Environment and Natural Resources Journal

Volume 23
Issue 6
2025

The Influence of Age and Management on Soil Physicochemical Properties and Heavy Metal Accumulation in Post-Tin Mining Lands on Bangka Island

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ARTICLE INFO

Received: 14 Mar 2025
Received in revised: 22 Jul 2025
Accepted: 29 Jul 2025
Published online: 9 Sep 2025
DOI: 10.32526/ennrj/23/20250066

Keywords:
Post-tin mining land age/ Post-tin mining management/ Soil physicochemical properties/ Heavy metal accumulation/ Partial least squares structural equation modeling

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ABSTRACT

Bangka Island is one of the largest tin producers in Indonesia and the world, covering an area of 156,531.3 hectares. Tin mining activities have significantly degraded post-mining land, altering soil properties and increasing heavy metal retention. This study aimed to evaluate the impact of post-tin mining land age and management on soil physical and chemical properties and total heavy metal concentration. Soil samples were collected using a stratified sampling method from three representative sites with similar climatic conditions: newly mined land (0 years), reclaimed land (7 years), and minimally managed land (20 years). Physical parameters were measured directly in the field, except for bulk density, air-dried soil moisture, and texture fraction, which were analysed in the laboratory alongside chemical parameters. The findings indicate that as post-tin mining land ages, soil physical properties such as bulk density, soil hardness, air-dried soil moisture, and texture fractions change, while infiltration decreases, indicating compaction. Meanwhile, post-tin mining management in the form of reclamation significantly improves soil chemical quality, including pH, organic carbon, organic matter, and phosphorus availability. Heavy metal accumulation is more strongly influenced by land age than management practices; however, appropriate management can reduce heavy metal availability and enhance overall soil quality. Partial least squares structural equation modeling (PLS-SEM) analysis confirms that soil physicochemical properties mediate the relationship between land age, management, and heavy metal accumulation in post-tin mining sites.

HIGHLIGHTS

- Post-tin mining land age and post-tin mining management affect soil properties
- Post-tin mining land age increases soil compaction
- Post-tin mining management improves soil chemistry
- Heavy metal accumulation is more influenced by the land age of the post-tin mining land
- Soil physicochemical properties mediate the relationship between land age, management, and heavy metals.

1. INTRODUCTION

Bangka Belitung Islands Province is the largest tin producer in Indonesia and globally, with the mining area increasing from 144,783.81 ha (2018) to 156,531.3 ha (2021), covering 27.56% of Bangka Island (Harahap, 2016; Provincial Government of the Bangka Belitung Islands, 2022; Maftukhah et al., 2023). Massive mining activities, especially in Central Bangka Regency, which has 18,069 ha of post-tin mining land (Sukarman and Gani, 2017), have caused soil degradation and heavy metal accumulation, limiting land recovery and creating serious environmental problems.

Citation: Erdaswin F, Rahayu, Rosariastuti R, Dewi WS, Herawati A, Fatimah, Ichsan N. The influence of age and management on soil physicochemical properties and heavy metal accumulation in post-tin mining lands on Bangka Island. Environ. Nat. Resour. J. 2025;23(6):537-551. (https://doi.org/10.32526/ennrj/23/20250066)

Post-tin mining soils on Bangka Island are generally characterized by low fertility, high acidity, and degraded physical properties, including high bulk density, low porosity, and poor soil structure (Irzon et al., 2018; Sukarman et al., 2020). In addition, heavy metal contamination, particularly Pb (Sari et al., 2023), Cd (Yang et al., 2021), Cr (Anda et al., 2022), and Cu (Liu et al., 2021), negatively affects microbial activity, reduces plant productivity, and pollutes water sources, further complicating land rehabilitation efforts. Although soil can recover naturally through weathering, organic matter accumulation, and microbial succession (Li et al., 2021; Nyenda et al., 2021), the age of the land alone is insufficient to restore soil quality. A study on post-gold mining soil in the Amazon revealed the progressive accumulation of heavy metals over time. For instance, the concentration of lead (b) increased from 4.05-5.03 mg/kg in land affected for 1.5-5 years to 7.04-7.94 mg/kg in land aged 6-8 years (Velásquez et al., 2020). Similar patterns of increase were observed for other heavy metals, such as As, Cd, and Cu. This phenomenon underscores the importance of active intervention in post-mining land management, such as in post-tin mining areas, to mitigate soil degradation and accelerate ecological rehabilitation (Li et al., 2020).

Post-tin mining land management in Bangka varies from abandoned land without reclamation to revegetation and organic matter application, yielding mixed results (Setyawan et al., 2019). However, many reclamation efforts remain ineffective due to poor planning (Haryadi et al., 2023), and some areas are even repurposed for tourism without adequate rehabilitation (Kivinen et al., 2018). These shortcomings leave the land unproductive and a persistent source of environmental problems (Duncan et al., 2020).

Various reclamation initiatives have been implemented; however, the interaction between land age, management practices, and heavy metal accumulation in tropical environments such as Bangka Belitung remains poorly understood. Furthermore, no studies have specifically examined these interactions in post-tin mining lands, either locally or globally. Therefore, this study aims to evaluate the influence of post-tin mining land age and management practices on soil physicochemical properties and heavy metal retention in post-tin mining sites on Bangka Island. The findings are expected to provide insights for more sustainable post-tin mining land management.

2. METHODOLOGY

2.1 Study sites and research duration

This study was conducted in Central Bangka Regency, Bangka Island, Indonesia, a region heavily impacted by tin mining (Figure 1). Field surveys and soil sampling were carried out in August 2024 to evaluate how post-tin mining land age and management influence soil properties and heavy metal accumulation. Three sites with contrasting reclamation histories were selected: Koba (0 years, unreclaimed), Belilik (7 years, reclaimed), and Nibung (20 years, partially reclaimed). At Koba, informal mining persists, and earlier reclamation efforts, such as planting *Acacia auriculiformis*, were abandoned. Vegetation is very sparse, dominated by remnant *A. auriculiformis*, *Lepironia articulata*, and a few scattered grasses. Belilik underwent structured reclamation using compost blocks (60% cow manure, 40% plant litter with EM4 and tapioca), supporting the growth of *A. auriculiformis*, *Casuarina equisetifolia*, and *Anacardium occidentale* as pioneer reclamation species, and mostly covered with grass. In contrast, Nibung received minimal intervention; although A. auriculiformis was planted, efforts were not sustained, and the site was later converted for tourism. Vegetation developed through natural succession, including *Dicranopteris linearis*, *Nepenthes* spp., and *Dillenia suffruticosa*. These sites were selected to represent a gradient of post-tin mining land age and management intensity, providing a basis for assessing their effects on soil physicochemical properties and heavy metal retention (Table 1).

