Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper

Reviving Ecosystems: Vegetation Structure and Biodiversity Recovery in Reclaimed Coal Mining Areas of Kalimantan

Slamet Isworo[1]†, Handung Nuryadi[2] and Poerna Sri Oetari[3]

[1]Department of Environmental Health, Universitas Dian Nuswantoro., Central Java, Indonesia.

[2]Tropical Biosphere Research Center, University of the Ryukyus, Okinawa, Japan

[3]Department of Public Health, Universitas Dian Nuswantoro., Central Java, Indonesia.

†**Email**: slamet.isworo@dsn.dinus.ac.id

Key Words	Post-Mining Restoration, Vegetation Diversity, Ecological Succession, Multivariate Analysis, Conservation Priority
DOI	https://doi.org/10.46488/NEPT.2025.v24i04.D1780 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Isworo, S., Nuryadi, H. and Oetari, P.S., 2025. Reviving Ecosystems: Vegetation Structure and Biodiversity Recovery in Reclaimed Coal Mining Areas of Kalimantan. *Nature Environment and Pollution Technology*, 24(4), p. D1780. https://doi.org/10.46488/NEPT.2025.v24i04.D1780

ABSTRACT

Post-mining landscapes in tropical regions often suffer from severe ecological degradation and biodiversity loss, posing long-term challenges to sustainability. This study investigates vegetation structure and biodiversity recovery across eight reclaimed coal mining sites in Kalimantan, Indonesia, with reclamation ages ranging from 6 to 18 years. A total of 80 stratified vegetation plots (10 × 10 m) were surveyed, recording 46 species from 23 families across herb, shrub, and tree strata. Key ecological metrics—including the Shannon–Wiener Index (H′), Importance Value Index (IVI), and Sørensen Similarity Index—were applied to assess diversity, dominance, and community similarity. Results indicate that species diversity significantly increased with reclamation age (H′ = 1.42–3.11; F = 5.27, $p < 0.01$), confirming progressive ecosystem recovery. Vegetation similarity across sites remained low (10–57.78%), suggesting diverse successional trajectories. Dominance by *Acacia mangium* and *Albizia chinensis* in upper strata was common, while *Ottochloa nodosa* and *Chromolaena odorata* contributed to soil stabilization. *Fabaceae* was the most dominant family, and the critically endangered *Peronema canescens* was identified, underscoring the conservation potential of reclaimed habitats. Multivariate regression and heatmap analysis revealed that biodiversity (H′) was negatively correlated with rainfall (r = –0.69) and temperature (r = –0.41), while positively associated with humidity (r = 0.54) and wind speed (r = 0.53). Cluster and NMDS analyses confirmed spatial biodiversity patterns and informed site-specific conservation priorities. Mixed-species revegetation consistently supported higher biodiversity than monocultures. These findings highlight the importance of time, microclimatic regulation, and adaptive species selection in post-mining restoration. By integrating biotic and abiotic interactions, this study provides a robust ecological framework for designing resilient, biodiversity-rich, and self-sustaining reclamation landscapes.

INTRODUCTION

The coal mining industry plays a crucial role in Indonesia's economy by creating employment opportunities, supporting infrastructure development, and contributing significantly to national revenues. In 2020, coal production reached 562.5 million tons, with East Kalimantan accounting for approximately 27% of the total output (Prakoso and Faturohman 2024). However, the environmental consequences of open-pit coal mining are substantial. This industry has been widely associated with deforestation, habitat fragmentation, and biodiversity loss (Riefani and Soendjoto 2021). Between 2010 and 2014, coal mining operations in Indonesia led to the loss of approximately 1,901 km² of forest and caused severe soil degradation, which significantly hindered the natural recovery of vegetation (Giljum et al. 2022) If left unmanaged, the ecological disruption caused by ongoing mining activities is likely to intensify, underscoring the urgent need for effective post-mining land reclamation strategies (Boru, Ingale, and Lemt 2024) Reclamation efforts typically require 6 to 18 years to show meaningful signs of ecosystem recovery, including increased vegetation diversity, improved soil conditions, and the gradual restoration of ecological functions. The duration and success of this recovery process depend on several factors, such as the extent of initial environmental damage, the effectiveness of reclamation techniques employed, and the use of adaptive native plant species (Harsono et al. 2024) (Maiti, Bandyopadhyay, and Mukhopadhyay 2021) To address these environmental consequences, the Indonesian government has enacted several regulations. Law No. 3 of 2020 on Mineral and Coal Mining mandates post-mining reclamation as a prerequisite for environmental stewardship (Wicaksono and Triasari 2024). This is reinforced by Ministerial Regulation No. 7 of 2014 on mine closure and Ministerial Regulation No. 60 of 2009, which outlines success criteria for post-mining ecosystem recovery (Narendra et al., 2021). These frameworks emphasize restoring ecological functions through strategies such as acid mine drainage management, soil stabilization, revegetation with adaptive species, and phytoremediation using hyperaccumulator plants (Zine et al. 2024) (Mahfud, Rosmawati, and Nurdin 2022) However, reclamation success depends not only on replanting vegetation but also on the ecological interactions among plants, soils, and abiotic environmental conditions.

Several studies have explored vegetation diversity in reclaimed mine sites. For instance, a study conducted at PT Indominco Mandiri in East Kalimantan identified 38 plant species across 18 families, showing a strong correlation between revegetation age and species diversity (Harsono et al. 2024) (Harsono et al., 2024). Similarly, variation in biodiversity indices was observed at PT Bukit Asam, influenced by revegetation techniques and timing, with many vegetation strata displaying only moderate levels of diversity (Asnawi, Windusari, and Harun 2023). The importance of phytoremediation in ecological restoration has also been emphasized (Thomas, Sheridan, and Holm 2022), while the role of restored vegetation in supporting wildlife return and ecological succession has been well demonstrated.

Despite these findings, critical research gaps remain. Most studies emphasize species identification and initial biodiversity indices but often lack in-depth analysis of ecological functionality and long-term sustainability. There is limited understanding of how specific environmental factors such as microclimate, soil composition, or hydrological conditions influence the recovery trajectory of biodiversity. Additionally, the effectiveness of various reclamation strategies, particularly in selecting native versus non-native species and optimizing revegetation methods for resilience, remains underexplored in the Indonesian context. Few studies integrate both biotic and abiotic indicators to holistically evaluate ecosystem regeneration.

Post-mining reclamation is not merely land repair it is the revival of ecosystems. It involves restoring habitats where vegetation can thrive, wildlife can return, and ecological functions can naturally regenerate. Beyond replanting, it reestablishes the intricate relationships between species and their environment, enabling long-term ecological balance and sustainability (Worlanyo and Jiangfeng 2021). Effective reclamation planning supports ecological healing by restoring the land's capacity to sustain life. It safeguards soil fertility, maintains natural water flow, and fosters optimal conditions for vegetation growth. Topography plays a vital role—guiding water, retaining nutrients, and shaping microhabitats. By aligning with natural processes, reclamation can restore ecological balance and promote long-term ecosystem recovery (Mishra and Agarwal 2024) Reviving post-mining landscapes begins with careful plant selection. While fast-growing non-native species aid in rapid land stabilization, their unchecked spread may displace native flora and disrupt ecological balance. A thoughtful, ecologically grounded approach is essential—one that restores not just vegetation, but fosters a resilient ecosystem that supports biodiversity and benefits both nature and communities for generations to come(Vachova et al. 2022) Reclamation is just the beginning ongoing environmental monitoring is key to making sure the land is truly coming back to life. By observing soil health, water quality, and plant growth, we can see what's working, what needs improvement, and make adjustments to help nature heal (Ivanova et al. 2024) This continuous care ensures that reclaimed land doesn't just look restored, but thrives, once again becoming a home for diverse life and a vital part of the natural world.(Sallay et al. 2023). Monitoring reclamation progress involves assessing key ecological indicators. Canopy cover and stand density reflect forest structure and recovery, while soil and microclimate conditions influence species survival. Aboveground biomass and biodiversity levels provide evidence of ecosystem rebuilding. Together, these metrics offer a holistic view of whether reclaimed lands are regaining their capacity to support resilient, thriving life.

This study aims to analyze vegetation diversity in reclaimed coal mining areas and evaluate the effectiveness of current reclamation strategies in supporting biodiversity recovery. It further seeks to identify key environmental factors influencing ecosystem regeneration and to provide science-based recommendations for enhancing the long-term sustainability of post-mining reclamation practices in Indonesia. Fieldwork was carried out in two officially designated post-mining reclamation regions—East and South Kalimantan. While East Kalimantan served as the primary study area, additional sampling in South Kalimantan was included to enhance comparative analysis. This dual-site approach allowed for a broader understanding of ecosystem recovery and informed the development of adaptive, ecologically grounded reclamation strategies. The study tested the following hypotheses:

1. Vegetation diversity (H′) increases significantly with reclamation age, reflecting progressive ecological recovery.
2. Sites with stable environmental conditions—moderate slopes, greater ground cover, and favorable microclimates—support higher species richness and vegetation density.
3. Mixed-species revegetation promotes greater biodiversity and structural balance compared to monoculture systems, enhancing ecological resilience.
4. Significant correlations exist between environmental variables (e.g., slope, wind speed, soil conditions) and vegetation attributes (diversity index, species richness) across reclamation stages.

These hypotheses were examined through multivariate analyses, correlation tests, and biodiversity assessments at eight reclaimed sites in Kalimantan to evaluate the ecological effectiveness and long-term sustainability of current reclamation practices.

