects occur when toxic waste accumulates in the soil, particularly over extended periods, potentially causing severe damage and risks to ecosystems and human health. Reports on vegetation growing in areas contaminated by mining residues in Mexico have been increasing [8,9]. Similarly, information regarding the concentrations of elements that species can accumulate has increased [10,11], along with knowledge about their adaptation

mechanisms; whether they accumulate contaminants in their tissues or prevent them from entering the root system.

Within the tailings, there is vegetation that thrives, and among them, there are plants that accumulate large amounts of PTEs. Based on their accumulation, they are classified as excluders, accumulators, and hyperaccumulators. The latter are of particular interest as they can accumulate PTEs in their living tissues at levels that can be hundreds or even thousands of times higher than normal for most plants [12–18]. These accumulator plants are highly valuable for use in the phytoremediation of soils contaminated with PTEs.

The phytoremediation process involves several phases. One of them is phytoextraction, which consists of the translocation of contaminants from the soil matrix, to the roots and above-ground parts of the plant where they accumulate [3,19]. Subsequently, the above-ground parts can be harvested, effectively removing the PTEs from the soil [20,21]. Additionally, it eliminates organic and inorganic contaminants from the soil, improves its physicochemical properties when vegetative cover is established, or when conventional agronomic activities are carried out. Phytoremediation can also be applied to water, sediments, and air, resulting in recycled water, recovered PTEs, and biomass. It is considered a cost-effective and environmentally friendly technique [22–24].

Various authors have documented more than 700 plant species that are capable of hyperaccumulating one or more PTEs (such as As, Cd, Cr, Co, Cu, Pb, Mn, Ni, Se, and Zn). The majority of hyperaccumulators are flowering plants [6,8,12,13,25–28].

Bioaccumulating plants serve as exceptional models for scientific understanding of PTEs regulation, including the physiology of absorption, transport, and sequestration, as well as evolution and adaptation in extreme environments [29–31]. The ecology of hyperaccumulating plants is also an active field of research, focusing on anti-herbivore defenses, allelopathy, and biotic interactions [32–34,20].

84 Reports regarding vegetation growing in sites contaminated by mine residues in Mexico have been increasing
85 [6,8,35–39]. Similarly, information about the concentrations of PTEs that species can accumulate has
86 increased [36,37,37,40–42], as well as the adaptation mechanisms they possess [43].

87
88 However, studies on floristic richness and abundance in mining tailings are still scarce [44–46]. Therefore, it
89 is important to consider biodiversity metrics that incorporate both richness and abundance as essential
90 dimensions of biodiversity [47]. Species richness alone is a limited indicator of biodiversity and is the most
91 commonly used metric in primary biodiversity studies [48]. The mining town of Taxco, in Guerrero State,
92 offers ideal conditions for evaluating floristic richness due to accumulation of mining waste from distinct
93 periods. The “La Hacienda” tailings deposit was in operation between the mid-18th century and the beginning
94 of the 19th century, and another is “Los Remedios” which was in operation during the first half of the 20th
95 century. To date, there is no information available on the study of the two oldest deposits in the Taxco region
96 in relation to the distribution of plant species in the ancient tailings; therefore, the following investigation was
97 carried out in the tailings of these old deposits, for which both tailings were sampled. That is why the purpose
98 of this work is to i) to evaluate the richness and distribution of plant species growing in “La Hacienda” and
99 “Los Remedios” tailings through quadrants, and ii) to correlate the presence of plants with the content of
100 PTEs in the substrates of the tailings, in order to identify tolerant plant species and Hazard quotient and
101 hazard index evaluation.

102 103 **Material and methods**

104 105 Study site

106
107 Tehuilotepic is located in the municipality of Taxco de Alarcón in the state of Guerrero, bordered to the north
108 by Tetipac, to the south by the municipalities of Iguala and Teloloapan, to the east by the municipality of
109 Buenavista de Cuellar and the state of Puebla; and to the west by the municipalities of Pedro Ascencio
110 Alquisiras and Ixcateopan. The town of Tehuilotepic is situated 8 km east of Taxco de Alarcón, in route to
111 Cuernavaca on the “Mexico libre” highway, at an altitude of 1,707 meters above sea level (masl).

The first sampling site, called "La Hacienda," is located between parallels 18°23'19.63'' N and 99°34'33.60'' O, at an altitude of 1607 masl. It is situated 4.6 km from Cuernavaca, in the direction of the town of San Juan de Dios. The second sampling site, named "Los Remedios," is located at 18°32'49.01'' N and 99°34'37.60'' O, at an altitude of 1620 masl. It is situated 2.1 km from Cuernavaca, heading towards the "Los Remedios" mine (Figure 2).

Field collection

Sampling of mining tailings

A total of 16 substrate samples were collected at a depth of approximately 20 cm, distributed as follows across two sites:

1) "La Hacienda" Mine Site: 10 samples were collected, with seven being from the rhizosphere of the most representative plant species in the area (*Acacia farnesiana* (L.) Willd. (2 samples), *Acacia cochliacantha* Willd. (2 samples), *Juniperus deppeana* Steud, *Cardiospermum haliacabum* L., and *Atractylolcarpus* sp.), along with one anthill. Additionally, two composite samples were created to provide a general overview of the site.

2) "Los Remedios" Mine Site: 6 samples were collected with two being from the rhizosphere of the most representative plant species in the area (*A. farnesiana*). Similarly, four composite samples were created to provide a general overview of the site.

Plant sampling

The collection of wild plants listed in Table 2 was conducted at the "La Hacienda" and "Los Remedios" sites using the method proposed by Lot and Chiang [49]. Field collection fully complied with local and national

guidelines for flora preservation under NOM-059-SEMARNAT-2010. No specific permits or licenses were required for this study, as the species are not endangered and the collection area is not a protected reserve.

Plant species collection was carried out within a general 25 m × 50 m quadrat at the "La Hacienda" and "Los Remedios" sites (Figure 2). This quadrat was further subdivided into 4 m × 4 m sub-quadrats for the taxonomic identification of trees and 1 m × 1 m sub-quadrats for herbaceous plants, in order to facilitate the calculation of Shannon and Simpson indices [50]. At each sampling site, three to four plant specimens were collected for botanical identification. The species were identified and documented by a specialist from the Metropolitan Herbarium of UAM-I (Universidad Autónoma Metropolitana-Iztapalapa). Additionally, a literature review of floristic and taxonomic studies covering the study area was conducted [51–54].

Diversity indices

The study employed two diversity indices. One of the most widely used is the Shannon-Wiener index, proposed by Claude Shannon in 1948 [55]. The Shannon index is used to measure species diversity (the number of different microorganisms and organisms in an ecosystem). Another commonly used index for community analysis is the Simpson index, introduced by Edward Hugh Simpson in 1949 [56]. From the values of these indices, the most significant species in the study sites were determined.

$$\text{Shannon index (H)} = \sum_{i=1}^s (P_i)(\ln P_i)$$

$$\text{Simpson index (D)} = \frac{\sum n(n-1)}{N(N-1)}$$

P_i = relative abundance of each species in the community, n = total number of organisms of a species, N = total number of organisms of all species

PTEs mine tailings

For the analysis of PTEs, samples of mine tailings were dried at 40°C, pulverized, homogenized, and sieved through a 0.63 mm mesh. The concentrations of Ag, As, Pb, Cu, Zn, Ni, Mn, and Fe were measured using a X-ray Fluorescence (XRF) analyzer (Thermo Scientific Niton XL3t). High-purity standards were used for

calibration curves. Three replicates of each substrate sample were used, and precision was assessed using the NIST Montana soil reference material 2711. The data from the sampling points were mapped using Kriging Surfer® (Golden Software, LLC) [57] (Figure 3 and 4).

