



RESEARCH PAPER



First Evaluation of Metal Contamination and Phytoremediation Potential in Wastes from Mine Tailings Retreatment in Touissit, Morocco

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Abstract

Mining activities pose environmental challenges, particularly in the management of mine tailings. This study evaluates metal contamination in wastes generated during the retreatment of mine tailings for residual lead (Pb) recovery. Physicochemical and biological analyses were conducted on mine tailings (Mt), muddy wastes (Mw), and sandy wastes (Sw). Among the waste types, Mw exhibited the highest organic matter (7.4%) and clay content. The retreatment process led to shifts in metal concentrations, particularly for Pb, with total levels increasing in Mw (12.4 g·kg⁻¹). However, calcium chloride extraction indicated that Pb was more bioavailable in Sw (8.15 mg·kg⁻¹) than in Mw (5.88 mg·kg⁻¹). Sequential extraction analysis identified Mw as the most contaminated waste, displaying the highest exchangeable Pb (41.24%) and Cu (21.87%), while Zn mobility was similar in Mw (7.69%) and Sw (8.20%). The mobility factor (MF) further highlighted the environmental risks, with Mw exhibiting greater metal mobility. Enzymatic activity assessments indicated a decline in soil quality due to elevated metal concentrations. Plant surveys revealed that vegetation was primarily restricted to the clay-rich Mw, where species diversity was low and dominated by Asteraceae, Amaranthaceae, and Poaceae families. Metal analysis in rhizospheric soil and plant organs identified potential metal accumulators and hyperaccumulators. Bioaccumulation (BCF) and translocation (TF) factors highlighted distinct phytoremediation potentials, with *Atractylis gummifera* and *Rhaptonticum acaule* emerging as promising hyperaccumulators. These findings provide valuable insights into metal speciation, soil contamination, and plant adaptation in newly generated wastes, supporting phytoremediation as a potential strategy for contaminant mitigation.

Keywords Mine tailings retreatment · Metal speciation · Metal availability · Environmental risk assessment · Phytoremediation · Hyperaccumulators

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Introduction

Mining activities, an integral part of historical and contemporary landscapes, have left irreversible environmental imprints worldwide. Mineral extraction has historically provided economic and social benefits (Haddaway et al., 2022), while its long-term environmental consequences have become increasingly apparent as practices have evolved (Blanco et al. 2023). The lasting environmental impacts of mining are largely driven by the accumulation of mining wastes, which represent a persistent environmental challenge. Indeed, the mining industry is one of the world's largest solid waste producers, generating several billion tons annually through extraction and processing activities (Guo et al., 2025). The most common wastes generated from mining include waste rock, slags and tailings (El Machi and Hakkou 2024). Among these, tailings are considered particularly problematic due to their specific composition and the challenges associated with their management. Tailings consist of fine-grained residues remaining after the separation of valuable minerals from ore (Hamraoui et al. 2024). Typically stored in surface impoundments, these wastes contain residual trace elements along with chemical additives used during mineral recovery (Mohapatra and Kirpalani 2016). Because of their distinct physicochemical properties, tailings are more prone to erosion and leaching, increasing the risk of environmental contamination by toxic elements (Ostovar et al. 2023; Ghosh et al. 2023; Koucham et al. 2025). This issue is becoming more urgent, as global solid tailings were estimated at 280 billion metric tons in 2021, with annual accumulation reaching 13 billion tons in 2020 and is expected to increase to 19 billion tons by 2025 (Franks et al. 2020; Araujo et al. 2022; Malafevskiy et al. 2025). To address these risks, various principles have been developed to guide tailings management. These focus on hazard assessment, reducing the volume of tailings, and encouraging reuse, while taking into account environmental, economic, and social considerations (Adiansyah et al. 2015). In line with these objectives, retreatment of tailings is increasingly explored as a means to mitigate long-term impacts and recover valuable metals present in the residues (Sarker et al. 2022). Despite the challenges posed by particle size and oxidation in aged tailings, several processing methods such as flotation, gravity separation, and magnetic separation have been adapted to improve metal recovery from these complex materials (Na et al. 2024). Yet, although this strategy is considered promising, improper management of newly generated wastes may worsen contaminant spread. Therefore, *in situ* approaches like phytoremediation are widely recommended. This cost-effective and environmentally friendly method uses specific plants to limit erosion and prevent metal transfer into the environment and food

chain (Desai et al. 2025). Phytostabilization, for instance, stabilizes metals in soil and prevents their mobility, uptake, and translocation to aerial parts. In contrast, phytoextraction relies on using hyperaccumulator plants to extract valuable metals from the soil for potential reuse (Merajul Islam et al. 2024; Aryal 2024).

Northeastern Morocco, with its diverse geology and long history of mining activities, has seen significant accumulation of mine waste over time (Michard et al. 2011; Khafouri et al. 2021). Indeed, within the mountain range known as “la Chaîne-des-Horsts”, at altitudes exceeding 1000 m, the Touissit-Boubker district is renowned as a Mississippi Valley Type (MVT) lead-zinc deposit (Bouabdellah et al. 2012). This classification arises from its unique mineralization process within dolomitic formations (Bouabdellah et al. 2015), a defining feature of the geological identity of this region, making it one of the largest MVT districts globally (Bouabdellah et al. 2021). The region witnessed significant mining activity during the 20th century and hosted lead and zinc extraction sites in Touissit and Boubker, along with the Oued el Heimer smelter, which specialized in refining metals from these mines and others (Smouni et al. 2010). However, since the closure of the Boubker site in 1975 and the Touissit site in 2002, these abandoned mines have undergone significant transformations. The remaining tailings, stored in the form of dykes, have been subjected to wind and water erosion, contributing to the spread of contamination to surrounding areas (El Khazanti et al. 2022). To limit erosion, an initiative led by regional environmental and economic authorities involved revegetating the tailings impoundments with pine and acacia trees (Smouni et al. 2010). The authors proposed incorporating sandy tailings from the Touissit-Boubker site into construction materials, thereby limiting their dispersion and the spread of metals into the environment (Lottermoser 2011; Argane et al. 2014). However, numerous studies have been conducted to assess their impact, providing detailed physicochemical and biological analyses. These studies have explored the interactions between soil, plants, and bacteria, aiming to develop effective remediation strategies to mitigate the effects of polymetallic contamination (Alami et al. 2021; Bennis et al. 2022). Interestingly, Oujdi et al. (2024) conducted a large-scale study on metal content in the Touissit tailings, including exhaustive sampling of spontaneously growing plant species to identify candidates suitable for future phytoremediation programs in the area.

More recently, in 2018, a reprocessing facility was strategically established in the Touissit-Boubker district to recover Pb from pre-existing tailings. While this valorization process aims to maximize resource use, it also introduces new environmental challenges, as significant amounts of Pb, Zn, and Cu remain in the newly generated wastes. Thus, this study focuses on the characterization and assessment of metal

concentrations throughout the retreatment process, addressing the balance between environmental protection and the long-term impacts of mining in the region. Furthermore, it examines the local flora and their capacity to accumulate and translocate metals, providing insights into the potential use of phytoremediation to alleviate contamination and limit the spread of fine particles to surrounding areas. The study is based on the following hypotheses: (1) retreatment of mine tailings leads to the redistribution of Pb, Zn, and Cu into new wastes, increasing their mobility, bioavailability, and environmental risk; (2) high metal concentrations negatively affect soil biological activity and overall soil quality; and (3) certain plant species in the study area are capable of accumulating and translocating heavy metals, making them potential candidates for phytoremediation.

Materials and methods

Study Site Description

This study focuses on a mine tailings reprocessing site located at an altitude of 1031 m, approximately 5 km from the city center of Touissit, and covering an area of about 12.5 hectares (Figs. 1 and 2). The site is dedicated

to recycling mine tailings (Mt) generated by former mining operations managed by the CMT Group (Compagnie Minière de Touissit) for the recovery of residual lead (Pb). The retreatment process generates two new waste types, muddy waste (Mw) and sandy waste (Sw), both deposited in the open air within the site (Fig. 2). Mw is the first waste produced, resulting from a screening process designed to eliminate stones and clay. The second waste stream, Sw, is the final residue left after the extraction of the Pb-rich heavy fraction. These wastes are stored in three separate heaps, occupying almost the entire site, with Sw alone covering approximately three-quarters of the total surface. It should be noted that the reprocessing site is surrounded by agricultural land and environmental features such as a river and water supply points.