2.2 Methods and characteristics of research sites

Field measurements included soil hardness (SH), assessed using a digital soil hardness tester, model TYD-2, and soil infiltration rate (IR), measured with a double-ring infiltrometer (Gregory et al., 2005). Laboratory analyses encompassed soil bulk density (BD) and air-dry soil moisture (ADSM) determined by gravimetric methods (Blake and Hartge, 1986; Jabro et al., 2020); soil texture was analyzed by the pipette method (Palihakkara and Vitharana, 2019); soil pH was measured via potentiometry using a Eutech pH 5+; electrical conductivity (EC) was determined via conductometry using a Eutech Cond 6+; total nitrogen (TN) was measured using the Kjeldahl method (Rhee, 2001); available phosphorus (AP) was analysed by the Olsen method (Olsen et al., 1954); available potassium (AK) and cation exchange capacity (CEC) were determined via ammonium acetate extraction (Madaras and Koubová, 2015; Jain and Taylor, 2023); soil organic carbon (SOC) was measured using the Walkley-Black method (Nelson and Sommers, 1983); and soil organic matter (SOM) was calculated by multiplying SOC by 0.58, a conversion factor proposed by van Bemmelen (Minasny et al., 2020). Finally, heavy metals (Pb, Cd, Cr, Cu) were determined using wet oxidation with HNO_3 and $HClO_4$ (BPSI, 2023). The concentrations were measured with a Thermo Scientific™ iCE™ 3000 Series Atomic Absorption Spectrophotometer (AAS) from Thermo Fisher Scientific Inc., with a detection limit of 0.01 mg/kg for all metals.

Table 2 presents the climate conditions and soil properties at the three study sites: Belilik, Koba, and Nibung. All locations share a similar climate, with an average annual temperature of 27.9°C, annual rainfall of 2,223 mm, and relative humidity of 85%, indicating a humid zone with high precipitation and no significant climatic differences. Drainage is classified as very good in Belilik and Koba, while in Nibung, it is considered moderately good.

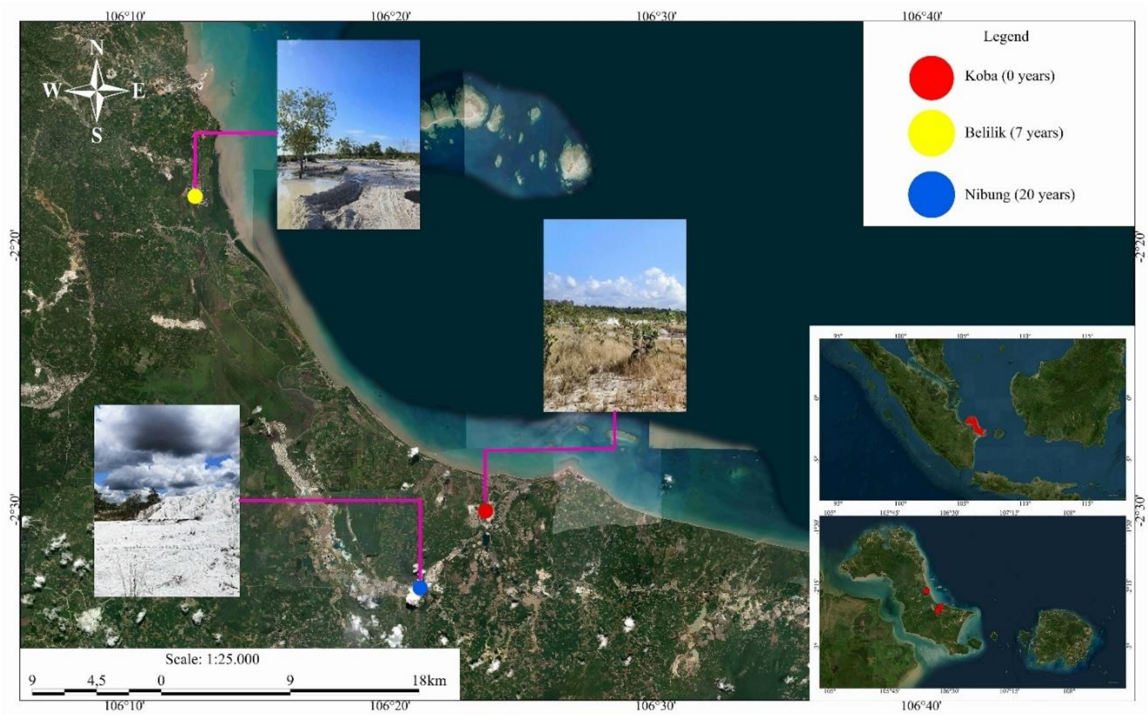

Figure 1. Map of sampling points in three post-tin mining lands on Bangka Island

Table 1. General information about each research and sampling sites

Sites	Altitude (MASL)	Coordinate		Area (ha)	Age of post-tin mining	Post-tin mining management
		X	Y			
Koba	4	-2°29'52.6"	106°23'36"	154.17	0	Previously mined but mined again by the community
Belilik	7	-2°18'05.4"	106°12'32.9"	100.1	7	Has been reclaimed
Nibung	43	-2°32'57.7"	106°21'09.6"	14.22	20	Focused on being a tourist attraction without optimal reclamation

Source: Data and Field Analysis

Table 2. Climate and study sites conditions

Sites	Mean annual temperature	Rainfall/Year (mm)	Relative humidity (%)	Drainage
Koba	27.9	2,223	85	Very good
Belilik	27.9	2,223	85	Very good
Nibung	27.9	2,223	85	Moderately good

Source: Data and Field Analysis

2.3 Data analysis

Field and laboratory data were processed using IBM SPSS version 27 and R Studio. ANOVA was performed, followed by Tukey's HSD post-hoc test (α=0.05) to identify significant differences between post-mining sites. Multivariate analyses, including hierarchical clustering analysis (HCA) and principal component analysis (PCA), were conducted to explore classification patterns and relationships between parameters. Additionally, partial least squares structural equation modeling (PLS-SEM) was applied to evaluate the relationships between post-mining land age, management practices, soil physicochemical properties, and heavy metal accumulation. Parameter estimation was performed using bootstrap resampling (1,000 iterations) to assess the significance of relationships between variables, while model evaluation was based on path coefficients and R^2 values to determine the proportion of explained variance.

3. RESULTS AND DISCUSSION

3.1 Soil physicochemical properties and heavy metal accumulation in the study area

3.1.1 Soil physical properties in the study area

The study results indicate significant differences in soil physical properties across post-tin mining sites on Bangka Island, influenced by land age and management practices (Table 3). Bulk density varied significantly between locations ($p<0.001$), with the highest value recorded in Nibung (20 years) (1.60±0.05 g/cm³) and the lowest in Koba (0 years) (1.39±0.05 g/cm³). The increase in BD with land age suggests soil compaction, which may hinder root growth and water infiltration. Meanwhile, Belilik (7 years), which underwent reclamation, exhibited an intermediate BD (1.50±0.01 g/cm³), highlighting the potential of reclamation efforts in reducing soil compaction.

Other parameters, including infiltration rate (IR), soil hardness (SH), air-dry soil moisture (ADSM), and soil texture fractions, also showed significant differences ($p<0.05$). Koba had the highest IR (135.75±9.13 cm/h), dominated by sand fraction (96.08±0.56%), whereas Nibung had the lowest IR (25.26±4.79 cm/h) due to increased clay content (14.08±8.31%). This trend was also reflected in SH values, with Nibung exhibiting the hardest soil (45.38±4.28 kg/cm²) and Koba the softest (25.88±1.22 kg/cm²). The highest ADSM was observed in Nibung (0.40±0.28%) and the lowest in Koba (0.14±0.02%) ($p=0.03$). These findings demonstrate that post-mining land age and management significantly influence soil physical properties. Soil compaction in Nibung may hinder ecosystem recovery (Zhang et al., 2019), while reclamation efforts in Belilik, incorporating organic matter, have improved soil quality compared to newly mined areas (Song, 2020).