MATERIALS AND METHODS

Study area and period

This research employed a **descriptive ecological survey design**, combining quantitative and spatial approaches to assess vegetation structure and biodiversity in post-coal mining reclamation areas. The study was **non-experimental and observational**, aimed at understanding the natural recovery processes without manipulating environmental conditions. This study was conducted within coal mining concession areas in East and South Kalimantan—provinces known for both high biodiversity and intensive mining. The tropical study region experiences distinct wet (November–April) and dry (May–October) seasons, with temperatures ranging from 28.7°C to 40.8°C, which influence post-mining ecosystem recovery. Fieldwork took place from May 7 to June 19, 2022, during the seasonal transition, to capture early dry-season effects on vegetation regeneration. Survey sites, selected via Quantum GIS (QGIS), represented diverse ecological conditions and reclamation ages (6–18 years), allowing for a robust analysis of recovery dynamics. Site coordinates and land-use classifications are detailed in Table 1 and spatially mapped in Figure 1.Table 1.

Table 1. Reclamation and land use status at various locations.

Location	Coordinates		Information
TAJ1-1	03°16'20.75"S	115°07'59.78"E	Reclamation in 2009
TAJ1-2	03°16'20.20"S	115°07'57.58"E	Rubber plantation dominated areas
TAJ1-3	03°15'28.53"S	115°08'21.20"E	Reclamation in 2004
TAJ1-4	03°15'30.54"S	115°08'21.20"E	Reclamation in 2013
TAJ4-5	03°12'19.91"S	115°09'40.80"E	Reclamation in 2008
TAJ4-6	03°12'14.13"S	115°09'59.21"E	Reclamation in 2011
TAJ4-7	03°12'08.37"S	115°09'45.76"E	Reclamation in 2013
TAJ5-8	03°11'44.20"S	115°09'59.16"E	Reclamation in 2016

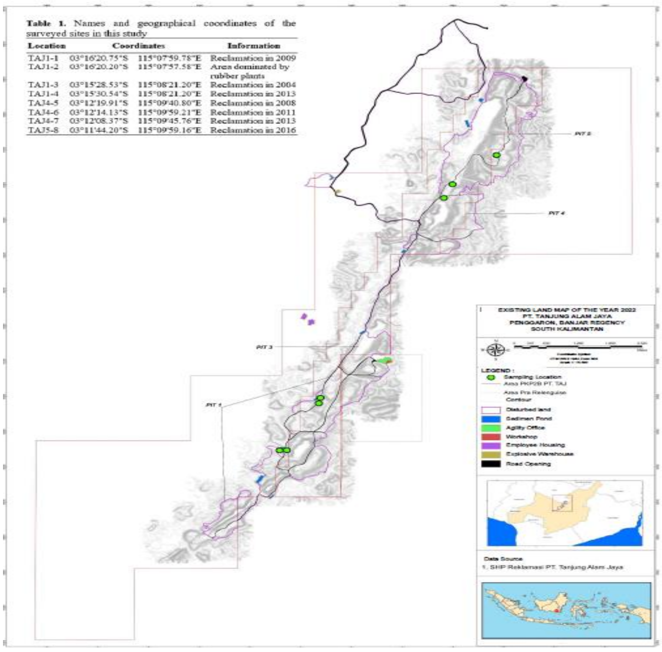

Figure 1. Map of the Observation Areas

Observation sites were systematically selected using Quantum GIS (QGIS) to ensure ecological representativeness across post-mining reclamation areas in East and South Kalimantan. Site selection considered reclamation age (6–18 years), land-use status, topography, and proximity to natural habitats, capturing the landscape's ecological heterogeneity. This spatially informed approach enhanced sampling accuracy, reproducibility, and served as the basis for assessing vegetation structure, biodiversity, and environmental variables

Sampling Design

A stratified purposive sampling approach was adopted to ensure ecological representativeness and field practicality. Stratification considered reclamation age (6–18 years), vegetation structure, land use, topography, and proximity to natural habitats. Plots were purposively selected based on accessibility, safety, and ecological variation, avoiding heavily disturbed or inaccessible areas. This method effectively captured ecosystem heterogeneity while maintaining consistency and efficiency in data collection. (Nugroho et al. 2022)

Sample Size Justification

The number of observation plots was determined based on ecological representativeness and field feasibility, rather than formal statistical formulas. Due to the high heterogeneity of post-mining landscapes, a non-probabilistic approach was used. Eight sites were purposively selected to capture variation in reclamation age, ecological conditions, and land-use types, enabling both spatial and temporal comparisons of ecosystem recovery.(Mao et al. 2022) The number of samples used was considered sufficient to reveal patterns in vegetation structure, biodiversity, and the relationships among environmental parameters. This approach is consistent with methodologies commonly employed in ecosystem restoration studies and biodiversity assessments in post-mining areas (Cardoso et al. 2021)

Object of observation

The stratified plot design in ecological surveys allows for a detailed view of vegetation structure at different scales within a single location. Larger trees are recorded in 20x20 m plots, while younger trees or poles are observed in 10x10 m plots. Shrubs and small saplings are studied in 5x5 m plots, and understory plants or herbs are examined in 2x2 m plots. This method maximizes efficiency, capturing multiple layers of vegetation without the need for additional survey sites. Widely used in forestry research and ecosystem restoration, it helps assess species diversity and forest regeneration, offering valuable insights into how ecosystems recover and thrive.(Warner et al. 2024) In the biodiversity survey of the mining site, flora was observed at predetermined observation points. The surveyed flora included perennial plants and understory vegetation, categorized into different strata based on their growth characteristics: trees (DBH > 20 cm), poles (DBH = 10–20 cm), stakes (DBH ≤ 10 cm, height > 1.5 m), and seedlings (height ≤ 1.5 m) (Safe'i et al. 2021). This classification aligns with the stratified plot design, ensuring that each vegetation layer is assessed according to its ecological significance and developmental stage.

Tools and materials

The biodiversity survey in the mining area combined traditional field methods and modern technology to ensure accurate and efficient data collection. Researchers used raffia rope, field meters, hammers, wooden pegs, and chalk to mark and measure trees, ensuring precise documentation. A digital map integrated into a mobile application facilitated site navigation and location recording, making data collection more efficient. Species identification was conducted using field guidebooks, while standardized observation forms and stationery maintained consistency in data recording, supported by photographic documentation for verification. This approach not only made the survey more structured and accurate, but also provided a comprehensive understanding of biodiversity conditions in the reclamation area. (Pambudi et al. 2023)

Data collection procedure

Vegetation analysis

Vegetation analysis in the reclamation area was carried out at eight predetermined sites using the plot/square method to capture the diversity and structure of plant life. Different plot sizes were used to observe various vegetation layers: 20 × 20 m for trees, 10 × 10 m for poles, 5 × 5 m for stakes, and 2 × 2 m for saplings (Figure 2). Additionally, a 2 × 2 m plot was used to study understory plants such as herbs and shrubs. To better understand how vegetation is recovering, researchers carefully measured the Diameter at Breast Height (DBH) for trees, poles, stakes, and saplings within each plot. This approach provided a detailed picture of plant growth and forest regeneration, helping to assess the success of the reclamation process. (Nufus, Pertiwi, and Sakya 2020) For understory plants, their coverage and growth were carefully assessed to understand their role in ecosystem recovery. Species identification was conducted directly in the field, and plant specimens were collected for further

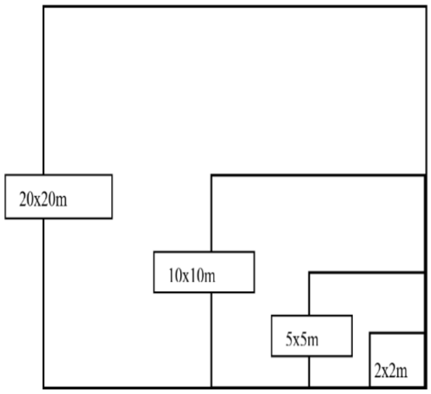

Figure 2. Plot design used in the survey

Figure 2 illustrates the stratified plot design used for vegetation surveys in post-coal mining reclamation areas, with plot sizes adapted to different vegetation strata (trees, poles, saplings, and seedlings).

Data analysis

The conservation status of plant species observed in reclaimed coal mining areas demonstrates a complex and ecologically diverse composition, marked by varying levels of conservation concern. According to the Regulation of the Minister of Environment and Forestry of the Republic of Indonesia No. P.106/MENLHK/SETJEN/KUM.1/6/2018 (Anwar and Triwibowo 2024), several species are officially recognized as nationally protected. Complementing this, assessments based on the IUCN Red List (IUCN, 2021) revealed the presence of species classified as Vulnerable (VU), Near Threatened (NT), and Endangered (EN), indicating that these reclaimed ecosystems host taxa of high conservation importance (IUCN 2021). Conservation-listed species were primarily found in sites reclaimed for over five years, reflecting a successional shift from pioneer species to ecologically sensitive taxa as habitat heterogeneity and ecosystem maturity increased. Heatmap-based multivariate analysis showed strong positive correlations between species abundance and environmental variables such as soil organic matter, canopy cover, and soil moisture highlighting the critical role of soil and microhabitat restoration in supporting sensitive and protected species within post-mining landscapes (Wang et al. 2022)

The Importance Value Index (IVI) revealed key species with high structural dominance across vegetation strata, reflecting their major role in shaping community composition. Dominant species varied with reclamation age, with pioneer species prevailing in younger sites and more complex taxa emerging in older areas. Similarly, the Shannon-Wiener Index showed a consistent increase with reclamation duration, indicating progressive enhancement in both species richness and evenness. (Ali et al. 2024) Environmental improvements over time, such as canopy development and soil enhancement, contribute to greater plant diversity. The presence of protected species in older reclamation sites indicates the formation of ecologically valuable plant communities.

