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Soil Characteristics in Post-Mining Reclamation Zones of a Clay Mine PT Solusi Bangun Indonesia Tbk Cilacap

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ABSTRACT

Former clay mining areas often face soil degradation that makes it difficult for vegetation to thrive, even after reclamation. This study explores the physical and chemical characteristics of soil in the reclaimed land of PT Solusi Bangun Indonesia Tbk in Cilacap, aiming to understand how effective the rehabilitation efforts have been Soil samples were collected from six sites selected based on variation in vegetation cover and topographic elevation. Analyses included pH, moisture content, temperature, specific gravity, porosity, and concentrations of macronutrients (K, Ca, Mg) and heavy metals (Cr, Zr, Sr, Cd, Pb, Ag, As) using X-Ray Fluorescence (XRF). The results showed that soil pH ranged from 6.1 to 7.1, with moisture content varying between 32.78% and 55.60%. Most samples exhibited adequate levels of macronutrients. However, elevated concentrations of cadmium and silver exceeded the recommended thresholds, indicating a potential environmental risk that requires further monitoring and management. Therefore, soil amendments such as liming and organic matter application are recommended to reduce metal bioavailability and improve fertility. This study underlines the importance of integrated reclamation strategies to ensure long-term soil and ecosystem health.

1. INTRODUCTION

Soil plays a vital role in the ecosystem that has an important role in supporting human life and other living things (Hardjowigeno, 1995). In addition to supporting plant growth, soil functions as a natural reservoir for water and nutrients, underpinning terrestrial ecosystem health. However, intensive human activities, especially mining, can severely degrade soil quality—physically, chemically, and biologically. In clay mining operations, the extraction process often disrupts soil structure, reduces organic matter content, and leads to nutrient imbalance and contamination, all of which can hinder land recovery (Nomicisio et al., 2023).

The extensive practice of clay mining in Indonesia, driven by the demand for raw materials in the cement industry, precipitates significant land degradation, especially within the susceptible tropical ecosystems characterized by intense rainfall, accelerating erosion, and nutrient depletion (Thalib, Kurniawan, Aliansa, & Maulani, 2020). The environmental consequences of this exploitation necessitate a comprehensive understanding of soil rehabilitation efforts to foster sustainable land management and ecological restoration (Nurcholis, Wijayani, & Widodo, 2013). Although government regulations mandate reclamation initiatives, the actual effectiveness of soil rehabilitation in regions affected by clay mining, especially those dominated by clay soils, shows inconsistent results and requires more research (Absori et al., 2021). Understanding the post-reclamation condition of soils—especially in clay-dominated terrains—is essential for guiding sustainable land management and ecological restoration. The legacy of mining operations frequently leaves behind soils

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characterized by structural instability, nutrient depletion, and, critically, the presence of elevated concentrations of heavy metals, including cadmium, lead, and arsenic (Sarathchandra, Rengel, & Solaiman, 2023). Revegetation, a cornerstone of land reclamation, hinges significantly on the intricate interplay between soil conditions and management practices, determining the trajectory of ecological restoration and long-term sustainability (Mohammed & Denboba, 2020). The objectives of this study are to assess the current physical and chemical properties of the soil, including parameters such as pH, texture, bulk density, porosity, macronutrient levels, and heavy metal concentrations, in reclaimed clay mine areas. This analysis seeks to determine the extent to which these factors reflect the success of land rehabilitation efforts and to identify potential risks to plant health and environmental safety. The findings are intended to inform and support the development of improved soil management strategies for sustainable post-mining land use.

PT Solusi Bangun Indonesia Tbk Cilacap Plant has reclaimed former clay mine land using various methods, including revegetation and conservation-based land management. Clay used in the cement industry is generally rich in aluminium (Al) and silica (Si), derived from clay minerals such as kaolinite ($Al_2Si_2O_5(OH)_4$), illite and montmorillonite (Grim, 2005). This study aims to analyse the physical and chemical characteristics of soil in the post-mining reclamation zones of PT Solusi Bangun Indonesia Tbk, Cilacap. The objective is to assess the extent of soil recovery and identify management strategies that support long-term ecological restoration. By providing site-specific insights, this research contributes to the broader understanding of soil rehabilitation in reclaimed clay mines and supports the development of more targeted, sustainable post-mining land management practices.