Hazard quotient and hazard index

The evaluation of potential health risks, based on the USEPA [58–60] and USDOE [61] models, was carried out for lifetime exposure, which in Mexico is 75 years, to soils contaminated with mining waste through ingestion, inhalation, and dermal contact during their passage through the mining waste. To this end, chronic daily intakes (CDIs) of Ag, As, and Pb through ingestion, inhalation, and dermal contact were calculated, these were the most representative in the comprehensive analysis of the evaluated EPTs. The CDI values were used to calculate the cancer risk, the hazard quotient (HQ), and the hazard index (HI).

$$CDI_{ing-ca} = [C \times IFS \times EF \times ED]/AT_{ca} \quad (1)$$

$$IF = \{[IRS_{adult} \times ED_{adult}]/BW_{adult}\} + \{[IRS_{child} \times ED_{child}]/BW_{child}\} \quad (2)$$

Where C is the concentration of PTEs in soil (mg/kg), IFS is intake factor soil (mg yr/kg d), EF is exposure frequency (d/yr), ED is exposure duration (yr), AT_{ca} is the average time for carcinogens, IRS is ingestion rate soil/sediments (kg/d), and BW is average body weight (kg).

$$CDI_{inh-ca} = \{[EF \times ET \times ED]/[PEF \times 24 \times AT_{ca}]\} \times 10^3 \quad (3)$$

where ET is exposure time (h/d) and PEF is soil-to-air particulate emission factor (m^3/kg).

$$CDI_{dermal-ca} = \{[C \times ABS_d \times EF \times DFS_{adj}]/AT_{ca}\} \times 10^{-6} \quad (4)$$

$$DFS_{adj} = \{[ED_{child} \times SA_{child} \times AF_{child}]/BW_{child}\} + \{[(ED_{adult} - ED_{child}) \times SA_{adult} \times AF_{adult}]/BW_{adult}\} \quad (5)$$

where ABS_d is the dermal absorption factor (unitless), DFS_{adj} is the soil dermal contact factor-age adjusted (mg yr/kg d), SA_{adult} is the skin surface area available for exposure ($cm^2/event$), and AF is the soil to skin adherence factor ($mg\ cm^{-2}$).

The data presented in Appendix A are the input parameters and their values for calculating CDI (carcinogenic and non-carcinogenic) through different exposure pathways. Carcinogenic risk through different exposure pathways was calculated using the following equations:

$$Risk_{ing} = CDI_{ing-ca} \times CSF_{ing} \quad (6)$$

$$Risk_{inh} = CDI_{inh-ca} \times IUR \quad (7)$$

$$Risk_{dermal} = [CDI_{dermal-ca} \times CSF_{ing}]/ABSGI \quad (8)$$

Chronic oral slope factor (CSF_{ing}), chronic inhalation unit risk (IUR), gastrointestinal absorption factor (ABSGI), and dermal absorption factor (ABS_d) for different PTEs.

Non-carcinogenic chronic daily intake through various exposure pathways was calculated using the following Equations:

$$CDI_{ing-nc} = [C \times IRS \times EF \times ED]/[BW \times AT_{nc}] \quad (9)$$

$$CDI_{inh-nc} = [C \times EF \times ET \times ED]/[PEF \times 24 \times AT_{nc}] \quad (10)$$

$$CDI_{dermal-nc} = \{[C \times SA \times AF \times ABS_d \times EF \times ED]/[BW \times AT_{nc}]\} \times 10^{-6} \quad (11)$$

HQ was calculated by dividing the non-carcinogenic chronic daily intake (CD_{Inc}) by the corresponding reference dose, as follows:

$$HQ = CD_{Inc}/RfD \quad (12)$$

RfD_{ing} , RfD_{inh} , and RfD_{dermal} values for Fe, Mn, Pb, and Zn.

The total risk is the sum of the cancer risk from each exposure pathway.

$$\text{Total risk} = \Sigma \text{Risk} = \text{Risk}_{\text{ing}} + \text{Risk}_{\text{inh}} + \text{Risk}_{\text{dermal}} \quad (13)$$

The cumulative non-carcinogenic hazard, expressed as the HI, is the sum of hazard quotients from each exposure pathway.

$$\text{HI} = \text{HQ} = \text{HQ}_{\text{ing}} + \text{HQ}_{\text{inh}} + \text{HQ}_{\text{dermal}} \quad (14)$$

Results and discussion

Concentration of PTEs in mine tailings

In the "La Hacienda" mine tailings, the association of analyzed plants includes *Acacia farnesiana*, *Juniperus deppeana*, *Acacia cochliacantha*, *Cardiospermum haliacabum*, *Atractylodes sp.*, and an anthill (Table 1). The results indicated that, according to the critical concentrations proposed by Alloway (1995), levels of Cd, Pb, Zn, Ni, and Hg were exceeded in both sites. For Cu, five points in the "La Hacienda" tailings did not surpass critical concentrations. Regarding the values established by NOM-147-SEMARNAT/SSA1-2004 [62], Cd concentrations were exceeded in almost all points, except for MC4R (33.72 mg/kg) in the "La Hacienda" site. Pb exceeded the limits in all points, with the highest concentration found in the anthill substrate (33626.75 mg/kg). Ni did not exceed the limits on any site. Ag was only exceeded in the RAF2H point (451.91 mg/kg) and in the anthill (557.71 mg/kg). All points exceeded the NOM limits for As, with the highest concentration in the anthill (1517.77 mg/kg), and the detectable concentration of Hg exceeded the NOM limits (Table 1). Therefore, the site with the highest concentrations was in the anthill substrate, which can be explained by the accumulation of leaves from the different plants present in the area.

The highest concentration of PTEs was found in quadrant 23, corresponding to the ant nest where *A. cochliacantha* (15 individuals) and *E. imbricata* (26 individuals) were discovered, with concentrations of Ag (557.71 mg/kg), As (1517.77 mg/kg), Pb (33626.75 mg/kg), Cu (330.73 mg/kg), and Fe (295273.47 mg/kg). However, this quadrant exhibited a lower concentration of Zn (949.64 mg/kg), possibly due to its essential

role in plant development. The highest concentration of Zn was observed in quadrant 45 (14321.79 mg/kg), where *T. recurvata* (1 individual) was located as an epiphyte on *A. cochliacantha* (4 individuals) and *E. imbricata* (6 individuals). Mn concentration was highest in quadrant 41, where *P. dulce* (1 individual) and *A. cochliacantha* (3 individuals) were found. Ni concentration peaked in quadrant 50 (134.39 mg/kg), where only *A. farnesiana* (2 individuals) was determined.

In the “Los Remedios” site, the distribution of PTEs varied (Figure 4). Ag, As, Pb, Cu, and Fe were highly concentrated in quadrant 41 (320.47 mg/kg, 1019.51 mg/kg, 15284.25 mg/kg, 328.69 mg/kg, and 210620.95 mg/kg, respectively), while Zn was concentrated in quadrant 50 (11331.8 mg/kg). In both quadrants, no plant species were found. Mn had the highest concentration in quadrant 6 (14826.92 mg/kg). In this area, plant species were abundant, including *A. capillus-veneris*, *Salvia* sp (7 individuals in a colony), and *A. farnesiana* (3 individuals).

Ni had the highest concentration in quadrant 1 (179.85 mg/kg). In this area, the plant species found were *A. farnesiana* (2 individuals), *Bursera* sp. (1 individual), and *Salvia* sp., which was very abundant. *Salvia* sp. was abundant in the area where it appeared in colonies in quadrants 1 and 6. The genus *Salvia* belongs to the Lamiaceae family, which is one of the most diverse plant species families in Mexico, ranking eighth in terms of species richness [63]. The genus is cataloged as the second in terms of diversity and endemism in Mexico, with approximately 300 species [64], and an endemism rate of around 88% [65]. It is distributed in temperate zones, growing in vegetation types such as coniferous forests, *Quercus* forests, and montane mesophyll, with a wide distribution in the states of Oaxaca, Puebla, Guerrero, Michoacan, and Jalisco [65].

It was observed that the highest concentrations of PTEs were in quadrants 23 (Ag, As, Pb, Cu, and Fe) and 45 (Zn) for the location “La Hacienda”, as well as quadrant 6 (Mn) and 1 (Ni) for the location “Los Remedios”.

Richness and abundance of plant species

Natural or artificial revegetation represents a sustainable way to stabilize soils contaminated with mine tailings and to reclaim affected lands [66,67]. These mining residues can hinder the establishment and development of vegetation, primarily due to the toxic effects of potentially harmful elements, the limited availability of essential mineral nutrients, and the physicochemical characteristics that restrict plant growth [68–70]. To establish an effective establishment of vegetative cover, it is necessary to select native species from the area and assess their resistance to the presence of potentially toxic elements. This enables an understanding of vegetation dynamics and ensures the success of reforestation and environmental restoration projects in areas degraded by mining activities, which pose an environmental risk.

The impact of mining on vegetation is complex and diverse, depending on the type and intensity of the mining operation. Alteration of the natural landscape and the creation of tailings dams are among the most observable impacts of mining [71]. During mineral extraction, large quantities of soil are removed to reach the mineral deposit. This top-soil layer is nutrient-rich and provides optimal conditions for plant growth due to its high organic matter content. Its removal affects the biological, chemical, and physical properties of the soil, ultimately impacting plant growth and leading to a loss of vegetative cover [72,73].

