ASIAN JOURNAL OF AGRICULTURE
Volume 9, Number 2, December 2025
Pages: 623-628

E-ISSN: 2580-4537
DOI: 10.13057/asianjagric/g090229

Assessment of soil quality changes following land reclamation at the Martabe Gold Mine, South Tapanuli, Indonesia

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Manuscript received: 28 July 2025. Revision accepted: 10 October 2025.

Abstract. *Anwar S, Mansor AB, Haris H, Dharsono M, Lubis A, Wahyudi R, Fathiya N. 2025. Assessment of soil quality changes following land reclamation at the Martabe Gold Mine, South Tapanuli, Indonesia. Asian J Agric 9: 623-628.* Mining at Martabe Gold Mine, South Tapanuli, North Sumatra, Indonesia, caused severe soil degradation, requiring effective reclamation. This study evaluated the recovery of soil chemical properties in reclamation sites aged 3, 6, and 10 years compared with adjacent natural forest. Soil samples were analyzed for pH, organic carbon (C), total nitrogen (N), C/N ratio, available phosphorus (P), exchangeable cations (Ca, Mg, K, Na), and Cation Exchange Capacity (CEC). Results showed age-dependent recovery. The 10 year sites had pH (5.03) closest to forest (4.96), while younger sites remained more acidic (4.80-4.88). Organic C (7.68%) and total N (0.15%) increased with age but were still below forest levels (16.99% and 0.37%). The C/N ratio distinguished recovery stages: 3-6 year sites showed rapid turnover (C/N=5.00-7.33), whereas 10 year sites resembled forest (53.67). Available P peaked at 6 years (21.38 mg/kg) before declining, and exchangeable cations showed variable patterns. CEC peaked in 10 year sites (86.30 cmol/100 g), exceeding forest (49.87 cmol/100 g), indicating improved nutrient retention. Correlation with forest soils was strong (R^2=0.87). These results demonstrate substantial recovery of soil chemical properties within a decade, though long-term organic matter accumulation and balanced nutrient management remain essential for full ecosystem restoration.

Keywords: Martabe Gold Mine, post mining land, soil fertility, soil reclamation

INTRODUCTION

Open-pit mining activities, such as those at the Martabe Gold Mine, South Tapanuli, North Sumatra, Indonesia, have caused notable damage to the environment, particularly concerning soil integrity and plant coverage. Mining causes significant disturbances to soil structure and function, including soil compaction, increased acidity, toxicity, nutrient availability limitations, and soil microbial process imbalances (Feng et al. 2019; Xiao et al. 2019). Additionally, these activities alter the biological communities in the soil, which can disrupt the natural regeneration of ecosystems. In this context, land reclamation is an essential process in efforts to restore ecological integrity and return the ecological functions of soil post-mining (Maiti 2012).

Land reclamation encompasses both physical and chemical-biological enhancement of soils adversely affected by mining. This process includes the management of disturbances in pH, fertility, microbial communities, and nutrient cycling. According to Ledesma et al. (2025), soil quality assessment can be conducted by observing indicators of changes in soil function in response to management practices. Topsoil management, which contains high levels of organic matter and serves as the primary habitat for soil microorganisms, is a critical step in the reclamation process. Topsoil management in mining is often overlooked because of inadequate quantity and quality, insufficient long-term planning and resources, technical difficulties such as soil loss and degradation during stockpiling, and the prevailing view of soil as a waste product rather than a valuable asset. Damage to this layer, such as stripping and piling, causes the loss of carbon and nitrogen sources that are essential for microbial life and vegetation growth (Soewandita 2010).

Post-mining soil structure damage worsens the soil's ability to provide growing space and store water and nutrients for plants. Soil compacted by mining has low porosity, which disrupts aeration and water absorption systems, thereby inhibiting root growth (Sun et al. 2018). This directly impacts vegetation growth, which is the primary indicator of successful reclamation success. Therefore, soil structure restoration is critical for successful revegetation efforts. The use of organic soil amendments, such as manure, wood chips, and other organic wastes, has been proven to enhance microbial activity and improve soil structure and nutrient content, including essential nutrients such as N, P, and K (Zhao et al. 2022; Rodríguez-Berbel et al. 2025).