This study has several limitations that should be acknowledged. First, the number of sampling points may not capture the full variability of the reclaimed site, especially in areas with complex microtopography (Carlon, Critto, Marcomini, & Nathanail, 2001). Second, while X-ray fluorescence (XRF) provides a rapid assessment of elemental concentrations, it may have limited sensitivity for certain elements at trace levels (Caponetti, Caminiti, Chillura Martino, & Saladino, 2007). Additionally, this research did not analyze soil biological parameters, such as microbial diversity or organic matter composition, which are also critical for evaluating long-term soil health (Bastida, Zsolnay, Hernández, & García, 2008). Future studies should consider integrating biological indicators and temporal monitoring to build a more comprehensive understanding of soil recovery in post-mining landscapes.

2. METHODS

This study was conducted in the clay mine reclamation area managed by PT Solusi Bangun Indonesia Tbk, located in Cilacap, Central Java. Soil sampling was carried out using a stratified approach, considering variations in reclamation age, vegetation type, and topographic conditions. Six sampling points were selected to represent diverse conditions across the reclamation zone. The coordinates and descriptions of each sampling location are presented in Table 1.

Table 1 Soil Sample Coordinates

Sample Code	East longitude	South latitude	Description
SBI_01	109.04489	-7.64781	Durian Block
SBI_02	109.04681	-7.64401	Orange Block
SBI_03	109.048841	-7.642354	Reclamation 2016
SBI_04	109.052158	-7.645519	Reclamation 2022
SBI_05	109.052708	-7.647182	Reclamation 2018
SBI_06	109.046063	-7.648845	Mango Block

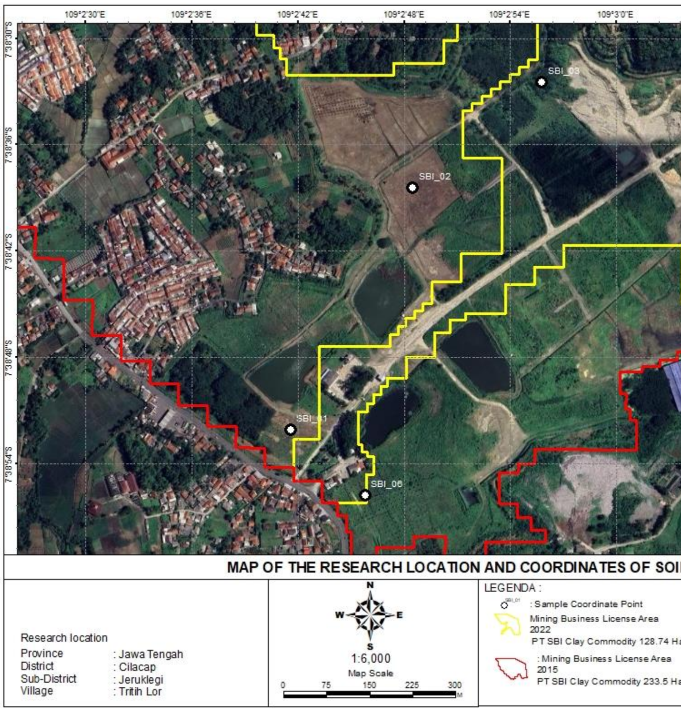

Figure 1 Map of Research Location and Sample Coordinates

Soil Physical Properties Analysis

In soil physical analysis to assess the effectiveness of green area management on reclaimed land, several important parameters are measured to determine the suitability of the soil to support vegetation growth. Soil texture is one of the parameters taken into account, which is the proportion of sand, dust and clay particles in the soil. This affects aeration, water retention and nutrient availability for plants. Texture analysis is carried out using the hydrometer method or triangular texture analysis which shows the classification of soil based on the composition of these particles (Darwis & Sc, 2018).