Floristic composition

The floristic composition was analyzed using the Important Value Index (IVI) to understand the role of each species in the ecosystem. For the tree stratum, IVI was calculated by adding relative density, relative frequency, and relative dominance. In the pole and stake strata, it was determined by summing relative density and relative frequency, while for sapling and herb strata, the focus was on dominance and frequency.(Atalitsa et al. 2021). Vegetation structure was analyzed using key parameters such as density, dominance, and frequency to understand species distribution and ecological roles. These parameters are essential for assessing biodiversity and guiding restoration strategies, as outlined below:

$$\text{Density (D)} = \frac{\text{Number of individuals of a species}}{\text{Area of observation plot}}$$

$$\text{Relative Density} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100\%$$

$$\text{Dominance (D)} = \frac{\text{Total basal area}}{\text{Sample plot size}}$$

$$\text{Relative Dominance (DR)} = \frac{\text{Dominance of a species}}{\text{Dominance all species}} \times 100\ \%$$

$$\text{Frequency (F)} = \frac{\text{Total plot of a species recorded}}{\text{Total sample plot}}$$

$$\text{Relative Frequency (RF)} = \frac{\text{Species}}{\text{Total of frequency of all species studied}} \times 100\ \%$$

1. Diversity index

Diversity was evaluated based on species richness and species abundance. Data from all analyzed taxa were used to calculate the Shannon-Wiener Diversity Index (H'), which is defined as follows::

$$H' = -\sum \frac{ni}{N} \times \ln \frac{ni}{N}$$

Note:

H' : Shannon-Wiener diversity index

ni : The importance value of species i

N : Total importance parameters of all species

The diversity index was classified as follows: H' < 1 = Low diversity, 1 < H' < 3 = Medium diversity, H' > 3 = High diversity (Setyono et al. 2023)

2. Similarity index

The Sørensen Similarity Index (SCSI) is a quantitative metric used to assess the degree of similarity in species composition between two ecological communities. In this study, the SCSI was applied to compare vegetation communities in reclaimed and non-reclaimed post-mining areas, aiming to evaluate the effectiveness of reclamation in restoring biodiversity and ecosystem functions. The index is calculated using the following formula: (Addi et al. 2020)

$$SCSI = \frac{2 \times EC}{A + B}$$

Where:

SCSI : The Sorensen Coefficient Similarity Index

C : Number of species found in the two study areas

A : Number of species in area A

B : Number of species in area B

The Sorensen Coefficient Similarity Index (SCSI) ranges from 0% to 100%, with higher values indicating greater similarity between two regions. The SCSI categories are as follows: 1–30% = Low similarity, 31–60% = Medium similarity, 61–90% = High similarity and 90% = Very high similarity (Oluyinka Christopher 2020)

3. Correlation Analysis (Heatmap Analysis)

This study employed systematic field surveys to evaluate vegetation diversity and environmental factors in post-mining reclamation areas in Kalimantan, Indonesia. Aimed at assessing ecological recovery and understanding environmental influences on vegetation reestablishment, the research combined spatially consistent sampling with geospatial tools to ensure robust, unbiased comparisons across sites of varying reclamation age and land-use history. By integrating vegetation and environmental data, the study offered a comprehensive view of recovery dynamics, supporting evidence-based restoration strategies aligned with global best practices in tropical ecosystem management (Cardoso et al. 2021) This study used line transects and systematic quadrat plots to assess plant distribution and quantify key vegetation metrics—species diversity, density, canopy cover, biomass, and composition—in post-mining reclamation sites. Environmental variables such as soil pH, humidity, rainfall, and temperature were measured to evaluate their influence on vegetation. Correlation analyses (Pearson's or Spearman's, based on Shapiro-Wilk normality tests) were conducted to explore relationships between biotic and abiotic factors. Results were visualized using Python-based heatmaps, highlighting key environmental drivers of vegetation recovery. This integrated, data-driven approach provides valuable insights for developing adaptive and ecologically sound reclamation strategies.(Mao et al. 2022). To ensure precise and efficient data processing, the study employed both Python and R (via RStudio), enabling seamless integration of statistical analysis and visualization. In the field, digital soil testers were used to measure soil pH and moisture, hygrometers recorded air humidity, and GPS devices accurately marked sampling locations. Plant height and structural characteristics were consistently assessed using measuring tapes and diameter tapes. By combining advanced computational tools with standardized field protocols, the study provided a rigorous and holistic understanding of vegetation regeneration, forming a robust scientific basis for effective, sustainable, and long-term ecosystem restoration in post-mining landscapes.(Ji et al. 2022). Understanding vegetation responses to environmental conditions is crucial for evaluating post-mining reclamation. This study employed correlation analysis to examine relationships between vegetation attributes and key environmental variables, including soil quality, climate, and site conditions. The statistical formulas used were as follows:

Pearson's correlation coefficient:

$$r=\sum(Xi-\bar{X})(Yi-\bar{Y})/\sum(Xi-\bar{X})^2\cdot\sum(Yi-\bar{Y})^2$$

Spearman's rank correlation coefficient:

$$\rho=1-6\sum d^2_i\,/n(n^2-1)$$

The strength and direction of variable relationships were interpreted using standard correlation classifications, ranging from very weak to very strong. All correlation coefficients (r or ρ) were tested for **statistical significance (p-values)** to determine whether the observed associations were meaningful or occurred by chance. Values close to **±1** indicated strong relationships, while values near **0** suggested weak or no correlation. A **significance level of $p < 0.05$** was used to identify statistically significant associations. This analytical framework provided a robust basis for identifying key environmental factors influencing vegetation patterns in reclaimed ecosystems.

RESULTS AND DISCUSSION

1. Analysis Based on Survey Location Coordinates

a) Spatial Assessment of Reclamation Sites

Spatial analysis of reclamation sites in South Kalimantan reveals that restoration activities were influenced by geographical features and logistical considerations, with survey locations aligned along accessible corridors and contour lines. The varied timelines of reclamation, from 2004 to 2016, provide a valuable basis for assessing ecological recovery across different successional stages. Older sites, such as TAJ1–3, show signs of advanced recovery—including mature vegetation, increased biodiversity, and soil stabilization—while more recent sites like TAJ5–8 are still in early succession, dominated by pioneer species and requiring continued monitoring. Topographical factors such as elevation, slope, and water flow clearly influence restoration outcomes, and land-use patterns, such as rubber plantations at TAJ1–2, reflect efforts to balance ecological restoration with productive land use. These findings highlight the importance of tailored, site-specific reclamation strategies that align with ecological conditions to ensure long-term sustainability.

b) Research Site Analysis

Geographical Distribution:

The research sites were strategically distributed across coal mining concession areas using Quantum GIS (QGIS), ensuring precise geolocation and broad ecological representation. Marked as green dots on the map, these sites encompass diverse environmental conditions—ranging in topography, soil types, and human disturbance capturing a temporal gradient from recently reclaimed areas to those restored over a decade ago. This spatial design supports a comprehensive evaluation of vegetation diversity and ecosystem recovery across varied post-mining landscapes.

Variation in Reclamation Age:

As presented in Table 1, the reclamation sites vary significantly in age, ranging from the oldest site (TAJ1-3), reclaimed in 2004, to the most recent (TAJ5-8), reclaimed in 2016. This temporal variation—spanning over 12 years—offers a valuable opportunity for longitudinal studies that examine and compare different stages of ecological recovery over time. Older sites tend to exhibit more advanced signs of ecosystem restoration, including complex vegetation structure, increased soil stability, and the presence of more diverse, climax species. In contrast, younger sites are typically in the early stages of ecological succession, often dominated by pioneer species and characterized by less stable soil and lower vegetation complexity. By analyzing sites with different reclamation ages, this study is able to track ecological trajectories and evaluate the long-term effectiveness of various restoration strategies. These insights are essential for informing evidence-based reclamation policies and designing more adaptive, sustainable approaches for future post-mining landscape recovery.

c) Reclamation Characteristics

Vegetation across the reclamation sites demonstrates notable variability, shaped by both planned interventions and natural succession. Sites like TAJ1-2, dominated by rubber plantations, reflect economically driven strategies, while others combine artificial revegetation with natural regeneration, using pioneer species such as *Acacia mangium* to promote soil stabilization. These variations highlight how species selection, planting techniques, and environmental factors—especially topography and hydrology—influence vegetation structure and recovery. Flat areas promote faster succession due to better soil conditions, whereas steeper slopes require intensive erosion control. Although vegetation recovery is evident, challenges remain, particularly the reliance on monocultures, which may hinder biodiversity and resilience. Effective reclamation should therefore integrate ecological considerations, including microclimate, soil restoration, hydrological balance, and biodiversity. Long-term monitoring and the use of native species can enhance resilience and ecological balance. Spatial analysis confirms the need for adaptive, site-specific strategies. Metrics such as the Sørensen Similarity Index offer insights into ecological similarity and reclamation success. Ultimately, ecologically grounded, integrative approaches are key to restoring ecosystem function and sustainability in post-mining landscapes.

2. Analysis of flora in the observation area

The survey identified a diverse array of plant families, with Fabaceae, Phyllanthaceae, Lamiaceae, and Poaceae as the most prominent. Fabaceae, with five recorded species, plays a key ecological role due to its nitrogen-fixing ability, aiding soil fertility and ecosystem regeneration. Phyllanthaceae and Lamiaceae contribute to habitat diversity and provide ecological and socio-economic benefits such as food, medicine, and timber. Poaceae species like *Imperata cylindrica* and *Ottochloa nodosa* are crucial for soil stabilization and erosion control in early restoration stages. The dominance of Fabaceae underscores its importance in soil improvement and succession, while the overall plant diversity reflects complex ecological interactions that support habitat formation, fauna, and microclimate regulation. These insights highlight the need for restoration strategies that emphasize functional plant groups to enhance resilience and long-term sustainability in post-mining ecosystems.

Protection and Conservation Status

Protection and conservation status evaluates a species' legal safeguards and extinction risk, based on national and international criteria. In Indonesia, protection is governed by Regulation No. P.106/MENLHK/SETJEN/KUM.1/12/2018, while the IUCN Red List provides global classifications such as

Vulnerable (VU), Endangered (EN), and Critically Endangered (CR). This assessment identifies species requiring conservation priority, particularly in ecologically fragile areas like post-mining landscapes. Incorporating the protection of rare and ecologically important species into restoration strategies is vital for promoting biodiversity recovery and ensuring long-term ecosystem resilience. (Listriani 2023) Table 2. *List of Plant Species Recorded at the Survey Sites* summarizes the plant species identified across the post-mining reclamation areas. It includes scientific names, plant families, conservation status according to the IUCN Red List and national regulations, as well as species frequency or individual counts per plot. This dataset offers a valuable overview of floristic composition, species diversity, and conservation value within reclaimed sites, serving as a key reference for evaluating ecosystem recovery and the success of restoration efforts. (IUCN 2021)

Table 2. List of plant species recorded at the survey sites.

