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Effects of post-mining land reclamation on heavy metal distribution in South Tapanuli, Indonesia

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Abstract. *Anwar S, Mansor AB, Haris H, Dharsono M, Lubis A. 2025. Effects of post-mining land reclamation on heavy metal distribution in South Tapanuli, Indonesia. Asian J For 9: 410-417.* Ecological restoration plays a crucial role in mitigating the impacts of gold mining on soil quality and ecosystem stability. This study evaluated the long-term dynamics of heavy metals (Fe, Mn, Zn, and Cu) in post-mining reclaimed land at the Martabe Gold Mine in Indonesia. Soil samples (0-20 cm) were analyzed using atomic absorption spectrophotometry, and the data were assessed using Principal Component Analysis (PCA). The results revealed temporal fluctuations in heavy metal concentrations, with initial increases during the early restoration stages and consistent declines by 2024. These declines were influenced by the development of vegetation, particularly fast-growing species such as *Falcataria falcata, Samanea saman* and *Gmelina arborea*, as well as microclimatic improvements that enhanced soil redox balance, organic matter accumulation, and pH stabilization. The PCA results showed that the first two components explained 58% of the variation in heavy metals, with Fe, Cu, and Zn clustering and Mn forming a distinct axis, reflecting differences in metal behavior under changing soil conditions. Sites with high Fe-Cu-Zn levels (ZD and BD) indicated less effective reclamation, whereas others (HD, EM, and LD3) displayed balanced metal levels consistent with successful restoration. This six-year monitoring highlights the novelty of assessing tropical post-mining reclamation over an extended timescale, linking vegetation recovery and microclimatic changes to heavy metal reduction, and offers practical implications for forestry-based reclamation and sustainable land management.

Keywords: Heavy metal, martabe, metal influence, phytoremediation, reclamation

INTRODUCTION

Heavy metals are heterogeneous elements with diverse functions and chemical properties; however, many are hazardous, non-biodegradable, and persist in the environment for long periods (Kiran et al. 2022). Elements such as arsenic (As), lead (Pb), cadmium (Cd), mercury (Hg), and chromium (Cr) are particularly concerning due to their toxicity and carcinogenicity, often associated with oxidative stress induced by Reactive Oxygen Species (ROS). These metal(loid)s act as systemic toxins capable of damaging multiple organs, leading environmental and health agencies to classify them as a serious threat to living organisms (Ondrasek et al. 2025). In contrast, other metals such as gold, silver, iridium, and platinum are less harmful and often valued for industrial applications (Saleh and Aglan 2018).

Anthropogenic activities including mining, smelting, industrial processes, agriculture, and waste disposal significantly increase heavy metal concentrations in the environment (Pratiwi et al. 2021). Among these sources, Acid Mine Drainage (AMD) is one of the most critical pathways for mobilizing metals from sulfide-rich tailings into surrounding ecosystems (Baquy et al. 2022; Kumkrong et al. 2022). Heavy metal accumulation in plants can suppress growth, interfere with reproduction, and reduce food quality, while in humans it is associated with chronic disease and carcinogenesis (Bartkowiak 2021). Various physicochemical technologies are typically required to reduce metals in mine waste, sewage sludge, and industrial effluents, though these methods can be costly and disruptive. Broadly, metal-contaminated environments may be restored using physical, chemical, biological, electrical, or thermal approaches depending on site conditions (Ondrasek et al. 2025).

Phytoremediation has emerged as a key approach in post-mining reclamation, leveraging the natural capacity of plants to extract, stabilize, degrade, or immobilize contaminants. Processes such as phytoextraction, phytostabilization, phytovolatilization, and rhizodegradation support soil recovery, reduce metal mobility, and enhance ecosystem functions, making phytoremediation suitable for long-term reclamation (Guerra et al. 2021; Ondrasek et al. 2025). Its in situ application also minimizes disturbance and offers ecological as well as socioeconomic benefits.

In Indonesia, reclamation is regulated under Law No. 4/2009 and Government Regulation No. 78/2010, requiring mining companies to restore disturbed land following approved plans (Listiyani et al. 2023). Gold mining activities, in particular, have pronounced impacts on soil quality, vegetation cover, and ecosystem integrity (Hapsari et al. 2020; Pratiwi et al. 2021), making reclamation essential for soil improvement and ecological recovery (Pratiwi et al. 2021; Iskandar et al. 2022). Although numerous studies globally have examined heavy metal behavior in reclaimed sites, long-term monitoring datasets from tropical gold-mining environments remain scarce. Most existing research is short-term, experimental, or model-based, limiting understanding of how metals stabilize under real field conditions. Furthermore, little is known about how vegetation development and microclimatic changes influence heavy metal dynamics during tropical reclamation. In Martabe specifically, studies on the temporal distribution of heavy metals after reclamation are still limited.

Given this gap, this study adopts a descriptive, monitoring-based approach to document six years of temporal changes in soil heavy metals (Fe, Mn, Zn, and Cu) across multiple reclaimed sites at the Martabe Gold Mine. Rather than testing mechanistic hypotheses or applying inferential statistics, the study focuses on characterizing trends, exploring multivariate patterns with Principal Component Analysis (PCA), and relating observed changes to vegetation recovery and soil condition improvements. This long-term dataset provides rare empirical evidence on the effectiveness of forestry-based reclamation in tropical post-mining landscapes.