Furthermore, soil moisture content is a parameter that describes the soil's ability to hold moisture accessible to plant roots. The measurement of moisture content was carried out using the drying oven method, where soil samples were weighed before and after drying at standard temperature for 24 hours. Soil moisture content was calculated using the formula:

$$Moisture\ Content\ (\%) = \frac{W_{wet} - W_{dry}}{W_{dry}} x\ 100$$

Bulk density or dry soil density describes the density of the soil, which plays a role in determining how compacted the soil is and whether it inhibits root growth. High bulk density tends to inhibit water infiltration and reduce air access. Bulk density is measured by the soil ring method, where soil taken in a specific cylinder is dried and then calculated by a formula:

$$Bulk\ Density = \frac{Dry\ Weight\ of\ Soil}{Total\ Volume}$$

Soil permeability indicates the ability of the soil to conduct water, which is very important for regulating drainage and preventing waterlogging or drought. Permeability rates are measured in the field using a permeameter or direct infiltration method which involves measuring the rate at which water falls on the soil surface in a given time.

Soil Chemical Properties Analysis

In the soil chemistry analysis for this study, the main focus was on measuring soil pH, nutrient content (Calcium, Magnesium, Potassium) and heavy metals. Each of these parameters plays an important role in assessing soil quality and fertility, especially in supporting vegetation growth on reclaimed land. Soil pH serves as a master variable, intricately influencing a cascade of chemical and biological processes that dictate the fate and transport of nutrients within the soil matrix, consequently impacting plant health and productivity. The optimal pH range for most plants, typically between 6.5 and 7.5, facilitates the efficient uptake of essential nutrients by maintaining their solubility and availability in the soil solution (Wang, Chi, & Song, 2024).

In addition to pH, the content of macronutrients such as Calcium (Ca), Magnesium (Mg) and Potassium (K) were also analysed as they are essential nutrients for plant growth. In this measurement, XRF was used to detect and measure the concentration of phosphorus and potassium as well as nitrogen.

Figure 2 Sample Preparation for X-Ray Fluorescence (XRF) Analysis

In addition to the main nutrients, this study also evaluated the content of heavy metals such as Lead (Pb), Cadmium (Cd), Silver (Ag), and Arsenic (As) which can be toxic to plants and ecosystems when in high concentrations. High presence of heavy metals also poses risks to human health and environmental quality. The analysis was conducted using the X-Ray Fluorescence (XRF) technique, which enables accurate detection and quantification of elemental concentrations in soil samples.

X-Ray Fluorescence stands as a pivotal analytical technique, grounded in the principles of atomic physics, enabling both qualitative and quantitative elemental analysis of diverse materials (Tsuji, 2019). When X-rays are fired at a sample, the atoms in the material absorb the energy and cause electrons at the inner shell level to escape. These vacancies are then filled by electrons from higher energy levels, resulting in the release of secondary X-rays that have unique characteristics for each element (Oyedotun, 2018). The resulting fluorescence spectra were analysed to identify the elements contained in the sample as well as determine their concentrations.

3. RESULT AND DISCUSSION

Soil Physical Characteristics

The results of the soil physical tests, summarized in Table 2, indicate considerable variation in soil conditions across the six sampling points in the reclamation area. The edaphic environment, specifically soil pH, plays a crucial role in dictating the bioavailability of essential nutrients required for optimal plant development and overall ecosystem health. Soil pH values, which in this study were observed to range from slightly acidic to neutral (6.1 to 7.1), generally indicate favorable conditions for a broad spectrum of plant species (Bosiacki, Kleiber, & Markiewicz, 2014). Soil temperature varied between 30–34 °C, which may influence microbial activity and nutrient mineralization (Antisari et al., 2021).

