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Phytoremediation potentials of eight plant species on the tropical gold mine reclamation site in North Sumatra, Indonesia

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Abstract. *Anwar S, Mansor AB, Haris H, Hayati QN, Fathiya N, Budiman. 2026. Phytoremediation potentials of eight plant species on the tropical gold mine reclamation site in North Sumatra, Indonesia. Asian J Agric 10 (1): g100148. https://doi.org/10.13057/asianjagric/g100148.* Post-mining landscapes are often characterized by degraded soils and elevated concentrations of metals, which may hinder ecological recovery and vegetation establishment. This study assessed the accumulation and translocation of metals, i.e., ferrum (Fe), manganese (Mn), zinc (Zn), copper (Cu), nickel (Ni), and aluminium (Al), in eight fast-growing plant species (i.e., *Falcataria falcata*, *Hibiscus tiliaceus*, *Ixonanthes reticulata*, *Macaranga conifera*, *Macaranga tanarius*, *Melaleuca cajuputi*, *Melastoma malabathricum*, and *Samanea saman*) at the Martabe gold mining reclamation site, North Sumatra, Indonesia. Soil and plant samples were collected from three reclaimed areas and analyzed using Atomic Absorption Spectrophotometry (AAS). Phytoremediation potentials were assessed using bioconcentration factors (BCF), translocation factors (TF), and phytomining potentials. The results showed that reclaimed soils were acidic and characterized by very high Al concentration (mean 110,100 mg kg^{-1}) and Fe concentrations (mean 83,309 mg kg^{-1}) and moderate concentrations of Mn (mean 653 mg kg^{-1}), Zn (mean 410 mg kg^{-1}), Cu (mean 277 mg kg^{-1}), and Ni (mean 513 mg kg^{-1}). Five planted species showed medium Mn accumulation (BCF 0.1-1), low Zn accumulation in all planted species (BCF 0.01-0.1) and low and negligible uptake in eight species of Fe, Cu, Ni, and Al. Translocation factors indicated Zn and Cu were preferentially translocated to shoots (TF>1), supporting phytoextraction, while Mn exhibited mixed translocation, with *M. conifera* acting as a phytostabilizer. Leguminous species, particularly *I. reticulata, M. cajuputi*, and *S. saman*, demonstrated relatively higher root-to-shoot translocation efficiencies. Preliminary phytomining estimates, based on single-plot biomass measurements, indicated a greater potential removal for Al (up to 13.7 kg ha^{-1}), Mn (up to 5.1 kg ha^{-1}), and Fe (up to 3.15 kg ha^{-1}) compared to other metals. The results demonstrate clear functional differentiation among planted species, and highlight the importance of trait-based species selection and mixed-species plantings to optimize phytoremediation and support revegetation on reclaimed gold mining lands.

Keywords: Heavy metals, phytoextraction, phytomining, phytostabilization, tropical soil reclamation

INTRODUCTION

Tropical gold mining operations worldwide leave extensive areas of degraded land, presenting severe ecological and human health risks due to persistent heavy metal contamination, which necessitate complicated reclamation processes to effectively remove such risks (Ekyastuti et al. 2016; Rai et al. 2019; Hu et al. 2021; Haghighizadeh et al. 2024; Wan et al. 2024). These sites often exhibit acidic soils enriched with metals such as iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), nickel (Ni), and aluminium (Al), which impair ecosystem recovery and hinder vegetation establishment (Fashola et al. 2016; Yan et al. 2017; Angulo-Bejarano et al. 2021). Phytoremediation offers an eco-friendly approach by employing plants capable of accumulating, extracting, or stabilizing these metals, thereby supporting post-mining reclamation and ecosystem recovery (Sabreena et al. 2022; Khan et al. 2023).