Family	Indonesian Name	Scientific Name	International Name	Status 1	Status 2	Status 3
Fabaceae	Tongke Hutan	*Acacia mangium*	Brown Salwood	Unprotected	LC	Stable
Rubiaceae	Tongkeu	*Aidia sp.*	Archer Cherry	Unprotected	LC	Stable
Fabaceae	Sengon	*Albizia chinensis*	Chinese Albizia	Unprotected	LC	Stable
Zingiberaceae	Lengkuas	*Alpinia galanga*	Siamese Ginger	Unprotected	LC	Stable
Phyllanthaceae	Buni	*Antidesma sp.*	Bignay	Unprotected	LC	Stable
Thymelaeaceae	Gaharu	*Aquilaria sp.*	Agarwood	Unprotected	LC	Stable
Fabaceae	Jengkol	*Archidendron pauciflorum*	Djenkol	Unprotected	LC	Stable
Phyllanthaceae	Semak Salju	*Breyna sp.*	Snowbush	Unprotected	LC	Stable
Fabaceae	Kaliandra Merah	*Calliandra calothyrsus*	Powder-puff	Unprotected	LC	Stable
Cyperaceae	Ballang-Ballang	*Carex perakensis*	True Sedges	Unprotected	LC	Stable
Fabaceae	Sentro	*Centrosema pubescens*	Butterfly Pea	Unprotected	LC	Stable
Rutaceae	Tikusan	*Clausena excavata*	Pink Lime-Berry	Unprotected	LC	Stable
Lamiaceae	Bunga Pagoda	*Clerodendrum paniculatum*	Pagoda Flower	Unprotected	LC	Stable
Melastomaceae	Senduduk Bulu	*Clidemia hirta*	Soapbush	Unprotected	LC	Stable
Fabaceae	Kacang Penutup.	*Colopogonium caeruleum*	Wild Jicama	Unprotected	LC	Stable
Costaceae	Pacing	*Costus sp.*	Crape Ginger	Unprotected	LC	Stable
Asteraceae	Kirinyu	*Chromolaena odorata*	Siamweed	Unprotected	LC	Stable
Cyperaceae	Rumput Teki	*Cyperus rotundus*	Nutgrass	Unprotected	LC	Stable
Davalliaceae	Paku Tertutup	*Davallia denticulata*	Closed Fern	Unprotected	LC	Stable
Fabaceae	Kutu Pengemis	*Desmodium sp.*	Beggar's Lice	Unprotected	LC	Stable
Gleicheniaceae	Resam	*Dicranopteris linearis*	Forked Fern	Unprotected	LC	Stable
Elaeocarpaceae	Ganitri	*Eleocarpus sp.*	Silver Quandong	Unprotected	LC	Stable
Gentianaceae	Pohon Kopi Palsu	*Fagraea racemosa*	False Coffee	Unprotected	LC	Stable
Moraceae	Pohon Ara	*Ficus simplicissima*	Fig Tree	Unprotected	LC	Stable
Phyllanthaceae	Sampare	*Glochidion sp.*	Cheese Trees	Unprotected	LC	Stable
Lamiaceae	Jati Putih	*Gmelina arborea*	Beechwood	Unprotected	LC	Stable
Malvaceae	Bayur	*Helicteres angustifolia*	Cowbush	Unprotected	LC	Stable
Euphorbiaceae	Karet	*Hevea brasiliensis*	Rubber Tree	Unprotected	LC	Stable
Poaceae	Alang-alang	*Imperata cylindrica*	Cogongrass	Unprotected	LC	Stable
Verbenaceae	Tahi Ayam	*Lantana camara*	Wild Sage	Unprotected	LC	Stable
Urticaceae	Daun Gatal	*Laportea aestuans*	Woodnettle	Unprotected	LC	Stable
Vitaceae	Girang	*Leea indica*	Bandicoot Berry	Unprotected	LC	Stable
Arecaceae	Palem	*Licuala sp.*	Spiny Licuala Palm	Unprotected	LC	Stable
Lauraceae	Pohon Huru	*Litsea elliptica*	Medang	Unprotected	LC	Stable
Lygodiaceae	Paku Kembang	*Lygodium flexuosum*	Twining Fern	Unprotected	LC	Stable
Lygodiaceae	Hata Leutik	*Lygodium microphyllum*	Climbing Fern	Unprotected	LC	Stable
Euphorbiaceae	Kayu Sepat	*Macaranga triloba*	Mahang Damar	Unprotected	LC	Stable
Melastomaceae	Harendong	*Melastoma malabathricum*	Melastoma	Unprotected	LC	Stable
Convulvulaceae	Mantangan	*Merremia peltata*	Merremia	Unprotected	LC	Decrease
Asteraceae	Bulou	*Mikania micrantha*	American Rope	Unprotected	LC	Decrease
Fabaceae	Putri Malu	*Mimosa pudica*	Sensitive Plant	Unprotected	LC	Decrease
Sapindaceae	Rambutan	*Nephelium sp.*	Rambutan	Unprotected	LC	Decrease
Poaceae	Rumput Buaya.	*Ottochloa nodosa*	Panic Grass	Unprotected	LC	Decrease
Poaceae	Rumput Kerbau	*Paspalum sp.*	Paspalum Grass	Unprotected	LC	Decrease
Lamiaceae	Sungkai	*Peronema canescens*	Sungkai Tree	Unprotected	CR	Decrease

Note: Status 1 (Indonesia regulation). Status 2 (IUCN). Status 3 (Global population). The protection status of the species documented in this study is based on Indonesia's Ministry of Environment and Forestry Regulation No. P.106/MENLHK/SETJEN/KUM.1/12/2018 and the IUCN Red List, which categorize species according to their conservation concern. The IUCN Red List, a globally recognized system for assessing extinction risks, classifies species into Least Concern (LC) for those widespread and abundant, Vulnerable (VU) for those at high risk of becoming endangered, and Critically Endangered (CR) for species facing an extremely high risk of extinction in the wild. In addition to risk classification, the IUCN Red List also monitors population trends, identifying species as stable if their population remains constant, increasing if their numbers are rising due to conservation efforts or natural recovery, and declining if they are experiencing population reduction due to habitat loss, climate change, or overexploitation. Understanding these classifications and trends is crucial for implementing effective conservation strategies, ensuring long-term ecosystem stability, and prioritizing protection efforts for species at higher risk. For more information on the conservation status of specific species, the official IUCN Red List website provides comprehensive assessments and updates.

Most plant species recorded in the reclaimed mining areas are classified as "Unprotected" nationally and "Least Concern (LC)" by the IUCN Red List, indicating that the vegetation is largely composed of common, resilient species well-suited to disturbed environments. However, the presence of *Peronema canescens* (Sungkai), listed as "Critically Endangered (CR)" and experiencing a global population decline, highlights both the recovery potential of these sites and the need for targeted conservation efforts. Additionally, several species—though still classified as LC—are also showing negative population trends. These findings underscore the importance of integrating conservation into reclamation planning through continuous species monitoring, inclusion of native and protected flora, and control of invasive species. This approach enhances restoration outcomes while supporting broader biodiversity conservation goals.

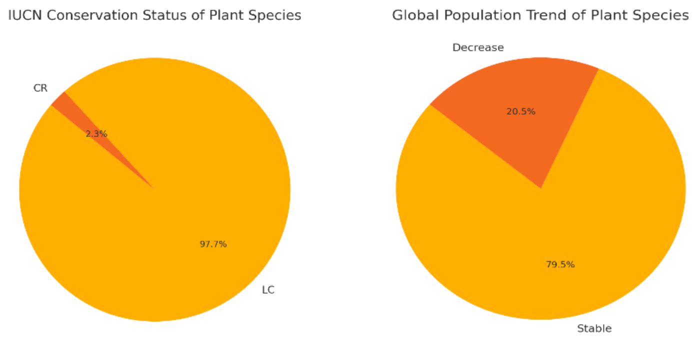

Figure 3. UCN Conservation Status of Plant Species and Global Population Trend of Plant Species

The pie chart in Figure 3 shows that 97.7% of plant species identified in the reclaimed areas are classified as Least Concern (LC), indicating a prevalence of generalist, disturbance-tolerant species. Notably, *Peronema canescens* appears as the only Critically Endangered (CR) species, suggesting that reclaimed lands may provide refuge for threatened flora. Around 20.5% of recorded species are experiencing global population declines, underscoring the need to incorporate conservation priorities into reclamation efforts. Table 2 further highlights taxonomic diversity, with 136 species from 26 families, dominated by adaptive groups such as Fabaceae, Poaceae, and Lamiaceae, which are largely stable and classified as LC. These findings support the ecological value of reclaimed sites and the importance of long-term biodiversity monitoring and native species enrichment.

Table 3 summarizes species richness across study sites (TAJ1-1 to TAJ5-8), encompassing 136 plant species from 101 occurrences, reflecting notable ecological complexity. TAJ4-7 and TAJ5-8 recorded the highest species diversity, with 20 and 19 species respectively, likely driven by favorable environmental conditions such as fertile soils, ample light, and stable microclimates. Conversely, TAJ4-6 exhibited the lowest diversity (12 species), potentially due to poor soil conditions or high interspecies competition. TAJ4-7 also hosted the highest number of plant families (15), identifying it as a local biodiversity hotspot within the reclaimed landscape.

Table 3. Number of families and species in the study area.