MATERIALS AND METHODS

Study area and duration

This study was conducted in a restored mining area at the Martabe Gold Mine in North Sumatra, Indonesia, situated within a tropical climate zone. In 2024, annual rainfall totaled 5,000 mm, with daily amounts ranging from 0 to 168 mm. The soils are predominantly inceptisols, a volcanic type with high water-retention capacity. Terrain varies across the site, featuring slopes of 10°-45° and elevations between 69 and 415 m above sea level. Data sampling was conducted from 2019 to 2024, while data analysis was conducted in 2025. Figure 1 and Table 1 show the map of the sampling point locations. Soil quality analysis in the form of heavy metals was carried out at the Institut Pertanian Bogor Integrated Laboratory and the Soil Laboratory SEAMEO Biotrop in Bogor, Indonesia.

Material, field procedures, and sampling analysis

Soil samples were collected using a composite sampling design. Field equipment included a GPS, soil auger, ring sampler, measuring tape, stainless steel knife, and sterile plastic bags to maintain sample integrity during transport in insulated containers. Sampling was conducted at a depth of 0-20 cm because this layer constitutes the biologically active topsoil and main rooting zone, where heavy metals from mining activities typically accumulate. In the surrounding natural forests, the upper soil horizon also averages 0-20 cm in thickness, making this depth ecologically relevant and consistent with standard practices in reclamation and soil-quality monitoring. The selection of sampling sites followed reclamation age to capture temporal variation in heavy-metal dynamics. Six sites were sampled between 2019 and 2022, and as reclamation activities expanded, six additional sites were included in 2023-2024, resulting in a total of twelve sites.

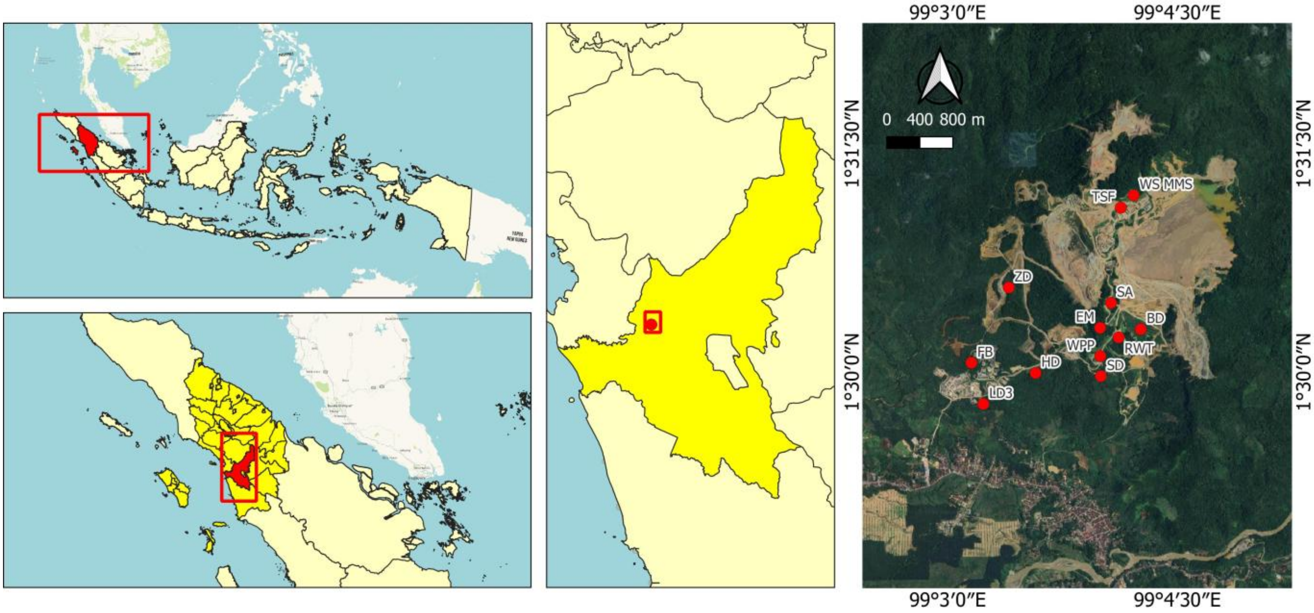

Figure 1. Map of the soil sampling location (see Table 1 for the site code)

Table 1. Description of the study sites including codes, locations, reclamation characteristics, and sampling details

Site code	Coordinates (N,E)	Reclamation age (years)	Vegetation type	Composites	Replicates
HD	506626.4,165787.5	9-11	Legume Cover Crops (LCC), Trees	5	2
ZD	506302.3,166821.3	9-11	Legume Cover Crops (LCC), Trees	5	2
WPP	507410.57,165991.01	12	Legume Cover Crops (LCC), Trees	5	2
LD3	505994.1,165412.6	12	Legume Cover Crops (LCC), Trees	5	2
FB	505849.63,165910.54	11	Legume Cover Crops (LCC), Trees	5	2
RWT	507633.2,166217.5	12	Legume Cover Crops (LCC), Trees	5	2
EM	507408.28,166333.47	3	Legume Cover Crops (LCC), Trees	5	2
WS MMS	507814.7,167936.9	3	Legume Cover Crops (LCC), Trees	5	2
SA	507540.4,166634.8	3	Legume Cover Crops (LCC), Trees	5	2
TSF	507899.7,166316.7	3-6	Legume Cover Crops (LCC)	5	2
BD	507658.84,167786.96	3	Legume Cover Crops (LCC), Trees	5	2
SD	507417.9,165749.6	3-4	Legume Cover Crops (LCC), Trees	5	2