Successful reclamation requires selecting plant species tolerant to multi-metal contamination and suited to site-specific soil chemistry, particularly under acidic, iron-dominated conditions. These species can function through different physiological mechanisms of phytoremediation: i.e. phytoaccumulation, the uptake and storage of metals within plant tissues to limit metal mobility; phytoextraction, involving absorption by roots and translocation to harvestable above-ground parts to remove contaminants; and phytostabilization, which immobilizes metals in the root zone to reduce leaching and erosion. An emerging approach, phytomining, entails harvesting metal-rich biomass to recover valuable metals, potentially providing economic incentives for remediation (Nedjimi 2021; Atav and Yüksel 2024; Geeta and Choudhary 2025).

Differentiating species by their extraction-oriented versus stabilization-oriented roles is crucial for achieving site-specific reclamation objectives.

Given these distinct mechanisms, selecting appropriate plant species for post-mining reclamation is paramount, as species differ in their tolerance to degraded soils and in their capacity to stabilize or extract heavy metals, thereby influencing the success of land reclamation efforts (Lestari et al. 2019). Pioneer and fast-growing species, in particular, offer significant advantages for remediating mining soils due to their rapid establishment and biomass accumulation, which are critical for stabilizing soils quickly and reducing erosion in degraded landscapes (Agus et al. 2018; Lestari et al. 2019; Gall et al. 2022). Their fast growth supports effective phytoremediation through mechanisms such as phytoextraction and phytostabilization, enabling the rapid uptake and accumulation of heavy metals. Moreover, due to their functional traits (e.g., eco-physiological and anatomical characteristics), these species often tolerate harsh soil conditions typical of mining sites, including acidic pH levels and multi-metal contamination, allowing them to survive and grow where other plants may fail. Their adaptation to local site conditions, including tolerance to the high bioavailability of metals like Al and Mn in acidic soils, makes them suitable candidates to initiate ecological recovery and facilitate succession toward more complex forest communities (Lu et al. 2017; Hasnaoui et al. 2020; Geeta and Choudhary 2024; Fiqa et al. 2025). However, despite these advantages, a comprehensive understanding of the species-specific phytoremediation capacities and functional differentiation of such pioneer species in multi-metal-contaminated tropical mining soils remains limited.

While the principles of phytoremediation are well established, a significant knowledge gap persists regarding species-specific metal accumulation patterns and associated functional traits within tropical post-mining forest reclamation, especially under complex multi-metal contamination scenarios (Fiqa et al. 2025). Existing studies often focus on single metals or isolated mechanisms, lacking integration of ecological functions relevant to restoration management (Edgar et al. 2021; Jach et al. 2022; Placido and Lee 2022; Sabreena et al. 2022). This study addresses these gaps by quantitatively evaluating the concentrations of multi-metal elements (Fe, Mn, Zn, Cu, Ni, Al) in soils and in eight fast-growing species locally adapted to post-mined land reclamation and restoration in tropical setting using the case study of Martabe gold mine reclamation site, North Sumatra, Indonesia. Unlike many prior investigations, it integrates bioconcentration factors (BCF) and translocation factors (TF) with an exploratory phytomining potentials analysis, linking species-specific metal uptake traits to ecological functions in a tropical forest reclamation context. Therefore, this study aimed to (i) quantify heavy metal concentrations in reclaimed soils at the Martabe site; (ii) assess metal accumulation and translocation patterns among selected fast-growing plant species using BCF and TF as quantitative indicators to identify species with optimal traits for phytoaccumulation, phytoextraction, and phytostabilization; and (iii) explore the phytomining potential of these species to inform ex-mined land revegetation.

MATERIALS AND METHODS

Study site

The study was conducted at the Martabe Gold Mine in North Sumatra, Indonesia (99°2′59.58″ E, 1°32′43.55″ N), on reclaimed post-mining land undergoing active revegetation for 3-12 years within a tropical rainforest climate (Figure 1). The region experiences high annual rainfall (3,500-4,000 mm), with 2025 recording 4,744 mm and daily precipitation ranging from 0 to 236 mm, and mean temperatures between 21 and 31°C, which affect soil weathering and metal mobility. Soils are predominantly acidic Podzol, Ultisol, and Inceptisol types, with Inceptisols being volcanic and having high water retention capacity. The terrain varies, with slopes of 10°-55° and elevations ranging from 115 to 318 m above sea level. Reclamation practices involved drainage and slope modification, soil amendment application, and topsoil spreading, followed by the establishment of legume-based cover crops and pioneer species to enhance soil conditions and support the development of subsequent vegetation.