Table 3. Comparison of soil physical properties on various post-tin mining lands in the study area

Sites And Ages	Parameters						
	BD (g/cm^3)	IR (cm/h)	SH (kg/cm^2)	ADSM (%)	Sand (%)	Silt (%)	Clay (%)
Koba (0 Years)	1.39±0.05^a	135.75±9.13^a	25.88±1.22^a	0.14±0.02^b	96.08±0.56^b	1.75±0.38^{ab}	2.16±0.93^b
Belilik (7 years)	1.50±0.01^b	74.16±5.49^b	29.09±3.84^a	0.18±0.05^{ab}	96.97±0.65^b	0.23±0.03^b	2.80±0.67^b
Nibung (20 Years)	1.60±0.05^c	25.26±4.79^c	45.38±4.28^b	0.40±0.28^a	80.08±13.62^a	5.84±5.31^a	14.08±8.31^a
p-value	**<0.001**	**<0.001**	**<0.001**	**0.03**	**0.003**	**0.018**	**<0.001**

BD=Bulk density, IR=Infiltration rate, SH=Soil hardness, ADSM=Air-dried soil moisture, ±; Standard deviation, Letter symbol=Numbers in the same column followed by different letters indicate significantly different according to Tukey's HSD test at the 5% level, while numbers in the same column followed by the same letter indicate not significantly different according to Tukey's test at the 5% level.

3.1.2 Soil chemical properties in the study area

The analysis of soil chemical properties revealed significant variations among the post-tin mining sites, particularly in pH, soil organic carbon (SOC), soil organic matter (SOM), and available phosphorus (AP). The highest pH was recorded in Belilik (6.34±0.94), whereas Koba (5.93±0.15) and Nibung (5.71±0.36) were more acidic ($p<0.001$). Belilik also exhibited the highest SOC (0.45±0.09%) and SOM (0.78±0.16%) compared to Koba (SOC: 0.24±0.06%; SOM: 0.42±0.10%) and Nibung (SOC: 0.33±0.11%; SOM: 0.56±0.19%) ($p=0.004$), indicating that reclamation efforts in Belilik have enhanced organic matter content, improved soil structure, and increased nutrient retention (Table 4).

Available phosphorus (AP) also varied significantly ($p=0.037$), with the highest concentration in Belilik (0.64±0.59 ppm) and the lowest in Koba

(0.10±0.06 ppm), while Nibung (0.19±0.14 ppm) was intermediate. The low AP in Koba suggests nutrient loss due to leaching and erosion. Other parameters, including electrical conductivity (EC), total nitrogen (TN), available kalium (AK), and cation exchange capacity (CEC), did not show significant differences among the sites (p>0.05). This can be attributed to the similar environmental conditions and post-mining land management practices, where short-term reclamation efforts primarily influence organic matter-related parameters (Li et al., 2021). These findings highlight that pH, SOC, SOM, and AP, which exhibited significant changes, are directly linked to organic matter dynamics.

Table 4. Comparison of soil chemical properties on various post-tin mining land in the study area

Sites and ages	Parameters							
	pH	EC (dS/m)	SOC (%)	SOM (%)	TN (%)	AP (ppm)	AK (meq/100g)	CEC (meq/100g)
Koba (0 Years)	5.93±0.15[b]	0.07±0.02[a]	0.24±0.06[b]	0.42±0.10[b]	0.12±0.01[a]	0.10±0.06[b]	0.29±0.11[a]	2.62±0.22[a]
Belilik (7 Years)	6.34±0.94[a]	0.06±0.01[a]	0.45±0.09[a]	0.78±0.16[a]	0.13±0.01[a]	0.64±0.59[a]	0.30±0.06[a]	2.50±0.33[a]
Nibung (20 Years)	5.71±0.36[b]	0.07±0.02[a]	0.33±0.11[b]	0.56±0.19[b]	0.13±0.01[a]	0.19±0.14[ab]	0.20±0.06[a]	2.79±0.32[a]
p-value	**<0.001**	0.828	**0.004**	**0.004**	0.699	**0.037**	0.086	0.246

Ec=Electrical conductivity, SOC=Soil organic carbon, SOM=Soil organic matter. TN=Total nitrogen, AP=Phosphorus availability, AK=Potassium availability, CEC=Cation exchange capacity, ±; Standard deviation, Letter symbol=Numbers in the same column followed by different letters indicate significantly different according to Tukey's HSD test at the 5% level, while numbers in the same column followed by the same letter indicate not significantly different according to Tukey's test at the 5% level.

3.1.3 Heavy metal accumulation of Cd, Cr, Cu, Pb in the study area

The analysis of total heavy metal concentrations in post-tin mining sites revealed variations across locations, although the differences were not statistically significant (Figure 2). Pb and Cd were not detected at any site, indicating either low concentrations or levels below detection limit. Despite being undetected, Pb and Cd remain a concern due to their persistent and toxic nature, posing risks to ecosystems (Angon et al., 2024). In contrast, Cr (45.64-49.58 mg/kg) and Cu (1.76-4.55 mg/kg) were detected at all locations, with the highest concentrations found in Nibung (20 years), though the differences were not statistically significant. Briffa et al., (2020) emphasized that while heavy metals play essential roles in biological functions, excessive concentrations can be toxic if not properly managed.

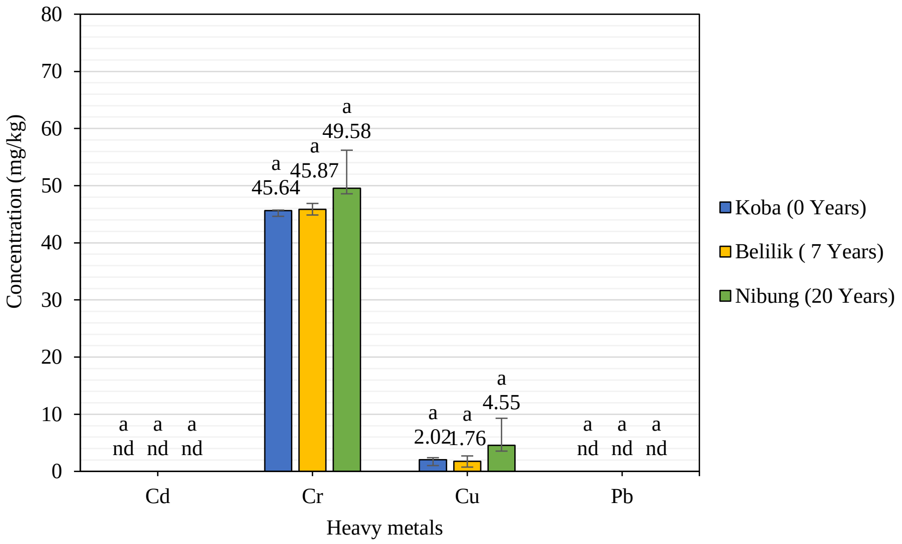

Figure 2. Comparison of total soil heavy metal on various post-tin mining lands in the study area with letter symbol which is mean numbers in the same bar followed by different letters indicate significantly different according to Tukey's HSD test at the 5% level, while numbers in the same bar followed by the same letter indicate not significantly different according to Tukey's test at the 5% level

3.2 Multivariate analysis of post-tin mining soils using hierarchical clustering and PCA

3.2.1 Soil classification based on Hierarchical Clustering Analysis (HCA)

The Hierarchical Clustering Analysis (HCA) of soil physicochemical properties in post-tin mining sites on Bangka Island is visualized through a dendrogram using standardized z-scores (mean=0, SD=1) (Figure 3), illustrating the soil characteristics at the three study sites. In the heatmap legend, blue denotes positive z-scores (above the overall mean), green ≈ 0, and yellow indicates negative z-scores (below the overall mean). The vertical dendrogram indicates that samples from Koba form a distinct cluster, reflecting the properties of newly mined soils. Belilik forms a relatively homogeneous group, though some outliers are present, whereas Nibung exhibits greater dispersion, indicating heterogeneous soil recovery due to inconsistent post-mining management.