Name of family	TAJ1-1	TAJ1-2	TAJ1-3	TAJ1-4	TAJ4-5	TAJ4-6	TAJ4-7	TAJ5-8	∑ Total Encounters
Zingiberaceae	1	1	1	1	1	1	1		7
Vitaceae	1					1	1	1	4
Verbenaceae	1			1	1			1	4
Urticaceae							1		1
Thymelaeaceae				1					1
Selaginellaceae			1						1
Sapindaceae							1		1
Rutaceae					1		1		2
Rubiaceae			1						1
Polygalaceae		1							1
Poaceae	1	1	2	1	1	2	1	2	8
Piperaceae					1		1	1	3
Phyllanthaceae	3	1	2	2	2			1	6
Nephrolepidaceae							1		1
Moraceae			1	2					2
Melastomaceae	1	1	1		1	1		2	6
Malvaceae	1	1	1	1					4
Lygodiaceae			1				1		2
Lauraceae					1				1
Lamiaceae	1	2	2	1		1	2	1	7
Gleicheniaceae			1						1
Gentianaceae		1	1	1		1			4
Fabaceae	3	3	2	3	3	2	4	5	8
Euphorbiaceae	1	2							2
Elaeocarpaceae				1					1
Davalliaceae							1		1
Cyperaceae		1		1	1			1	4
Costaceae			1		1	1	1	1	5
Convulvulaceae	1				1		1	1	4
Asteraceae	1			1	2	2	2	2	6
Arecaceae		1							1
Apocynaceae				1					1
Number of species	16	16	18	18	17	12	20	19	136
Number of family	12	12	14	14	13	9	15	12	101

The study identified 136 plant species across 101 encounters, reflecting high ecological complexity in the post-mining landscape. TAJ4-7 and TAJ5-8 recorded the highest species richness and family diversity, likely due to favorable soil, light, and microclimate conditions, while TAJ4-6 exhibited the lowest diversity, potentially due to poor soil quality and higher competition. Widely distributed families such as Poaceae and Fabaceae dominated, highlighting their adaptability and ecological importance, especially in soil stabilization and nitrogen fixation. The presence of rare families like Arecaceae and Apocynaceae suggests specialized niches and potential conservation priorities. The Shannon-Wiener index (H' = 2.07) indicates moderate to high diversity, suggesting a balanced and stable community structure. TAJ4-7 and TAJ5-8 are recommended as conservation hotspots, while TAJ4-6 requires targeted restoration. Cluster analysis supports these priorities by grouping sites based on biodiversity patterns. This integrative analysis—combining species richness, family composition, and environmental factors underscores the importance of site-specific and data-driven reclamation strategies. It provides a foundation for adaptive ecosystem management that supports long-term biodiversity recovery in reclaimed mining areas.

Table 4 presents the results of a Pearson correlation analysis between the number of plant species and plant families across all reclamation plots. This correlation reflects the statistical relationship that indicates the extent to which greater species richness within a plot corresponds to increased taxonomic diversity at the family level.

Table 4. Correlation between the number of plant species and plant families across all study plots.

	Number of species	Number of family
Number of species	1,00	0,88
Number of family	0,88	1,00

The analysis revealed a strong positive correlation (r = 0.884) between species diversity and family richness, indicating that more diverse plots also support a wider range of plant families. This reflects healthy ecological succession, where vegetation recovery enhances both taxonomic and functional diversity. Such complexity suggests improved ecological stability and ecosystem functions, including soil protection, nutrient cycling, and habitat provision. These findings highlight the importance of biodiversity-based restoration strategies that integrate species and family-level diversity to promote resilient, self-sustaining post-mining ecosystems. Table 5 summarizes species and family counts across plots and categorizes sites into three biodiversity-based clusters. Cluster 0 (e.g., TAJ4-7, TAJ1-3, TAJ1-4) includes sites with high species and family richness, indicating stable and ecologically complex ecosystems. Cluster 1 (TAJ1-1, TAJ1-2, TAJ4-5, TAJ5-8) represents moderately diverse, transitional areas needing adaptive management, while Cluster 2 (TAJ4-6) reflects the lowest biodiversity and a priority for restoration. These clusters reinforce the strong correlation (r = 0.884) between species and family diversity and offer a strategic, site-specific basis for guiding post-mining reclamation and conservation planning.

Table 5. Number of families and species in the study area.

Parameter	Number of Species	Number of Families	Cluster Group
TAJ1-1	16	12	1
TAJ1-2	16	12	1
TAJ1-3	18	14	0
TAJ1-4	18	14	0
TAJ4-5	17	13	1
TAJ4-6	12	9	2
TAJ4-7	20	15	0
TAJ5-8	19	12	1

Cluster analysis grouped the study sites into three ecological categories based on species and family diversity. Cluster 0 includes high-biodiversity sites with stable ecosystems suitable for conservation focus. Cluster 1 represents moderately diverse areas requiring habitat enrichment, while Cluster 2 identifies low-diversity sites facing ecological stress, warranting intensive restoration. This classification supports site-specific, adaptive management to enhance biodiversity and ensure effective post-mining ecosystem recovery. Cluster analysis followed by correlation analysis: correlation test between the number of species and the number of families at each location

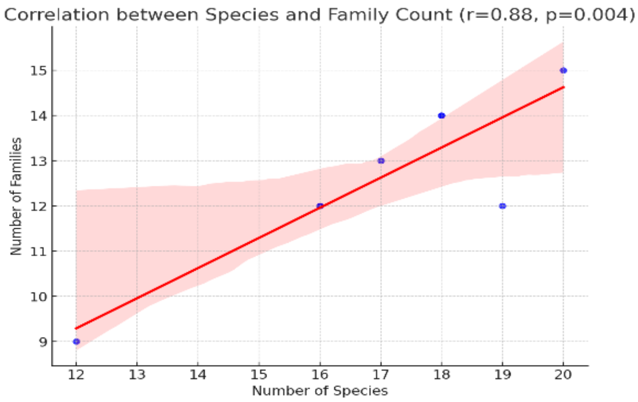

Fig 4. Assessing the Correlation Between Species Richness and Taxonomic Diversity

The scatter plot and regression analysis presented in Figure 4 further reinforce the findings of the cluster and correlation analyses, revealing a strong and statistically significant positive correlation ($r = 0.88$, $p = 0.004$) between species richness and family-level diversity across the study sites. This result confirms that areas with a higher number of species also exhibit broader taxonomic representation, suggesting that biodiversity within the reclaimed plots is not randomly distributed, but structured across multiple taxonomic groups (Hughes et al. 2021) These findings align with the previously identified clusters, where Cluster 0 includes biodiversity-rich plots such as TAJ4-7, TAJ1-3, and TAJ1-4, characterized by high species and family richness. These areas serve as biodiversity hotspots, highlighting their ecological importance and the need for focused conservation efforts to preserve their structure and function. Conversely, plots in Cluster 2, such as TAJ4-6, display lower biodiversity and are likely constrained by environmental stressors—thus requiring intensive restoration interventions, including soil enhancement, habitat management, and reintroduction of native species. This strong correlation also underscores the ecological value of taxonomic diversity, as a higher number of plant families indicates a wider range of functional traits, contributing to ecosystem resilience and adaptability to environmental changes. Therefore, conservation and reclamation strategies should not only aim to increase species richness but also ensure the inclusion of diverse taxonomic groups. An effective ecosystem management framework should prioritize high-biodiversity areas for long-term protection while applying adaptive revegetation and ecological restoration practices in more degraded or less diverse regions. By integrating cluster analysis and correlation findings, this approach enables data-driven decision-making in post-mining restoration, enhancing the ecological stability and sustainability of reclaimed landscapes (Chahar et al. 2023).

Table 6 reinforces and complements the previous findings by providing a more comprehensive overview of vegetation composition and structure based on plant strata. This table includes key ecological indicators such as the Importance Value Index (IVI), species count, and diversity index values for each vegetation layer (upper canopy, understory/shrubs, and ground cover).

Table 6**.** Importance Value Index (IVI), number of species and diversity index of vegetation in the studied area based on plant stratum.

Species name	TAJ1-1	TAJ1-2	TAJ1-3	TAJ1-4	TAJ4-5	TAJ4-6	TAJ4-7	TAJ5-8
Tree								
Acacia mangium	300		300		300	300		73.35
Albizia chinensis							300	226.65
Antidesma sp.				85.17				
Archidendron pauciflorum				70.32				
Hevea brasiliensis		300						
Vitex pinnata				144.52				
Number of species	1	1	1	3	1	1	1	2
Diversity Index (H')	0	0	0	0.96	0	0	0	0.39
Pole								
Acacia mangium			117.58		300	210.67		