One of the most effective reclamation strategies is revegetation, which involves replanting various types of plants on former mining sites to restore ecosystem functions. This strategy can increase soil organic matter content, reduce erosion, and create habitats for local flora and fauna (Midor et al. 2021). Revegetation also plays a role in phytoremediation, which is the process of absorbing and reducing heavy metal or toxic compound content in the soil by plants. Therefore, the success of reclamation is not only measured by vegetative land cover but also through the evaluation of plants' ability to improve soil quality and reduce pollutant content (Kalamandeen et al. 2020; Chambi-Legoas et al. 2021). Native species accelerate forest succession, restore biodiversity, and enhance ecological resilience (Gairola et al. 2023).

Evaluating the success of post-mining reclamation is crucial, as the ultimate goal is to restore the ecological function of the soil as closely as possible to its original condition prior to mining. According to SERI (2004), there are three approaches to land restoration: reclamation, rehabilitation, and restoration. This evaluation involves measuring soil fertility, vegetation composition, phytoremediation potential, and the activity of enzymes or soil microorganisms that contribute to environmental stabilization (Cooke and Johnson 2002).

The Martabe Gold Mine, one of the gold exploration and mining sites in North Sumatra, faces significant challenges in managing the environmental impact of its activities. In addition to affecting soil structure and microorganisms, these activities pose risks of water pollution, increased air emissions, and disruption of the hydrogeological system (Nefilinda et al. 2024). Therefore, effective post-mining management must be designed in an integrated manner using an ecosystem-based approach. An ecosystem approach to effective post-mining management refers to landscape-scale planning and multi-trophic recovery integrated into a single, comprehensive strategy. The two components are interdependent, as proper ecosystem recovery requires consideration of the entire affected area and the complex food web within it (Pratiwi et al. 2021). Reclamation strategies must also consider the physical, chemical, and biological characteristics of the soil to ensure long-term success in restoring ecosystem functions (Mao et al. 2024). To achieve sustainable reclamation, it is important to conduct in-depth research on the evaluation of soil quality changes in former gold mine reclamation areas. This study aimed to measure soil fertility levels based on land characteristics and plant age in the restoration area. Thus, the evaluation results can be used as a basis for designing more effective and sustainable restoration strategies to support ecosystem habitat suitability for both flora and fauna, thereby approaching their natural environmental conditions.

This study quantitatively assessed the recovery of soil fertility in gold mine reclamation sites of varying ages (3-4, 6-7, and 10-11 years) through a comparative analysis of soil properties, including pH, CEC, macronutrients, and organic carbon dynamics, against adjacent natural forest soils, while collecting critical soil quality indicators such as organic carbon content, total nitrogen, C/N ratio, available phosphorus, base cations (Ca, Mg, K, Na), and Cation Exchange Capacity (CEC).

MATERIALS AND METHODS

Study area and duration

This study was conducted from January 2018 to June 2024 within the Martabe Gold Mine reclamation area (South Tapanuli, North Sumatra, Indonesia), an open-pit gold-silver operation exhibiting significant soil degradation. Field sampling targeted reclamation sites of different planting years to assess soil properties and heavy-metal content in vegetationas showed on Figure 1.