Soil Sampling

Soil sampling was conducted to investigate the physical, chemical, and biological properties of unprocessed mine tailings (Mt) as well as the two newly generated wastes (Mw and Sw) produced during lead extraction from Mt. These soils were deposited in three distinct heaps, each with different dimensions, with Sw being the largest (Fig. 2). However, the structure and texture of these heaps were

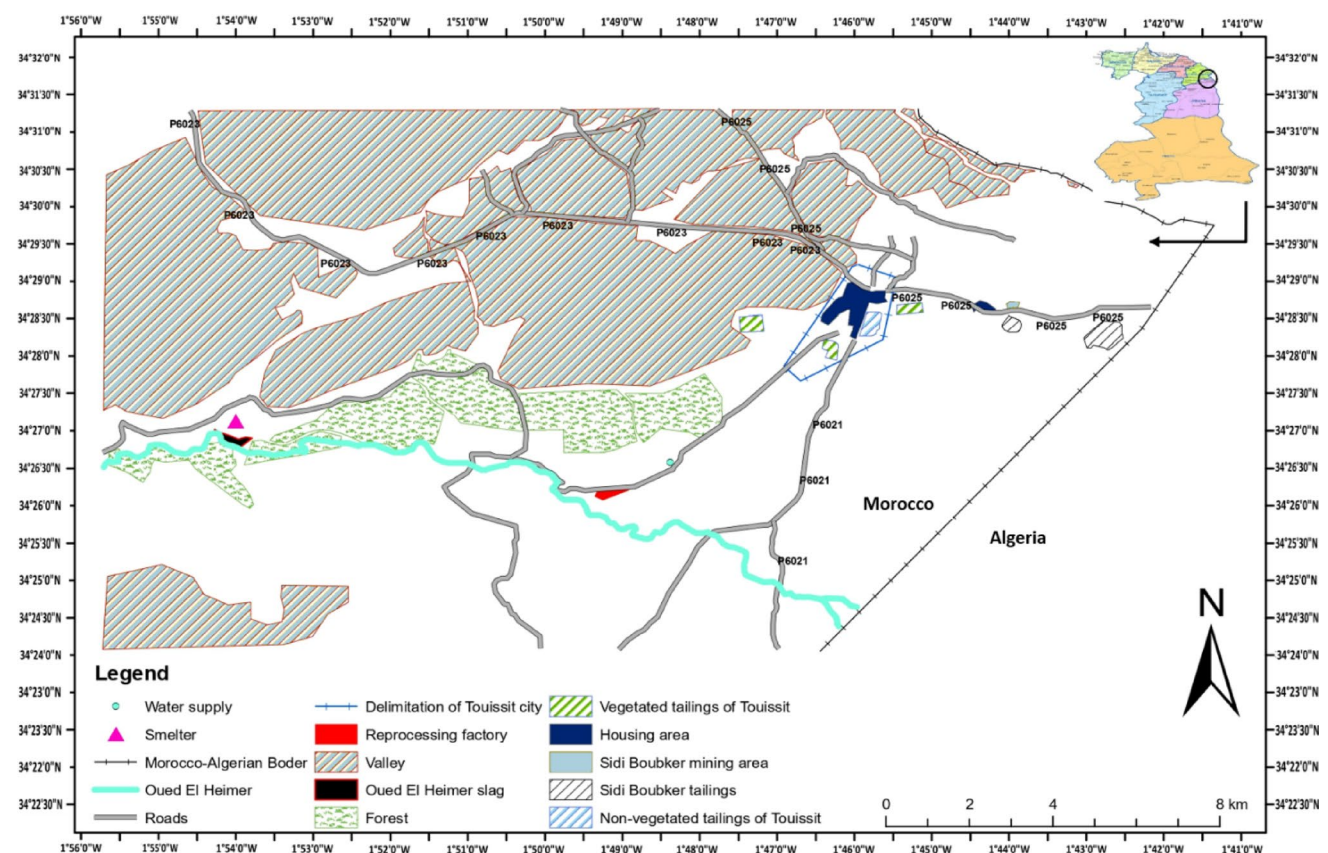


Fig. 1 Map showing the location of the reprocessing site in the Touissit district and its position concerning the eastern region

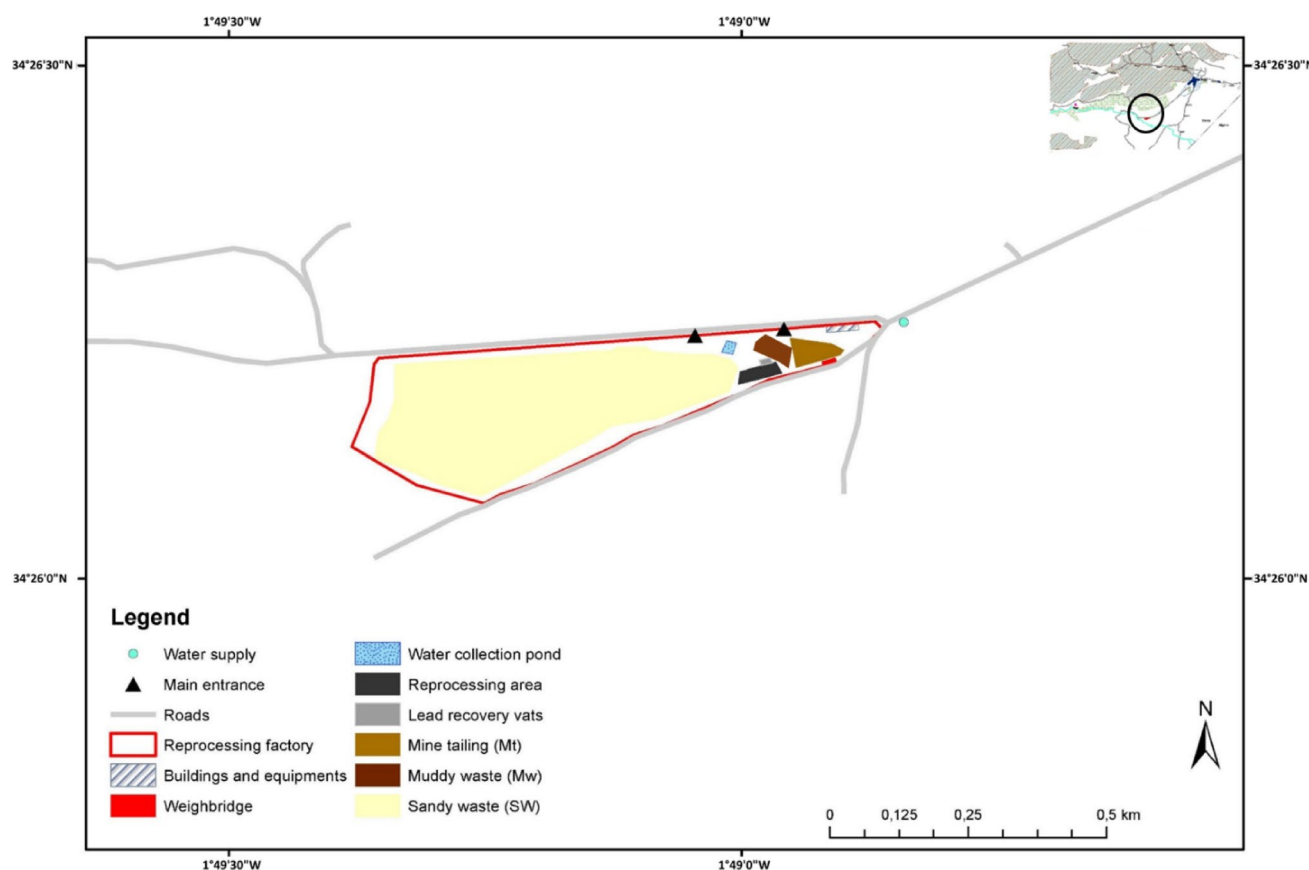


Fig. 2 Map of the studied reprocessing site indicating mainly the location of the different wastes namely Mine tailing (Mt), Muddy waste (Mw) and Sandy waste (Sw)

relatively homogeneous. Therefore, to ensure representative sampling, soil samples were collected from a depth of 0–30 cm. For Mt and Mw, samples were taken at 10-meter intervals along a linear trajectory, while for Sw, due to its larger size, sampling was conducted every 100 m along a similar path. Each heap was sampled along its longest linear trajectory with ten collection points positioned at regular intervals from the base to the crest. The collected samples from each heap were then pooled to create three composite samples representing Mt, Mw, and Sw.

Floristic Composition and Inventory

Plant sampling was carried out in late spring of 2022 to maximize plant diversity and obtain a comprehensive understanding of the flora present on each heap. The vegetation survey followed a circular path from the base to the summit of each heap, ensuring complete area coverage. In zones with denser vegetation, 10 m × 10 m quadrats were established. Nevertheless, vegetation was notably sparse, with all plant species confined to Mw. Particular care was taken during plant collection, with samples separated into aerial parts, root systems, and rhizospheric soil. Taxonomic

Table 1 Braun-Blanquet cover-abundance scale used for vegetation assessment

Code	Description	Estimated Cover (%)
r	Solitary or few individuals	<0.1%
+	Few individuals	<1%
1	Numerous individuals	1–5%
2	Moderate coverage	5–25%
3	Considerable coverage	25–50%
4	Extensive coverage	50–75%
5	Very dense; near-total coverage	75–100%

identification and nomenclature of plant species were based on the “Catalog of Vascular Plants of Northern Morocco” (Valdés 2002) and “Practical flora of Morocco” (Fennane et al. 2014). Vegetation cover was assessed using the Braun-Blanquet cover-abundance scale (Braun-Blanquet 1946), which classifies species into seven cover classes ranging from “r” to “5” (Table 1).

Physicochemical Characterization

Waste Texture and Water Holding Capacity (WHC) Determination

The texture of the three distinct waste types was determined through particle size analysis. Coarse sand particles were separated using a wet sieving technique with mesh sizes ranging from 50 μm to 2 mm. The finer fractions of silt and clay were analyzed using a sedimentation method (jar test).

Water holding capacity (WHC) was assessed by first air-drying the samples. The dried samples were weighed, placed in pots, and gradually saturated with water. After 6 h of drainage, the stable mass was recorded, and WHC was calculated using the following formula:

$$WHC (\% \text{ mass}) = \frac{W_s - D_s}{D_s} \times 100$$

Where W_s is the mass of the drained sample and D_s is the mass of the dry sample.

pH, Electrical Conductivity (EC) and Cation Exchange Capacity (CEC) Measurements

To determine pH and electrical conductivity (EC), 3 g of each waste sample was mixed with 21 mL of ultrapure water and shaken at 200 rpm for 4 h at room temperature. After filtration, pH and EC were measured using a multi-parameter device (Seven Excellence, Mettler-Toledo AG, Switzerland), calibrated according to the AFNOR standard NF T01-013.