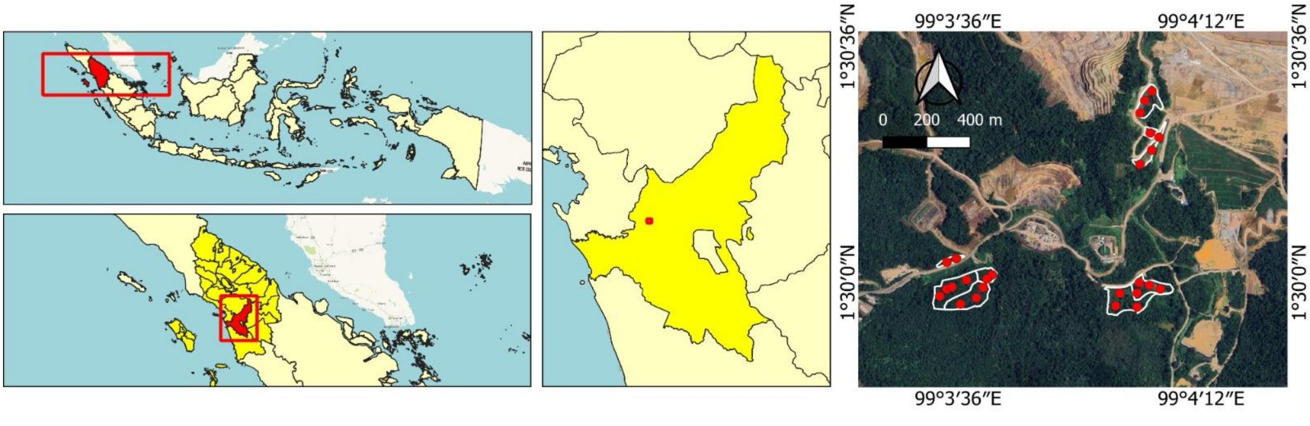

Figure 1. Map of study area in the Martabe Gold Mine, North Sumatra, Indonesia showing the reclaimed areas

Collection of soil and plant samples

The study was conducted from June 2024 to July 2025. Eight fast-growing pioneer species commonly used in forest restoration and post-mine reclamation in Indonesia were selected: *Falcataria falcata*, *Hibiscus tiliaceus*, *Ixonanthes reticulata*, *Macaranga conifera*, *Macaranga tanarius*, *Melaleuca cajuputi*, *Melastoma malabathricum*, and *Samanea saman,* the latter being an introduced species originating from Central and South America while the rest are native to Indonesia. Species selection was based on dominance, as indicated by the highest Importance Value Index reported for the Martabe reclamation area (Anwar et al. 2025).

Soil sampling was designed to provide indicative baseline conditions rather than a detailed spatial representation of reclaimed sites. Soil samples were collected at a depth of 0-20 cm using a five-point sampling method at each of three reclaimed sites - Henny Dump (9-12 years), Sabar Dump (3-4 years), and Southern Access (3 years) - resulting in one composite sample per site (n = 3). Due to the limited number of composite samples and the inherent spatial heterogeneity of reclaimed mine landscapes aged 3-12 years, soil metal concentrations were treated as exploratory and site-specific, with inferences restricted to the sampled locations. Consequently, phytoremediation indices derived from these soil data (BCF, TF, and PP) were interpreted as indicative trends rather than exact quantitative values.

Meanwhile, six individual plants of the same species were pooled into one composite sample per species and site. Plant samples were harvested and separated into roots, stems, and leaves, then cleaned and weighed. All soil and plant samples were placed in clean polyethylene bags, labeled, and transported to the Integrated Laboratory of IPB University for metal analysis.