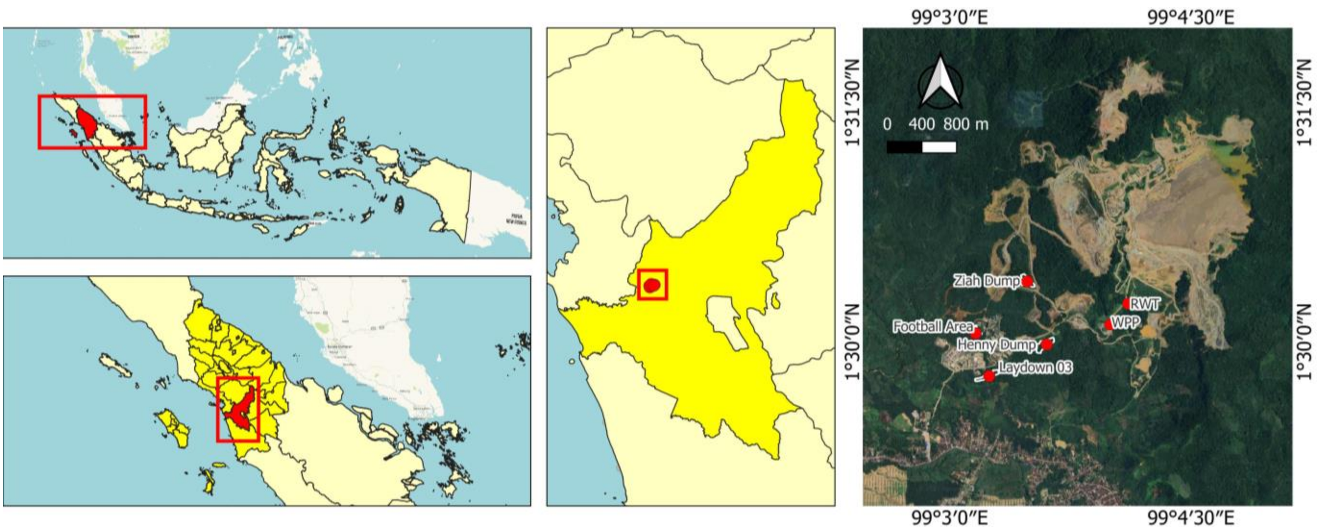

Figure 1. Map of soil sampling location of the Martabe Gold Mine in South Tapanuli, North Sumatra, Indonesia

Field equipment and sampling design

Field equipment included a Global Positioning System (GPS), soil auger/drill, ring sampler, measuring tape, stainless steel knife, digital camera, sample labels, and standard field supplies. Soil samples were collected in clean plastic bags, transported in insulated containers (styrofoam) to preserve sample integrity, and clearly labelled to maintain chain of custody. Reagents used for laboratory digestion and chemical analyses included nitric acid (HNO_3) and perchloric acid ($HClO_4$); analyses were performed at the Integrated Laboratory of Institut Pertanian Bogor (IPB), West Java, Indonesia.

At each reclamation site, seven observation clusters were selected according to the year of planting. Within each cluster five random sampling points were established. Soil from the five points in a cluster was homogenized to form a single composite sample (≈1 kg) representing that cluster. Composite samples were collected from the 0-20 cm depth. All samples were labelled in the field, stored under controlled conditions during transport, and processed on arrival at the laboratory.

Laboratory analysis

Soil chemical analysis were carried out at the Integrated Laboratory of IPB and Soil Laboratory SEAMEO Biotrop. Soil pH was measured in a 1:5 soil-to-water suspension using an electrometric pH meter (Kusuma and Yanti 2021). Available phosphorus was analyzed by the Olsen method with sodium bicarbonate extraction and spectrophotometric measurement (Eviati and Sulaeman 2009). Exchangeable potassium was extracted with 1 M NH_4-acetate (pH 7) and quantified using an Atomic Absorption Spectrophotometer (AAS). Total nitrogen was determined by the Kjeldahl method, involving acid digestion followed by titration (Wiyantoko et al. 2017), while organic carbon was measured by the Walkley and Black method through potassium dichromate oxidation (Bahadori and Tofighi 2016). Exchangeable base cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were assessed according to the USDA Soil Survey Laboratory Methods Manual (Burt 2004), using 1 N ammonium acetate (pH 7.0) as the extractant and quantified by AAS or titration (for Ca and Mg) (Eviati and Sulaeman 2009).

Data processing and statistical analysis

Laboratory results were tabulated and initially explored through descriptive statistics. Initially, descriptive statistics summarized soil properties across reclamation age groups and the natural forest reference site. Inferential analyses included correlation tests (Minitab 19) to evaluate relationships between paired variables. Correlation coefficients were interpreted as follows: positive values indicate that increases in one variable are associated with increases in the other, whereas negative values indicate an inverse relationship. Statistical significance criteria and any transformations applied to meet test assumptions are described in the results.