The horizontal dendrogram highlights relationships between soil properties, with BD and SH clustering together, indicating their association with soil compaction. Clay, silt, and ADSM group within the moisture retention category, while CEC, TN, and EC are linked to nutrient retention and salinity potential. Furthermore, SOC, SOM, AP, and pH correlate with soil chemical quality in Belilik, whereas sand, IR, and AK are associated with the sandy soils of Koba, which exhibit high infiltration rates. A z-score-based heatmap reveals that Koba has negative values for fertility parameters, reflecting degraded soil quality. The Belilik site exhibits moderate to high z-scores for organic matter content and nutrient retention, indicating an improvement in these properties. In contrast, the Nibung site displays high z-scores for compaction alongside variable fertility parameters, suggesting that its recovery is hindered by suboptimal management practices.

HCA also reveals patterns of heavy metal accumulation across the three sites (Figure 4). Nibung (20 years) forms a distinct cluster with higher Cr and Cu concentrations due to limited reclamation efforts, as reflected by darker shades in the heatmap. In contrast, Belilik (7 years) and Koba (0 years) cluster more closely together, indicating lower metal concentrations. The clear separation of Nibung from the other sites underscores the long-term environmental impact of inadequate reclamation practices.

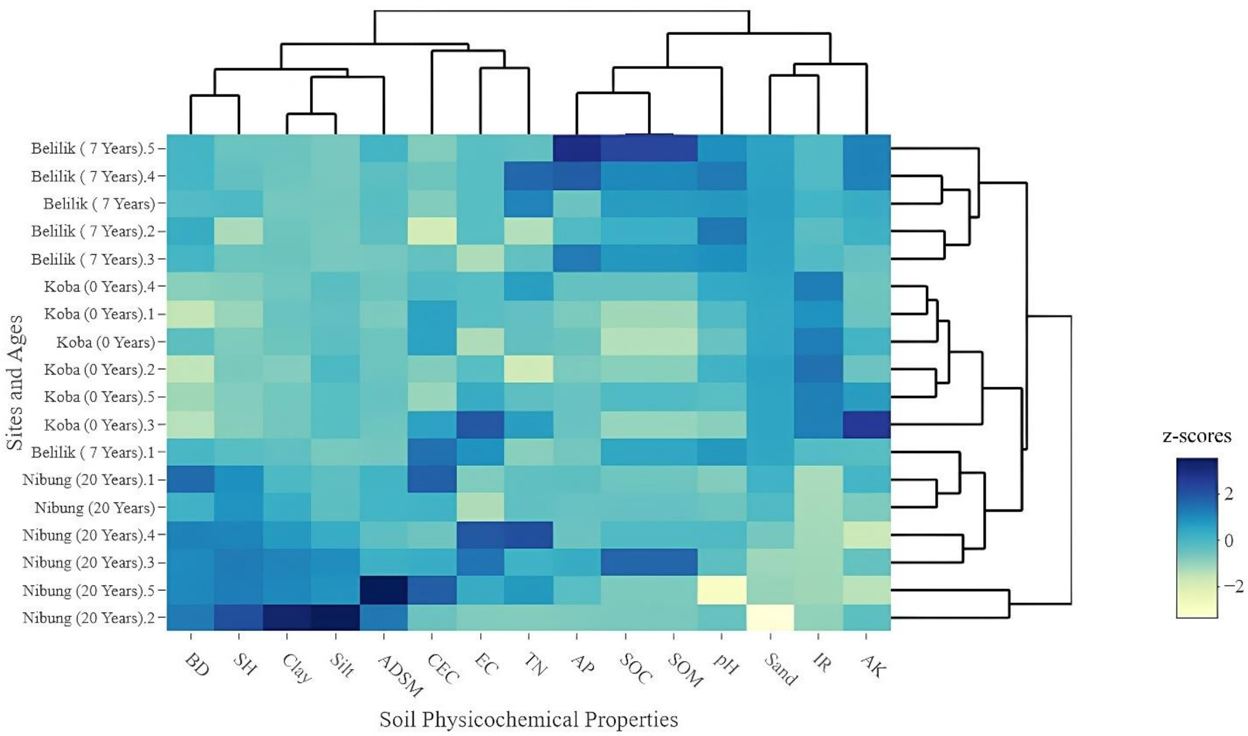

Figure 3. Hierarchical Clustering Analysis (HCA) of soil physicochemical properties in post-tin mining land on Bangka Island

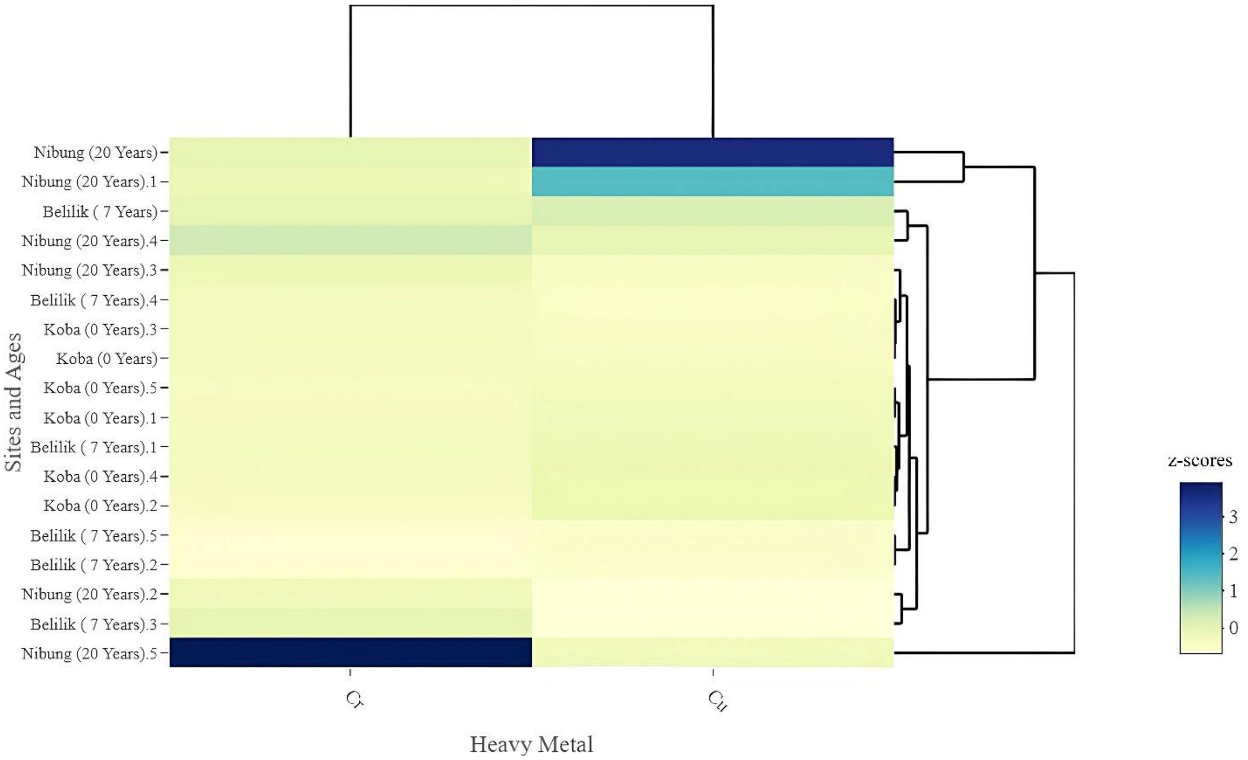

Figure 4. Hierarchical Clustering Analysis (HCA) of heavy metal (Cr and Cu) in post-tin mining land on Bangka Island

3.2.2 Principal Component Analysis (PCA) for key soil property differentiation

The Principal Component Analysis (PCA) biplot (Figure 5) illustrates differences in soil characteristics based on post-mining land age and management. The first two principal components, Dim1 and Dim2, account for 62.5% of the total variance, with contributions of 39.7% and 22.8%, respectively, indicating that site-specific factors strongly influence soil properties.