Albizia chinensis						89.33	300	300
Hevea brasiliensis		300						
Vitex pinnata	300		182.42	300				
Number of species	1	1	2	1	1	2	1	1
Diversity Index (H')	0	0	0.6	0	0	0.5	0	0
Stake								
Acacia mangium		40.5		99.81		155.84		110.05
Albizia chinensis							181.43	189.95
Antidesma sp.		89				54.65		
Aquilaria sp.					71.37			
Ficus simplicissima				56.92	195.29			
Litsea elliptica						89.51		
Piper aduncum							118.57	
Vitex pinnata		170.5		143.27				
Number of Species		3	-	3	2	3	2	2
Diversity Index (H')		0.79	-	1.06	0.56	0.9	0.64	0.64
Sapling								
Acacia mangium	28.21		29.17		66.67	107.14		43.18
Aidia sp.			50					
Albizia chinensis								61.36
Antidesma sp.	35.9		33.33	36.67	50			
Clausena excavata					33.33			
Clerodendrum paniculatum							56.25	
Eleocarpus sp.				30				
Ficus simplicissima				43.33				
Glochidion sp.	35.9			36.67				
Gmelina arborea		22.55	29.17					
Hevea brasiliensis		75.49						
Licuala sp.		22.55						
Macaranga triloba	24.36	22.55						
Nephelium sp.							50	
Peronema canescens							43.75	
Piper aduncum					50			43.18
Samanea saman	24.36	28.43	25	30			50	
Vitex pinnata	51.28	28.43	33.33			92.86		52.27
Willughbeia sp.				23.33				
Number of species	6	6	6	6	4	2	4	4
Diversity Index (H')	1.65	1.32	1.69	1.71	1.27	0.68	1.37	1.34
Herbaceous plant								
Alpinia galanga	10.93	14.05	11.45	11.86	8.6	12.06	9.2	
Breynia sp.	13.74	12.7	12.24		9.39			12.02
Calliandra calothyrsus							3.39	
Carex perakensis		11.35						
Centrosema pubescens	12.8	12.7		13.37	11.77			10.24
Clausena excavata							12.53	
Clidemia hirta								8.45
Colopogonium caeruleum					9.66		9.22	11.13
Costus sp.			11.45		9.13	13.02	9.31	12.02
Chromolaena odorata				25.02	29.5	15.4	5.06	37.92
Cyperus rotundus								9.35
Davallia denticulata							11.75	
Desmodium sp.		61.35						
Dicanopteris linearis			42.95					
Fagraea racemosa		14.05	9.88			11.59		
Helicteres angustifolia	12.8	15.41	12.24					
Imperata cylindrica			24.05	13.74		91.11		10.24
Lantana camara	13.74			13.37	10.45			15.6
Laportea aestuans							10.98	
Leea indica	12.8					12.06	7.67	9.35

Lygodium flexuosum			12.24					
Lygodium microphyllum							12.59	
Macaranga triloba				11.49				
Melastoma malabathricum	14.67	16.76	20.9		9.92	20.16		10.24
Merremia peltata	11.87				13.62		7.56	9.35
Mikania micrantha	11.87			14.49	14.42	12.06	14.28	13.81
Mimosa pudica								10.24
Nephrolepis sp.							14.2	
Ottochloa nodosa	84.77			74.27	58.33		72.27	
Paspalum sp.								20.06
Pogonatherum crinitum						12.54		
Polygala paniculata		24.86						
Scleria bancana		16.76	19.33	22.39	15.21			
Selaginella sp.			23.26					
Number of species	10	10	11	9	12	9	14	15
Diversity Index (H')	1.1	1.66	1.96	1.25	1.61	0.83	1.39	2.33

Dominance and Diversity Across Vegetation Strata

Dominance and Diversity Across Vegetation Strata" refers to the analysis of species dominance and diversity within the vertical layers of vegetation in an ecosystem. These strata reflect the structural organization of plant communities and are generally categorized into four main layers: the tree stratum, the pole or stake stratum, the sapling stratum, and the herbaceous stratum. This analysis is essential for understanding vegetation dynamics, natural successional processes, and overall ecological conditions—particularly in the context of ecosystem recovery and post-mining land reclamation. The following is a more detailed explanation :

Tree and Pole Strata: Patterns of Monodominance

Observations across multiple plots revealed a strong dominance of single species in the tree and pole strata, primarily *Acacia mangium*, *Hevea brasiliensis*, and *Albizia chinensis*. This pattern is reflected in their consistently high Importance Value Index (IVI), often approaching the maximum score of 300. Such monodominance indicates that these ecosystems have likely experienced prior disturbances, such as monoculture plantation development, selective logging, or deforestation followed by limited natural regeneration. The corresponding low, and in some cases zero, Shannon-Wiener diversity indices (H′) further confirm a lack of species richness at these strata. These conditions suggest that ecological succession is either still in its early stages or constrained by the competitive exclusion effects of dominant species.

Sapling and Stake Strata: Indicators of Natural Regeneration

In contrast, the sapling and stake strata exhibited significantly higher diversity values, reflecting more dynamic and advanced stages of natural regeneration. The elevated H′ values indicate a competitive coexistence of multiple plant species at early growth stages, contributing to increased structural and compositional complexity. Notably, plots such as TAJ1-4 and TAJ1-3 displayed particularly high diversity in the sapling stratum, positioning them as key regeneration hotspots. These areas warrant focused ecological management and protection to support uninterrupted successional development.

Herbaceous Stratum: Microclimatic Richness and Cautionary Signs

Among all vegetation layers, the herbaceous stratum demonstrated the highest biodiversity, with the Shannon-Wiener index reaching up to 2.33 in plot TAJ5-8. This high diversity reflects favorable microclimatic conditions that enable a wide variety of herbaceous species to thrive, including early successional pioneers such as *Chromolaena odorata* and *Imperata cylindrica*, as well as numerous local native species. These plants play essential ecological roles in stabilizing soil, enhancing nutrient cycling, and supporting early ecosystem balance. However, the dominance of aggressive or invasive species—especially *Imperata cylindrica*—indicates past disturbances and presents a potential threat to long-term biodiversity recovery. Without intervention, these species may suppress succession and alter habitat trajectories.

Management Implications: Supporting Succession and Controlling Invasion

The observed patterns of dominance and diversity across strata highlight critical priorities for ecosystem restoration and management. While the upper strata (tree and pole) require interventions to mitigate dominance and promote species diversification, the lower strata (sapling, stake, and herbaceous) offer encouraging signs of natural regeneration. Management efforts should focus on protecting high-diversity zones, especially in the sapling and stake layers, while implementing control measures against invasive herbaceous species. Recommended strategies include enrichment planting using native or site-adapted species, continuous monitoring of regeneration dynamics, and strategic removal or containment of invasive species. Such proactive and stratified approaches will support the development of ecologically balanced and resilient post-mining ecosystems.

Table 7 . Correlation matrix of diversity index (H') among plant strata.

Strata	Tree	Pole	Stake	Sapling	Herbaceous
Tree	1.00	(0.30)	0.60	0.37	0.05
Pole	(0.30)	1.00	0.24	(0.27)	(0.09)
Stake	0.60	0.24	1.00	0.08	(0.51)
Sapling	0.37	(0.27)	0.08	1.00	0.33
Herbaceous	0.05	(0.09)	(0.51)	0.33	1.00

The analysis of vegetation across sites TAJ1-1 through TAJ5-8 reveals clear patterns of species diversity, dominance, and ecological interactions, highlighting important implications for ecosystem management and long-term recovery. Dominance Patterns and Ecological Succession:Strong dominance by single species, such as Acacia mangium, Hevea brasiliensis, and Albizia chinensis, is evident in the tree and pole strata, with Importance Value Index (IVI) scores reaching up to 300. This dominance indicates previous ecosystem disturbances like logging, deforestation, or monoculture plantation establishment (Adman, Nugroho, and Yassir 2020) Consequently, species richness in these upper strata is limited, with a maximum diversity index (H') of only 0.96 observed at TAJ1-4, suggesting ecosystems are either in an early stage of ecological succession or experiencing inhibited recovery. Active Natural Regeneration and Ecosystem Recovery : Conversely, the stake and sapling strata demonstrate significantly higher diversity indices, reflecting active natural regeneration and ecological resilience (Yuningsih et al. 2021) Sites such as TAJ1-4 and TAJ1-3 exhibit notably high sapling diversity indices (1.71 and 1.69, respectively), marking them as important conservation and protection areas. The vigorous competition among diverse species in these layers underscores their critical role in sustaining ecological recovery, emphasizing the need for targeted management to maintain and enhance biodiversity. Ecological Significance of the Herbaceous Layer:The herbaceous layer shows the highest species diversity among all vegetation strata, with a diversity index (H') reaching 2.33 at site TAJ5-8. This high diversity reflects favorable microclimatic and soil conditions, emphasizing the herbaceous layer's vital roles in ecosystem functions such as soil stabilization, nutrient cycling, and supporting initial stages of regeneration (Serviss and Tumlison 2021) (Valencia et al. 2020) However, the presence of invasive species such as Imperata cylindrica and Chromolaena odorata indicates past disturbances and presents potential threats to long-term regeneration if unmanaged. Insights from Ecological Correlation Analysis:Correlation analysis further enhances understanding of inter-strata ecological interactions. A strong positive correlation (0.64) between the tree and stake strata highlights the important role of mature trees in supporting younger plant regeneration through seed provision and microhabitat creation. Conversely, a significant negative correlation (-0.51) between stake and herbaceous layers suggests competitive interactions, with dense stake vegetation potentially limiting herbaceous growth through shading and resource competition. Other moderate to weak correlations among strata indicate complex ecological interactions influenced by environmental variability and historical human disturbances. Site-Specific Management Recommendations:Sites TAJ5-8 and TAJ4-7, characterized by high biodiversity and advanced stages of recovery, should be prioritized for protection and minimal disturbance. Conversely, site TAJ1-2, dominated by monoculture plantations, highlights negative ecological impacts and requires targeted management interventions (Arévalo et al. 2023)

Predicted Ecological Recovery Over 10 Years

A 10-year ecological recovery analysis reveals a clear pattern in vegetation succession, where biodiversity increases during the early stages and begins to stabilize between years two and four. The herbaceous and stake strata exhibit rapid initial recovery, reaching peak diversity by the second year (H' = 1.6), after which the values plateau, indicating early stabilization. Saplings, in contrast, show a slower but steady increase in diversity, with stabilization occurring around the fourth year. This reflects their need for a longer adaptation period before establishing a stable community structure (De Leijster et al. 2021) .