Note: HD: Henny Dump, ZD: Ziah Dump, WPP: Water Polishing Plant, LD3: Laydown 3, FB: Football, RWT: Raw Water Tank, EM: Ex Magazine, WS MMS: Workshop Macmahon Mining Services, SA: Soutthern Access, TSF: Tailing Storage Facility, BD: Backdoor, SD: Sabar Dump

At each site, five subsamples were collected from clustered points and homogenized. The homogenized soil was then divided into two composite samples (main and duplicate) as part of QA/QC procedures to verify analytical consistency and to anticipate potential anomalies in laboratory results. Each composite weighed approximately 1 kg. This procedure was repeated across three sampling rounds to obtain replication and ensure data reliability. All sampling was carried out during the rainy season to maintain temporal consistency and minimize seasonal variation in soil moisture and metal mobility. Chemical digestion using HNO_3 and $HClO_4$ was conducted at Institut Pertanian Bogor's Integrated Laboratory and the SEAMEO BIOTROP Soil Laboratory.

Laboratory analysis and QA/QC

Data collected from the certificate of analysis of soil samples from the Integrated Laboratory of Institut Pertanian Bogor and the Soil Laboratory of SEAMEO Biotrop were tabulated and analyzed to assess heavy metal concentration variables in reclaimed areas. Soil samples were air-dried, crushed, and sieved (2 mm) before digestion with aqua regia (HNO_3:HCl, 1:3). The extracts were analyzed for Fe, Mn, Zn, and Cu using Atomic Absorption Spectrophoto-metry (AAS). Analytical procedures followed the U.S. EPA Method 7000B (for Cu, Zn, and Mn) and IK.LP-04.10-LT-1.0 (for Fe). The instrument using AAS Thermo ICE 3000 by the lamp (Metal Fe using Hollow Cathode Lamp Fe, Metal Mn using Hollow Cathode Lamp Mn, Metal Zn using Hollow Cathode Lamp Zn, Metal Cu using Hollow Cathode Lamp Cu), while the wave length (Metal Fe; 248.3 nm, Metal Mn; 279.5 nm, Metal Zn; 213.9 nm, Metal Cu; 324.7 nm), and the matrix modifiers using double distilled water or aqua bidest is utilized as a metal matrix solvent, acid digestion involves preparing soil samples using a solution of HNO_3 and HCl or $HClO_4$ + HNO_3. Metal analysis uses Certified Reference Materials (CRMs), such as CRM 500 and CRM 697, for calibration and validation.

Statistical analysis

The heavy metal concentration data from the restored sites were subjected to Principal Component Analysis (PCA) in order to simplify the multivariate structure and identify significant gradients. Z-score transformation was used to standardise all variables before analysis in order to eliminate scale effects. PAST (Hammer et al. 2001) was used for PCA, and Microsoft Excel was used for additional processing. Following Hartati and Sudarmadji (2022), this study used the eigenvalue > 1 rule (Kaiser criterion) as the main basis for component selection. Common items used to determine the number of retained components include cumulative variance, eigenvalues > 1, and the inflection point in the scree plot. This method was selected because the Kaiser criterion was the most suitable and comprehensible given the small number of variables in the dataset. PCA results were further analysed by looking at the variable loadings and pairwise correlations to make sure the relationships between metals were consistent, which strengthened pattern identification.

RESULTS AND DISCUSSION

Heavy metal temporal dynamics and PCA interpretation

The results revealed distinct degradation patterns for heavy metals (Fe, Cu, Zn, and Mn) across the restoration sites (Figure 2). This variation likely stems from factors such as vegetation composition, physico-chemical conditions, microbial adaptation, and precipitation (Iskandar et al. 2022; Liu et al. 2023; Truong et al. 2023). Encouraging active participation in reforestation and planting on vacant land is essential to the restoration process (Pratiwi et al. 2021; Utomo et al. 2024; Rizky et al. 2025). Proper management of land use areas requires clear roadmaps to guide rehabilitation and reforestation, identify suitable locations, and support communities in developing settlements, roads, and services such as health and education facilities (Hapsari et al. 2020; Pratiwi et al. 2021; Maftukhah et al. 2023). Figures 2 and 3 show fluctuating heavy metal concentrations following restoration; these heavy metals have health impacts, as described in Table 2.