Cation exchange capacity (CEC) was assessed using the cobalt-hexamine chloride method (NF X 31–130), following the protocol described by Aran et al. (2008).

Organic Matter (OM) Content

The organic matter (OM) content was determined using a muffle furnace (L 9/11/C6, NABERTHERM). Samples (3 g) were first dried at 105 $^{\circ}\text{C}$ overnight to remove residual moisture, then heated at 375 $^{\circ}\text{C}$ for 16 h to oxidize organic matter (Beyer et al. 1998). The OM content was calculated as a percentage of mass loss using the following equation:

$$OM (\% \text{ mass}) = \frac{D_s - I_s}{D_s} \times 100$$

where D_s is the dry sample weight and I_s corresponds to the incinerated sample weight after combustion.

Metal Content in Soil and Plant Tissues

The pseudo-total concentrations of Pb, Zn, and Cu in wastes were determined using the aqua regia digestion method (1:2 v/v, HNO_3 (65%)/ HCl (37%)), using a solid-to-liquid ratio of 1:45. This involved digesting 0.2 g of soil in 3 mL of HCl and 6 mL of HNO_3 , followed by microwave-assisted digestion (Multiwave GO Plus, Anton Paar), with temperature ramping to 180 $^{\circ}\text{C}$ over 30 min, followed by a 15-min cooling period. The digested samples were then diluted to 25 mL with ultrapure water (18 $\text{M}\Omega\cdot\text{cm}^{-1}$) and filtered using a vacuum pumping system equipped with a hemicellulose membrane filter.

The same procedure was followed to evaluate metal accumulation in plant tissues. The harvested plants were thoroughly washed with ultrapure water, then dried at 60 $^{\circ}\text{C}$ for three days. A 0.2 g portion of the dried material was subsequently digested using aqua regia. The concentrations of Pb, Zn, and Cu in the digested solutions were quantified using inductively coupled plasma atomic emission spectrometry (ICP-AES, ULTIMA 2, HORIBA, Labcompare, San Francisco, USA).

Based on the pseudo-total metal concentrations in wastes, the pollution index (PI) was calculated using the following equation:

$$PI = \frac{\frac{[Pb]}{100} + \frac{[Zn]}{300} + \frac{[Cu]}{300}}{3}$$

In this formula, the constants 100, 300, and 300 represent the reference background concentrations for Pb, Zn, and Cu, respectively (Kabata-Pendias 2000). These values are based on established geochemical studies that have identified typical metal concentrations in uncontaminated soils. A PI above 1 indicates soil contamination, as it means metal levels exceed natural background concentrations (Weissmannová and Pavlovský 2017; El Hasnaoui et al. 2020).

Metal bio-extractable Concentration

Bio-extractable concentrations of Pb, Zn, and Cu were determined using 0.01 M calcium chloride (CaCl_2) as a selective extractant, following the procedure described by (Houba et al. 2000), with a soil-to-extractant ratio of 1:10 ($\text{g}\cdot\text{mL}^{-1}$). The soil suspensions were shaken at 50 rpm for 2 h at room temperature, followed by centrifugation at 3000 $\times g$ for 10 min. The resulting supernatant was filtered using Whatman filter paper, and a 5 mL aliquot was acidified with 83 μL of HNO_3 before elemental analysis by ICP-AES.

Sequential Extraction

To determine the distribution of mobile Pb, Zn, and Cu within the different fractions in Touissit soils, the BCR (European Community Bureau of Reference) sequential extraction procedure was applied, following the modifications proposed by Pérez-Cid et al. (1998) and further detailed by Pascaud et al. (2014). Briefly, 0.5 g of finely ground soil was subjected to a three-step sequential extraction process, yielding the following fractions: (1) the weak acid-soluble fraction, (2) the reducible fraction, and (3) the oxidizable fraction. After each extraction step, samples were subjected to ultrasonic treatment using an Elmasonic P 120 H (sweep mode, 37 kHz, 330 W), followed by centrifugation at $3300 \times g$ for 15 min (3K15 centrifuge, SIGMA). The supernatants from each fraction were carefully collected for individual elemental analysis via ICP-AES. Finally, the residual fraction was digested using aqua regia to determine the pseudo-total metal content (fraction 4), in accordance with previous methodologies.

To assess environmental risk, the mobility factor (MF) was used to interpret the potential risks associated with the labile fraction. This factor was calculated from BCR sequential extraction data using the following equation:

$$MF = \left(\frac{\text{Fraction 1}}{\sum_{i=1}^4 \text{Fraction}_i} \right) \times 100$$

Where Fraction 1 corresponds to the weak acid-soluble fraction, and the sum includes all four extracted fractions (weak acid-soluble, reducible, oxidizable, and residual).

Biogeochemical Indexes: Bioconcentration and Translocation Factors

The bioconcentration factor (BCF) and translocation factor (TF) were used to assess the relationship between Pb, Zn, and Cu concentrations in rhizospheric soil and their accumulation in plant tissues. Precisely, the BCF reflects the plant's capacity to accumulate metals in the roots relative to their concentration in the soil, while the TF indicates the capacity for metal transfer from roots to shoots. Due to variations in terminology usage, we adopted the BCF and TF calculations as described by Afonso et al. (2020):

$$BCF = \frac{[\text{metal in roots}] \text{ mg kg}^{-1}}{[\text{pseudo-total metal in soil}] \text{ mg kg}^{-1}}$$

$$TF = \frac{[\text{metal in shoots}] \text{ mg kg}^{-1}}{[\text{metal in roots}] \text{ mg kg}^{-1}}$$

A BCF greater than 1 indicates a plant's potential for metal accumulation, while a TF greater than 1 signifies effective root-to-shoot translocation. Species exhibiting both BCF and TF values greater than 1 are considered suitable for phytoextraction, whereas those with $BCF > 1$ and $TF < 1$ are better suited for phytostabilization (Buscaroli 2017; Afonso et al. 2020; El Hasnaoui et al. 2020).

Soil Enzymes Activity

Soil enzymatic activities, including fluorescein diacetate (FDA) hydrolysis, β -glucosidase, acid phosphatase, and urease, were measured to assess soil quality and fertility. Soil samples were dried at room temperature, ground to < 2 mm, and weighed before analysis.

For FDA hydrolysis, 0.1 g of dried soil was mixed with 5 mL of 60 mM potassium phosphate buffer (pH 7.6) and 50 μL of 50 mM FDA solution, then incubated at 37°C , 150 rpm for 3 h. After centrifugation, absorbance was measured at 490 nm (SpectroStarNano, BMGLabtech, France) (Schnürer and Rosswall 1982), and activity was expressed as nmol of fluorescein per minute per gram of soil, using:

$$\varepsilon_{FDA} = 8000 \text{ L mol}^{-1} \text{ cm}^{-1}$$

For β -glucosidase activity, 0.1 g of soil was incubated with phosphate-citrate buffer (pH 4–5, $0.15 \text{ mol} \cdot \text{L}^{-1}$) and $10 \text{ mmol} \cdot \text{L}^{-1}$ PNPG solution at 37°C for 2 h. The reaction was stopped by adding 2% sodium carbonate solution, and absorbance was measured at 410 nm (Li et al. 2009). Activity was expressed as $\text{nmol} \cdot \text{min}^{-1} \cdot \text{g}^{-1}$ and calculated using:

$$\varepsilon_{PNPG} = 18400 \text{ L mol}^{-1} \text{ cm}^{-1}$$

For acid phosphatase activity, 2 g of soil was shaken overnight at 150 rpm with 0.1 M sodium acetate buffer (pH 5.0). After centrifugation, 100 μL of the supernatant was mixed with 100 μL of 5 mM PNPP solution in a microplate, incubated at 25°C for 1 h, and stopped by adding 0.1 M NaOH. Absorbance was measured at 410 nm (García-Gil et al. 2000), and activity was expressed as $\text{nmol} \cdot \text{min}^{-1} \cdot \text{g}^{-1}$ and calculated using:

$$\varepsilon_{PNPP} = 19500 \text{ L mol}^{-1} \text{ cm}^{-1}$$

For urease activity, 4 g of soil was mixed with 10.2 mL of $50 \text{ mmol} \cdot \text{L}^{-1}$ sodium acetate buffer (pH 5.0), 400 μL of $80 \text{ mmol} \cdot \text{L}^{-1}$ urea, and 6 mL of $2 \text{ mol} \cdot \text{L}^{-1}$ KCl solution. After 2-hour agitation at 18°C , additional KCl solution was added, followed by 30-minute agitation. The supernatant (75 μL) was analyzed for NH_4^+ concentration using a colorimetric

method (Cordero et al. 2019). Results were expressed as $\mu\text{g NH}_4^+$ per hour per gram of soil.

The Geometric Mean Enzyme Activity (GMEA) was used as a soil quality index, integrating multiple enzymatic activities (Paz-Ferreiro et al. 2012), calculated as follows:

$$GMEA = (FDA \times \beta\text{-glucosidase} \times \text{phosphatase} \times \text{urease}) \times e^{\frac{1}{4}}$$

Data treatment, Statistics and Graphics

Data processing was conducted using Microsoft Excel, while statistical analyses were performed with IBM-SPSS Statistics 25. Data normality was assessed using the Shapiro-Wilk test, and homoscedasticity was evaluated with Levene's test. For normally distributed data, one-way ANOVA was used for mean comparisons, followed by Tukey's test to determine significant differences ($p < 0.05$). For non-normal data, the Kruskal-Wallis test was applied as a non-parametric alternative. For spatial analysis and mapping, ArcGIS Desktop was used, with Google Maps as the base layer. Data integration, processing, and cartographic design followed standard procedures.