Dim1 is primarily influenced by Nibung, while Dim2 separates Belilik and Koba, with Belilik positioned in the positive quadrant and Koba in the negative. Koba (0 years) correlates with infiltration rate and sand content, reflecting its coarse texture and high infiltration capacity due to mining disturbances. Belilik (7 years), which underwent reclamation, exhibits higher soil organic carbon, soil organic matter, available phosphorus, and available kalium, indicating improvements in soil chemical quality. Although Nibung (20 years) is the oldest site, it is closely associated with BD, SH, clay, silt, ADSM, CEC, and TN, suggesting significant soil compaction despite having higher CEC and TN. The increase in CEC and TN in Nibung is likely due to the dominance of fine particles (Leinweber et al., 1993), while compaction over time may result from inadequate management, accelerating soil structural degradation, and reducing infiltration (Ngo-Cong et al., 2021). This distribution highlights the effectiveness of reclamation efforts in Belilik, whereas Nibung reflects the long-term negative impacts of poor management. Therefore, targeted rehabilitation is necessary for older post-mining land to restore soil structure and function optimally.

The PCA biplot of heavy metals (Figure 6) reveals that the first two principal components, PC1 (50.8%) and PC2 (49.2%), together explain 100% of the data variation. This indicates that the distribution of heavy metals in the post-mining sites can be fully described by these two components. The analysis considers only Cr and Cu, as Pb and Cd were not detected (Figure 3).

The biplot shows that Nibung (20 years) has a higher PC1 value, indicating a strong correlation with Cr and Cu. In contrast, Koba (0 years) and Belilik (7 years) are positioned near the centre, suggesting lower heavy metal concentrations compared to Nibung. These findings align with the HCA results (Figure 5), which previously highlighted a clear separation between Nibung and the other sites. The results indicate that without optimal management, heavy metals tend to accumulate over time, hindering long-term ecosystem recovery (Zhang et al., 2024).

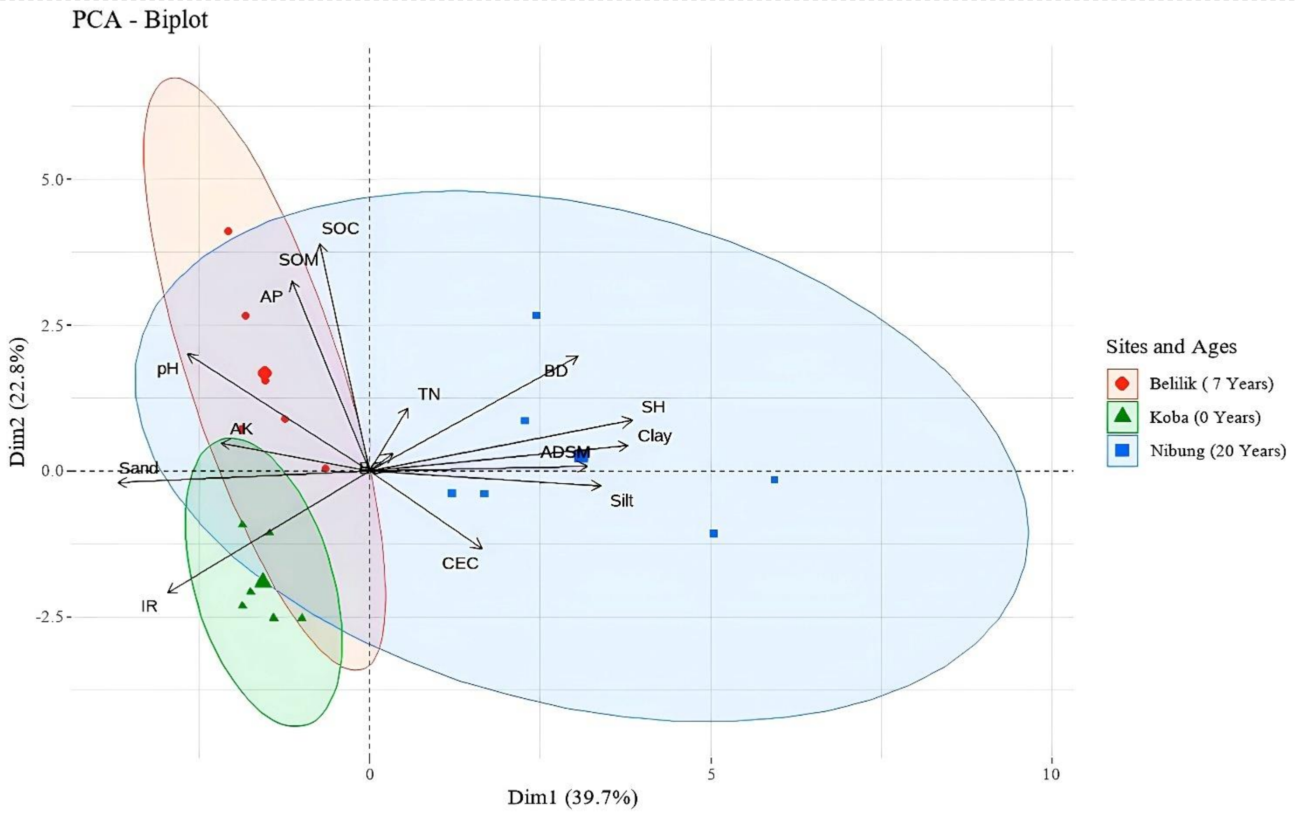

Figure 5. Biplot of Principal Component Analysis (PCA) of soil physicochemical properties in post-tin mining land on Bangka Island