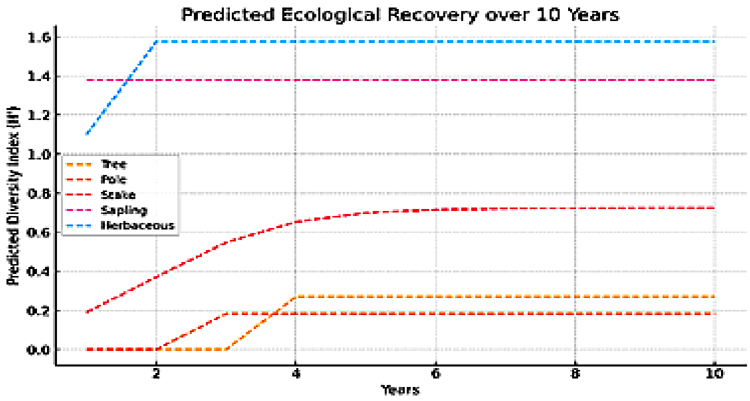

Figure 5. Predicted ecological recovery over 10 years

Lower vegetation layers, including herbs and small shrubs, recover quickly in post-mining areas due to their adaptability and role in early ecosystem functions like soil stabilization and erosion control. In contrast, tree and pole strata recover more slowly, often requiring three or more years to stabilize due to environmental constraints such as poor soil and limited water. These findings highlight the need for a multistrata restoration strategy that combines early-establishing ground cover with long-term investment in native tree species and soil improvement. Effective rehabilitation should integrate growth dynamics, species diversity, and environmental conditions to ensure full vegetation recovery and ecosystem resilience over time..

An analysis of the Importance Value Index (IVI), species richness, and the Shannon-Wiener Diversity Index (H') indicates that the most sustainable observational sites are those characterized by high biodiversity, a well-balanced distribution of species across vegetation strata, and strong natural regeneration potential. Sites with higher H' values demonstrate greater ecological stability and resilience, suggesting that diverse and evenly distributed plant communities are better equipped to support long-term ecosystem recovery. These qualities enhance the capacity of ecosystems to withstand environmental disturbances, facilitate successional progression, and maintain ecological functionality. Therefore, evaluating vegetation structure and diversity through IVI and H' provides a reliable basis for identifying and managing ecologically sustainable sites in post-mining reclamation landscapes**.** (Mustapha, Adamu, and Inuwa 2022). Sustainability is strengthened when tree and pole strata have low monodominance, while sapling and herbaceous strata maintain high diversity, ensuring a balanced and resilient ecosystem. These layers play a crucial role in supporting natural regeneration and ecosystem stability. Additionally, the positive correlation between species count and H' confirms that greater species diversity enhances long-term sustainability. Understanding these factors is essential for evaluating and managing reclaimed sites, helping to create healthy, self-sustaining ecosystems that can thrive over time.

TAJ1-4 stands out as the most sustainable site, with balanced biodiversity across all vegetation strata. The H' values increase from the tree layer (0.96) to the herbaceous layer (1.25), indicating a smooth ecological transition and effective natural regeneration. TAJ5-8 also shows strong sustainability potential, especially in the herbaceous layer (H' = 2.33), though some monodominance in the upper strata suggests the need for further diversity enhancement. Similarly, TAJ1-3 exhibits high diversity in the sapling (H' = 1.69) and herbaceous layers (H' = 1.96), signaling promising natural regeneration, but remains dominated by Acacia mangium in the upper canopy. Overall, TAJ1-4 is the most ecologically stable, while TAJ5-8 and TAJ1-3 demonstrate strong recovery potential, particularly in the lower vegetation strata. These findings highlight the importance of active restoration efforts, such as species enrichment, to further enhance ecosystem sustainability and ensure long-term biodiversity resilience..(Helfenstein et al. 2022)

Vegetation similarity

Vegetation similarity refers to the degree of resemblance in species composition between two or more locations or areas. This concept is quantified using similarity indices, such as the Sørensen Similarity Index, which measures the overlap of species between two locations, providing an indication of how similar their vegetation communities are. A higher similarity value indicates greater overlap of species, suggesting that the locations have comparable vegetation structures and habitat potentials. Conversely, lower similarity values indicate significant differences in species composition, which may be influenced by various ecological factors, including climate, soil conditions, topography, or differing stages of ecological succession. (Ivanova, Fomin, and Kusbach 2022). The analysis of vegetation similarity offers valuable insights into species distribution patterns, ecosystem dynamics, and differences in the stages of vegetation recovery or development across various regions. Additionally, understanding vegetation similarity can aid in the design of more effective, site-specific conservation and restoration strategies, tailored to the unique characteristics of each location, thereby enhancing ecosystem management efforts (Table 8)

Table 8 **.** Matrix of Sorensen Similarity Index to compare the similarity between observation locations.

	TAJ1-1	TAJ1-2	TAJ1-3	TAJ1-4	TAJ4-5	TAJ4-6	TAJ4-7	TAJ5-8
TAJ1-1		35.90%	**50.00%**	42.86%	57.14%	38.89%	27.91%	44.44%
TAJ1-2	35.90%		43.90%	20.51%	25.64%	24.24%	10.00%	19.05%
TAJ1-3	50.00%	43.90%		31.82%	45.45%	**52.63%**	13.33%	34.04%
TAJ1-4	42.86%	20.51%	31.82%		38.10%	22.22%	23.26%	22.22%
TAJ4-5	57.14%	25.64%	45.45%	38.10%		44.44%	32.56%	**57.78%**
TAJ4-6	38.89%	24.24%	52.63%	22.22%	44.44%		32.43%	51.28%
TAJ4-7	27.91%	10.00%	13.33%	23.26%	32.56%	32.43%		39.13%
TAJ5-8	44.44%	19.05%	34.04%	22.22%	57.78%	51.28%	39.13%	

The Sørensen Similarity Index measures the degree of similarity between observation locations based on specific ecological parameters, with values ranging from 0% (no similarity) to 100% (perfect similarity). The analysis reveals that the highest similarity is observed between TAJ4-5 and TAJ5-8 (57.78%), indicating that these two locations share many common ecological characteristics. Additionally, TAJ1-1 and TAJ4-5 also exhibit a strong relationship (57.14%), suggesting similar species composition or environmental factors. In contrast, the lowest similarity is found between TAJ1-2 and TAJ4-7 (10.00%) and between TAJ1-3 and TAJ4-7 (13.33%), reflecting significant differences in their species composition or environmental conditions. When analyzing location groups, TAJ1 (which includes TAJ1-1, TAJ1-2, TAJ1-3, and TAJ1-4) maintains relatively high internal similarity but exhibits greater variation when compared to the TAJ4 and TAJ5 groups. The TAJ4 group (which includes TAJ4-5, TAJ4-6, and TAJ4-7) shows mixed relationships, with TAJ4-5 and TAJ4-6 sharing relatively high similarity, while TAJ4-7 appears significantly distinct. Furthermore, TAJ5-8 seems more closely related to TAJ4-5 and TAJ4-6 than to the TAJ1 group, further reinforcing the observed grouping pattern. These findings suggest that locations within each group share more similar ecological conditions or species composition, while locations between groups exhibit clearer ecological differences. This analysis underscores the importance of grouping locations based on similarity to identify common ecological characteristics, which can inform more targeted conservation and restoration efforts.

These variations in similarity suggest that locations with higher indices likely experience similar environmental conditions, such as vegetation, soil composition, or other ecological factors, while those with lower similarity may be shaped by differences in elevation, land use, or human activity. The similarity matrix provides valuable insights for understanding species distribution patterns, selecting conservation sites, and assessing ecosystem dynamics within the study area, ultimately supporting more informed ecological management and restoration efforts.

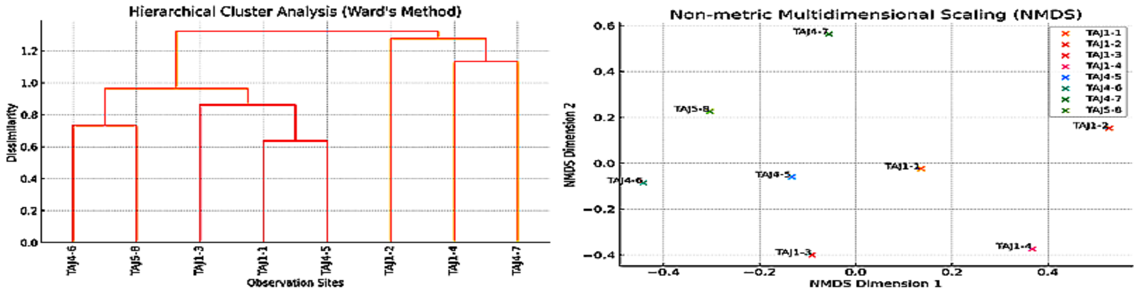

Fig 6. a) Hierarchical Cluster Analysis b) Non-metric Multidimensional Scaling (NDS)

The Sørensen Similarity Index results were further tested using Hierarchical Cluster Analysis (HCA) and Non-metric Multidimensional Scaling (NMDS). The findings from both HCA and NMDS generally align with the Sørensen Similarity Index, confirming that these multivariate analyses effectively support the calculated vegetation similarity between locations.(Cabon et al. 2024), This suggests that these multivariate analyses effectively reinforce the calculated vegetation similarity between locations. In HCA (Dendrogram), the clustering pattern reflects the relationships between locations based on vegetation similarity. Locations with the highest Sørensen similarity, such as TAJ4-5 and TAJ5-8 (57.78%), are grouped closely together, indicating that their vegetation communities share a similar species composition. On the other hand, locations with low similarity, like TAJ1-2 and TAJ4-7 (10.00%), appear on separate branches, emphasizing the significant differences in their vegetation structures. A similar trend is observed in NMDS, where locations with high Sørensen similarity are positioned close to each other in the multidimensional space, while those with low similarity are more spread out. This suggests that the spatial distribution of vegetation communities in NMDS corresponds well with the Sørensen Similarity Index. It further reinforces the idea that while some locations may have comparable species diversity, their ecological development and trajectories still differ..(Armstrong et al. 2021).