Table 2. Toxicity effects of heavy metal

Metal	Phytotoxic effects
Fe	Chlorosis, growth inhibition
Mn	Chlorosis, necrosis, growth inhibition
Cu	Growth stunting, chlorosis, reduced crop quality
Zn	Chlorosis, growth stunting, yield reduction

Fe concentrations exhibited heterogeneous temporal trends between 2023 and 2024 across the sampled sites (Figure 3). Some locations peaked in 2023, followed by a decline in 2024, whereas others continued to increase through 2024. Despite these site-specific differences, Fe and Cu levels remained within the non-toxic thresholds. These patterns indicate that restoration trajectories vary spatially, with short-term increases in some plots before stabilization, which is consistent with previously reported restoration dynamics (Baquy et al. 2022; Maftukhah et al. 2023; Sae-Tun et al. 2024). Nevertheless, any concentration exceeding the established thresholds should prompt targeted assessment and mitigation.

Zinc and manganese showed different reduction patterns than Fe and Cu (Kumkrong et al. 2022; Li et al. 2022). At HD and ZD, Zn levels initially increased but declined by 2024, whereas at other locations, Zn levels have been decreasing steadily since 2019 (Hartati and Sudarmadji 2022; Maftukhah et al. 2023). This suggests that adaptation processes promoting metal reduction were progressing, although transient increases 2-5 years after restoration are common (Baquy et al. 2022; Iskandar et al. 2022). However, manganese concentrations have consistently declined across all sites since 2019 (Landrot and Khaokaew 2018; Li et al. 2022), reflecting more stable recovery dynamics. Such temporary fluctuations are typical of post-restoration systems and likely indicate ongoing soil-plant-microbe adaptation (Kumkrong et al. 2022).

The decline in heavy metals coincided with the establishment of fast-growing and tolerant species in reclaimed areas, particularly *Falcataria falcata* (synonym: *Falcataria moluccana*) (IVI 150%), *Gmelina arborea* (IVI 150%), *Samanea saman* (IVI 100%), and *Eurya acuminata* (IVI 100%), which dominated the vegetation with high Important Value Index (IVI) scores (Anwar et al. 2023). These species contribute to reducing heavy metal concentrations while supporting ecosystem recovery. Their successful establishment highlights the link between vegetation development and metal reduction in post-mining landscapes. We analyzed temporal trends from 2019 to 2024 for Fe, Cu, Zn, and Mn across the reclaimed sites.

In 2023, additional locations (EM, WSMMS, SA, TSF, BD, and SD) were included to observe the four metal parameters (Figure 3). Consistent with earlier observations, the Fe, Cu, Zn, and Mn concentrations decreased in 2024. This indicates that the ongoing restoration has produced positive outcomes (Guerra et al. 2021; Hartati and Sudarmadji 2022). We examined heavy metal decline patterns using Principal Component Analysis (PCA) (Figure 4 and Table 3). In general, the PCAs identified spatial distribution patterns and differentiated sites according to dominant metals, providing a basis for evaluating reclamation effectiveness at each location.

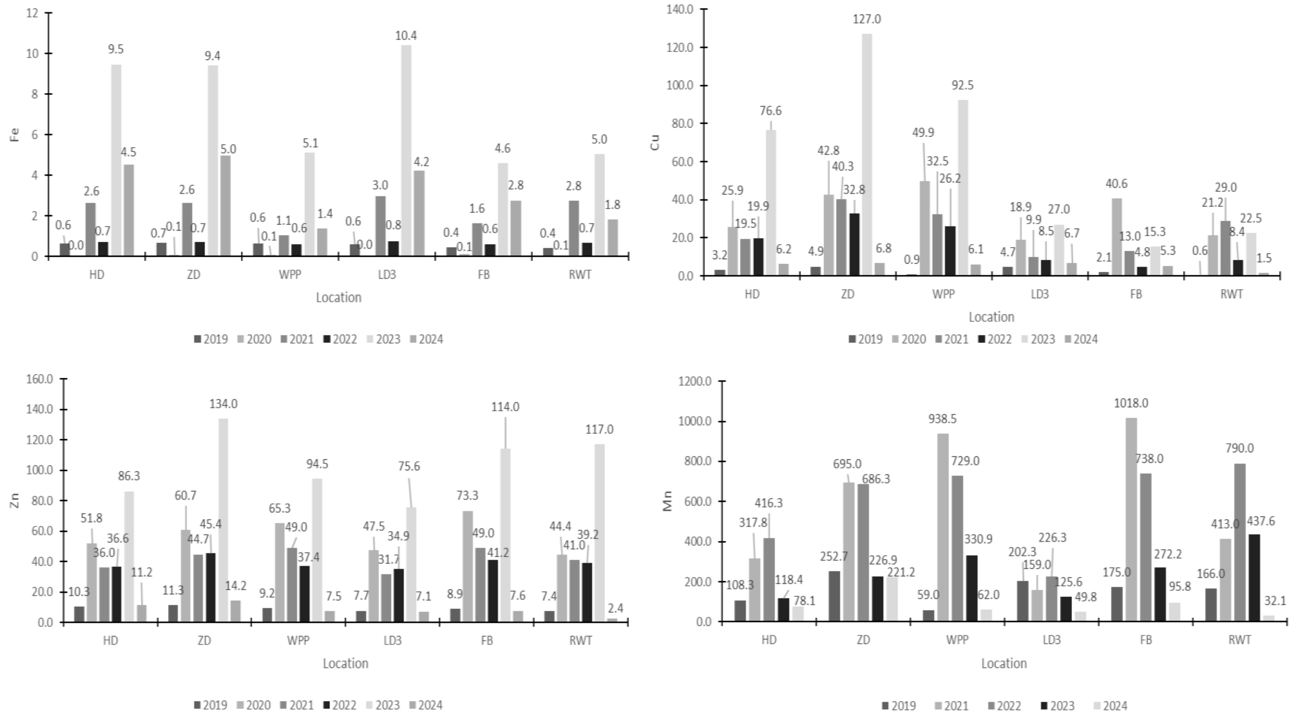

Figure 2. Heavy metal values from 2019-2024 (see Table 1 for the site code)