Results and Discussion

Physicochemical and Biological Analysis of Wastes

Main Physicochemical Parameters

The lead extraction process from Mine Tailings (Mt), composed of sandy clay loam, generated two by-products: Muddy waste (Mw) with a clay-rich texture and Sandy waste (Sw) with a sandy loam nature. Table 2 presents the main physicochemical characteristics of Mt and its derived wastes after retreatment. Mw exhibited the highest organic matter (OM) content at 7.4%, while Sw had the lowest at 5%. The clay-rich texture and elevated OM content of Mw contributed to its higher water holding capacity (WHC) of 23%, significantly exceeding Mt (21%) and Sw (20%). This observation aligns with the findings of Lal (2020), which indicated that OM enhances WHC due to its hydrophilic properties and its role in increasing soil porosity, thereby reducing bulk density. The pH remained consistently alkaline across all samples, with Mt (9.44) and Sw (9.45) exhibiting the highest values, while Mw showed a slightly lower pH of 8.38. This alkaline nature is attributed to the presence of carbonates, which are known to influence soil pH (Smouni et al. 2010). Similar pH levels (~8.5) were also reported in Touissit wastes (Oubohssaine et al. 2022), further supporting these observations.

Table 2 Physicochemical characterization of the three sampled soils namely mt: mine tailing, mw: muddy waste, and sw: sandy waste. Bioextractable concentration was measured using CaCl₂. CEC: cation exchange capacity; EC: electrical conductivity; OM: organic matter and WHC: water holding capacity. Letters (a, b, c) indicate significant difference between treatments at $p < 0.05$ ($n = 3-5 \pm \text{SE}$)

Soil	[Metal] Pseudo total ($\text{mg} \cdot \text{kg}^{-1}$)										[Metal] Bio-extractable ($\text{mg} \cdot \text{kg}^{-1}$)			
	WHC %	pH	EC ($\mu\text{S} \cdot \text{cm}^{-1}$)	CEC ($\text{cmol}^+ \cdot \text{kg}^{-1}$)	OM %	C%	H%	Pb	Zn	Cu	Pb	PI	Zn	Cu
Texture														
Mt Sandy clay loam	20.82±0.09 a	9.44±0.06 a	197±1.70 a	0.29±0.20 a	6.65±0.21 a	10.8±0.09 a	0.11±0.004 a	8664.76±552.12 a	4755.26±68.10 a	1882.3±137.48 a	5.06±0.79 a	40.44 a	0.62±0.34 a	0.55±0.05 a
Mw Clay	22.93±0.25 b	8.38±0.01 b	173.18±1.20 b	2.38±0.15 b	7.40±0.09 b	7.94±0.08 b	0.29±0.01 b	12493.09±155.14 b	5344.87±45.98 b	1208.73±34.09 b	5.88±0.23 a	51.61 b	1.46±0.09 a	0.58±0.02 a
Sw Sandy loam	19.93±0.22 c	9.45±0.02 a	73.2±0.20 c	0.52±0.10 c	5.15±0.11 a	11.57±0.35 c	0.08±0.007 c	5546.33±172.71 c	3512.14±122.44 c	827.07±46.22 c	8.15±0.51 b	25.14 c	2.91±0.3 b	0.81±0.05 b

The highest electrical conductivity (EC) was recorded in Mt ($197 \mu\text{S}\cdot\text{cm}^{-1}$), followed by Mw ($173.18 \mu\text{S}\cdot\text{cm}^{-1}$), with both values nearly double that of Sw. Mw also showed the highest cation exchange capacity (CEC) at $2.38 \text{ cmol}^+\cdot\text{kg}^{-1}$, likely due to its higher clay and OM content (Bi et al. 2023). In terms of metal contamination, Mw was the most polluted waste, with Pb and Zn concentrations of $12.5 \text{ g}\cdot\text{kg}^{-1}$ and

$5.3 \text{ g}\cdot\text{kg}^{-1}$, respectively, whereas Mt exhibited the highest pseudo-total Cu concentration ($1.8 \text{ g}\cdot\text{kg}^{-1}$). Although Sw had the lowest pseudo-total metal concentrations, it presented the highest bioavailable fractions of Pb ($8.15 \text{ mg}\cdot\text{kg}^{-1}$), Zn ($2.91 \text{ mg}\cdot\text{kg}^{-1}$), and Cu ($0.8 \text{ mg}\cdot\text{kg}^{-1}$). This indicates that the sandy texture of Sw, which has low organic matter and cation exchange capacity as detailed in Table 1, provides few binding sites for metals (Wang et al. 2021; Ciric et al. 2023). As a result, these physicochemical conditions enhance the mobility and bioavailability of the measured metals in the environment, making them more readily accessible (Cao et al. 2022). Such conditions may increase the risk of metal leaching and plant uptake, making effective management essential for coarse-textured soils, even when total metal levels are low. Consequently, rather than relying solely on pseudo-total metal concentrations, it is widely recognized that the toxicity of heavy metals to plants and microorganisms is primarily determined by their bioavailability within the soil matrix (Kim et al. 2015; Pelfrène et al. 2020). These results highlight the interactions between soil properties and metal bioavailability, and the importance of a comprehensive assessment of environmental risks related to mining activities.

Metals Speciation

The Fig. 3 illustrates the fractionation of the geochemical forms of Pb, Zn, and Cu, revealing distinct patterns of metal distribution among the exchangeable, reducible, oxidizable, and residual fractions in the waste samples. In Mt, Pb was distributed across all fractions, with the highest proportion in the exchangeable fraction (29.36%). In contrast, Zn and Cu were predominantly found in the residual fraction, accounting for 78.29% and 54.37%, respectively. In Mw, Pb was primarily concentrated in the exchangeable fraction (41.24%), while its presence in the residual fraction was minimal (7.64%). Conversely, Cu exhibited a different pattern, being mainly present in the residual (29.84%) and oxidizable (28.65%) fractions. Similarly, Zn in Mw was predominantly found in the residual fraction (56.84%), with the lowest proportion in the exchangeable fraction (7.69%). In Sw, Pb and Cu reached their highest proportions in the reducible fraction, at 40.18% and 28.99%, respectively. However, Pb also showed its lowest percentage (11.89%) in the residual fraction, whereas Cu had the lowest proportion in the exchangeable fraction. Zn in Sw followed a pattern similar to that observed in Mt and Mw, with the majority found in the residual fraction (53.49%).

Overall, the fractionation analysis of Pb, Zn, and Cu across all waste samples revealed distinct metal speciation patterns within each waste type. Significant variations were observed in Pb distribution, with Mw displaying a

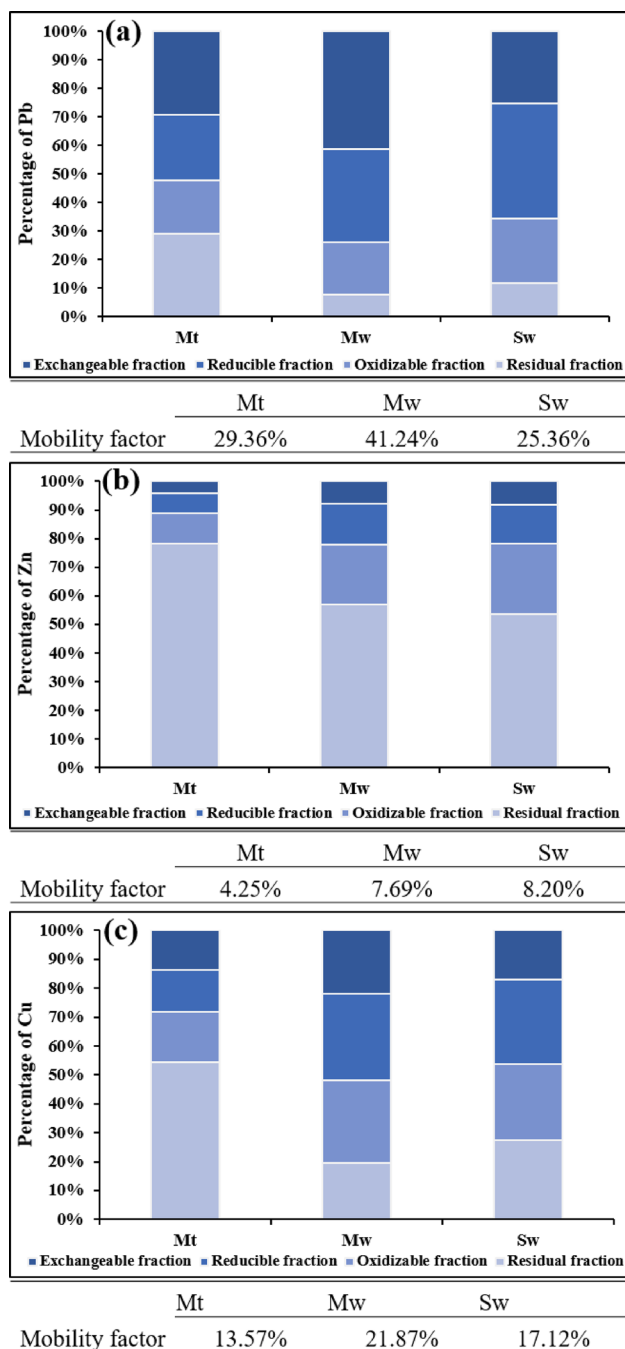


Fig. 3 Distribution of Pb, Zn, and Cu in the sampled soil samples namely Mt: Mine tailing, Mw: Muddy waste, and Sw: Sandy waste. Following the Protocol of Tessier four different fractions were characterized: Exchangeable, Reducible, Oxidizable, and residual fraction

strong affinity for the exchangeable fraction. This suggests that under increased soil acidity, Pb's water solubility and exchangeability would rise, while its associations with carbonates would weaken, thereby enhancing its bioavailability and posing environmental risks (Anju and Banerjee 2010). In contrast, Pb in Mt and Sw exhibited a preference for non-residual fractions, being highly concentrated in both the reducible and oxidizable fractions. Similar enrichment of Pb in the most mobilizable fractions of mine wastes has been reported in European sites (Opara et al. 2022). In the reducible fraction, heavy metals (except Cu and Cd), which bind strongly to Fe/Mn oxides or hydroxide colloids (Sundaray et al. 2011) can be easily released under reducing conditions. Under oxidative conditions, metals may also be released despite their solid associations with soil organic matter (Yiika et al. 2023) and/or sulfur (Zhang et al. 2020), indicating that natural decomposition processes could contribute to metal mobilization (Anju and Banerjee 2010).