Soil fertility was evaluated by comparative descriptive analysis between natural forest reference sites and post-mining lands at different recovery stages (stratified by planting year). Results were presented spatially and as summary tables to facilitate interpretation of reclamation progress.

RESULTS AND DISCUSSION

Soil properties across the gold mine reclamation ages

In general, the results of descriptive observations show that there are striking differences in several soil quality parameters between natural forests and reclaimed lands with various levels of recovery age, as shown in Table 1.

Soil acidity (pH)

Oil on reclaimed land was generally more acidic than soil from the natural forest reference. The mean pH in the natural forest was 4.96, while reclaimed plots showed lower pH values: 10-year reclaimed sites = 5.03 (closest to reference), 6-year = 4.80, and 3-year = 4.88. Meanwhile, younger reclaimed land (6 and 3 years old) showed lower pH values of 4.80 and 4.88, respectively. According to Tang (2025), after 11 years, soil quality (pH, moisture, and organic matter) improved significantly and approached or exceeded that of natural soil. This suggests that the initial reclamation process may not have completely neutralized the acidic conditions often arising from mining activities.

Table 1. Soil chemical properties across reclamation ages compared to natural forest

Soil quality parameters	Years after reclamation			Natural forest
	10-years	6-years	3-years	
pH	5.03	4.80	4.88	4.96
C Org (%)	7.68	0.24	0.42	16.99
N Total (%)	0.15	0.03	0.08	0.37
C/N ratio	53.67	7.33	5.00	54.74
P Available (mg/kg)	10.50	21.38	14.55	8.28
Ca (cmol/100 gr)	3.16	3.34	13.48	3.53
Mg (cmol/100 gr)	3.83	2.15	25.62	0.18
K (cmol/kg)	0.07	0.30	1.33	0.28
Na (cmol/100 gr)	0.02	1.56	0.86	0.16
CEC (cmol/100 gr)	86.30	22.30	16.96	49.87

Organic matter and nitrogen content

The most significant differences were seen in the organic carbon and total nitrogen content. Natural forest soils contained substantially higher organic carbon (16.99%) and total nitrogen (0.37%) than all reclaimed age classes. Reclaimed sites showed much lower organic matter even after ten years (10-year = 7.68% organic C). This indicates that even after a decade, soil organic matter inputs from litter and root turnover remain insufficient for restoring natural levels. Total N followed a similar pattern: lowest in the 6-year reclaimed land (0.03%) and highest among reclaimed sites in the 10-year plots (0.15%), but still well below the natural forest reference.

Carbon to nitrogen ratio (C/N ratio)

The C/N ratio indicates the rate of organic matter decomposition and nutrient availability. The natural forest and 10-year-old reclaimed land showed relatively high and similar C/N ratios (approximately 54), which are generally associated with slower rates of decomposition and the potential for nitrogen immobilization. In contrast, the younger reclaimed sites (6-year and 3-year) displayed much lower C:N ratios (7.33 and 5.00, respectively), consistent with more rapid decomposition and greater potential for mineralization at early reclamation stages.

Phosphorus availability (P available)

The highest phosphorus availability was found in the 6-year reclaimed land (21.38 mg kg^{-1}), followed by 3-year (14.55 mg kg^{-1}), 10-year (10.50 mg kg^{-1}), and the lowest in the natural forest (8.28 mg kg^{-1}). The high phosphorus levels in young reclaimed land may be related to early fertilization practices during the reclamation process.

Base cations (Ca, Mg, K, and Na)

The content of base cations showed complex dynamics. The reclaimed 3-year-old land had very high calcium (13.48 cmol/100 g) and magnesium (25.62 cmol/100 g) contents compared to the other conditions. Meanwhile, the 6-year-old reclaimed land stood out with its high sodium content (1.56 cmol/100 g). The highest potassium content was also found in the 3-year reclamation land (1.33 cmol/100 g). This variation is likely influenced by the type of parent rock, reclamation practices, and weathering processes at each location.