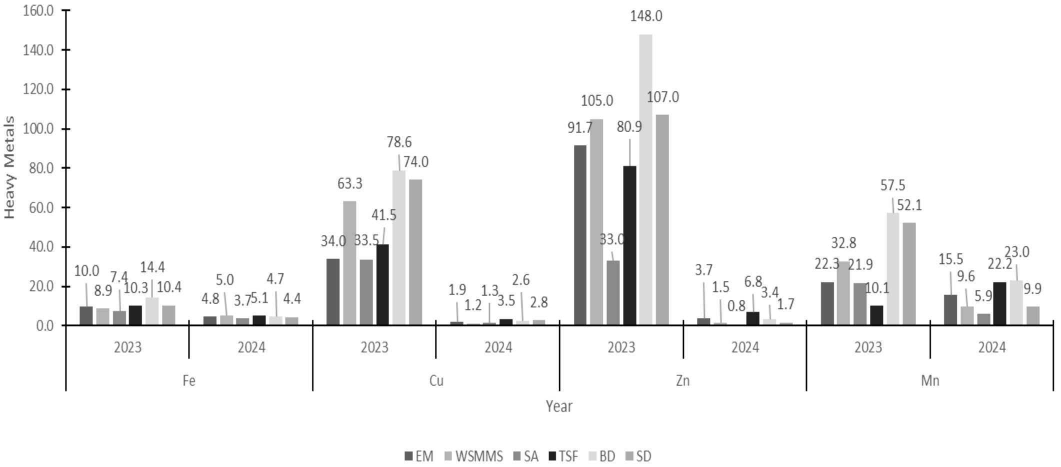

Figure 3. Heavy metal values from the other six locations (see Table 1 for the site code)

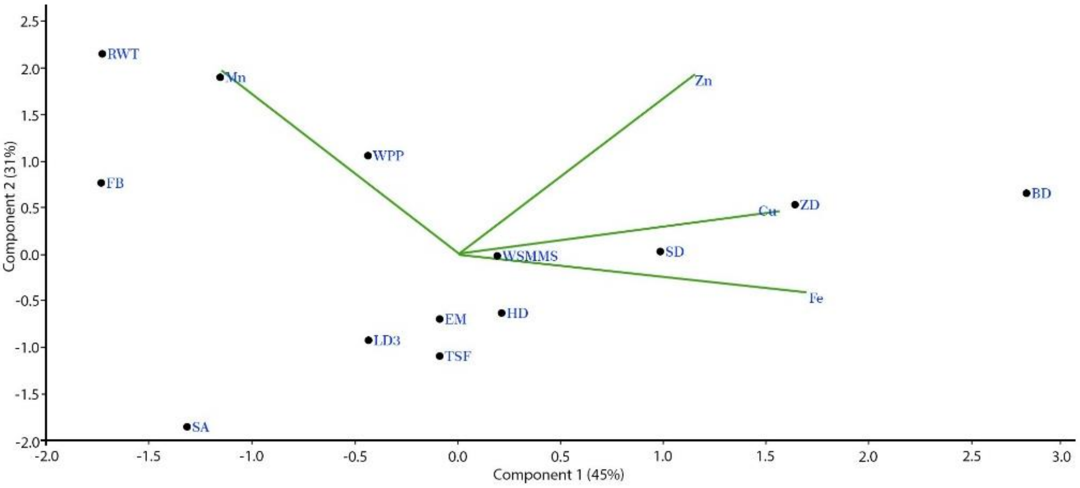

Figure 4. Patterns of metal content decline at various reclamation sites. RWT: Raw Water Tank, FB: Football, SA: Southern Access, WPP: Water Polishing Plant, LD3: Laydown 3, EM: Ex Magazine, TSF: Tailing Storage Facility, HD: Henny Dump, WS MMS: Workshop Macmahon Mining Services, SD: Sediment Dump, ZD: Ziah Dump, BD: Back Door

PCA analysis showed that the first two components accounted for 58% of the total variance in heavy metal concentrations (PC1 = 45%, PC2 = 13%). Fe, Zn, and Cu exhibited positive correlations along PC1, whereas Mn demonstrated a negative correlation with these metals, indicating contrasting geochemical behavior that is likely governed by redox-sensitive processes (Landrot and Khaokaew 2018). Sites such as ZD and BD were positioned along the Fe-Zn-Cu correlation axis, indicating elevated concentrations of these metals. This interpretation is supported by field observations and the study result that these locations showing slower vegetation recovery and relatively low flora diversity at these locations (Roffi et al. 2025). In contrast, RWT and FB were positioned closer to the Mn axis, suggesting stronger Mn influence potentially associated with localized reducing conditions or vegetation-specific effects (Hartati and Sudarmadji 2022). HD, EM, and LD3 were situated near the ordination center, reflecting balanced metal conditions indicative of a stabilizing reclamation trajectory (Maftukhah et al. 2023; Sae-Tun et al. 2024).