Sample analysis

Soil sampling at each designated location consisted of five subsamples collected from aggregated points and subsequently homogenized. The resultant homogenized soil was thereafter partitioned into two composite samples (primary and duplicate) as a component of the Quality Assurance/Quality Control (QA/QC) protocols, aimed at validating analytical uniformity and preemptively identifying potential discrepancies in laboratory findings. Each composite sample exhibited an approximate mass of 1 kg. This methodology was reiterated across three distinct sampling rounds to achieve replication and to fortify the reliability of the data. All sampling activities were conducted during the precipitation season to uphold temporal consistency and to mitigate seasonal fluctuations in soil moisture and the mobility of metals. The chemical digestion process employing HNO_3 and $HClO_4$.

Soil and plant tissues (roots, stems, and leaves) were oven-dried, weighed (0.45-0.55 g), and digested using concentrated HNO_3 following standard microwave-assisted digestion procedures. Briefly, samples were digested until complete mineralization was achieved, diluted to a fixed volume, filtered (0.20 μm), and prepared for analysis. The resulting extracts were subjected to analytical assessment for the trace elements (Fe, Mn, Zn, Cu, Ni, and Al) utilizing Atomic Absorption Spectrophotometry (AAS) by the type Agilent 200 Series AA, the detection limit (Fe 0.3mg/L, Mn 0.006mg/L, Zn 0.1mg/L, Cu 0.06 mg/L, Ni 0.14 mg/L, Al 1 mg/L. The analytical methodologies adhered to the guidelines established by the U.S. EPA Method 7000B (applicable to Fe, Mn, Zn, Cu, Ni, and Al). The AAS employed the Agilent 200 series AA, utilizing appropriate hollow cathode lamps for the respective metals (Hollow Cathode Lamp for Fe, Mn, Zn, Cu, Ni, and Al), with wavelengths specifically calibrated (Fe at 248.3 nm, Mn at 279.5 nm, Zn at 213.9 nm, and Cu at 324.7 nm, Ni at 232.0 nm, and Al at 309.3 nm), and matrix modifiers such as double distilled water or aqua bidest employed as metal matrix solvents; the acid digestion procedure involved the preparation of soil samples through the application of a solution comprising HNO_3 and HCl, or $HClO_4$ in conjunction with HNO_3. The metal analytical procedures used Certified Reference Materials (CRMs), specifically CRM 500 and CRM 697, to ensure robust calibration and to validate the accuracy and precision of the analytical results. These CRMs served as independent quality-assurance benchmarks, enabling verification of instrumental performance, method reliability, and matrix-specific recovery throughout the analysis. Detailed procedural steps are provided to ensure analytical reproducibility, but do not differ from standard AAS-based metal determination protocols.

Calculation of phytoremediation indices and data analysis

The Bioconcentration Factor (BCF) was computed to assess how effectively the plant absorbs metals from the soil. Meanwhile, the Translocation Factor (TF) was determined to assess the plant's capability to move heavy metals from the roots to the shoots. The phytoremediation indices were derived using the formula provided by Wu et al. (2021).

$$BCF = \frac{C_{plant}}{C_{Soil}}$$

$$TF = \frac{C_{Plant\ shoot}}{C_{Plant\ root}}$$

Where, C_{plant} denotes the metal concentration in the plant tissue, and C_{soil} represents the metal concentration in the soil. The TF for Cu and Ni in *M. tanarius* was not determined due to the concentration in the roots being below the Limit of Detection (LoD). According to the criteria for BCF values (Kurniawan et al. 2022), BCF values ranging from 1 to 10 signify high accumulator plants; BCF values between 0.1 and 1 indicate medium accumulator plants; BCF values from 0.01 to 0.1 suggest low accumulator plants; and BCF values less than 0.01 denote non-accumulator plants. According to Azab and Hegazy (2020), a TF value less than 1 indicates a phytostabilization mechanism, and a TF value greater than 1 signifies a phytoextraction mechanism.