Cation Exchange Capacity (CEC)

CEC indicates the soil's nutrient retention and provision, and showed the highest value in 10-year-old reclaimed land (86.30 cmol/100 g), followed by natural forest (49.87 cmol/100 g). Younger reclaimed land had lower CEC values (22.30 cmol/100 gr for 6 years and 16.96 cmol/100 gr for 3 years). The increase in CEC with increasing reclamation age is likely related to the increase in organic matter content and the development of the soil structure.

Analysis correlation

The scatterplot comparing a selected soil property between 10-year reclaimed plots and adjacent natural forest, as shown in Figure 2, shows a strong, positive linear relationship. This visualization strongly indicates a significant positive correlation between the two land conditions for the observed properties.

The distribution of data points showed a clear upward linear trend, as illustrated in Figure 2. The relationship was represented by the regression equation $y = 0.67x + 2.5184$, with a coefficient of determination ($R^2 = 0.8718$). This indicates that approximately 87.18% of the variation in the natural forest values can be explained by the values observed in the 10-year reclaimed sites. The corresponding Pearson correlation coefficient ($r = 0.934$) confirmed a very strong positive linear association between the two variables. All values were derived from the actual measured data rather than estimates. These findings support Rashmi et al. (2024) and Jinger et al. (2024) investigations, which highlight the need for prolonged efforts and a multi-pronged approach to restoring soil fertility in a post-mining context, both ecologically and functionally. It is often shown that as reclamation progresses, several soil quality parameters such as organic matter content, nutrient availability, and soil structure gradually approach natural soil conditions. However, it is crucial to remember that several variables, such as the type of mining activity, can affect the pattern and degree of recovery.

Although the correlation is strong, several points of interpretation and caution are warranted. First, correlation does not imply causation; a strong relationship indicates that the two systems vary together, not that one causes the other. Second, the regression slope (0.67) and intercept (2.5184) indicate a systematic offset between the two land types: values in the natural forest increase less steeply with the exact change in the reclaimed sites, and there is a non-zero baseline difference. In practical terms, this suggests that functional similarity is developing, but absolute equivalence has not yet been reached. Studies on organic carbon recovery in post-mining lands often show slow increases and may not fully reach natural forest levels, even after decades. Other parameters, such as pH, may show faster recovery through the application of soil ameliorants, such as lime. In this context, the high correlation observed for the analyzed soil properties (which need to be further identified) could indicate that these specific aspects are relatively responsive to reclamation efforts over 10 years. However, to obtain a more holistic picture of reclamation success, an analysis of other soil properties is essential.

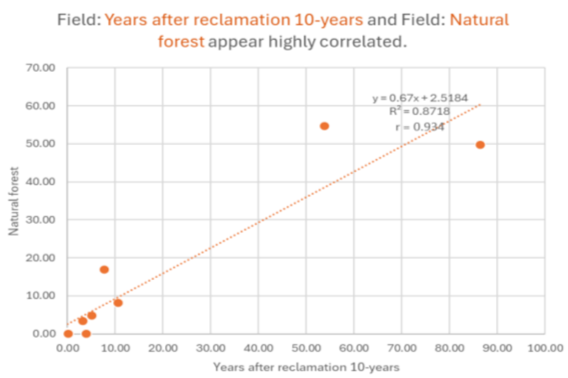

Figure 2. Analysis correlation

Discussion

Soil chemical and physical recovery trajectory

Soil chemical properties in the Martabe reclamation chronosequence indicate partial recovery over time but a clear divergence from adjacent natural forests. Soil pH at 10-year reclaimed plots was close to natural-forest values, while younger sites remained more acidic, which aligns with regional findings showing progressive stabilization of soil chemical properties with increasing revegetation age. For example, restoration studies in phosphate mine landscapes and other mineral extraction sites have documented substantial changes in pH, SOC, and nutrient status over the first 10-40 years, with pH often stabilizing before slower pools, such as total organic carbon, fully recover (Xu et al. 2023). Empirical results from Berau show that SOC stocks increase with revegetation age (up to ~12 years), reinforcing that OC accrual is a central metric of reclamation success in tropical coal landscapes (Hartati and Sudarmadji 2022).