The predominant vegetation in the municipality is the deciduous tropical forest, characterized by foliage changes during the dry season (including species like *Lysiloma*, *Bahamensis*, and *Xotermani*). Pine forests (*Pinus lawsonii* and *P. pringlei*) and oak forests consisting of various species, as well as isolated gallery forests, are also present. According to Jiménez et al., [74]; Martínez et al., [75]; Gómez-Bernal et al., [8]; Morales et al., [76], a total of 1342 species, 566 genera, and 134 families of vascular plants have been recorded in the region. This richness represents 22.4% of the species in Guerrero State, 6.1% of the species in Mexico, and 30.2% of the species in the Balsas River basin. The best represented families in the area are *Compositae*, *Leguminosae*, *Gramineae*, and *Euphorbiaceae*.

A total of 26 plant species were collected in the tailings, of which 6 have significant ecological importance, as they were found in abundance (Figure 3). The plants collected in the "La Hacienda" tailings include: *Elytraria imbricata*, *A. cochliacantha*, *Tillandsia recurvata*, *Sedum jaliscanum*, *Ipomea murucoides*, *Ficus citrifolia*, *Physalis angulata*, *Pithecellobium dulce*, *Wigandia urens*, *C. haliacabum*, *A. farnesiana*, *Rhynchelytrum repens*, *Croton* sp., *Clematis dioica*, *Iresine interrupta*, *J. deppeana*, *Agave* sp., *Argemone mexicana*, *Selaginella* sp., *Atractylodes* sp., *Sanvitalia procumbens*, and *Tabernaemontana arborea*. In the "Remedios" tailings, the following plant species were associated: *A. farnesiana*, *P. angulata*, *C. haliacabum*, *Adiantum capillus-veneris*, *Stachys agraria*, *Salvia* sp., *Bursera* sp., and *C. dioica* (Table 2).

The study by Elizondo et al. [77] found that the vegetation in the vicinity of the mine tailings in Zimapán, Hidalgo, corresponds to a pine-oak forest, composed of associations of *Pinus patula*, *P. pseudostrobus*, *P. teocote*, *Quercus laurina*, *Q. rugosa*, *J. deppeana*, and *J. flaccida*. In the youngest tailing of the study site, the most abundant species was *Ricinus communis*. In the oldest tailing, they found a higher frequency of trees such as *A. farnesiana*, *J. flaccida*, *A. greggii*, *J. deppeana*, and *Quercus* spp. Comparing with our study, the species that share similar revegetation behavior are *A. farnesiana*, *J. deppeana*, and *Argemone mexicana*, suggesting they are globally distributed species. Additionally, the genera *Ipomea*, *Physalis*, *Crotón*, *Salvia*, *Clematis*, and *Agave* were found, although with different species, indicating their potential application in phytoremediation. It was also observed that on the outskirts of the tailings, the presence of limestone rocks promotes revegetation, as observed in the "La Hacienda" study site [78–80].

Noriega-Luna et al. [81] identified plant species associated with tailings in the mining district of Guanajuato. They found common species such as *A. farnesiana*, *P. dulce*, *Selaginella* sp., and plants from the *Physalis* genus. Similarly, Puga et al. [82] conducted a study in San Francisco del Oro, located in the southern part of the state of Chihuahua. They found *A. farnesiana*, *J. deppeana*, among others (*Baccharis glutinosa*, *Prosopis juliflora*, and *Cynodon dactylon*). These species stood out for their ability to accumulate arsenic (As) and zinc (Zn) in an area with mine tailings.

Márquez-Huitzil et al. [83] utilized historical Google Earth images to identify the absence of changes in vegetation associated with tailings in Huautla, Morelos, between seasons and years, in an area characterized by contrasting changes in vegetation, including seasonal lowland forest (deciduous lowland forest, dense deciduous lowland forest, and secondary vegetation of deciduous lowland forest). This method of analysis over time enables an understanding and prediction of changes in mine waste and its impacts on various scales, thereby preventing, avoiding, or mitigating the effects generated by tailings. This approach could be applied to the studied sites given the similar characteristics of both work areas, enabling the assessment of ecological succession in the Taxco mining district.

Osuna-Vallejo et al. [84] found fragmented vegetation associated with primary succession dominated by *J. deppeana* in the mine tailings of Tlalpujahua, Michoacán. On the periphery of the tailings, they observed remnants of the original mixed pine-oak forest, which included species such as *Abies religiosa*, *P. pseudostrobus*, and *J. deppeana*. This suggests that the established vegetation differs significantly from the original vegetation, similar to what was observed in the tailings studied at both sites.

Comparing our study with previous reports, we found that *E. imbricata*, *A. cochliacantha*, *T. recurvata*, *P. dulce*, *C. haliacabum*, *A. farnesiana*, *I. interrupta*, *A. capillus-veneris*, *J. deppeana*, and *A. mexicana* are plants that are tolerant to PTEs and have been reported (Table 2). These studies highlight the diverse capabilities of different plant species in relation to heavy metal accumulation and their potential roles in phytoremediation strategies. *E. acaulis* is highlighted for its resilience to conditions like drought, heavy metal accumulation, and salinity [85].

Tillandsia species are recommended for monitoring atmospheric pollution in tropical areas due to their adaptation to hot and dry conditions, making them highly tolerant to water stress [86–89]. *T. recurvata* is mentioned as a species naturally occurring in polluted and urbanized sites [90].

Several *Sedum* species, including *S. alfredii* and *S. plumbizincicola*, have been identified as hyperaccumulators of heavy metals without displaying toxicity symptoms. These plants have been studied for

their ability to accumulate Cd, Zn, and Pb in contaminated soils [91–95]. However, its phytoremediation efficiency may be constrained by slow growth and low metal bioavailability in the soil [96], as well as the differences in the geographical distribution, growth habits, anatomy, and genetic characteristics of different *Sedum* species, including *S. plumbizincicola* and *S. alfredii*.

In Guanajuato, Guanajuato State, species like *Baccharis salicifolia*, *Schinus molle*, and *I. murucoides* have been reported to be capable of bioaccumulating heavy metals in an old mining area [97]. The addition of organic materials, particularly charcoal, increases the solubility and mobility of Cu metal in the soil-water-plant system, enhancing its uptake by plants like *Ipomea reptans*. There is no observed toxicity of Cu metal when its level is around 900 mg/kg in the soil [98].

De Abreu et al. [99] found that in *P. angulata* plants, the levels of Mn, Mo, and Zn were affected by different concentrations of aluminum in the culture medium. The addition of P to the stems and roots indicated a tolerance mechanism to the toxic metal. Aluminum also influenced the levels of various other nutrients in the plants. Ameh et al. [100] reported on the potential of various plant species for phytostabilization and phytoextraction of different metals. *P. angulata* showed potential for phytoextraction of Pb.

P. dulce and *A. farnesiana*, which establish themselves in mine tailings, have been found to bioaccumulate Cu, Zn, and Pb in their leaf tissue at higher concentrations than those present in the tailings in Huautla, Morelos [101,102]. Specifically, for *P. dulce* trees growing in mine tailings in this region, they accumulate Cu, Pb, and Zn in their leaf tissue. The heavy metal enrichment values showed higher concentrations of Cu (5.75 mg/Kg), Pb (8.69 mg/Kg), and Zn (6.30 mg/Kg) in the leaf tissue of *P. dulce* compared to what was detected in the tailings [101].

Stachys species have been studied. Dudić et al. [103] found varying concentrations of Fe, Cr, and Ni in different parts (root, stem, and leaf) of *Stachys recta* var. *chrysophaea* from a serpentine deposit in Western Serbia. *Stachys inflata* is identified as an accumulator of Cu, Ni, and Cd, particularly in polluted environments [104]. Moradi et al. [105] observed that *Scariola orientalis* and *S. inflata* have the capability to bioaccumulate

Pb, Cr, and Zn, indicating a potential risk of heavy metals entering the food chain through plant tissues. Hajmoradi and Moghadami [106] reported the concentrations of Zn, Cd, Cu, and Pb in the root and shoot of *S. inflata* plants, both in polluted and non-polluted environments. In polluted environments, the concentrations were significantly higher.