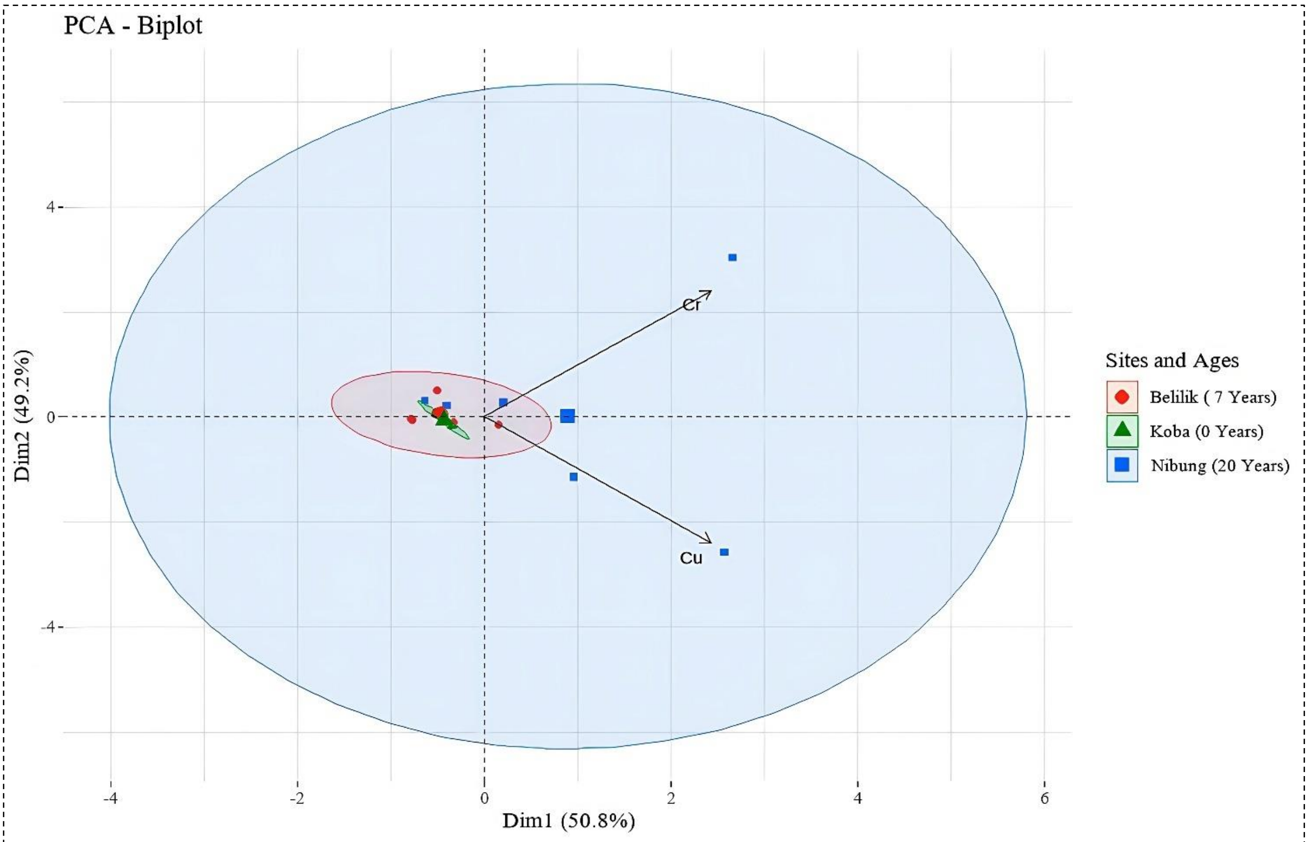

Figure 6. Biplot of Principal Component Analysis (PCA) of heavy metal (Cr and Cu) in post-tin mining land on Bangka Island

3.3 Modeling the influence of post-mining land age and management on soil physicochemical properties and heavy metal accumulation using partial least squares structural equation modeling (PLS-SEM)

The PLS-SEM analysis (Figure 7) indicates that soil physicochemical properties act as mediate in the relationship between land age, management practices, and heavy metal accumulation in post-tin mining sites on Bangka Island. Land age exerts a strong positive influence on soil physical properties (β=0.949), while management practices have a minor negative effect (β=-0.089). Together, these factors explain 84.9% of the variation in physical properties (R^2=0.849). As land age increases, bulk density (BD) (β=0.859) and soil hardness (SH) (β=0.958) rise, contributing to greater soil compaction and reduced root penetration. In contrast, infiltration rate (IR) declines (β=-0.844), elevating the risk of erosion. Textural shifts are also evident, with a decrease in sand content (β=-0.891) and increases in silt (β=0.79) and clay content (β=0.927), resulting in diminished soil aeration. The observed increase in air-dry soil moisture (ADSM) (β=0.738) indicates enhanced moisture retention, which is closely associated with clay accumulation. Overall, aging land tends to develop more compact soils due to organic matter buildup, clay migration, and mineral weathering, as described by Smart and Singer (2023) in their study on mined lands.

Regarding soil chemical properties, post-mining management has a positive influence (β=0.790), whereas land age has a negative effect (β=-0.471), with both factors together explaining 58.9% of the variation (R^2=0.589). Soil chemistry shows a strong positive correlation with SOC and SOM (β=0.861), as well as total nitrogen (TN) (β=0.788), available phosphorus (AP) (β=0.449), and available kalium (AK) (β=0.79). However, long-term recovery is constrained by nutrient leaching and weathering, which are common in post-tin mining sites (Macdonald et al., 2017). Cation exchange capacity exhibits a strong negative relationship (β= -0.624), particularly in Nibung, where high clay content but minimal management reduces nutrient retention efficiency.

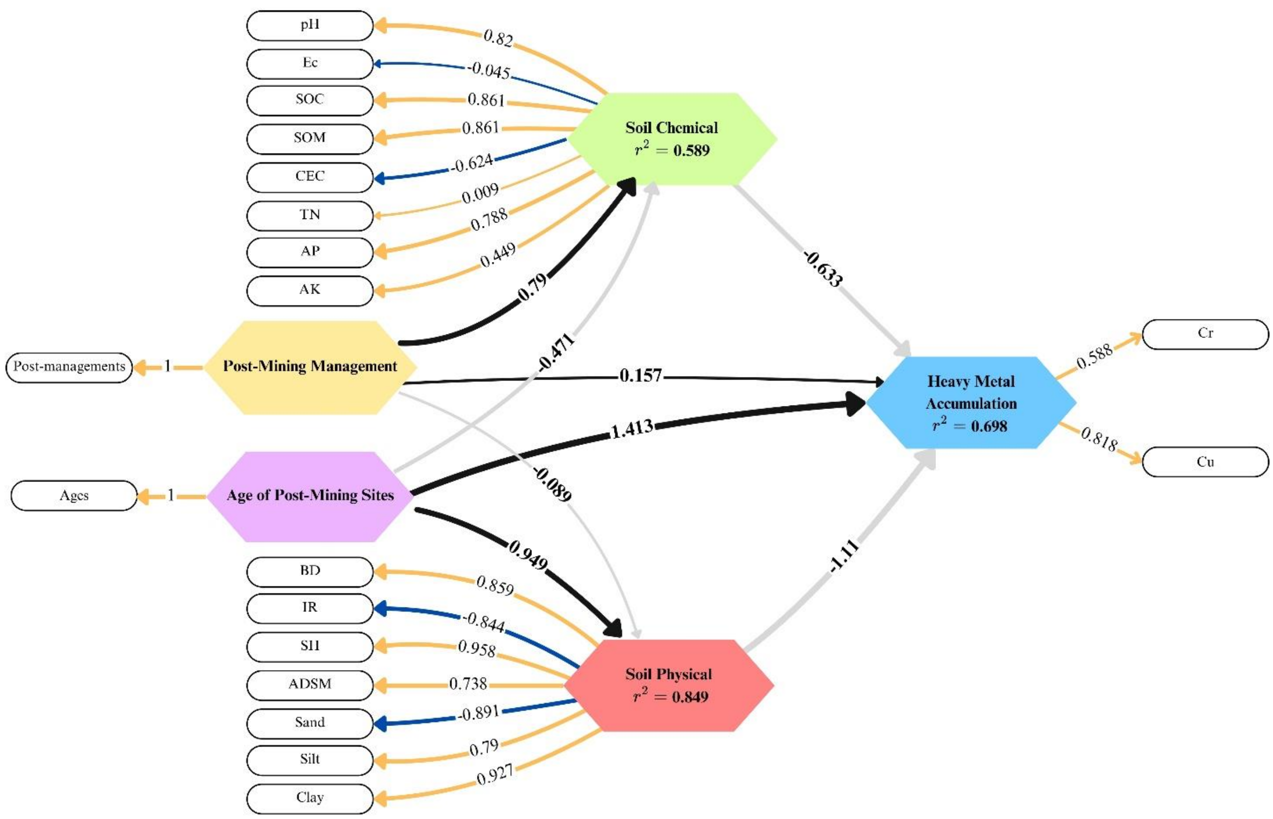

Figure 7. Partial Least Squares Structural Equation Modeling (PLS-SEM) illustrating the structural relationships between post-tin mining age, post-mining management, soil physicochemical properties, and heavy metal accumulation across several post-tin mining sites on Bangka Island