The natural forest and 10-yr reclaimed sites had high C/N (~54), consistent with slower decomposition and a tendency toward N immobilization in litter-dominated systems. In contrast, the younger reclaimed sites (C/N ≈ 5-7) indicated relatively faster organic matter turnover and potential for short-term N mineralization, where labile inputs (e.g., early litter from pioneer species or applied amendments) dominate. The available phosphorus and base cation trends in the Martabe plots appear to be shaped by both management (fertilization or amendment history) and parent/substrate effects. Elevated available P in the 3- and 6-yr plots relative to the forest and 10-yr sites likely reflects early fertilization or surface amendments commonly applied during reclamation. Conversely, the variable Ca, Mg, K, and Na concentrations across ages point to local substrate/mineralogy and management differences rather than a simple time since reclamation effect. This mechanistic interpretation aligns with revegetation chronosequence studies work in East Kalimantan which shows linear increases in organic C, total N and available P and logarithmic decreases in bulk density with time since revegetation, demonstrating vegetation is a primary driver of early soil recovery in tropical mine substrates (Iskandar et al. 2022)

Vegetation succession and management implications

The structure of seedlings, stakes, poles, and trees is formed through a combination of planted species and other naturally growing species. According to Aili et al. (2025), revegetation and land improvement are effective when reclamation is carried out in a planned, ecological manner. Complete restoration can take 10 years or longer. Woody plant species consist of cultivated species, natural species resulting from the natural regeneration of planted plants (natural plant regeneration), and naturally growing species resulting from succession (natural plant succession). The study found 46 species over 10 years, spread across various strata (trees, poles, saplings, and seedlings).

These findings necessitate targeted management, such as accelerating organic matter accrual through stable amendments (e.g., composts and legume covers), as demonstrated in Bangka Island tin tailings remediation (Maftukhah et al. 2023), mitigating acidity via strategic liming, and monitoring nutrients to avoid masking organic deficits by fertilization effects. Species selection should prioritize mixed communities that have been proven to enhance carbon sequestration (Zhang et al. 2020) and leverage grass-based phytostabilization for metal immobilization, as validated in Philippine copper tailings (delos Angeles and Cuevas 2018).

In conclusion, the pH of the reclaimed land was close to that of natural forests but still below that of natural forests. This also applies to organic matter and nitrogen, which are still far below those levels found in natural forests. Phosphorus, calcium, magnesium, potassium, sodium, and CEC levels are close to those found in natural forests, and some even exceed those found in natural forests due to fertilization. Future efforts should prioritize organic amendments, acidity mitigation, and diverse revegetation to accelerate full functional restoration.

ACKNOWLEDGEMENTS

The authors thank the General Manager Operations of PT Agincourt Resources Martabe Gold Mine, North Sumatra, Indonesia, for allowing this research to be conducted in the Company's operational area, and all the team in the Rehabilitation Subsection, who assisted in collecting field data.

REFERENCES

Aili A, Zhang Y, Lin T, Xu H, Waheed A, Zhao W, Kuerban A, Liu K, Dou H. 2025. Optimizing vegetation restoration: A comprehensive index system for reclaiming abandoned mining areas in arid regions of China. Biology 14 (1): 23. DOI: 10.3390/biology14010023.

Bahadori M, Tofighi H. 2016. A modified Walkley-Black method based on spectrophotometric procedure. Commun Soil Sci Plant Anal 47 (2): 213-220. DOI: 10.1080/00103624.2015.1118118.

Burt R. 2004. Soil survey laboratory methods manual (Soil Survey Investigations Report No. 42, Version 4.0). USDA Natural Resources Conservation Service. https://www.govinfo.gov/content/pkg/GOVPUB-A57-PURL-gpo93947/pdf/GOVPUB-A57-PURL-gpo93947.pdf

Chambi-Legoas R, Ortega Rodriguez DR, de Marques de Figueiredo F, Valdeiglesias JP, Pollito PAZ, Marcelo-Peña JL, Rother DC. 2021. Natural regeneration after gold mining in the Peruvian Amazon: Implications for restoration of tropical forests. Front For Glob Change 4: 594627. DOI: 10.3389/ffgc.2021.594627.