W. urens is a plant species found in secondary vegetation of pine and pine-oak forests, abandoned agricultural plots, highly eroded soils, and secondary vegetation from volcanic eruptions [107]. In Mexico, it is associated with various ecosystems. It naturally establishes itself in disturbed, abandoned, or contaminated soils [28] and has the capacity to bioaccumulate certain heavy metals like Co, Cu, Fe, Mg, Mn, Ni, Pb, and Zn in its leaf tissue [28,108]. It is known for its ability to naturally break seed dormancy through metabolic processes promoted by rain, as well as its high germination rate, making it well-suited for open canopy sites with little vegetation [109].

Studies have shown that individuals of *W. urens* growing on exposed substrates accumulate heavy metals, displaying the following pattern: Fe (5093.80 to 5215.80 mg/kg), Zn (104.47 to 111.72 mg/kg), Pb (104.43 to 106.70 mg/kg), and Cu (29.79 to 41.67 mg/kg) in two mine tailings deposits at Huautla in the municipality of Tlaquiltanago, Morelos State, Mexico [110].

Under greenhouse conditions, *W. urens* individuals growing on exposed substrates also accumulate Cu, Fe, Pb, and Zn in their leaf tissue. The accumulation of these elements can be attributed to the bioavailability of Cu, Fe, Pb, and Zn in mine tailings from Huautla, Morelos, as reported in previous studies [28,108,111]. *W. urens* is known to translocate both essential and non-essential metals in its leaf tissue. In terms of heavy metal bioaccumulation, the pattern observed in *W. urens* foliar tissue (Fe > Pb > Zn > Cu) aligns with findings reported by Fuentes-Reza [112].

C. haliacabum was found in a mining region of Zimapan, Hidalgo, Mexico by Carmona [113], although it was not analyzed in detail. Maldonado-Magaña et al., [114] focused on *A. farnesiana* ability to tolerate and accumulate Pb in seedlings. Seedlings exposed to 250 and 500 mg Pb²⁺ L⁻¹ showed increased growth,

achieving tolerance indexes of nearly 100%. However, seedlings exposed to 1000 mg Pb²⁺ L⁻¹ experienced significant growth inhibition, with an effective concentration 50% (EC50) ranging from 720 to 766 mg Pb²⁺ L⁻¹. *A. farnesiana* showed significant Pb accumulation in roots (up to 51,928 mg/kg of air-dried tissue) when exposed to 1000 mg Pb²⁺ L⁻¹. This indicates its suitability for lead-phytostabilization efforts, with high bioconcentration (>8.5) and low translocation (≤0.03) factors. This legume species holds ecological value due to its role in controlling soil erosion and enhancing soil fertility through symbiosis with *Rhizobium* and mycorrhizal fungi [115]. Additionally, *A. farnesiana* demonstrates significant differences in Pb phytoextraction rates between roots, stems, and leaves [116].

In the case of *R. repens*, it was observed that the highest concentrations of Zn, Cd, and As were found in the roots, shoots, and whole plant. The translocation factors for these metals were 4.70 for Zn, 1.06 for Cd, and 0.09 for As in a Gold Mining Area in Ghana [117]. Furthermore, the concentrations of Cu, Ni, and Pb in the plant extract from *R. repens* were measured to be 0.02 mg/kg, 0.1 mg/kg, and 0.02 mg/kg, respectively [118].

Aromatic and medicinal plants have demonstrated their capacity to uptake and accumulate toxic heavy metals from polluted environments, making them potential candidates for use as biomonitors or accumulators of pollutants. In one study Gaudchau et al. [119] found that clary sage (*Salvia* sp.) tends to exclude Cd, while Zheljazkov et al. [120] and Angelova et al. [121] concluded that it can be successfully grown on sites with severe air and soil heavy metal contamination, potentially serving as a substitute for some other edible crops. In the case of clary sage (*Salvia sclarea*), limited information is available regarding its potential for heavy metal accumulation and its suitability for phytoextraction. Studies on growing clary sage in contaminated soil are also scarce and sometimes yield conflicting results.

Angelova et al. [121] observed that the distribution of Pb, Zn, and Cd in *Salvia officinalis* followed the order: leaves > inflorescences > roots > stems, and for Cu, it was leaves > roots > inflorescences > stems. Blagojević et al. (2009) determined the concentration of heavy metals in leaves and variously obtained extracts of *S. officinalis* at distances of 0 m, 50 m, and 100 m from a major road. Before the flowering period, zinc was the most abundant metal in sage leaves. Its content decreased at distances of 50 m (51.12 mg/kg) and 100 m

(40.18 mg/kg) compared to samples at 0 m from the road (66.62 mg/kg). Similarly, concentrations of Cu showed a decreasing trend: 12.29 mg/kg near the road, 10.73 mg/kg at 50 m, and 9.25 mg/kg at 100 m from the road. The concentration of Pb in sage leaves at 50 m (6.90 mg/kg) and 100 m (6.48 mg/kg) from the road, in both herb samples, decreased compared to samples at the edge of the road (10.42 mg/kg).

Angelova et al. [122] studied contaminated soils in agricultural fields contaminated by Zn, Pb, and Cd near Plovdiv, Bulgaria. In soil 1 (0.5 Km) and soil 2 (2 Km), the content of Pb in the roots of *S. sclarea* ranged from 281 mg/kg to 471 mg/kg, Zn from 501.2 mg/kg to 657.7 mg/kg, and Cd from 17.5 mg/kg to 23.2 mg/kg. In the stems, Pb content ranged from 80.7 mg/kg to 244.0 mg/kg, Zn from 195.5 mg/kg to 369.3 mg/kg, and Cd from 1.6 mg/kg to 6.0 mg/kg.

The reported Cu content for *Valeriana officinalis* was 57.4 ppm, while *Tilia platyphyllos* and *S. officinalis* had Cu contents of 2.08 and 4.60 ppm, respectively [123], in teas sold in Kütahya, Turkey. The Zn content of *Salvia aramiensis* was found to be 35.02 ppm grown naturally in the Hatay region of Turkey [124], which was higher than the Zn content of *S. officinalis* in leaves of wild-growing sage in Dobra voda of Montenegro [125]. In sage (*S. aramiensis*), the Zn content was determined to be 35.02 ppm, showing similarities to the reported Zn contents of *S. viridis*, *S. verticillata*, subsp *amasiaca*, *S. sericeo-tomentosa*, and *S. tomentosa*, which were 31.55, 21.01, 24.49, and 29.08 ppm, respectively [126]. Fe levels for *S. aramiensis* were found to be 379.27 ppm [127]. Similar results were reported for Fe contents in *S. viridis*, *S. tomentosa*, and *S. aramiensis* [128,124].

A. capillus-veneris has shown efficient arsenic detoxification abilities, allowing it to survive in environments with arsenic concentrations as high as 10 mg/L in a mediums hydroponics [129]. While arsenic is not considered an essential nutrient for plants, no visible signs of toxicity were observed in *P. vittata* up to 600 mg/kg of arsenic, and in *A. capillus-veneris* up to 500 mg/kg. However, *A. capillus-veneris* plants did start showing toxicity symptoms at 600 mg/kg and eventually dried up. Like *P. vittata*, *A. capillus-veneris* also accumulated higher concentrations of arsenic in the fronds, ranging from 4886 µg/g in *P. vittata* to 2017 µg/g in *A. capillus-veneris*. This high accumulation of arsenic and strong resistance to its toxic effects in *A.*

capillus-veneris may be attributed to the potential role of arsenic as a nutrient component during the plant's growth and development [129].

Regarding *J. deppeana*, concentrations of PTEs were observed in different zones (pine areas, oak areas, eucalyptus areas, and grassland areas) in “Flor del Bosque” in Puebla State, with the highest values corresponding to Pb (3.91 mg/kg) and Cr (2.76 mg/kg) in eucalyptus areas, while the lowest values were for Cd (0.15 mg/kg) in grassland areas. The highest values for the different metals were found in eucalyptus areas, except for Hg, which was higher in pine areas, while grassland areas showed the lowest values. Although no significant differences were found in any of the metals, there was a correlation between Cr-Cu (0.52) and Hg-Ni (0.53) [130].