Heavy metal accumulation (R^2=0.698) is primarily driven by land age (β=1.413), with older sites exhibiting higher concentrations, aligning with findings by Zhu et al. (2024). In contrast, post-mining management has a comparatively lower impact (β=0.157). Soil physical (β=-1.110) and chemical properties (β=-0.633) contribute to reducing heavy metal bioavailability, highlighting the role of reclamation in mitigating accumulation impacts (Zhang et al., 2024). Chromium (Cr) (β=0.588) and Copper (Cu) (β=0.818) show significant accumulation, with Cu emerging as the most dominant element in this study.

4. DISCUSSION

4.1 Influence of post-tin mining age on soil physicochemical properties

As post-tin mining land ages, significant soil compaction occurs, as indicated by increased BD (1.39 → 1.60 g/cm³) and SH (25.88 → 45.38 kg/cm²) over 20 years (Table 3). This compaction reduces porosity, restricts root growth, and impedes vegetation recovery (Shah et al., 2017). Infiltration rate also declines sharply (135.75 → 52.49 cm/h), increasing the erosion risk (Ma et al., 2020). The elevated bulk density (BD) at the Nibung site (20 years post-mining) is primarily due to the accumulation of fine particles, such as clay (14.08%) and silt (5.84%), and reduced sand content (80.08%), as shown in Table 3. This shift in texture, resulting from the absence of reclamation, promotes macropore narrowing and aggregate densification. PLS-SEM analysis confirms a strong positive correlations between land age and clay (β=0.927) and silt (β=0.790) fractions. These changes enhance natural compaction and restrict infiltration, consistent with the observed decline in water movement at Nibung (Putra et al., 2024; Zhang et al., 2019; Huang et al., 2020).

The Principal Component Analysis (PCA) (Figure 6) further highlights a shift in soil texture towards finer particles, increasing compaction and reducing drainage, thus elevating the risk of waterlogging (Elkady et al., 2017). PLS-SEM (Figure 7) also shows that land age strongly influences physical properties (BD, SH, ADSM, Clay, and Silt), while its effect on chemical properties is negative. This is reflected in Table 4, where SOC, SOM, pH, and AP initially improve at year 7 (Belilik) but decline by year 20 (Nibung). Although CEC increases with clay content, it fails to enhance nutrient availability due to low organic matter (Rahayu et al., 2023b). Compaction further suppresses microbial activity and nutrient cycling (Longepierre et al., 2022), indicating that without active management, older post-tin mining soils continue to degrade.

These findings align with Putra et al. (2024), who reported increased compaction and reduced infiltration in aging post-tin mining soils in Belitung. However, unlike their study, which found slight increases in organic carbon, our results suggest that land age alone has limited influence on chemical recovery. This is consistent with Oktavia et al. (2014), who observed rising clay content and CEC in older tin mining lands in East Belitung, but not necessarily an improved fertility.

4.2 The role of post-tin mining management in restoring soil physicochemical properties

Post-tin mining land management plays a crucial role in improving soil chemical properties and accelerating ecosystem recovery. This study shows that active reclamation, as implemented in Belilik (7 years), significantly improves soil chemical quality compared to Nibung (20 years), which lacks consistent management, and Koba (0 years), which remains in an early post-mining state (Table 4). Reclamation through organic matter application and revegetation enhances soil carbon content, supporting nutrient retention and microbial activity (Beillouin et al., 2023). In contrast, Nibung suffers from nutrient and organic matter depletion due to minimal intervention, despite its older age, a pattern consistent with findings by Wang et al. (2021), who reported substantial nutrient loss in unmanaged post-mining soils.

Multivariate analyses reinforce these observations. HCA (Figure 3) groups Belilik with more fertile soils, while Nibung is associated with compact, nutrient-poor profiles, and Koba with sandy, highly permeable soils. PCA (Figure 5) further links Belilik to key chemical indicators (SOC, SOM, AP), whereas Nibung aligns with high bulk density and low infiltration. PLS-SEM (Figure 7) confirms that reclamation significantly improves soil chemical properties (β=0.790), with SOC and SOM being the most influential factors (β=0.861), although it has a limited effect on alleviating compaction (β=-0.089). These results align with Li et al. (2021), who found that organic matter-based reclamation enhances nutrient availability and microbial diversity. Similarly, Guan et al. (2020) reported that reclaimed grasslands exhibit higher phosphorus availability, a trend also observed in Belilik, where dense grass cover likely contributed to elevated AP levels (Table 4). However, despite this improvement, AP remains low, reflecting the legacy of intensive tin mining, which involved methods that intensified the leaching of macro and micronutrients from the soil, an effect that persists on the landscape despite subsequent reclamation efforts (Wulandari et al., 2022).

Overall, these findings confirm that natural recovery based solely on land age is insufficient to restore soil chemical quality. Instead, active post-mining management, particularly through organic amendments and revegetation, is more effective in achieving sustainable soil improvement. This conclusion is supported by Nyenda et al. (2021), who found that changes in soil properties do not consistently correlate with land age, and by König et al. (2023), who emphasized that active reclamation is more effective than passive recovery, especially in severely degraded tailing zones.

4.3 Comparison of soil physicochemical properties in post-tin mining and non-mining lands

Soils in post-tin mining sites investigated in this study exhibit significant differences compared to non-mined soils, both in physical and chemical properties. Wulandari et al. (2022) reported that natural forest and agroforestry soils possess more stable textures, with sand contents of 61.97% and 67.67%, SOC levels of 2.25% and 2.35%, and CEC values of 11.18 and 10.34 meq/100 g, respectively. In contrast, the post-mining soils examined in this study are highly degraded, characterised by elevated sand content (80-97%), low SOC (0.24-0.45%), and CEC values ranging from only 2.5 to 2.79 meq/100 g. Rachman et al. (2019) also reported BD values of 1.23 and 1.27 g/cm³ for natural forest and agricultural land, respectively, substantially lower than those of post-tin mining soils, which ranged from 1.39 to 1.60 g/cm³. Although the Belilik site has undergone more optimal reclamation efforts compared to other locations we studied, these data indicate that post-tin mining soil remains inherently infertile and requires intensive and sustainable management to restore stable and productive soil conditions.

4.4 Heavy metal accumulation and environmental risks in post-tin mining land

Analysis of heavy metal distribution (Figure 3) shows that Cr and Cu were detected at all sites, with the highest concentrations in Nibung (20 years), likely due to its clay-rich, compacted soils and low infiltration, which limit metal mobility (Yan et al., 2017). In contrast, Pb and Cd were not detected, suggesting natural attenuation, consistent with previous findings on post-tin mining lands (Putra et al., 2024; Anda et al., 2022; Oorts et al., 2021). This may result in heavy metal concentrations declining naturally from leaching into former mining ponds (Mulligan and Javid, 2021), as observed by Saputra et al. (2023), who reported elevated Pb and Cd levels in pond sediments at Nibung. A similar process may have occurred in Koba and Belilik, given their comparable climatic conditions.