Across reclaimed sites, Fe and Cu concentrations generally decreased between 2019 and 2024, corresponding with increases in vegetation cover recorded through field assessments. Given that this study applies a descriptive analytical framework, convergence toward forest reference conditions is interpreted through visual PCA patterns and temporal trends rather than statistical hypothesis testing. The selection of Fe, Mn, Zn, and Cu reflects their established roles as indicators of acid-generating processes in post-mining environments. Oxidation of sulfide minerals promotes acidity and enhances the solubility of these metals, making them effective proxies for identifying low-pH conditions and potential mobilization of toxic metals (Fan et al. 2016; Dong et al. 2023). Although Pb, Cd, Hg, and As were not included, the selected metals sufficiently represent acid-driven dissolution dynamics and environmental risk associated with sulfide exposure (Guo et al. 2022).

Table 3. Principal component loadings of heavy metal variables

Location	Parameters (ppm)			
	Fe	Cu	Zn	Mn
HD	4.9	70.4	75	40
ZD	4.4	120.2	119.8	6
WPP	3.7	86.4	86.9	269
LD3	6.2	20.4	68.5	76
FB	1.8	10.0	106.4	176
RWT	3.2	21.0	114.6	405
EM	5.1	32.1	88	7
WSMMS	3.8	62.1	103	23
SA	3.7	32.2	32.3	16
TSF	5.2	38	74.1	-12
BD	9.7	76	144.6	35
SD	6.0	71.2	105.3	42

Note: See Table 1 for the site code

Table 4. Heavy metal concentrations at 20 cm depth in natural forest controls

Location	Parameters (ppm)			
	Fe	Cu	Zn	Mn
Barani	2.50	2.07	12.94	8.88
TMF East	7.85	26.84	15.95	14.86
TMF West	7.87	17.13	33.80	52.40
Conservation Area Aek Pahu	11.71	14.12	44.81	38.89

Compared to the reclaimed plots, the forest control soils generally showed lower Fe and Cu concentrations, while Zn and Mn were higher in some cases, reflecting the natural variability associated with parent material and vegetation type (Table 4). These observations provide a qualitative reference for interpreting the reclaimed sites, although the comparison remains descriptive because the control data were not included in PCA or formal statistical tests. The patterns suggest that several reclaimed sites particularly those closer to TMF areas still maintain relatively elevated Fe and Cu, consistent with ongoing geochemical adjustments. Meanwhile, the forest control values represent stable background conditions typical of mature ecosystems. Although not assessed statistically, the gradual convergence of reclaimed-site concentrations toward these forest baselines in 2024 offers contextual support for the ongoing recovery process.

Mechanistic drivers and management implications

Decreased heavy metal levels on reclaimed land are closely related to microclimatic changes during ecosystem restoration (Li et al. 2022; Truong et al. 2023; Wan et al. 2024). Soil temperature, moisture, light intensity, aeration, and pH collectively influence metal bioavailability (Landrot and Khaokaew 2018; Li et al. 2022). For example, increased vegetation cover after reclamation can lower surface temperatures and increase soil moisture, altering redox conditions (Hapsari et al. 2020; Iskandar et al. 2022). More oxidizing and stable redox conditions tend to lower the solubility of Fe and Mn (and can affect Zn and Cu), reducing metal mobility and bioavailability (Landrot and Khaokaew, 2018; Li et al. 2022). Increased litter and organic matter from plant growth can complex metal ions and sequester them in less bioavailable forms (Sae-Tun et al. 2024). Plant roots also secrete exudates that can immobilize heavy metals, accelerating phytostabilization (Truong et al. 2023). Taken together, the improvements in vegetation cover, organic matter inputs, and soil microclimate function synergistically rather than independently, thereby driving the progressive decline in metal concentrations observed during reclamation (Hartati and Sudarmadji 2022; Maftukhah et al. 2023).

Temporal patterns revealed that Fe and Cu concentrations often increased during the first years of restoration before declining, reflecting transitional dynamics as soils and vegetation were stabilized (Kumkrong et al. 2022; Li et al. 2022). In contrast, Zn and Mn showed more consistent declines, particularly at sites with established vegetation. Such patterns are consistent with other post-mining studies, where heavy metals decline after 5-7 years of vegetation establishment, although site-specific factors, such as hydrology and tailing composition, can delay recovery (Guerra et al. 2021; Baquy et al. 2022). Vegetation plays a central role in remediation. Fast-growing and tolerant species, such as *F. falcata* (synonym: *F. moluccana*), *G. arborea*, and *S. saman*, contribute organic inputs and phytoaccumulation capacity, thereby reducing metal mobility (Iskandar et al. 2022; Anwar et al. 2023). In this study area, *F. falcata* and *S. saman* primarily support phytostabilization through root-mediated immobilization, whereas *G. arborea* shows greater potential for phytoextraction of Zn and Cu as noted in comparable tropical mining sites. This differentiation clarifies the functional pathways through which vegetation enhances remediation success. Similar findings have been reported in coal mine reclamation in Kalimantan and bauxite mines in Thailand, where tolerant tree species significantly accelerated heavy metal stabilization (Kumkrong et al. 2022; Maftukhah et al. 2023).