In waste mining in the municipality of San Francisco del Oro, Chihuahua, Puga et al. [82] found concentrations of As in *J. deppeana* in the root (2.17 ppm), leaf (12.57 ppm), and stem (27.74 ppm) in site 3 (at a distance of 900 m, with 17.3 ppm As), in site 8 (at a distance of 2,400 m, with 2.65 ppm As), root (0.61 ppm), leaf (2.87 ppm), and stem (3.61 ppm), and site 9, root (1.53 ppm), leaf (3.73 ppm), and stem (2.31 ppm). They also found concentrations of Zn in root (25.16 ppm), leaf (206.24 ppm), and stem (112.71 ppm) in site 3 (at a distance of 900 m, with 17.3 ppm As), in site 8 (at a distance of 2,400 m, with 2.65 ppm As), root (46.36 ppm), leaf (37.80 ppm), and stem (28.71 ppm), and site 9 (at a distance of 2,700 m, with 3.55 ppm As), root (82.80 ppm), leaf (65.67 ppm), and stem (42.34 ppm).

Different species of Agaves have been studied. *A. lechuguilla* may potentially have tolerance to heavy metal toxicity, and it contains steroidal saponins (yuccagenin and ruizgenin) that can serve as natural chelating agents for removing PTEs like Cr, Cd, Cu, Pb, and Zn from soil and waste [131]. Regarding *A. americana*, it was found to be an excluder of Cd rather than a hyperaccumulator [132]. However, it can play a significant role in the phytostabilization of soils contaminated with Cd by establishing an evergreen cover over the contaminated land surface, which helps stabilize and initiate biological processes in the soil.

A. mexicana, it has demonstrated the ability to accumulate various PTEs such as Cr, Cu, and Pb in its aerial parts. This plant species has natural capabilities to grow in soil contaminated with PTEs and accumulate them in its shoots [133]. It is noteworthy for its economic and medicinal importance, as it is commonly used to treat stomach ulcers and possesses anti-parasitic characteristics [134]. Additionally, *A. mexicana* has shown hyperaccumulation of Cr, Cu, and Pb, indicating its potential for phytoremediation of soils contaminated with these metals.

Muhammad et al., [135] collected *Selaginella jacquemonii* in Pakistan and found the following concentrations in Mg (5780-15116 mg/kg), Fe (3793-4443 mg/kg), Mn (785-915 mg/kg), Cr (453-510 mg/kg), Ni (1233-2042 mg/kg), Cu (92-97 mg/kg), Pb (12-13 mg/kg), and Zn (27-36 mg/kg).

Regarding *S. procumbens*, Cho-Ruk et al. [136] analyzed the bioaccumulation of Pb in three plant species under greenhouse conditions. One of these species was *S. procumbens*, which ranked second in accumulating the highest concentration of Pb in the entire plant tissue, with 12.33 mg/kg, absorbing 16.44% of the total Pb from the soil. González and González [6] studied the bioaccumulation of plant species associated with tailings contaminated with Ni, Pb, Cu, Zn, and Cd in Zacatecas. Among the species found was *S. procumbens*, which bioaccumulated 71 mg/kg of Pb and 400 mg/kg of Zn in the root tissue of the plant.

The Shannon index is based on a crucial concept in ecology: evenness. This parameter refers to the extent to which species are represented throughout the sample. Values below 2 indicate ecosystems with relatively low species diversity, while values above 3 indicate high diversity. For the evaluated sites, the Shannon index showed low species diversity in the "La Hacienda" (1.66) and "Los Remedios" (1.44) mine tailings (Table 3). On the other hand, the Simpson index demonstrated low dominance of a single species due to the high diversity of vegetation surrounding the "La Hacienda" (0.26) and "Los Remedios" (0.34) mine tailings (Table 4). These results align with observations outside the study perimeter, where a large number of species are present, with mine tailings-contaminated soil acting as a limiting factor to their distribution (Figure 5).

Hazard Quotient and Hazard Index

The chronic daily intake of metals is of significant concern, as their cumulative effect could result in several health complications for children and adults engaging in anthropogenic activities in the Tehuilotepic area of the Taxco region. This may result in greater chronic daily intake (CDI) values of different PTEs for children than for adults from soils. The total hazard quotient (HQ) for different PTEs through ingestion and inhalation pathways is less than 1. Dermal contact was not quantified in sediments for Ag, As, and Pb (Tables 5-7, respectively).

The behavior of PTEs in non-carcinogenic hazard index for child in the “La Hacienda” sites for oral ingestion of Ag was in the range $1.89\text{--}5.78\text{E-}03$ mg/kg-day, for As was $2.04\text{--}6.4$ mg/kg-day, and $2.92\text{--}7.26\text{E-}02$ mg/kg-day for Pb; in inhalation was $3.19\text{E-}07$ to $1.04\text{E-}03$ mg/m³ for Ag, $1.88\text{--}5.89$ mg/m³ for As, and Pb was $1.61\text{--}4\text{E-}06$ mg/kg-day, and dermal contact was null for Ag and Pb, $2.42\text{--}7.60\text{E-}04$ mg/kg-day for As in CDI (Table 5-7 for Ag, As, and Pb, respectively).

The HQ for children only was in oral ingestion with a range of $3.78\text{E-}01$ to 1.16 mg/kg-day for Ag, $6.8\text{--}21.3$ mg/kg-day for As, and for Pb was null; in Inhalation was null in Ag and Pb, and $1.25\text{--}3.92\text{E-}02$ mg/m³ for As. In case of dermal contact was null in Ag and Pb, and $8.07\text{E-}01$ to 2.53 mg/kg-day for As.

The CDI in adults by oral ingestion was $1.77\text{--}5.42\text{E-}04$ mg/kg-day for Ag, $1.91\text{--}6$ mg/kg-day for As, and $2.74\text{--}6.8$ mg/kg-day for Pb; in inhalation was $1.04\text{--}3.19\text{E-}07$ mg/m³ for Ag, $1.88\text{--}5.89$ mg/m³ for As, and $1.61\text{--}4\text{E-}06$ mg/m³ for Pb; and dermal contact was null for Ag and Pb, $6.98\text{E-}05$ to $1.27\text{E-}04$ mg/kg-day for As, (Table 5). For HQ only was in oral ingestion with a range of $5.57\text{E-}02$ to $1.08\text{E-}01$ mg/kg-day for Ag, $8.87\text{E-}01$ to 2 mg/kg-day for As, and was null for Pb; in inhalation was null for Ag and Pb, $1.25\text{--}3.92\text{E-}02$ mg/m³ for As; and dermal contact was null for Ag and Pb, $1.35\text{--}4.22\text{E-}01$ mg/kg-day for As for different exposure pathways from soils.

For the child total hazard index (HI) the following range was in “La Hacienda” sites were 5.94E-01 to 1.16 for Ag, 9.58-23.9 for As, and was null for Pb and adult total hazard index was 5.57E-02 to 1.08E-01 for Ag, 9.86E-01 to 2.46 for As, and was null for Pb.

In addition to the fact that Ag was not representative at any site for Ingestion risk, Dermal risk, Inhalation risk, and Total risk (Table 5). However, in As the range was 5.55E-04 to 1.01E-03 for ingestion risk, 7.81E-05 to 1.42E-04 for dermal risk, 2.8-8.78E-07 for inhalation risk, and 6.34E-04 to 1.15E-03 for Total risk; in Pb the range was null to 4.49E-05 for Ingestion risk, was null in Dermal risk, the range was null to 1.16E-08 in Inhalation risk, and in Total risk was null to 4.49E-05.

In the “Remedios” sites in the non-carcinogenic hazard index for child for Ag was in the range in oral ingestion was 2.02-4.1E-03 mg/kg-day, in As was 2.43-7.82 mg/kg-day, and 3.13E-02 to 1.95E-01 mg/kg-day for Pb; in inhalation was 1.11-2.26E-07 mg/m³ for Ag, 2.23-7.19E-07 mg/m³ for As, and 1.73E-06 to 1.08E-05 mg/m³ for Pb; and dermal contact was null for Ag and Pb, 2.88-9.28E-04 mg/kg-day for As in CDI (Table 5, 6, and 7, respectively). For HQ only was in oral ingestion with a range of 4.04-8.19E-01 mg/kg-day for Ag, 8.09-26.1 mg/kg-day for As, and was null for Pb; in inhalation was null for Ag and Pb, 1.49-4.79E-02 mg/m³ for As; and dermal contact was null for Ag and Pb, in As was 9.6E-01 to 3.09 mg/kg-day.

For the non-carcinogenic hazard index for adults the range in oral ingestion was 1.89-3.84E-04 mg/kg-day for Ag, 2.27-7.33 mg/kg-day for As, and 5.06E-03 to 1.83E-02 mg/kg-day for Pb; in inhalation was 1.11-2.26E-07 mg/m³ for Ag, 2.23-7.19 mg/m³ for As, and 2.98E-06 to 1.08E-05 mg/m³ for Pb; and dermal contact was null for Ag and Pb, and 6.23E-05 to 1.55E-4 mg/kg-day for CDI (Table 5).