Lower Cr and Cu levels in Belilik (7 years) indicate that reclamation can effectively suppress heavy metal accumulation (Anda et al., 2022). PCA (Figure 7) and HCA (Figure 5) further show that Nibung forms a distinct cluster, reinforcing the role of land age in metal retention. Older soils with finer textures and higher bulk density tend to adsorb more metals while limiting leaching (Huang et al., 2020; Chileshe et al., 2020). Additionally, lower pH in Nibung enhances Cr retention (Zhang et al., 2023), while Cu is more closely associated with organic carbon fractions (Akbarpour et al., 2021). The absence of vegetation also limits phyto uptake and microbial degradation of metals (Sari et al., 2016).

PLS-SEM (Figure 7) confirms that land age is the dominant factor influencing heavy metal accumulation, while management plays a lesser role. Soil physicochemical properties contribute to metal stabilization, with Cu emerging as the most dominant element. These results align with Dusengemungu et al. (2022), who found that older, unmanaged post-mining sites tend to retain more heavy metals due to poor infiltration and low organic matter.

In summary, unmanaged older sites like Nibung are more prone to heavy metal retention, highlighting the need for targeted reclamation to stabilize contaminants. Although Cr and Cu levels remain within permissible limits (Table 5), Cr poses a potential long-term risk if left unaddressed (Jiang et al., 2023; Zulfiqar et al., 2023). Sampling in this study was conducted in August. Therefore, it is important to acknowledge that seasonal variations may influence the mobility of heavy metals such as Pb and Cd. Future studies involving repeated seasonal sampling are recommended to provide a more comprehensive understanding of Pb and Cd behavior in post-tin mining landscapes, particularly to verify the proposed leaching mechanisms.

Table 5. Permissible limits of heahay metals in soil

Elements	Cd (Cadmium)	Cr (Chromium)	Cu (Copper)	Pb (Lead)	Source
Normal limits of soil (mg/kg)	0.01-2.0	5-1,500	2-250	2-300	Alloway, (1995), BPSI, (2023)
Critical limit of soil (mg/kg)	3-8	75-100	60-125	100-400	

4.5 Phased reclamation strategy and sustainable management of post-tin mining land

Sustainable post-mining land use requires reclamation strategies tailored to site-specific conditions. The findings indicate that as land ages, it tends to undergo compaction and a decline in soil chemical quality, whereas post-tin mining management can mitigate these effects. Heavy metal accumulation is higher in older sites, necessitating efforts to reduce metal mobility through amelioration, revegetation, and microbial assistance (Agrawal et al., 2024).

All three study sites require remediation before being repurposed for agriculture, despite Pb and Cr concentrations remaining within permissible limits. To meet regulatory thresholds and ensure long-term soil productivity, heavy metal concentrations must be further reduced. Among the sites, Belilik shows the greatest potential for agricultural use due to its improved chemical properties following reclamation, although further enrichment with organic matter is still needed. In contrast, Nibung, characterised by severe compaction and inconsistent management, is more suitable for forestry or conservation purposes, though its current use as a tourism site can be maintained with continued ecological restoration. Koba, being recently mined and unmanaged, requires comprehensive rehabilitation before any productive use is possible.

Soil improvement across these sites can be effectively achieved through organic-based amendments such as compost and biochar. These materials enhance soil aeration, water retention, and nutrient availability, while also stabilizing heavy metals through adsorption and organo-metal complex formation (Tang et al., 2020). In parallel, revegetation plays a critical role in restoring soil structure and biological function. Deep-rooted species such as *Acacia mangium*, *Schima wallichii*, and *Albizia falcata* are effective in alleviating compaction, while shallow-rooted species like *Imperata cylindrica*, *Panicum maximum*, *Melastoma malabathricum*, and *Paspalum vaginatum* contribute to organic matter accumulation and soil aggregation (Bohrer et al., 2017; Cao et al., 2023; Rahayu et al., 2023a; Sari et al., 2023). Grassland revegetation, as demonstrated by Buta et al. (2019), has also been shown to enhance microbial activity, increase SOC, and reduce compaction, an approach that has proven effective in Belilik and could be replicated in Nibung and Koba.

To ensure long-term success, a phased reclamation strategy with measurable benchmarks is essential. In the initial 0-3 years, intensive interventions such as high-dose organic amendments (≥50 ton/ha), microbial inoculation, and pioneer vegetation should be applied to stabilize bulk density, reduce heavy metal concentrations, and raise SOC above 1%, a critical threshold in tropical soils (Lal, 2004). The 3-7 year phase should continue these efforts to achieve SOC>2% to enhance soil structure, water retention, and CEC (Patrick et al., 2013). Long-term management (10-20 years) should aim to increase and maintain SOC>2.5% and ensure heavy metals remain at safe levels (Haghighizadeh et al., 2024). This framework offers practical guidance for sustainable reclamation of post-tin mining landscapes.

5. CONCLUSION

This study demonstrates that the interaction between post-mining land age and management practices significantly influences soil physicochemical properties and heavy metal retention. As land age increases, soil compaction intensifies, with bulk density rising from 1.39±0.05 g/cm³ (0 years) to 1.60±0.05 g/cm³ (20 years) and infiltration rate declining from 135.75±9.13 cm/h to 25.26±4.79 cm/h, exacerbating soil structural degradation. A seven-year reclamation period has been proven to enhance soil chemical quality by increasing SOC, SOM, and AP, whereas older unmanaged land exhibits declines in soil quality. The accumulation of Cr (45.64-49.58 mg/kg) and Cu (1.76-4.55 mg/kg) is higher in 20-year-old land, with PLS-SEM analysis revealing that land age exerts a dominant influence on heavy metal accumulation (β=1.413), whereas post-mining management has a comparatively smaller impact (β=0.157). The deterioration of soil physical properties, including increased bulk density (β=0.859) and soil hardness (β=0.958), further exacerbates heavy metal retention. Overall, these findings highlight that while natural processes contribute to increased compaction and heavy metal accumulation, effective reclamation interventions, such as organic matter amendments and revegetation, are crucial in improving soil quality and mitigating heavy metal contamination risks, underscoring the necessity of active management strategies to restore ecosystem function in post-tin mining lands.

ACKNOWLEDGEMENTS

This research was conducted with funding support from BIMA, provided by the Ministry of Education, Culture, Research and Technology of the Republic of Indonesia with Contract Letter Number: 086/E5/ PG.02.00.PL/2024 for the 2024 fiscal year. We would also like to thank the Central Bangka Regency Government and the Regional Development Planning and Research Agency of Kepulauan Bangka Belitung Province for granting permission to conduct regional research.

AUTHOR CONTRIBUTIONS

Farhan Erdaswin led the conceptual design, methodology, software development, formal analysis, investigation, data curation, draft writing, and visualization. Rahayu, Retno Rosariastuti, and Widyatmani Sih Dewi contributed to conceptualization, methodology, validation, supervision, manuscript review, and data curation. Aktavia Herawati assisted with validation and formal analysis, while Nurul Ichsan focused on investigation. Fatimah and Widyatmani provided resources, with additional visualisation support from Fatimah. All authors were involved in funding acquisition.

DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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