The potential for phytomining (PP) of heavy metal uptake in the environment was calculated based on the total amount of a heavy metal in the plant and the plant's dry weight biomass per hectare (Chaney and Baklanov 2017). The potential of phytomining (PP; kg.ha^{-1}) calculation was as follows:

$$PP = \frac{C_{Plant} \times \mathit{Dry\ weight\ biomass}}{1{,}000{,}000}$$

Where, C_{plant} is the metal concentration in the above-ground and below-ground parts (mg.kg^{-1}), and dry weight biomass is in kg.ha^{-1}. The dry weight biomass was estimated from plants harvested within a 5 × 10 m^2 plot. The estimated value of the dry weight biomass for *F. falcata, H. tiliaceus, I. reticulata, M. conifera, M. tanarius, M. cajuputi, M. malabathricum,* and *S. saman* were 64561 kg.ha^{-1}, 21947 kg.ha^{-1}, 10234 kg.ha^{-1}, 19786 kg.ha^{-1}, 14677 kg.ha^{-1}, 10348 kg.ha^{-1}, 2712 kg.ha^{-1}, and 49768 kg.ha^{-1}, respectively. These biomass values were derived from single-plot measurements without replication and thus represent approximate estimates rather than statistically robust parameters. As a result, phytomining potential values are interpreted as exploratory indicators of relative metal recovery potential and should not be used for operational or large-scale extrapolation.

The study did not account for plant age as a source of variation in calculating phytoremediation indices (BCF, TF, and PP), despite the sampled plants ranging from 3 to 12 years old. This limitation is significant, as age-related differences could influence metal uptake and translocation, potentially affecting results alongside species and plant-part variability. Therefore, interpretations of the phytoremediation indices should be considered indicative trends rather than precise quantitative measures, acknowledging that age-related variation was neither explicitly controlled nor analyzed.

Given the limited sample size and the use of composite samples, statistical analyses of BCF, TF, and estimated PP values were conducted for exploratory purposes only. Differences among species were assessed using the Kruskal-Wallis test followed by the Mann-Whitney post hoc test, as the data did not meet normality assumptions. Different letters indicate statistically significant differences ($p < 0.05$) based on exploratory non-parametric tests.

RESULTS AND DISCUSSION

Metal concentrations in the reclaimed soil

Metal concentrations in the reclaimed soils at the Martabe gold mine showed variability among Fe, Mn, Zn, Cu, Ni, and Al (Figure 2). Al was the dominant metal, occurring at very high concentrations mean 110,100 mg kg^{-1}, while Fe was moderate concentrations mean 83,309 mg kg^{-1}, whereas Mn, Zn, Cu, and Ni had lower concentrations at one to two orders of magnitude, with mean values of 653, 410, 277, and 513 mg kg^{-1}, respectively. Furthermore, these values are presented as baseline soil metal characterization for the reclaimed sites and serve as reference inputs for subsequent BCF and TF calculations.

Bioconcentration and translocation factors

The Bioconcentration Factor (BCF) values for six metals (Al, Fe, Ni, Mn, Cu, and Zn) across eight plant species are shown in Figure 3. Based on the calculated indicative BCF values, five species (*I. reticulata, M. conifera, M. tanarius, M. cajuputi,* and *M. malabathricum)* appeared to exhibit medium Mn accumulation, likely due to enhanced Mn solubility under acidic conditions, though these findings require verification with more robust soil sampling. In contrast, Fe, Cu, Ni, and Al generally showed low BCF values (0.01-0.1), suggesting limited uptake from soil. In contrast, Zn showed consistently low accumulor BCF values across all species.

Translocation Factor (TF) values varied among metals and species (Figure 4). Zn and Cu consistently exhibited TF values greater than 1 across all species, indicating preferential allocation to above-ground tissues. Mn showed both TF>1 and TF<1, depending on species, with *M. conifera* displaying TF<1. For Ni, TF values were generally close to or above unity, although extreme TF values were observed in *I. reticulata*. Fe and Al exhibited mixed translocation patterns, with TF values spanning above and below unity among species.