For HQ in adults only was in oral ingestion with a range of 3.79-7.68E-02 mg/kg-day for Ag, 9.84E-01 to 2.44 mg/kg-day for As, and was null for Pb; in inhalation was null for Ag and Pb, 1.49-4.79E-02 mg/m³ for As; and dermal contact was null for Ag and Pb, and 1.60-5.16E-01 mg/kg-day for As.

The child total hazard index (HI) the range was 4.04-8.19E-01 for Ag, 9.06-29.2 for As, and was null in Pb; and adult total hazard index the range was 3.79-7.68E-02 in Ag, 9.65E-01 to 3.01 in As, and was null in Pb; and was observed the same pattern in the “La Hacienda” site for Ingestion risk, Dermal risk, Inhalation risk, and Total risk for Ag (Table 5). However, in As the range was 4.96E-04 to 1.23E-03 for ingestion risk, 6.98E-05 to 1.73E-04 for dermal risk, 4.32E-07 to 1.07E-06 for inhalation risk, and 5.66E-04 to 1.41E-03 for Total risk. In Pb the range was 4.82E-05 to 1.74E-04; was null in Dermal risk; 7.19E-09 to 4.49E-08 in Inhalation risk, and Total risk was 4.82E-05 to 1.74E-04.

The HQ and HI studies found that As and Pb, by ingestion, dermal exposure, and inhalation are more dangerous for children than for adults. It is crucial to analyze the accumulation of PTEs in soils to observe the impact on the population that live on the site. The population of Tehuilotepic is 2,200 comprising 1,097 men and 1,103 women. Of these, the economically active population is 793. Of these people, 15% cross the mining tailings they encounter to go to school or to work, and the passage of grazing animals was also observed. This interaction represents a latent risk, as they are constantly in contact with the tailings, as indicated by HQ and HI.

Conclusion

The mine tailings represent an obstacle to ecological succession in the affected areas. The concentrations of potentially toxic elements are generally high, which could pose a risk to the nearby population. The presence of vegetation helps reduce the dispersion of these contaminants, as some plants can accumulate them in their tissues. The levels of Cd, Pb, Zn, Ni, and Hg were exceeded in “La Hacienda” and “El Fraile” tailings. However, for Cu, in five points in the “La Hacienda” tailings did not exceed critical concentrations in soils. In the case of NOM-147-SEMARNAT/SSA1-2004 Cd concentrations were exceeded in almost all points in the “La Hacienda” site. All points exceed the NOM limits for Pb, Ag, and As in the mine tailings. The richness and abundance of plants species was predominant for *A. cochliacantha*, *E. imbricata*, and *S. jaliscanum* in “La Hacienda” tailings and *Salvia* sp., *Physalis angulata*, *A. farnesiana* in “Remedios” tailings. Of these plants, four are species tolerant to heavy metals and two are not tolerant, which is interesting to propose an

ecological succession study in the tailings to create a buffer zone. The Shannon index showed low species diversity in the mine tailings. However, Simpson index demonstrated low dominance of a single species due to the high diversity of vegetation in the tailings. Hazard quotient and hazard index showed that As and Pb, by ingestion, dermal exposure, and inhalation are more dangerous for children than for adults. Further research is needed to determine if contaminants are dispersed into different environments. This study provides crucial information for future research in areas abandoned by mining, with the aim of preventing the spread of contaminants and highlighting the ecological importance of species such as *A. farnesiana*, *J. deppeana*, and *A. cochliacantha*, which show wide abundance and distribution in the study area.

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Author contributions

Ruiz-Huerta Esther Aurora and **Gómez-Bernal Juan Miguel**: Conceptualization, methodology, investigation, formal analysis, resources, data curation, writing– original draft, writing– review & editing, visualization, and supervision. **Armienta Hernandez Maria Aurora**: Conceptualization, writing – review & editing.

Declarations

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Conflict of Interest/Competing Interests The authors declare that they have no conflict of interest.

Availability of data and material Not applicable.

Code Availability Not applicable.

Ethics and consent to participate

The collection of wild plants listed in Table 2 was conducted at the "La Hacienda" and "Los Remedios" sites. Field collection fully complied with local and national guidelines for flora preservation in Mexico under the regulation NOM-059-SEMARNAT-2010. No specific permits or licenses were required for this study, as the collected species are not listed as endangered or protected under this regulation, and the collection areas are not part of any protected natural reserve. All plant specimens were taxonomically identified and documented by Santana Carrillo Jorge MSc at the Metropolitan Herbarium UAMIZ (Universidad Autónoma Metropolitana-Iztapalapa), where the voucher specimens have been deposited and are publicly accessible under the deposition numbers listed in Table 2.

Permissions to collect the plants parts

The authors declare that no specific permits, permissions, or licenses were required for the collection of the plant specimens or seeds analyzed in this study. This is because the field collection at the "La Hacienda" and "Los Remedios" sites was conducted outside of federal or local Protected Natural Areas (ANPs). Furthermore, none of the collected species are listed under any risk category (such as threatened or endangered) according to the Mexican official standard NOM-059-SEMARNAT-2010, allowing for academic and research collection without the necessity of formal environmental licensing.

Consent to participate statement

Not applicable

Consent for publication statement Not applicable.

Human or animal rights Since this study did not involve animal research, no consents were required to participate and publish data on animals. Therefore, the inclusion of these forms and other ethical issues related to the publication of this type of data do not apply to this study.

Data Availability Statement. Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

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Table 1. Concentration of potentially toxic elements in the rhizosphere of plants collected at different points in tailings of Tehuilotepic, Guerrero. Values are in mg/kg. n=3, <DL (below the detection limit).

Table 2. Species found in the “La Hacienda” and “Los Remedios” tailings

Table 3. Shannon index in the “La Hacienda” and “Los Remedios” tailings.

Table 4. Simpson index in the “La Hacienda” and “Los Remedios” tailings.

Table 5. Non-carcinogenic hazard index for children and adults for different exposure pathways, soils risk in waste mining of Taxco for Ag. CDI= Chronic Daily Intake, HQ= Hazard Quotient, HI= Hazard Index

Table 6. Non-carcinogenic hazard index for children and adults for different exposure pathways, soils risk in waste mining of Taxco for As. CDI= Chronic Daily Intake, HQ= Hazard Quotient, HI= Hazard Index

Table 7. Non-carcinogenic hazard index for children and adults for different exposure pathways, soils risk in waste mining of Taxco for Pb. CDI= Chronic Daily Intake, HQ= Hazard Quotient, HI= Hazard Index

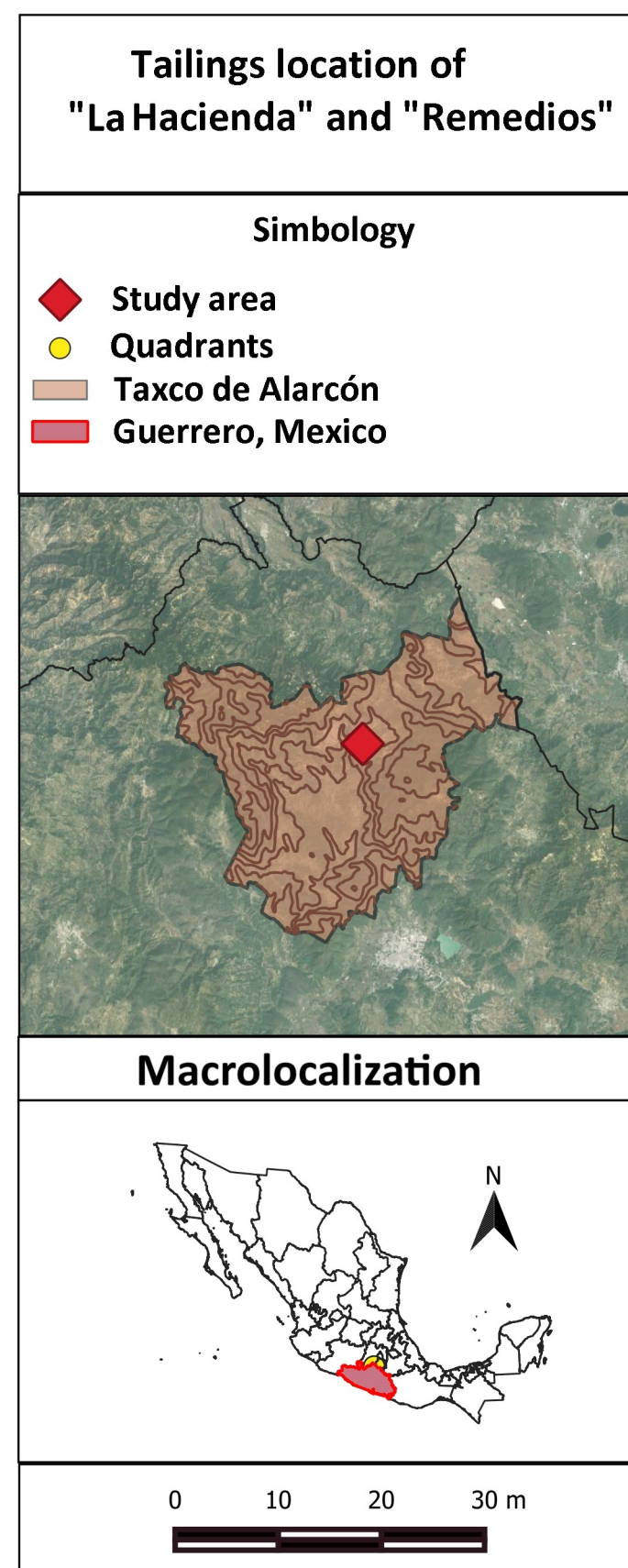
Figure 1. Macrolocalization map of tailings, collection of plant species and soils.