Cooke JA, Johnson MS. 2002. Ecological restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. Environ Rev 10 (1): 41-71. DOI: 10.1139/a01-014.

delos Angeles MD, Cuevas VC. 2018. Phytoremediation potential of Paspalum conjugatum and the role of compost amendment in rehabilitation of soil materials from high copper-containing mine tailings ponds. Philipp Agric Sci 101 (2): 206-215. DOI: 10.62550/MA206215.

Eviati E, Sulaeman S. 2009. Technical Guidelines: Chemical Analysis of Soil, Plants, Water, and Fertilizers. Soil Research Institute, Bogor.

Feng Y, Wang J, Bai Z, Reading L. 2019. Effects of surface coal mining and land reclamation on soil properties: A review. Earth-Sci Rev 191: 12-25. DOI: 10.1016/j.earscirev.2019.02.015.

Gairola SU, Bahuguna R, Bhatt SS. 2023. Native plant species: A tool for restoration of mined lands. J Soil Sci Plant Nutr 23: 1438-1448. DOI: 10.1007/s42729-023-01181-y.

Hartati W, Sudarmadji T. 2022. The dynamics of soil carbon in revegetated post-coal mining sites: A case study in Berau, East Kalimantan, Indonesia. Biodiversitas 23 (10): 4984-4991. DOI: 10.13057/biodiv/d231004.

Iskandar I, Suryaningtyas DT, 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 of East Kalimantan: A chronosequence study. Catena 215: 106355. DOI: 10.1016/j.catena.2022.106355.

Jinger D, Kaushal R, Nandha Kumar N, Kala S, Sirohi C, Mandal BS, Verma A, Joshi E. 2024. Amenable agroforestry approaches for restoration of mine spoil areas. In: Sharma GK, Rashmi I, Ali S, Kala S, Kumar A, Madhu M (eds). Ecological Impacts of Stone Mining: Assessment and Restoration of Soil, Water, Air and Flora. Springer Nature Singapore, Singapore. DOI: 10.1007/978-981-97-4746-7_13.

Kalamandeen M, Gloor E, Johnson I, Agard S, Katow M, Vanbrooke A, Ashley D, Batterman SA, Ziv G, Holder-Collins K, Phillips OL, Brondizio ES, Vieira I, Galbraith D. 2020. Limited biomass recovery from gold mining in Amazonian forests. J Appl Ecol 57 (9): 1730-1740. DOI: 10.1111/1365-2664.13669.

Kusuma YR, Yanti I. 2021. The effect of soil moisture content on organic carbon content and acidity (pH). Indones J Chem Res 6 (2): 92-97. DOI: 10.20885/ijcr.vol6.iss2.art5.

Ledesma J, Neilson JW, Maier RM, Babst-Kostecka A, Rasmussen C. 2025. Effects of stockpiling on topsoil biogeochemistry for semiarid mine reclamation. Min Metall Explor 42 (1): 15-26. DOI: 10.1007/s42461-024-01164-2.

Maftukhah R, Keiblinger KM, Ngadisih N, Murtiningrum M, Kral RM, Mentler A, Hood-Nowotny R. 2023. Post-tin-mining agricultural soil regeneration using local organic amendments improve nitrogen fixation and uptake in a legume–cassava intercropping system. Land 12 (5): 1107. DOI: 10.3390/land12051107.

Maiti SK. 2012. Ecorestoration of the Coalmine Degraded Lands. Springer Science & Business Media, New York. DOI: 10.1007/978-81-322-0851-8.

Mao Z, Harris J, Zhang Z. 2024. Responses of natural microorganisms to land reclamation and applications of functional microorganisms in biorestoration of coal mining area. Diversity 16 (2): 86. DOI: 10.3390/d16020086.