Potential of phytomining

Estimated phytomining potentials (PP) varied among metals and species (Figure 5). Higher PP values were observed for Mn, Al an Fe relative to other metals, while Ni, Cu, and Zn showed comparatively lower estimated removal rates. Highly preliminary estimates, based on unreplicated biomass, suggested *M. tanarius* might remove up to 13.7 kg ha^{-1} of Al , 5.14 kg ha^{-1} for Mn, and S.saman might remove up to 3.15 kg ha^{-1} for Fe.These PP values represent approximate estimates derived from single-plot biomass measurements and should be interpreted as indicative rather than definitive due to the absence of biomass replication and variance estimates.

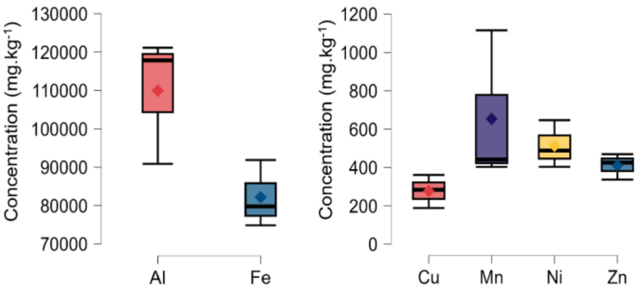

Figure 2. Metal concentrations in the reclaimed soils at the Martabe gold mine, North Sumatra, Indonesia. The diamond symbol shows the mean value

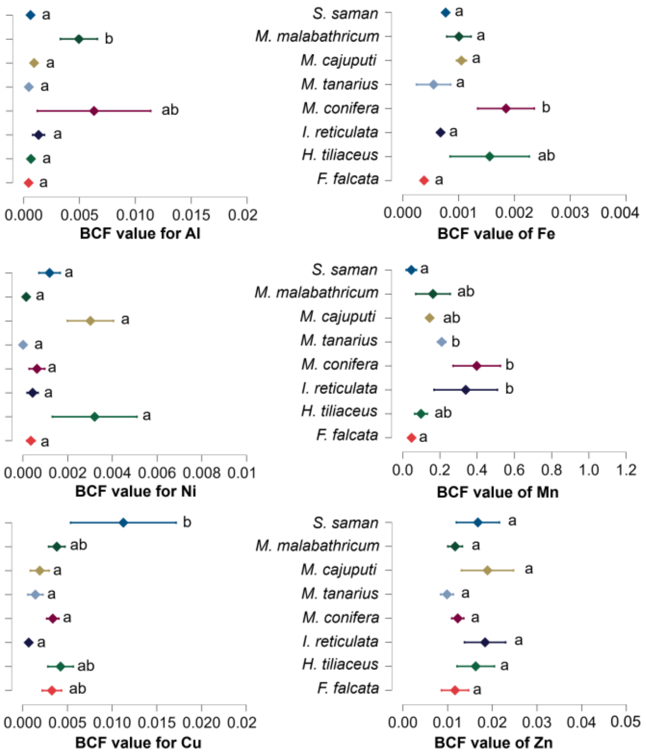

Figure 3. Bioconcentration Factor (BCF) value (mean ± SE) of Al, Ni, Cu, Fe, Mn, and Zn of eight plant species at the Martabe gold mine. Different letters indicate significant differences in the BCF value of different plants ($p<0.05$)