Regarding Zn, it was primarily concentrated in the residual fraction across all waste samples, with proportions ranging from 53% to 78%. The residual fraction is considered a stable component (Baran et al. 2019), where metals are tightly bound to minerals within the soil matrix, reducing their bioavailability and posing a lower environmental risk (Liu et al. 2022). A study by Elmayer et al. (2020) on Pb, Zn, and Cd speciation in alkaline mining soils from Tunisia reported similar findings, particularly for Zn. Their research demonstrated that Zn predominantly existed in the residual fraction, with values reaching up to 44%, suggesting the presence of recalcitrant minerals that strongly bind to this metal. In contrast, Cu exhibited diverse distribution patterns, being notably present in the reducible and oxidizable fractions in Mw, the reducible fraction in Sw, and the residual fraction in Mt. A study conducted in China on the distribution, speciation, and ecological risk assessment of heavy metals in contaminated soils found that, despite being the most prevalent contaminant, Cu was strongly associated with the residual fraction, forming complexes with iron (Fe) and manganese (Mn) due to their high specific surface area (Cui et al. 2021).

The geochemical behavior of Pb, Zn, and Cu is intricately influenced by the distinct characteristics of each waste type. The alteration of Mt during the retreatment process induced shifts in metal speciation, primarily leading to

a transition from the residual fraction to increased availability in non-residual fractions, mainly the reducible and oxidizable fractions. Notably, despite the alterations caused by the process, Zn maintained its stability within the residual fraction, although its proportion decreased in the final by-product (Sw).

To further assess environmental risk, the mobility factor (MF) was calculated to determine the labile fraction of the measured metals. The results revealed three distinct ranges across all waste samples, depending on the individual metal (Fig. 3). Zn exhibited the lowest mobility, with MF not exceeding 10%, followed by Cu, which showed moderate mobility, ranging between 10% and 20%. Pb showed the highest mobility, with values ranging from 29% to a maximum of 42%. These findings provide valuable insights into environmental risk assessment, categorizing the first range as “low risk,” the second as “moderate risk,” and the third as “high risk” (Zafeiriou et al. 2023). Moreover, they highlight the importance of understanding metal distribution within different geochemical fractions for effective waste management strategies and environmental risk mitigation. All in all, these MF-based risk categories are consistent with other studies on mine tailings, where Pb showed the highest labile fraction and environmental risk compared to Zn and Cu (Nassiri et al. 2022).

Soil Enzymes Activity

To evaluate the biological quality of the waste soils, several enzymatic activity tests were conducted on Mine Tailings (Mt), Muddy Waste (Mw), and Sandy Waste (Sw). These tests included fluorescein diacetate (FDA), β -glucosidase (GLU), alkaline phosphatase (ALP), acid phosphatase (ACP), and urease (URS) (Table 3). These enzymes were selected as reliable indicators of key soil processes: FDA for overall microbial activity, GLU for carbon cycling, ALP and ACP for phosphorus cycling, and URS for nitrogen cycling, together offering a comprehensive evaluation of soil biochemical functioning. Soil enzymes, primarily derived from microbial metabolic activities (Piotrowska-Długosz et al. 2022), act as natural catalysts in biochemical reactions. They play a pivotal role in modifying soil chemistry (Lemanowicz et al. 2020), improving agronomic quality, and enhancing nutrient availability for plants (Piotrowska-Długosz

Table 3 Enzymatic activities namely fluorescein diacetate (FDA), β -glucosidase, urease, alkaline phosphatase, and acid phosphatase of the sampled wastes namely mt: mine tailing, mw: muddy waste, and sw: sandy waste. Letters (a, b) signify a significant difference between soil treatments at $p < 0.05$ ($n = 3 \pm \text{SE}$)

	FDA ($\text{nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$)		β -glucosidase ($\text{nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$)		Urease ($\text{nmol} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$)		Alkaline phosphatase ($\text{nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$)		Acid phosphatase ($\text{nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$)	
Mt	0.004 ± 0.002	a	0.012 ± 0.002	a	0.047 ± 0.005	a	0 ± 0	a	0.037 ± 0.002	a
Mw	0.034 ± 0.008	b	0.04 ± 0.003	b	0.051 ± 0.003	a	0.011 ± 0.0003	b	0.067 ± 0.018	a
Sw	0.009 ± 0.002	a	0.007 ± 0.001	a	0.057 ± 0.001	a	0.0006 ± 0.0005	b	0.044 ± 0.002	a

and Wilczewski 2014). Microbial-mineral interactions are widespread, as microorganisms influence the physical and chemical properties of minerals, as well as the speciation and availability of metals (Sullivan and Gadd 2019). However, enzymatic activity was consistently low or even absent across all waste samples, particularly for alkaline phosphatase, which was entirely undetectable in Mt. According to Dotaniya et al. (2023), elevated Pb concentrations in soil negatively impact microbial activity, altering microflora composition and enzyme functionality. This interference hampers the mineralization of organic matter, leading to reduced activities of key soil enzymes such as dehydrogenase, urease, catalase, and phosphatase. These observations are in line with meta-analytical evidence showing that heavy metals generally depress soil enzyme activities, particularly phosphatases and urease (Aponte et al. 2020). Nevertheless, previous studies have shown that Zn and Cu may have variable effects on soil enzyme activity. Within permissible thresholds, these metals can enhance enzymatic activity, even under high metal concentrations (Cele and Maboeta 2016). Thus, the extremely low enzymatic activity observed in our waste samples is likely due to high Pb content combined with poor nutrient availability.

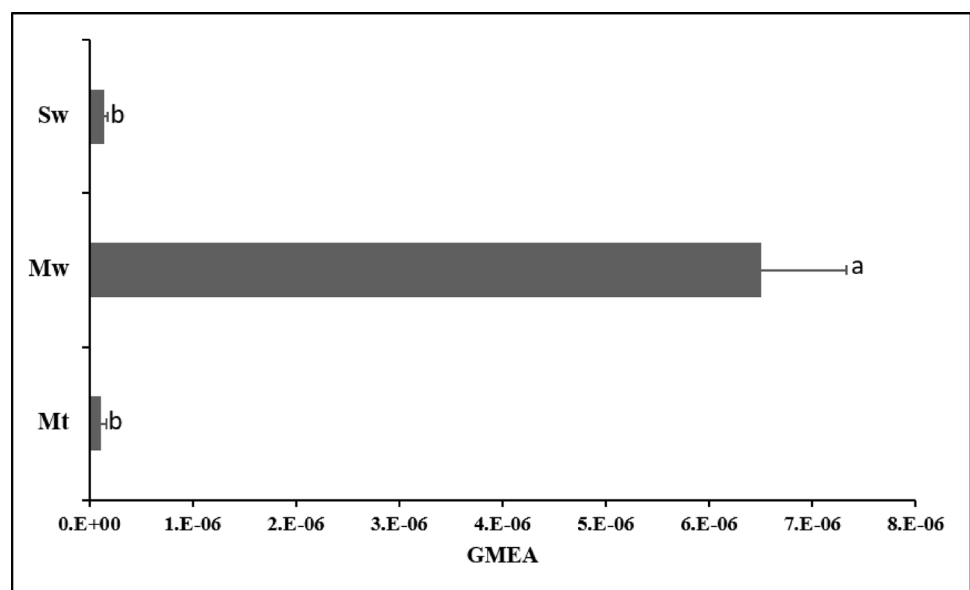
Interestingly, Mw exhibited statistically significant differences compared to Mt and Sw, particularly in FDA ($0.034 \text{ nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$) and GLU ($0.04 \text{ nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$) in while no variation was observed for URS. Although Mw had the highest alkaline phosphatase value ($0.011 \text{ nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$), it was not significantly different from Sw ($0.0006 \text{ nmol} \cdot \text{g}^{-1} \cdot \text{min}^{-1}$).

According to Ciarkowska et al. (2014), urease activity serves as a reliable indicator of soil-rehabilitation progress in Zn and Pb-contaminated areas. Previous research has shown that HMs have a more pronounced effect on sandy

soils compared to clay soils. This suggests that these enzymatic activities were predominantly influenced not only by metal type and concentration but also by soil texture (Haddad et al. 2019). Our results align with this trend, as soils with a clay texture, higher organic matter, and increased pseudo-total metal concentrations, displayed the highest enzymatic activity. In fact, low organic matter exacerbates metal-induced enzyme inhibitions, while higher organic matter content mitigates these effects and can enhance soil enzyme activities (Xian et al. 2015). Additionally, enzyme-clay and enzyme-organic polymer complexes provide protection against denaturation (Ma et al. 2015; Ali et al. 2017), highlighting the pivotal role of clay-rich textures in sustaining microbial communities, despite elevated metal content. Although enzymatic activities were predominantly low in Mt, moderate in Sw and high in Mw; the Geometric Mean Enzyme Activity (GMEA), showed a remarkable difference between Mw, and the other waste types (Fig. 4). The GMEA integrates multiple enzyme activities into a single index, facilitating a more comprehensive assessment of soil quality (Xu et al. 2021). It has been recognized as an effective tool for evaluating soils contaminated with heavy metals (Lesard et al. 2014; Batista et al. 2020).