PCA provided additional ecological insights by distinguishing sites according to metal behavior. The first two components explained 58% of the variation in the metal content. Fe, Cu, and Zn clustered together, suggesting a shared anthropogenic origin, whereas Mn formed a distinct axis, reflecting its sensitivity to redox conditions. ZD and BD were grouped with the Fe-Cu-Zn cluster, indicating less effective reclamation, whereas EM, HD, and LD3 showed balanced metal levels consistent with more successful restoration. Such multivariate approaches help identify priority areas where remediation is incomplete (Kodat and Tepe 2023)

Despite these positive trends, some limitations must be acknowledged in this study. The study was restricted to four metals, and the six-year monitoring period may not fully capture the long-term stabilization. In addition, a broader assessment of soil biological processes, particularly microbial community activity, which influences metal redox cycling, organic-metal complexation, and rhizosphere immobilization, would enhance mechanistic interpretation (e.g., roles of Fe-reducing bacteria, mycorrhizal associations, or organic-acid-producing microbes). Even though microbial data were not collected in this study, integrating such indicators in future monitoring would provide a more holistic evaluation of restoration progress**.** Broader monitoring, including Pb, Cd, and As levels, along with deeper soil layers, and hydrological parameters would provide a more comprehensive evaluation of restoration effectiveness.

Conclusion, this study demonstrated that heavy metal concentrations in reclaimed areas of the Martabe Gold Mine generally declined between 2019 and 2024, although the temporal dynamics varied by metal and site. Declines were associated with microclimatic stabilization, increased organic matter input, and the establishment of tolerant vegetation, particularly fast-growing tree species. PCA highlighted the differences among the sites and identified areas where remediation was less effective. However, the study is limited by its focus on only four metals and a single soil depth, constraining the capture of vertical heterogeneity and finer-scale geochemical processes with descriptive comparison. The findings emphasize that successful post-mining restoration depends on planting, long-term monitoring, and management. Restoration strategies should prioritize fast-growing, tolerant tree species that enhance organic matter and metal stabilization. For future monitoring, we recommend the inclusion of additional metals such as Pb, Cd, and As, along with deeper soil layers, hydrological parameters, soil microbial, and soil fauna to better track subsurface metal mobility and stabilization processes. These results suggest that integrated ecological and soil monitoring frameworks are essential for policy and management to ensure reclamation success, improve soil quality, and accelerate the recovery of biodiversity and ecosystem functions in post-mining landscapes. Importantly, this six-year dataset represents a rare long-term tropical record of post-mining soil metal dynamics, a data type seldom available in Southeast Asia and therefore provides valuable novelty for understanding reclamation trajectories in tropical environments.

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REFERENCES

Anwar S, Dharsono M, Zaery FP, Subagya M, Ananto H, Lubis A, Susilowati A. 2023. Assessing phytoremediation potentials of heavy metals on selected plant species in restoration environments of gold mining areas. IOP Conf Ser Earth Environ Sci 1271: 012054. DOI: 10.1088/1755-1315/1271/1/012054.

Baquy M, Nkoh JN, Mia S, Xu RK, Ajibade F, Atakpa E, Odii E. 2022. Reduction of heavy metal uptake from polluted soils and associated health risks through biochar amendment: A critical synthesis. J Hazard Mater Adv 6: 100086. DOI: 10.1016/j.hazadv.2022.100086.

Bartkowiak A. 2021. Influence of Heavy Metals on Quality of Raw Materials, Animal Products, and Human and Animal Health Status. IntechOpen Limited, London, UK. DOI: 10.5772/intechopen.102497.

Dong X, Li Z, Wang Y, Chen S. 2023. Study on the effectiveness of sulfate reducing bacteria to remove heavy metals (Fe, Mn, Cu, Cr) in acid mine drainage. Sustainability 15 (6): 5486. DOI: 10.3390/su15065486.

Fan L, Zhou X, Luo H, Deng J, Dai L, Ju Z, Zhu Z, Zou L, Ji L, Li B, Cheng L. 2016. Release of heavy metals from the pyrite tailings of Huangjiagou Pyrite Mine: Batch experiments. Sustainability 8 (1): 96. DOI: 10.3390/su8010096.

Guerra SBE, Muñoz GJ, Sokolski S. 2021. Phytoremediation of heavy metals in tropical soils: An overview. Sustainability 13 (5): 2574. DOI: 10.3390/su13052574.

Guo X, Hu Z, Fu S, Dong Y, Jiang G, Li Y. 2022. Experimental study of remediation of acid mine drainage using Maifan stones combined with sulfate-reducing bacteria. PLoS One 17 (1): e0261823. DOI: 10.1371/journal.pone.0261823.

Hammer O, Harper DAT, Ryan PD. 2001. PAST: Paleontological statistics software package for education and data analysis. Palaeontologia Electronica 4: 1-9.

Hapsari L, Trimanto T, Budiharta S. 2020. Spontaneous plant recolonization on reclaimed post-coal mining sites in East Kalimantan, Indonesia: Native versus alien species and succession progress. Biodiversitas 21 (5): 2003-2018. DOI: 10.13057/biodiv/d210527.