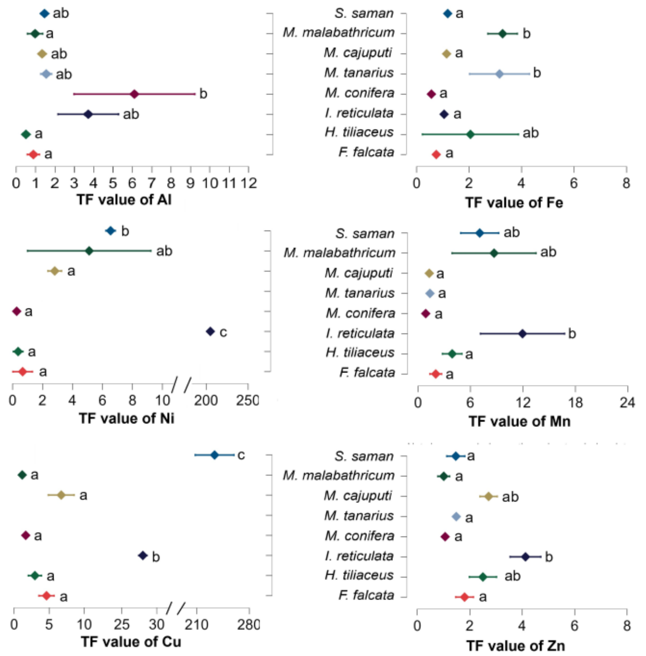

Figure 4. Translocation Factor (TF) value (mean ± SE) of Al, Ni, Cu, Fe, Mn, and Zn of eight plant species at the Martabe gold mine. Different letters indicate significant differences in the TF value of different plants ($p<0.05$)

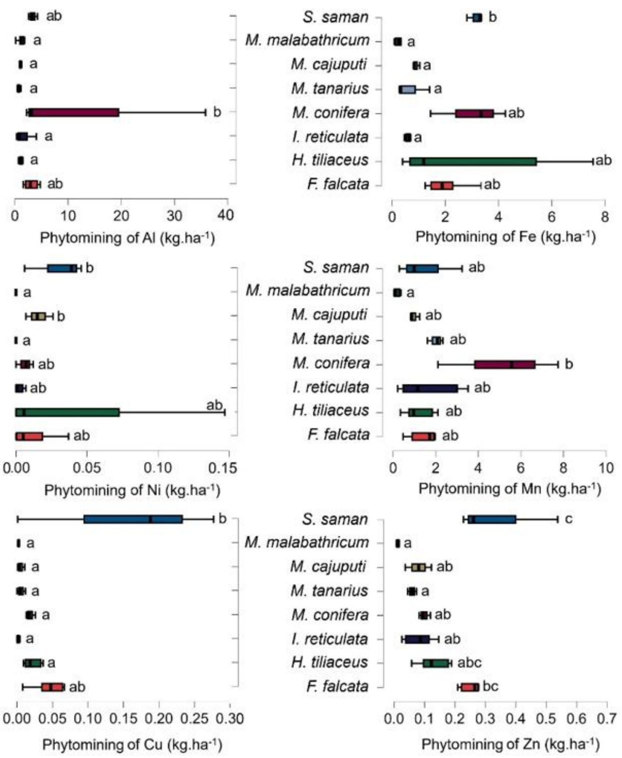

Figure 5. The estimated phytomining potential of eight plant species across six metals at the Martabe gold mine reclamation area. Different letters indicate significant differences in the estimated phytomining value of different plants ($p<0.05$)

Discussion

The reclaimed soils at the Martabe gold mine exhibited pronounced spatial variability, characterized by very high Al and Fe concentrations and moderate levels of Mn, Zn, Cu, and Ni. These values are presented as site characterization rather than definitive indicators of contamination, due to the absence of pre-mining baseline data or regulatory threshold comparisons. Comparable patterns of elevated Al, Fe and moderate concentrations of Mn, Zn, Ni, and Cu have also been reported in several post-mining reclamation sites across Indonesia, where acidic soils and metal-rich parent materials commonly influence metal availability and distribution in reclaimed substrates (Mustafa et al. 2022; Erdaswin et al. 2025). Nevertheless, the dominance of Fe, combined with acidic soil conditions (pH<5) previously reported for Martabe's reclaimed soils, establishes a geochemical context that strongly influences metal mobility and plant-soil interactions (Anwar et al. 2025). Such iron-rich environments are widely recognized as imposing multiple, simultaneous metal stresses during vegetation establishment.