In general, high concentrations of Pb, Zn, and Cu are associated with reduced enzymatic activity, indicating increased soil pollution severity. Despite the alkaline pH of these soils which typically reduces metals mobility (Zhong et al. 2020; Kicińska et al. 2022), enzymatic activity was more pronounced in soils with greater organic matter (OM) content. Similar relationships between organic matter, soil texture, heavy metal content and enzyme activities were reported for Moroccan soils, where higher OM and finer textures buffered the inhibitory effect of metals (Zerrari et al. 2023). This suggests that even when metal toxicity is less

Fig. 4 The geometric mean of enzyme activities (GMEA), except alkaline phosphatase, of the three mining soils namely Mt: Mine tailing, Mw: Muddy waste, and Sw: Sandy waste. Letters (a, b) refers to significant difference between treatments at $p < 0.05$ ($n = 3$)



severe, enzymatic activity remains suppressed, highlighting the detrimental impact of heavy metals on soil biochemical processes. Soil enzymes play a fundamental role in nutrient cycling, and serve as indicators of soil health and ecological potential. Their suppression due to contamination reflects the extent of soil degradation. Consequently, enzymatic activity analysis represents a valuable biological tool for assessing soil modification and toxicity, providing essential insights for the development of effective remediation strategies.

Floristic Inventory and Metal Assessment

Plant Sampling

Plant sampling at the reprocessing site revealed significantly lower species diversity compared to the non-polluted surrounding areas, where the highest species densities were observed (Oujdi et al. 2024). Plant specimens were only found in the area where Mw residues were deposited, while no vegetation was observed on either Sw or Mt residues, despite the latter occupying the largest area available for sampling. Nine different plant species were identified in the Mw area, belonging to five families: Asteraceae (*Rhaponticum acaule*, *Onopordum macracanthum*, and *Atractylis gummifera*), Poaceae (*Panicum repens* and *Phragmites australis*), Amaranthaceae (*Beta macrocarpa* and *Beta vulgaris* subsp. *maritima*), Juncaceae (*Juncus maritimus*), and Plantaginaceae (*Plantago lanceolata*). The few plant specimens collected were scattered within the Mw-dominated area. This observation can be explained by the fact that Mw was derived from the retreatment of Mt, which had previously been amended with clay during rehabilitation programs to support the growth of pine and acacia trees (Smouni et al. 2010), thus justifying the presence of clay in Mw. This suggests that a significant portion of diverse biological forms, including seeds and microorganisms, may have been transferred from Mt to Mw by clay particles during the lead retreatment process. Additionally, the use of water in lead extraction increased humidity within the clay fraction, creating more favorable conditions for biological activity. Consequently, the finer texture of Mw, combined with its higher water-holding capacity and potentially greater nutrient retention, contributed to improved soil fertility compared to Sw. Collectively, these factors contributed to the greater plant diversity observed in Mw.

The Braun-Blanquet abundance-dominance scale revealed consistently low levels of abundance and dominance among the plant species recorded in the reprocessing area. Notably, *Rhaponticum acaule*, *Phragmites australis*, and *Atractylis gummifera* exhibited an abundance score of 1, indicating limited but noticeable coverage. In contrast,

Juncus maritimus, *Beta macrocarpa*, and *Panicum repens* were present with lower abundance and minimal spatial coverage. Other species such as *Plantago lanceolata*, *Beta vulgaris*, and *Onopordum macracanthum* were rare or had isolated occurrences.

Species diversity in the reprocessing area (Mw) was notably low; however, certain plant families were more prominently represented than others. The Asteraceae family included three species, while both the Amaranthaceae and Poaceae families comprised two species each. This floristic composition likely reflects the ability of certain species within these families to tolerate harsh environmental conditions, particularly metal contamination and limited soil fertility. Asteraceae, recognized as the largest botanical family among vascular plants worldwide (Benítez et al. 2021), also plays a prominent role in the flora of Morocco (Dobignard and Chatelain 2011). Their success in such degraded environments can be attributed to traits like high reproductive potential, effective seed dispersal mechanisms, and adaptability to degraded soils (Ortiz et al. 2008). These characteristics likely support the successful establishment of species like *Rhaponticum acaule*, *Onopordum macracanthum*, and *Atractylis gummifera* in such challenging environments. Moreover, species within this family have demonstrated notable biochemical responses to metal-induced stress (Nikolić and Stevović 2015), supporting their development in mining areas. Similarly, *Beta vulgaris* subsp. *maritima* and *Beta macrocarpa* from the Amaranthaceae family are known for their tolerance to salinity and arid conditions (Puccinelli et al. 2022; Mahmoud et al. 2024). These adaptive traits likely help them establish in the metal-stressed environment of Mw. In contrast, the Poaceae family is recognized for their rhizomatous growth and their capability to stabilize contaminants through extensive root networks (Ghosh et al. 2017; Patra et al. 2021). This may explain the presence of both *Panicum repens* and *Phragmites australis*, with the latter exhibiting a more prominent representation and better illustrating the adaptive response of this family in the region (Oujdi et al. 2024).

Metals Assessment in Rhizospheric Soils and Plant Tissues

The rhizospheric soils of the sampled plant species were analyzed for both their pseudo-total and bio-extractable concentrations (Fig. 5). No significant differences were observed in Pb pseudo-total and bio-extractable concentrations among plant species. Similarly, Zn bio-extractable concentrations remained statistically uniform across all plants. However, in terms of Zn pseudo-total concentrations, *Rhaponticum acaule* (2973.87 mg·kg⁻¹) and *Juncus maritimus* (2988.89 mg·kg⁻¹) exhibited the lowest values, which were significantly different from *Beta macrocarpa*

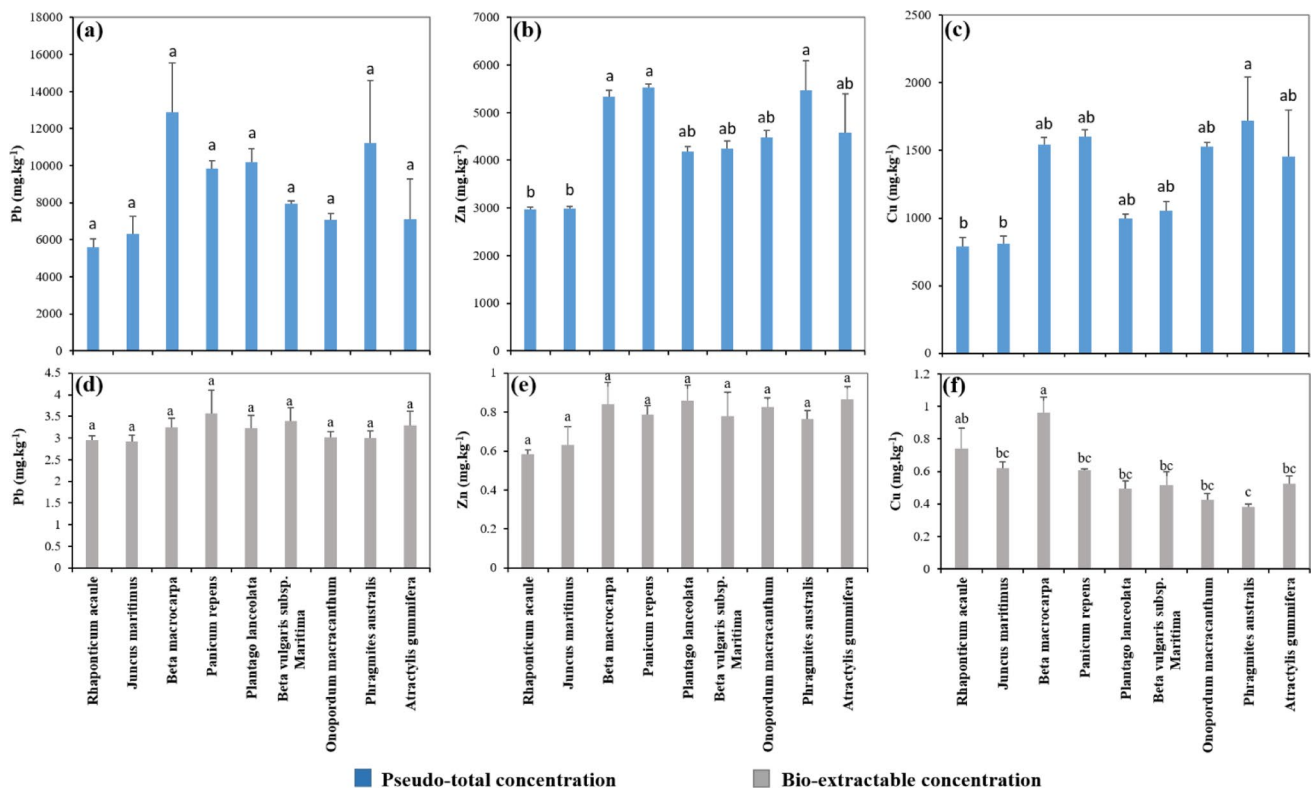


Fig. 5 Pseudo-total concentrations of metals: **A** Pb, **B** Zn, and **C** Cu, along with their bio-extractable concentrations: **D** Pb, **E** Zn, and **F** Cu in the rhizospheric soils of the sampled plant species. Letters (a, b, c) signify significant differences at $p < 0.05$ ($n = 3 \pm SE$)