Table 2 Soil Physical Laboratory Test Results

Sample	**pH**	**Temperature (^{0}C)**	**Moisture Content (%)**	**Specific Gravity**	**Bulk Density (gr/cm2)**	**Saturation (%)**	**Porosity (%)**
SBI_01	7.1	31	32.782	2.383	0.991	67.28	58.419
SBI_02	6.5	33	55.596	2.336	0.993	78.772	57.478
SBI_03	6.4	30	43.785	2.336	1.015	78.901	56.526
SBI_04	6.1	32	40.824	2.368	1.108	68.296	53.224
SBI_05	6.8	32	49.263	2.250	1.509	55.158	32.962
SBI_06	6.2	34	55.043	2.331	1.626	92.016	30.259

Soil moisture content was relatively high at certain locations (e.g., SBI_02 and SBI_06), suggesting good water retention in parts of the reclamation area. Bulk density ranged from 0.99 to 1.63 g/cm^3, a range generally suitable for root growth, though higher values may indicate localized compaction. The interplay between reclamation age, vegetation type, and microtopography significantly molds the development of soil physical properties in restored ecosystems, influencing critical factors such as porosity and saturation (Fan, Song, Zhu, Balzter, & Bai, 2021).

Table 2. Soil Physical Laboratory Test Results presents the parameters in detail and supports the conclusion that while reclamation has promoted soil recovery, targeted soil management is still required to improve uniformity in soil physical conditions.

Soil Chemical Properties

As shown in Table 3, the chemical composition of the soils was dominated by high levels of silica (Si) and aluminium (Al), consistent with the clay-dominated parent material typical of the region. Silica concentrations ranged from 45.7% to 56.9%, suggesting a sandy or silty soil texture, which is generally low in fertility due to reduced cation exchange capacity and poor water-holding capability (Ahmad & Li, 2021).

Table 3 Silica, Aluminium and Macronutrient Content

Sample	Silica (Si) %	Aluminium (Al) %	Potassium (K) %	Calcium (Ca) %	Magnesium (Mg) %
SBI_01	45.7	14.6	1.59	21.8	2.66
SBI_02	54.3	19	1.56	5.94	1.86
SBI_03	55.1	20.2	1.31	2.84	1.88
SBI_04	56.2	19.9	1.69	4.67	2.34
SBI_05	56.9	20.4	1.76	2.79	2.12
SBI_06	56.6	19.7	1.56	4.97	2.09

Macronutrient content, including potassium (K), calcium (Ca), and magnesium (Mg), varied between samples, indicating uneven fertility status across the reclamation area. Higher concentrations of Ca and Mg in some blocks (e.g., SBI_01) may be attributed to longer reclamation time and natural or artificial amendments. The relatively low Ca content at other locations suggests that additional fertilization may be needed to support robust vegetation growth (Arefieva, Nazarkina, Gruschakova, Skurikhina, & Kolycheva, 2019).

These variations reflect different stages of soil formation and nutrient accumulation in post-mining environments and highlight the importance of continued soil monitoring and amendment.

Heavy Metal Content and Environmental Implications

The results of heavy metal analysis are summarized in Table 4, with a regulatory comparison shown in Table 5. Several heavy metals were detected in the soil samples, including chromium (Cr), zirconium (Zr), strontium (Sr), lead (Pb), cadmium (Cd), silver (Ag), and arsenic (As).

Table 4 Heavy Metal Content in Soil Samples

Sample	Chromium (Cr) ppm	Zirconium (Zr) ppm	Strontium (Sr) ppm	Lead (Pb) ppm	Cadmium (Cd) ppm	Silver (Ag) ppm	Arsenic (As) ppm
SBI_01	696	226	663	35,1	ND	18,7	12,9
SBI_02	317	266	416	ND	ND	ND	23,2
SBI_03	322	267	239	48,8	46,8	16,9	ND
SBI_04	279	247	340	48,4	49,4	22,0	ND

SBI_05	324	300	265	47,9	ND	ND	19,3
SBI_06	309	273	341	ND	53,8	18,0	57,3

Although the levels of Pb and As remained below the allowable thresholds as set by the Minister of Health Regulation No. 2 of 2023, both Cd and Ag were detected at concentrations exceeding these environmental safety limits . Notably, Cd was present in three out of six samples above the 3 ppm threshold, while Ag surpassed the 10 ppm threshold in multiple locations.