Figure 2. Structure of the general quadrants in the tailings to determine the Shannon and Simpson index.

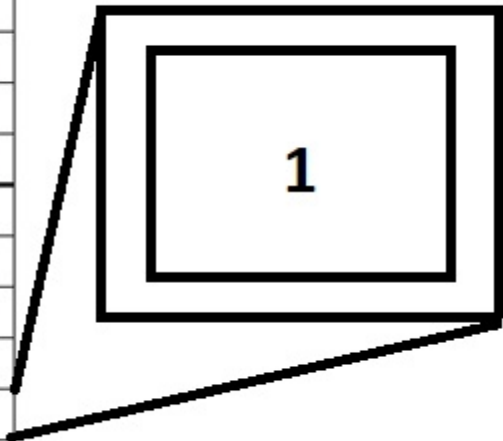
Figure 3. Distribution of potentially toxic elements (Ag, As, Pb, Cu, Zn, Ni, Mn, and Fe) in the “La Hacienda” tailings of Tehuilotepic, Guerrero.

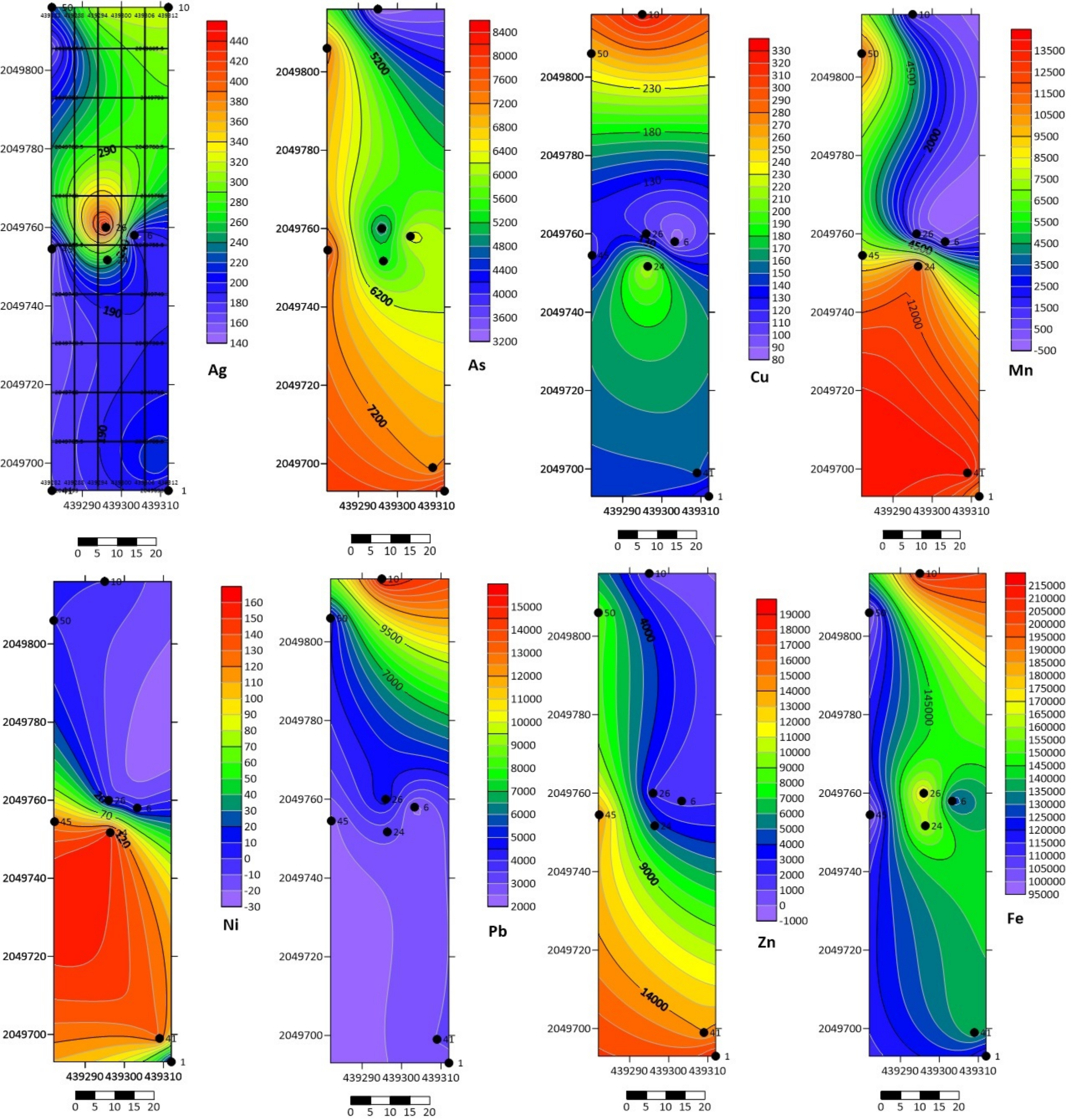
Figure 4. Distribution of potentially toxic elements (Ag, As, Pb, Cu, Zn, Ni, Mn, and Fe) in the “Los Remedios” tailings.

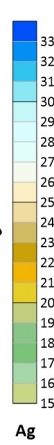
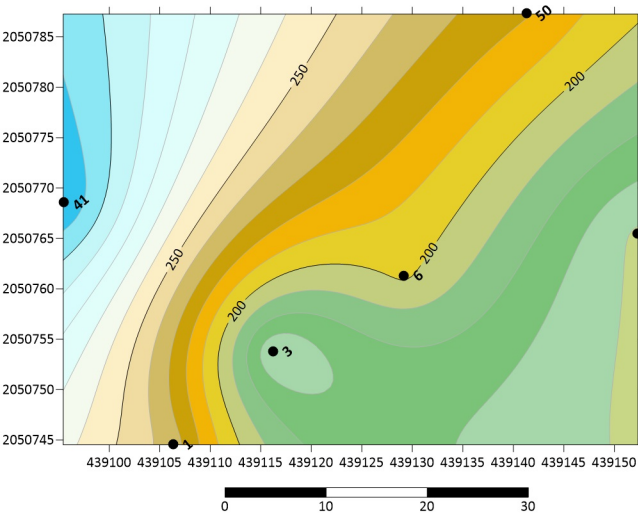
Figure 5. Tehuilotepic tailings quadrants are presented: A) General quadrant of "La Hacienda" tailings; B) *Elytraria imbricata* in "La Hacienda" tailings; C) *Acacia farnesiana* in "La Hacienda" tailings; D) General quadrant of "Los Remedios" tailings; E) *Acacia farnesiana* in "Los Remedios" tailings; F) *Bursera* sp. in "Los Remedios" tailings.