While these soil characteristics provide a baseline, the study's reliance on a limited number of composite soil samples (n=3) likely underrepresents spatial variability across the 3-12-year-old reclamation landscape, introducing uncertainty into the mean soil concentration values used for Bioconcentration Factor (BCF) calculations. Consequently, BCF and Translocation Factor (TF) values should be interpreted as indicative trends rather than precise quantitative indices. Future studies should increase soil sampling density and incorporate stratified replication to enhance the robustness of phytoremediation assessments in heterogeneous post-mining environments.

The total concentration of Al in the soil is relatively high, and three out of the eight species studied act as accumulators with a BCF value of 0.01-0.1, categorized as low accumulators. This pattern can be explained by enhanced Al solubility under acidic conditions, where metal mobility rather than total concentration governs plant uptake (Ofoe et al. 2023). Similar responses have been reported in other acidic post-mining soils, where Al bioavailability acts as a physiological stressor even at modest total concentrations. In contrast, Fe exhibited consistently low BCF values despite its high abundance, reflecting limited bioavailability due to the precipitation of Fe^{3+} as insoluble oxides and hydroxides under oxidizing soil conditions (Cornell and Schwertmann 2003; McCauley et al. 2017). This geochemical contrast explains the selective accumulation of Al and Mn over Fe and highlights the importance of considering metal speciation rather than total concentration when interpreting uptake patterns.

The generally low uptake of Fe, Cu, Ni, and Zn further suggests the presence of species-specific physiological controls that limit metal entry to avoid toxicity, including exclusion and sequestration mechanisms (Rengel 2015; Feki et al. 2021). Mining-induced changes in soil properties, such as reduced organic matter content and altered cation exchange capacity, may also constrain the bioavailability of certain metals. In addition, variability in symbiotic associations, particularly mycorrhizal partnerships, may contribute to interspecific differences in metal acquisition efficiency, a factor widely recognized as critical for post-mining forest establishment (Lofgren et al. 2021; Pratiwi et al. 2021).

TF analysis suggested functional differentiation among species. Zn and Cu consistently showed TF values greater than 1, indicating preferential translocation to above-ground tissues and potential for phytoextraction. Mn displayed species-dependent behavior, with some species functioning primarily as phytostabilizers, notably *M. conifera*. Fe and Al exhibited mixed translocation patterns, suggesting that remediation pathways are strongly governed by plant functional traits rather than metal identity alone. Although *I. reticulata* exhibited high TF values for Ni, overall Ni removal remained minimal, underscoring that efficient translocation does not necessarily translate into effective ecosystem-scale extraction.

Observational trends indicated that leguminous species (*I. reticulata, M. cajuputi* and *S. saman*) might have higher TF values across multiple metals, which could reflect efficient root-to-shoot transfer and supporting their potential role in extraction-oriented strategies. However, their contribution should be viewed as functional rather than definitive, given the exploratory nature of the dataset. These findings reinforce the concept that mixed-species plantings can integrate complementary functions, combining phytoextraction and phytostabilization to enhance overall reclamation outcomes in tropical post-mining ecosystems (Rai et al. 2019; Trimanto et al. 2021).

Estimated phytomining potential varied markedly among species and metals and should be interpreted cautiously. Biomass values were derived from single-plot measurements without replication, and no variance estimates were available. As a result, phytomining potential values represent exploratory approximations rather than operational yields. High-biomass species achieved greater total metal removal per hectare despite moderate tissue concentrations, while species with higher accumulation efficiency but lower biomass contributed less to overall removal. This trade-off highlights the importance of integrating biomass production with accumulation efficiency when evaluating phytomining feasibility.

In conclusion, reclamation species at the Martabe gold mine exhibit distinct and complementary functional roles rather than uniform remediation capacity. Trait-based species selection and mixed-species plantings offer a pragmatic approach to managing metal-rich, acidic post-mining soils by balancing stabilization and targeted extraction. While phytomining remains exploratory in this context, the observed trends provide a scientific basis for adaptive reclamation planning and informed species selection in tropical gold mining landscapes.

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