Hartati W, Sudarmadji T. 2022. Dynamics of soil carbon in revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia. Biodiversitas 23. DOI: 10.13057/biodiv/d231004.

Iskandar I, Suryaningtyas D, Baskoro DPT, Budi SW, Gozali I, Suryanto A, Kirmi H, Dultz S. 2022. Revegetation as a driver of chemical and physical soil property changes in a post-mining landscape: A chronosequence study. Catena 215: 106355. DOI: 10.1016/j.catena.2022.106355.

Kiran, Bharti R, Sharma R. 2022. Effect of heavy metals: An overview. Mater Today Proc 51: 880-885. DOI: 10.1016/j.matpr.2021.06.278.

Kodat E, Tepe Y. 2023. Holistic assessment of heavy metal levels and associated risks in coastal sediments of Giresun, Southeast Black Sea. Environ Monit Assess 195 (6): 781. DOI: 10.1007/s10661-023-11339-5.

Kumkrong P, Dy E, Tyo DD, Jiang C, Pihilligawa IG, Kingston D, Mercier PHJ. 2022. Investigation of metal mobility in gold and silver mine tailings using sequential extraction. Environ Monit Assess 194: 423. DOI: 10.1007/s10661-022-10054-3.

Landrot G, Khaokaew S. 2018. Lead speciation and association with organic matter in various particle-size fractions of contaminated soils. Environ Sci Technol 52 (12): 6780-6788. DOI: 10.1021/acs.est.8b00004.

Li Q, Wang Y, Li Y, Li L, Tang M, Hu W, Chen L, Ai S. 2022. Speciation of heavy metals in soils and immobilization at micro-scale interfaces. Sci Total Environ 825: 153862. DOI: 10.1016/j.scitotenv.2022.153862.

Listiyani N, Said MY, Khalid A. 2023. Strengthening reclamation obligations through mining law reform: Indonesian experience. Resources 12 (5): 56. DOI: 10.3390/resources12050056.

Liu J, Kang H, Tao W, Li H, He D, Ma L, Tang H, Wu S, Yang K, Li X. 2023. Spatial distribution-principal component analysis model for assessing soil heavy metal pollution. Sci Total Environ 859: 160112. DOI: 10.1016/j.scitotenv.2022.160112.

Maftukhah R, Keiblinger KM, Ngadisih N, Murtiningrum M, Kral RM, Mentler A, Hood-Nowotny R. 2023. Post-tin-mining soil regeneration using local organic amendments. Land 12 (5): 1107. DOI: 10.3390/land12051107.

Ondrasek G, Shepherd J, Rathod S, Dharavath R, Rashid MI, Brtnicky M, Shahid MS, Horvatinec J, Rengel Z. 2025. Metal contamination as a global environmental issue: Sources, impacts, and mitigation advances. RSC Adv 15 (5): 3904-3927. DOI: 10.1039/d4ra04639k.

Pratiwi NBH, Siregar CA, Turjaman M, Hidayat A, Rachmat HH, Mulyanto B, Suwardi, Iskandar, Maharani R, Rayadin Y, Prayudyaningsih R, Yuwati TW, Prematuri R, Susilowati A. 2021. Managing and reforesting degraded post-mining landscapes in Indonesia: A review. Land 10 (6): 658. DOI: 10.3390/land10060658.

Rizky W, Deni E, Samsuri. 2025. Productivity of Betung and Belangke Bamboo Based on Site Characteristics in North Sumatra. IOP Conf

Ser Earth Environ Sci 1463: 012016. DOI: 10.1088/1755-1315/1463/1/012016.

Roffi AI, Djuita NR, Anwar S, Hamim. 2025. The Dynamics of Plant Diversity during Revegetation Period at Martabe Gold Mine, North Sumatra, Indonesia. IOP Conf Ser Earth Environ Sci 1550: 012013. DOI: 10.1088/1755-1315/1550/1/012013.

Sae-Tun O, Maftukhah R, Susanto S, Ngadisih N, Murtiningrum M, Hood-Nowotny R, Mentler A, Bodner G, Keiblinger KM. 2024. Organic carbon-based amendments reclaim post-tin mining sites via modified SOC characteristics. Plant Soil. DOI: 10.1007/s11104-024-06833-1.

Saleh HEDM, Aglan R (eds). 2018. Heavy Metals. BoD-Books on Demand, Hamburg.

Truong XV, Stephen J, Nguyen T, Cao V, Pham D. 2023. Heavy metal speciation in contaminated soil incubated with biochar and apatite. Molecules 28 (5): 2225. DOI: 10.3390/molecules28052225.

Utomo B, Nizar R, Wahyudi R, Yunasfi, Samsuri, Basyuni M. 2024. Land cover change and sustainable reforestation in Samosir Regency, Indonesia. OnLine J Biol Sci 24 (4): 572-583. DOI: 10.3844/ojbsci.2024.572.583.

Wan Y, Liu J, Zhuang Z, Wang Q, Li H. 2024. Heavy metals in agricultural soils: Sources, influencing factors, and remediation strategies. Toxics 12 (1): 63. DOI: 10.3390/toxics12010063.