(5340.18 mg·kg⁻¹), *Panicum repens* (5523.55 mg·kg⁻¹), and *Phragmites australis* (5463.05 mg·kg⁻¹), the species with the highest concentrations. For Cu, *Rhaponticum acaule* (791.29 mg·kg⁻¹) and *Juncus maritimus* (809.25 mg·kg⁻¹) had the lowest pseudo-total concentrations, significantly different from the highest concentration of 1721.83 mg·kg⁻¹ recorded in *Phragmites australis* rhizospheric soils. Conversely, *Phragmites australis* exhibited the lowest Cu bioavailable concentration (0.38 mg·kg⁻¹), contrasting with the highest values recorded in *Beta macrocarpa* (0.96 mg·kg⁻¹) and *Rhaponticum acaule* (0.74 mg·kg⁻¹). In summary, while Zn concentrations in the plants' rhizospheric soils varied, the bioavailability of this metal remained consistent across all samples. Similarly, despite the notable differences in Cu pseudo-total concentrations, these variations were not reflected in bioavailable concentrations. These findings suggest that Pb and Zn bioavailability was primarily driven by the soil's physicochemical characteristics rather than plant species, as evidenced by the lack of variation in Pb, and the consistency of Zn bioavailability despite differences in pseudo-total concentration. Indeed, the availability of metals in soil depends on factors such as intrinsic metal solubility, their binding to soil particles, and other soil properties such as pH (Uchimiya et al. 2020; Zhang et al. 2022). Conversely, the variations in Cu bioavailability,

which did not align with differences in pseudo-total concentrations, suggest that its bioavailability could be influenced by plant effects. Certain plant species may modify heavy metal biogeochemistry, through root exudates either directly via metabolic processes or indirectly by modifying the soil's physicochemical and biological characteristics (Agarwal et al. 2023).

The analysis of Pb, Zn and Cu accumulation in plant tissues revealed clear differences between shoots and roots (Fig. 6). Based on their metal accumulation capacity, the studied species were grouped into two categories: (1) high metal accumulators (*Atractylis gummifera*, *Rhaponticum acaule*, *Panicum repens*, *Beta vulgaris subsp. maritima*, *Plantago lanceolata*, and *Juncus maritimus*), and (2) low metal accumulators (*Beta macrocarpa*, *Onopordum macracanthum*, and *Phragmites australis*). Significant differences were observed in Pb, Zn, and Cu accumulation between shoots and roots. For instance, *Atractylis gummifera* exhibited exceptional accumulation, recording the highest concentrations of Pb (3 g·kg⁻¹), Zn (1 g·kg⁻¹), and Cu (250.7 mg·kg⁻¹) in shoots. Interestingly, it showed the lowest Zn accumulation in roots, with a concentration of 131 mg·kg⁻¹. Although *Atractylis gummifera* and *Rhaponticum acaule* have long been studied for their medicinal properties, they have never been investigated for metal

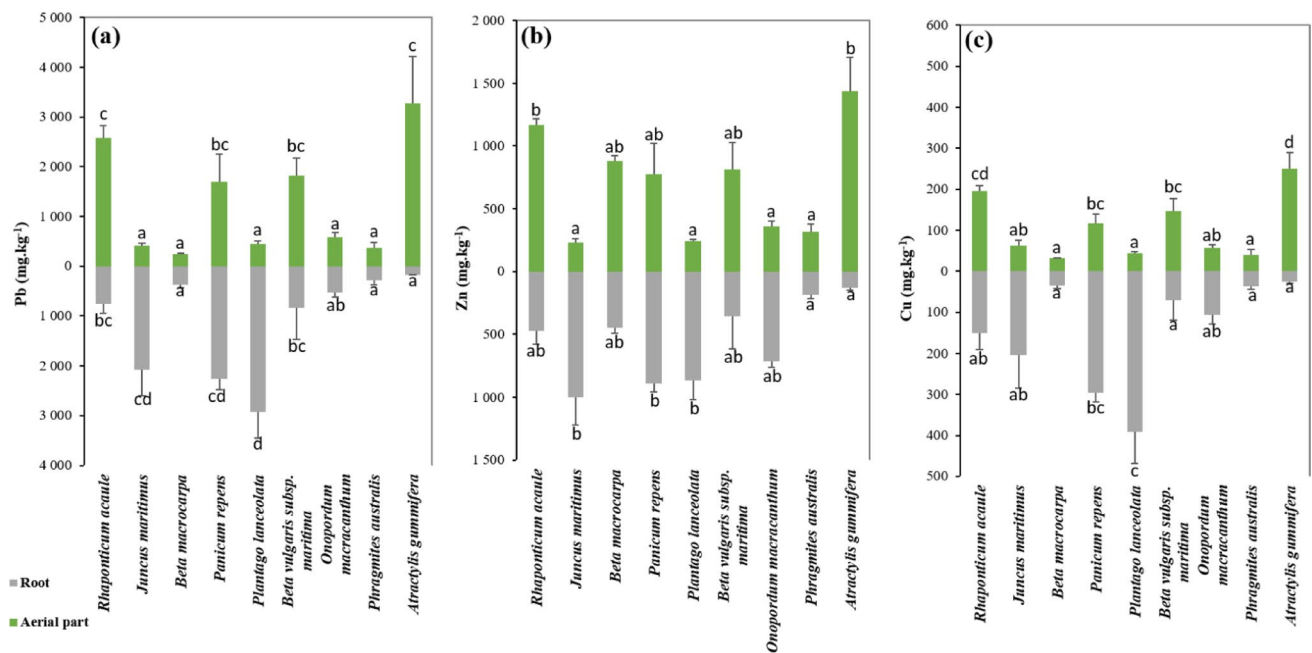


Fig. 6 Metals Accumulation **A** Pb, **B** Zn, **C** Cu in Various Plant Organs, Including Aerial Parts (in green) and Root Systems (in grey), in the Sampled Plants (Mainly found on Mw). Letters (a, b, c) signify significant differences at $p < 0.05$ ($n = 5 \pm SE$)

accumulation (Mosbah et al. 2018; Bouabid et al. 2020; Mejdoub et al. 2022; Hammoudi et al. 2023). Therefore, this is the first study showing their significant metallic accumulation and potential use in phytoextraction.

In root tissues, *Plantago lanceolata* demonstrated the highest Pb ($3 \text{ g} \cdot \text{kg}^{-1}$) and Cu ($392.2 \text{ mg} \cdot \text{kg}^{-1}$) concentrations, reinforcing its suitability for phytoremediation due to, its high surface coverage, biomass, and nutrient accumulation (Muhamedagić and Cero 2020). Similarly, *Juncus maritimus* exhibited significant root metal accumulation particularly for Zn (almost $1 \text{ g} \cdot \text{kg}^{-1}$), Pb ($2 \text{ g} \cdot \text{kg}^{-1}$) and Cu ($203.6 \text{ mg} \cdot \text{kg}^{-1}$), while its shoot concentrations remained relatively low, compared to other plant species. Conesa et al. (2011), in their exploration of mining-polluted wetlands and salt marshes, reported high root metal accumulation in *Juncus maritimus* in mining polluted wetlands, notably for arsenic (As), while displaying lower shoot Cd, Cu and Zn concentrations compared to *Phragmites australis*. However, environmental conditions may also influence metal accumulation patterns. The arid climate of the Touissit region, strongly influenced by the Sahara (Mkadmī et al. 2018), creates extreme conditions that can affect biomass production and, consequently, metal accumulation. For example, Gao et al. (2017) reported that *Panicum repens* ecotypes from wet environments produced higher biomass but accumulated lower Pb and Cd than those from dry zones, suggesting a metal dilution effect. Despite these variations, all *Panicum repens* ecotypes displayed greater adaptation to polluted areas.

On the other hand, among the Beta genus *Beta vulgaris* subsp. *maritima* demonstrated notable shoot accumulation, ranking third among the studied species, with high Pb ($1.8 \text{ g} \cdot \text{kg}^{-1}$) and Cu ($147.2 \text{ mg} \cdot \text{kg}^{-1}$) concentrations. In contrast, *Beta macrocarpa* consistently exhibited the lowest concentrations of Pb ($236.3 \text{ mg} \cdot \text{kg}^{-1}$) and Cu ($32.2 \text{ mg} \cdot \text{kg}^{-1}$) in shoots. *Beta vulgaris* subsp. *maritima*, the wild ancestor of beets, is known for its stress tolerance, particularly to salinity and drought (Yolcu et al. 2021). Furthermore, *Beta vulgaris* L. var. *cicla* has been widely recognized for its exceptional ability to accumulate heavy metals, playing a crucial role in Cd phytoremediation (Tang et al. 2019; Gu et al. 2020). However, these observed accumulation differences are not necessarily attributable to species as they may also result from variations in soil metal concentrations. Therefore, broader field surveys combined with controlled laboratory experiments are needed to confirm the accurate accumulation potential of each species.