Midor K, Bialy W, Rogala-Rojek J, Matusiak P. 2021. The process of designing the post-mining land reclamation investment using process maps: Case study. Energies 14 (17): 5429. DOI: 10.3390/en14175429.

Nefilinda RE, Putri RE, Agustin M, Rahmanto Y, Setiawan FG. 2024. The impact of gold mining activities on the environment and community in Nagari Tambang, IV Jurai District, South Pesisir District. Intl J Soc Sci Humanit Res 7 (7): 119. DOI: 10.47191/ijsshr/v7-i07-119.

Pratiwi, Narendra BH, 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 reforestering degraded post-mining landscape in Indonesia: A review. Land 10 (6): 658. DOI: 10.3390/land10060658.

Rashmi I, Kala S, Sharma GK, Kumar A, Ali S, Kumar K, Kumawat A, Meena GL, Meena HR, Pal R, Roy T, Chaithra TS, Karthika KS, Shinoji KC. 2024. Impact of post-mining restoration techniques on soil health. In: Sharma GK, Rashmi I, Ali S, Kala S, Kumar A, Madhu M (eds). Ecological Impacts of Stone Mining: Assessment and Restoration of Soil, Water, Air and Flora. Springer Nature Singapore, Singapore. DOI: 10.1007/978-981-97-4746-7_14.

Rodríguez-Berbel N, Fox A, Ortega R, Schloter M, Schulz S, Miralles I. 2025. Restoring soil quality in semi-arid mining-degraded soils: Effects of different combinations of organic amendments on microbial nutrient cycling after 40 months of application. J Environ Manag 378: 124733. DOI: 10.1016/j.jenvman.2025.124733.

Society for Ecological Restoration Internasional (SERI). 2004. The SER International Primer on Ecological Restoration. SERI, Science & Policy, Bern.

Soewandita H. 2010. Development of Nutrient Blocks to Support Post-Mining Land Rehabilitation. KRT Engineer Incentive Program Final Report No. 25. Center for Regional Land Resource Management Technology and Disaster Mitigation, Agency for the Study and Application of Technology, Jakarta.

Sun X, Zhou Y, Tan Y, Wu Z, Lu P, Zhang G, Yu F. 2018. Restoration with pioneer plants changes soil properties and remodels the diversity and structure of bacterial communities in rhizosphere and bulk soil of copper mine tailings in Jiangxi Province, China. Environ Sci Pollut Res 25 (22): 22106-22119. DOI: 10.1007/s11356-018-2244-3.

Tang Y, Zhao Y, Li Z, He M, Sun Y, Hong Z, Ren H. 2025. A comprehensive evaluation of land reclamation effectiveness in mining areas: An integrated assessment of soil, vegetation, and ecological conditions. Remote Sens 17 (10): 1744. DOI: 10.3390/rs17101744.

Wiyantoko B, Kurniawati P, Purbaningtias TE. 2017. Testing of total nitrogen, water content, and lead metal contamination in solid NPK inorganic fertilizers. J Sci Technol 6 (1): 51-60. DOI: 10.23887/jstundiksha.v6i1.9439.

Xiao L, Bi Y, Du S, Wang Y, Guo C. 2019. Effects of re-vegetation type and arbuscular mycorrhizal fungal inoculation on soil enzyme activities and microbial biomass in coal mining subsidence areas of northern China. Catena 177: 202-209. DOI: 10.1016/j.catena.2019.02.019.

Xu C, Kuang S, He L, Wang C, Zu Y. 2023. Effects of changing restoration years on soil nutrient traits and plant community diversity in a phosphate mining area. Forests 14 (7): 1468. DOI: 10.3390/f14071468.

Zhang X, Zhang X, Zhang Z, Zhang J, Fan P. 2020. Measures, methods and cases of river ecological restoration. IOP Conf Ser: Earth Environ Sci 601: 012025. DOI: 10.1088/1755-1315/601/1/012025.

Zhao R, Liu Y, Page-Dumroese DS, Dumroese RK, Wang K. 2022. Enhancing soil quality of short rotation forest operations using biochar and manure. Forests 13 (12): 2090. DOI: 10.3390/f13122090.