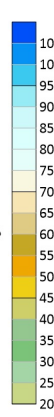
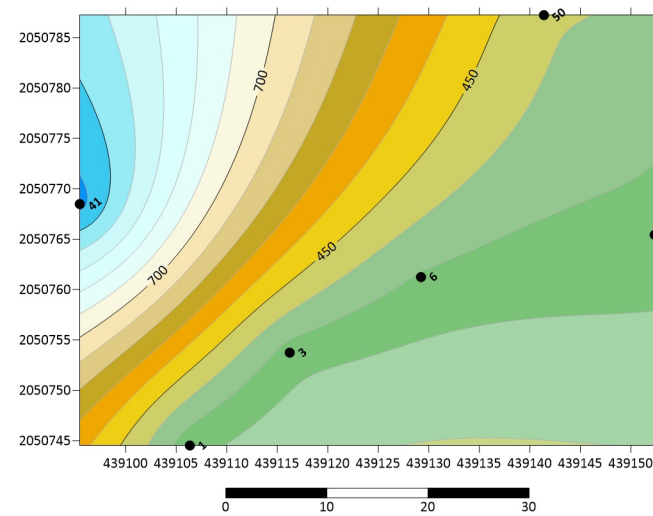
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49	39	29	19	9
48	38	28	18	8
47	37	27	17	7
46	36	26	16	6
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44	34	24	14	4
43	33	23	13	3
42	32	22	12	2
41	31	21	11	1



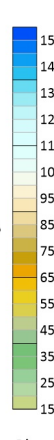
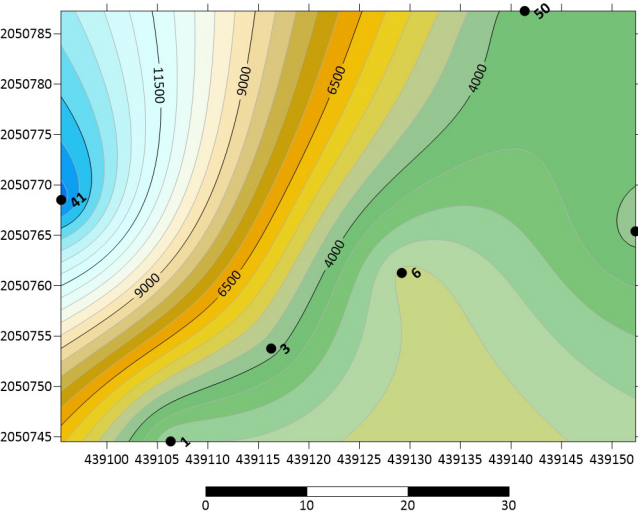




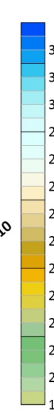
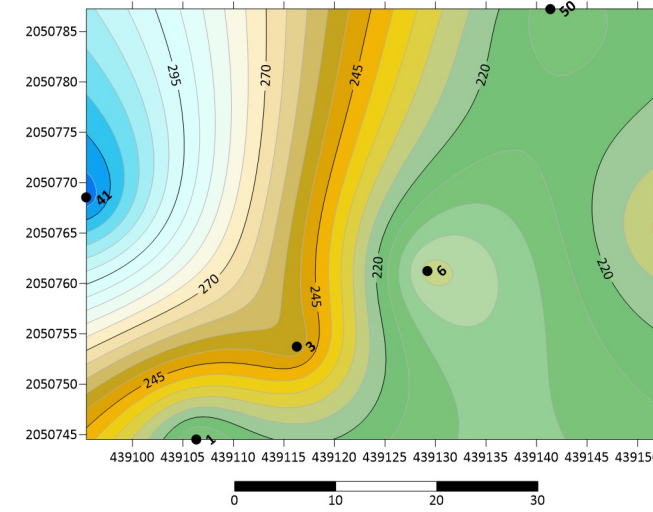
Ag



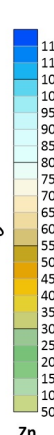
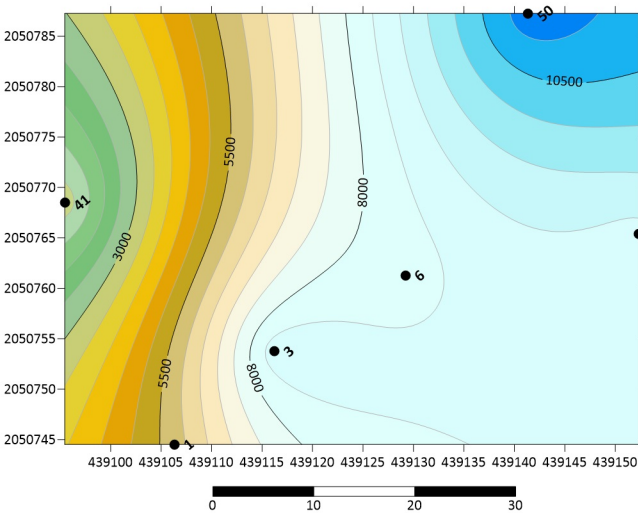
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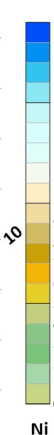
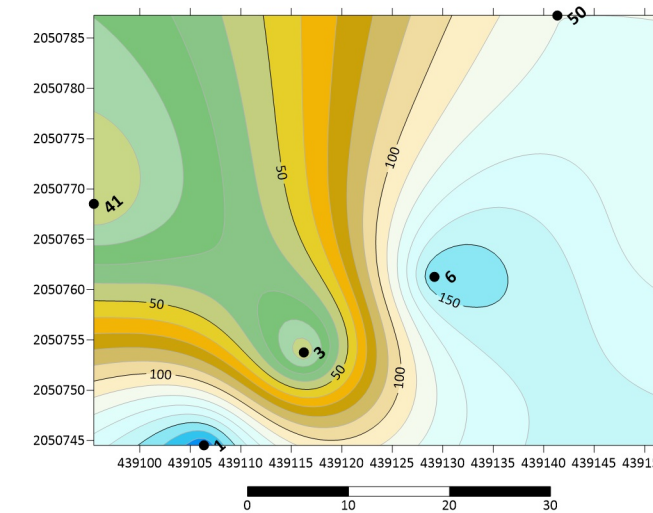
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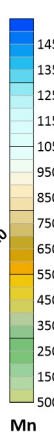
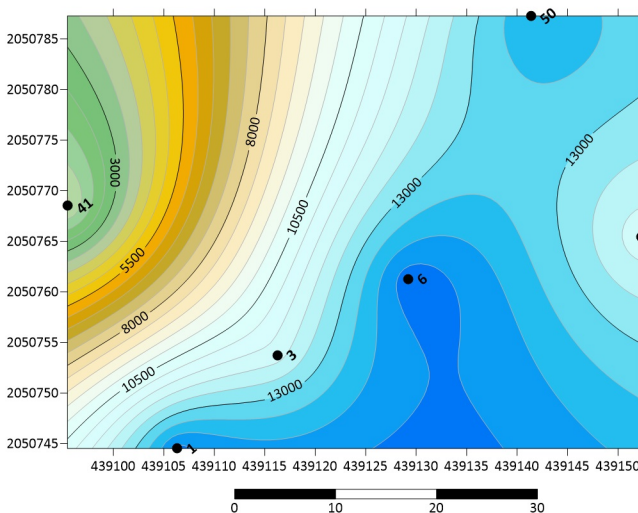
Cu



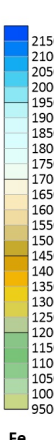
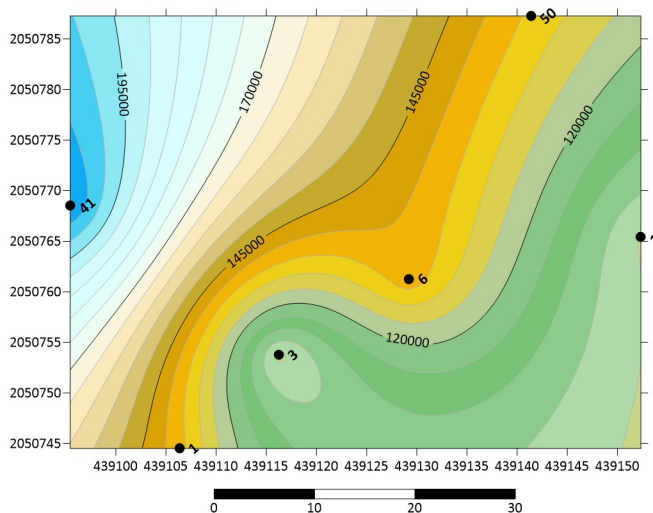
Zn



Ni



Mn



Fe



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