Table 5 Evaluation of Metal Levels in Samples against Environmental Thresholds

Elements	Average Test Results	Threshold	Description
Chromium (Cr)	374.5	-	Not yet available standard
Zirconium (Zr)	263.17	-	Not yet available standard
Strontium (Sr)	377.33	-	Not yet available standard
Lead (Pb)	30.03	≤ 300	Below threshold
Cadmium (Cd)	25	≤ 3	Above threshold
Silver (Ag)	12.6	≤ 10	Above threshold
Arsenic (As)	18.78	≤ 20	Below threshold

These findings are consistent with studies that have identified mining activities as a source of persistent heavy metal contamination, even after reclamation efforts. The elevated levels of Cd are particularly concerning due to its known toxicity and classification as a human carcinogen by the WHO. Similarly, silver in high concentrations has been shown to cause argyria and poses ecotoxicological risks, especially in nanoparticulate form (Cancer, 1993).

Heavy metal content that exceeds thresholds suggests that, despite successful physical reclamation, chemical stabilization of the soil has not been fully achieved. This has direct implications for environmental safety and human health, particularly if the area is used for agriculture or public green space in the future.

The findings of this study underscore the importance of integrating both physical and chemical considerations in post-mining land reclamation. Although the reclaimed soils generally exhibit favorable physical characteristics that can support vegetation growth, the presence of heavy metals such as cadmium (Cd) and silver (Ag) above regulatory thresholds highlights ongoing environmental concerns. These metals, known for their toxicity and persistence, can pose risks to both plant and human health if not properly managed. Therefore, reclamation strategies should not only focus on restoring soil structure but also on improving soil chemical quality through targeted interventions. Liming can be employed to raise soil pH and reduce metal solubility, while the addition of organic matter—such as compost or biochar—can enhance the soil's capacity to immobilize heavy metals and improve overall fertility. Phytoremediation, using specific plant species capable of accumulating heavy metals, offers a natural and sustainable remediation approach. Regular soil monitoring is also essential to track changes in heavy metal concentrations and evaluate the effectiveness of mitigation efforts. Collectively, these strategies are critical to ensuring that reclaimed lands are not only physically stable but also chemically safe for long-term ecological function and human use.

4. CONCLUSION

This study underscores the complexity of soil recovery in post-mining landscapes, with specific reference to the reclaimed clay mining zones of PT Solusi Bangun Indonesia Tbk in Cilacap. While physical indicators such as pH (6.1–7.1), temperature (30–34°C), and moisture content (32.78%–55.60%) fall within acceptable ranges for vegetation growth, variations across sites suggest that soil recovery remains uneven. Some areas show promising signs of fertility, marked by adequate macronutrient levels—

especially potassium and calcium—while others continue to face challenges such as compaction, low porosity, or chemical imbalances.

Of greater concern is the presence of cadmium and silver in concentrations that exceed environmental safety thresholds. These findings reveal that while reclamation efforts have improved basic soil conditions, they have not fully addressed the lingering threat of heavy metal contamination. This has direct implications not only for plant health but also for the safety of ecosystems and potential human use, especially if the land is intended for agriculture or community green space.

On a practical level, the study emphasizes the importance of incorporating more holistic and adaptive strategies into reclamation planning. The application of liming agents serves to elevate the pH of acidic soils, thereby mitigating the solubility and bioavailability of heavy metals, while the introduction of organic amendments, such as compost or biochar, enhances soil structure, water retention capacity, and nutrient availability, fostering a more conducive environment for plant establishment and microbial activity (Courtney & Pietrzykowski, 2018). Beyond technical measures, consistent soil monitoring and community engagement will be crucial to ensure that restored landscapes remain productive, safe, and ecologically resilient.

Future research should consider expanding the spatial scope of soil sampling to better capture variability across different parts of the reclamation zone. Long-term monitoring is also crucial to understand how soil quality evolves over time and how interventions perform in the long run. Additionally, introducing biological indicators—such as microbial activity, organic matter content, and soil enzyme levels—would provide a more complete picture of soil health and ecosystem function. Experimental trials using organic amendments like compost, biochar, or phytoremediating plant species could also help evaluate effective strategies for immobilizing contaminants and enhancing fertility. Finally, researchers should explore the practical applications of reclaimed land by examining its suitability for agriculture, forestry, or public green space. This broader perspective will support the development of more sustainable and multifunctional post-mining landscapes that are both environmentally safe and socially beneficial.

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