Plants Effectiveness in Phytoremediation

To better understand the relationship between metal levels in rhizospheric soil and their accumulation in plants, the bioaccumulation factor (BCF) for metal uptake and the translocation factor (TF) for root-to-shoot metal movement were calculated (Table 4). Distinct patterns emerged in this study, as BCF and TF values spanned a range from low (< 0.1), low but notable (< 1), high (> 1), to very high (> 10). In this regard, *Rhaponticum acaule* showed low but notable BCF values for Pb (0.14), Zn (0.16), and Cu (0.19),

Table 4 Sampled plant species from the contaminated area (Mw) of the reprocessing site. The table presents various parameters, including plant taxonomy, abundance in the area, and biogeochemical factors that indicate the potential of these species for phytoremediation

Plant species	Family	Abundance	BCF index			TF index			Cited as phytoremediation plant		References
			Pb	Zn	Cu	Pb	Zn	Cu	Elements	Remarks	
<i>Rhaponiticum acaule</i>	Asteraceae	1	0.137	0.159	0.192	3.358	2.468	1.291	-	-	-
<i>Juncus maritimus</i>	Junceaceae	+	0.330	0.335	0.252	0.200	0.230	0.311	Zn, Cu, and Cd Hg	Phytoextraction (or phytostabilization)	(Almeida et al. 2004) (Figueira et al. 2012)
<i>Beta macrocarpa</i>	Amaranthaceae	+	0.029	0.084	0.023	0.635	1.956	0.924	-	-	-
<i>Panicum repens</i>	Poaceae	+	0.228	0.161	0.185	0.75	0.873	0.397	Pb, Zn, and Cd	High tolerance and accumulation	(Gao et al. 2017)
<i>Plantago lanceolata</i>	Plantaginaceae	r	0.287	0.207	0.394	0.153	0.283	0.110	Zn	Phytostabilization of Zn	(Jordanovic et al. 2024)
<i>Beta vulgaris</i> subsp. <i>maritima</i>	Amaranthaceae	r	0.105	0.084	0.067	2.165	2.281	2.086	-	-	-
<i>Onopordum macracanthum</i>	Asteraceae	+	0.074	0.159	0.069	1.126	0.502	0.531	-	-	-
<i>Phragmites australis</i>	Poaceae	1	0.025	0.034	0.022	1.298	1.695	1.070	Pb and Cd	Used in phytoremediation Phytostabilization	(Bello et al. 2018) (Mohsin et al. 2023)
<i>Atractylis gummifera</i>	Asteraceae	1	0.024	0.029	0.018	19.386	10.991	9.835	-	-	-

while exhibiting high TF values for Pb (3.36), Zn (2.47), and Cu (1.29), indicating efficient translocation to above-ground parts. In contrast, *Juncus maritimus* showed similar BCF values for Pb (0.33), Zn (0.33), and Cu (0.25), but its TF values for Pb (0.20), Zn (0.23), and Cu (0.31) were relatively low, indicating limited translocation ability. Similar values for both BCF and TF were observed in *Panicum repens* and *Plantago lanceolata*. Conversely, *Beta macrocarpa* displayed low BCF values for Pb (0.03), Zn (0.08), and Cu (0.02), with low but notable TF values, except for Zn (1.96), suggesting limited metal uptake capacity with relatively low (Pb and Cu) to high (Zn) translocation. Notably, *Beta vulgaris* subsp. *maritima* exhibited metal accumulation (BCF: Pb: 0.11, Zn: 0.08, Cu: 0.07) but high root-to-shoot translocation (TF: Pb: 2.17, Zn: 2.28, Cu: 2.09), indicating its potential for phytoextraction. *Phragmites australis* followed a similar trend, with low bioaccumulation and high translocation capacity. *Onopordum macracanthum* demonstrated low bioaccumulation in roots and low translocation from roots to shoots, except for Pb, where TF was 1.13. Among all species, *Atractylis gummifera* emerged as an exceptional hyperaccumulator, with remarkably high TF values (Pb: 19.39, Zn: 10.99, Cu: 9.84) despite its low BCF values, highlighting its strong metal translocation capacity and phytoextraction potential.

- Table 4 Sampled plant species from the contaminated area (Mw) of the reprocessing site. The table presents

various parameters, including plant taxonomy, abundance in the area, and biogeochemical factors that indicate the potential of these species for phytoremediation (Almeida et al. 2004; Figueira et al. 2012; Gao et al. 2017; Bello et al. 2018; Mohsin et al. 2023; Jordanovic et al. 2024).

- The observed variations in BCF and TF values among species likely reflect differences in rhizospheric metal solubility and chemical complexity (Chaabani et al. 2017). Additionally, the capacity of roots to absorb or adsorb metals plays a crucial role, as roots can act as barriers limiting metal transfer to shoots (Omeka and Igwe 2021). Therefore, selecting suitable species for phytoremediation should also consider additional traits such as reproductive capacity, growth rate, and biomass production (Dung et al. 2023), which enhance the plant's ability to colonize degraded soils and sustain remediation efforts in field conditions.

Although the studied species did not show BCF and TF values typical of phytoremediation, their survival and establishment on these contaminated wastes, together with the generally moderate metal concentrations measured in their aerial parts, indicate that they already tolerate the prevailing conditions and contribute to in situ phytostabilization. In most cases the BCF was below 1, indicating that even at high metal concentrations, the plants did not accumulate significant amounts of metals from the soil. This suggests

that plants with both BCF and TF below 1 could potentially be suitable for phytostabilization. Comparable patterns have been observed for native herbaceous species in other mining areas, where moderate BCF and low TF values still supported their use in phytostabilization strategies (Matanzas et al. 2021). However, it is essential to note that bioconcentration factor values can differ significantly depending on the calculation method employed. In this study, BCF was calculated as the ratio of metal concentration in roots to that in soil. Nevertheless, other studies often use shoot-to-soil ratios or whole-plant-to-soil ratios, which typically yield higher BCF values and can indicate a stronger potential for phytoextraction (Buscaroli 2017; Ramírez et al. 2021). Thus, in the current study, the suitability of some of the inventoried plants for phytoremediation does not rely solely on BCF and TF but also on the overall plant characteristics and previous findings. This combined use of bioconcentration indices and ecological traits is also recommended in recent work on native species colonizing Pb and Zn mine tailings (Azizi et al. 2023). For instance, Poaceae species such as *Panicum repens* and *Phragmites australis* may be advantageous due to their rapid growth and extensive ground coverage. Meanwhile, Asteraceae species like *Atractylis gummifera* and *Rhaponticum acaule* demonstrated significant tolerance and effective metal accumulation in their aerial parts. El-Gendy et al. (2017) found that *Panicum repens* effectively accumulated Pb, Zn and Cu from sewage sludge and efficiently translocated them to its shoots, aided by its exceptional evapotranspiration capacity. Likewise, Abdulraheem et al. (2022) identified *Panicum repens* as one of the most promising grass species in heavy metal accumulation and tolerance, noting a BCF for Pb that exceeded 1 in their comparative analysis of 40 grass species. Besides, *Phragmites australis* has emerged as a promising candidate for phytoremediation, with Chitimus et al. (2023) documenting significant accumulation of Cu, Zn, and Pb in this species across various contaminated sites. Its relevance to the present study is further supported by findings from Oujdi et al. (2024), which indicate its frequent presence and extensive coverage within the Touissit mining area, confirming its natural adaptation to local heavy metal-polluted soils. In addition, although this research on the phytoremediation potential of *Rhaponticum acaule* and *Atractylis gummifera* remains somewhat limited, particular attention should be given to *Atractylis gummifera*, which has demonstrated a remarkable capacity for metal accumulation in its aerial parts. This trait is especially significant considering its traditional medicinal uses and pharmacological importance linked to its phytochemical compounds (Bouabid et al. 2020). Complementing these findings, both *Juncus maritimus* and *Plantago lanceolata* exhibit traits of interest. Despite not meeting the expected BCF and TF

thresholds, *Plantago lanceolata* displays low metal accumulation in shoots while possessing a dense root system that may facilitate phytoexclusion and enhance soil conditions (Yee et al. 2025). Similarly, *Juncus maritimus* has been observed retaining high levels of organic mercury only in its roots within contaminated marshes and sediments, indicating its potential for phytostabilization (García-Ordiales et al. 2020). Altogether, these observations emphasize the diverse mechanisms and potential of local species in phytoremediation. While some may not fulfill conventional criteria, their adaptive traits and metal tolerance need further investigation to validate and expand upon these promising preliminary findings.

Conclusion

Altogether, this study highlights the physicochemical changes induced by the retreatment of mine tailings and their impacts on soil toxicity and biological responses. Among the generated wastes, Mw presented favorable characteristics such as finer texture, higher organic matter content, and enhanced enzymatic activity, while also exhibiting the highest pseudo-total concentrations of Pb and Zn. In contrast, Sw showed lower pseudo-total contamination but higher bio-extractable metal fractions, confirming that metal bio-availability was more closely influenced by soil texture and chemical properties than by pseudo-total concentrations. Notably, the retreatment process led to a clear increase in metal availability in both Mw and Sw compared to the untreated Mt, raising potential environmental concerns. These variations shaped the biological responses, as several plant species naturally established in Mw, indicating their capacity to withstand elevated metal concentrations and limited nutrient conditions. Their occurrence likely results from both specific soil properties and natural recolonization capacities. Species such as *Atractylis gummifera* displayed strong metal accumulation and translocation, while others, including *Panicum repens*, *Plantago lanceolata*, and *Phragmites australis*, showed varying metal uptake and translocation capacities. Although these species did not show BCF and TF values typically associated with phytoremediation, their spontaneous establishment on Mw and their tolerance to high metal contents support their relevance for in situ phytostabilization and future site-specific remediation efforts. Lastly, the floristic survey complemented soil analyses by illustrating how mining waste retreatment influenced spontaneous vegetation. The persistence of local species under these harsh conditions confirms their ecological relevance and resilience. These findings contribute to a clearer understanding of metal–soil–plant interactions and support

the integration of local vegetation into future site-specific rehabilitation strategies.

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Data Availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no conflicts of interest.

Human and Animal Rights This article does not include any research involving human participants or animals conducted by any of the authors.

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