The analysis confirms that while some locations exhibit similar levels of vegetation diversity, their ecological development follows different paths. This variation is likely driven by environmental factors such as soil conditions, microclimate, and ecological disturbances, which influence species composition and vegetation structure in each reclamation area. Therefore, the results of HCA and NMDS strongly support and align with the Sørensen Similarity Index, further validating the observed patterns of vegetation similarity across the study sites (Fernandes 2021)

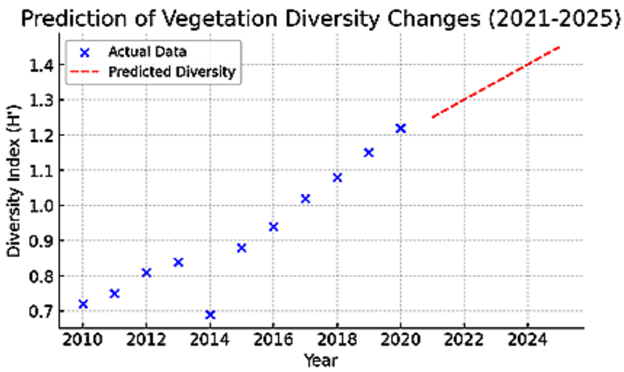

Figure 7. Historical and predicted vegetation diversity index (2010-2025)

The projected increase in vegetation diversity (H') from 2021 to 2025, with an annual growth rate of 0.0485, reflects positive ecological succession. A linear regression model ($R^2 = 0.748$, $p = 0.00123$) suggests that 74.8% of biodiversity variation can be explained by this trend, highlighting the role of natural regeneration and human interventions such as revegetation and environmental management. However, this progress is influenced by factors like rainfall, temperature, humidity, and human activities, all of which play a critical role in maintaining ecosystem stability. The study area is characterized by moderate hills (0–180 m above sea level) with slopes ranging from 10% to 40%, which impact runoff and erosion rates (131.59–2149.87 tons/ha/year). The region's dendritic and rectangular river system, shaped by topography, further influences water flow and soil stability. Climate conditions, including rainfall (13.86–72.95 mm), temperatures (21.0–35.4°C), and humidity (69.91–82.17%), directly affect plant growth and ecosystem dynamics. Additionally, wind speeds (1.27–13.38 m/s) and solar radiation levels (38.15–73.59%) regulate photosynthesis and help maintain a balanced microclimate.(Gautam et al. 2022) The presence of Podsolic and Cambisol soils affects water retention capacity, which in turn influences vegetation succession. Despite generally good air quality, noise levels (53.5–70.9 dB) from both natural and human activities may pose challenges to ecological stability. (Piotrowska-Długosz et al. 2022) A heatmap analysis reveals that rainfall and humidity are key factors in supporting biodiversity, while high erosion rates and steep slopes present challenges by degrading soil quality and making it difficult for plants to establish and grow. While overall trends indicate that reclamation efforts have been successful, long-term sustainability depends on effective soil conservation, water management, and adaptive land-use planning. Without these measures, erosion could destabilize habitats, and limited water resources might hinder plant regeneration. To ensure lasting ecosystem resilience and continued biodiversity recovery, it is essential to implement ongoing monitoring, reforestation with native species, and science-based conservation strategies. (Huang et al. 2021)

Table 9: Multivariate regression analysis of environmental factors affecting biodiversity (h') in reclamation. areas

Environmental Factor	Rainfall	Temperature	Humidity	Wind Speed	Solar Radiation	Biodiversity (H')
Rainfall	1	-0.53	0.46	-0.36	-0.36	-0.69
Avg. Temperature	-0.53	1	0.36	-0.59	-0.12	-0.41
Avg. Humidity	0.46	0.36	1	-0.11	0.21	0.54
Wind Speed	-0.36	-0.59	-0.11	1	0.33	0.53
Solar Radiation	-0.36	-0.12	0.21	0.33	1	0.18

The heatmap visualization confirms the validity and linearity of the multivariate regression analysis, revealing strong and consistent correlations between environmental variables and biodiversity (H′ index). These relationships align with ecological principles, showing that factors such as rainfall, temperature, humidity, wind speed, and solar radiation significantly influence vegetation diversity and successional processes. The findings demonstrate both statistical robustness and ecological relevance, providing critical insights for developing adaptive, site-specific restoration strategies to support sustainable post-mining ecosystem recovery.

The multivariate regression heatmap (Table 9) illustrates key relationships between environmental variables and biodiversity (H') in reclaimed post-mining areas. Rainfall shows a strong negative correlation ($r = -0.69$), indicating that excessive precipitation may impede succession by causing erosion and waterlogging, especially in unstable soils. Conversely, humidity ($r = 0.54$) and wind speed ($r = 0.53$) have moderate positive correlations with biodiversity, highlighting their supportive role in plant growth and species richness. A moderate negative correlation with temperature ($r = -0.41$) suggests that higher temperatures may reduce diversity by limiting heat-sensitive species. These relationships are statistically consistent with the biodiversity trend observed from 2021 to 2025, as a linear regression model ($R^2 = 0.748$; $p = 0.00123$) demonstrates a steady increase in diversity over time. The results confirm that biodiversity recovery in reclamation areas is not solely driven by restorative interventions, but is also strongly influenced by local environmental conditions. Therefore, the heatmap visualization serves as both an analytical and management tool, offering practical insights to support adaptive restoration planning, particularly in addressing limiting factors such as rainfall-induced erosion and thermal stress.

Figure 8. Multivariate regression heatmap illustrating the influence of key environmental variables on biodiversity (H' index) within post-mining reclamation areas. The visualization reveals clear and consistent

patterns of correlation between abiotic factors—including rainfall, temperature, humidity, wind speed, and solar radiation—and vegetation diversity across multiple reclamation sites. Notably, rainfall exhibits the strongest negative correlation with biodiversity (r = -0.69), suggesting that excessive precipitation may impede ecological succession by increasing surface runoff, erosion, and waterlogging, particularly in unstable reclaimed soils..

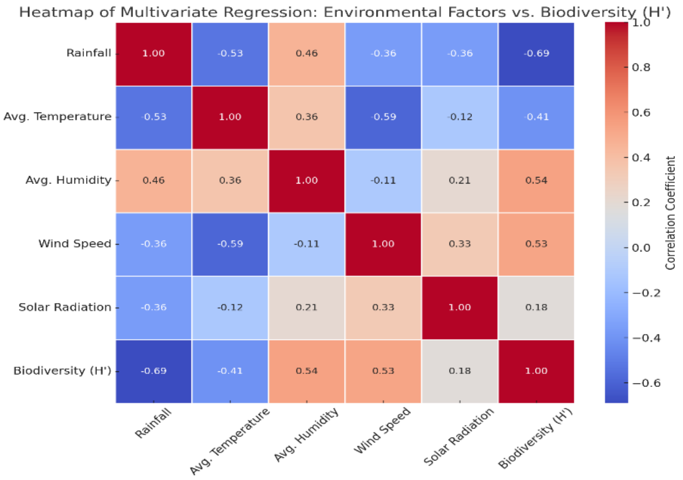

Figure 8. Multivariate regression heatmap: environmental drivers of biodiversity in reclamation areas

Average humidity (r = 0.54) and wind speed (r = 0.53) show moderate positive correlations with biodiversity, indicating that favorable microclimates enhance vegetation growth. In contrast, average temperature correlates moderately negatively (r = -0.41), suggesting that higher temperatures may limit heat-sensitive species. These findings are consistent with the 2021–2025 biodiversity trend, where a linear regression model ($R^2 = 0.748$; $p = 0.00123$) demonstrates steady biodiversity recovery over time. This highlights the combined influence of environmental conditions and restoration efforts. The heatmap thus serves as a practical tool for guiding adaptive restoration by identifying and addressing key limiting factors.

Analysis and Discussion: Multivariate Regression Analysis of Environmental Factors Affecting Biodiversity (H') in Reclamation Areas

Table 9 presents the results of a multivariate regression analysis that explores the relationship between several environmental factors and biodiversity (H') in reclamation areas. The environmental factors examined include rainfall, temperature, humidity, wind speed, and solar radiation, with their respective correlations with biodiversity shown in the final column. The analysis reveals that rainfall has a strong negative correlation with biodiversity (r = -0.69), indicating that higher rainfall may be associated with lower biodiversity in the reclamation areas. This could be due to the potential for waterlogging or soil erosion in areas with heavy rainfall, which may inhibit the growth of certain plant species. Temperature also shows a negative relationship with biodiversity (r = -0.41), suggesting that higher temperatures may create stressful conditions for species survival, potentially affecting biodiversity. This is consistent with the idea that extreme temperature fluctuations may limit the ability of species to thrive in disturbed environments, particularly in reclaimed areas that are still undergoing ecological recovery. On the other hand, humidity has a positive correlation with biodiversity (r = 0.54), indicating that higher humidity levels may promote plant growth and enhance biodiversity in these areas. Humidity likely contributes to the maintenance of soil moisture, supporting the growth of vegetation and providing favorable conditions for species to establish and proliferate. Similarly, wind speed also shows a moderate positive correlation with biodiversity (r = 0.53), which may be linked to the role of wind in seed dispersal, promoting the establishment of new plant species and contributing to biodiversity.

Solar radiation demonstrates a relatively weak positive correlation with biodiversity (r = 0.18), suggesting that while solar radiation plays an essential role in photosynthesis and plant growth, its direct influence on biodiversity in reclaimed areas may be less pronounced compared to other factors such as humidity or rainfall.

Overall, the multivariate regression analysis indicates that the environmental factors influencing biodiversity in reclamation areas are complex and multifaceted. The findings highlight the importance of understanding how these factors interact to shape the ecological recovery of disturbed areas. Rainfall and temperature emerge as significant negative factors affecting biodiversity, while humidity and wind speed appear to have more positive influences. These insights can help guide more effective reclamation and restoration efforts by considering the environmental conditions that promote or hinder biodiversity recovery.

Strategic Approach to Biodiversity Management in Reclamation Areas

A comprehensive multivariate and stepwise regression analysis revealed that approximately 90.5% of biodiversity variability (H') in post-mining reclamation areas is influenced by environmental factors, notably wind speed, rainfall, temperature, humidity, solar radiation, and erosion. Despite this, the adjusted R^2 of 0.338 suggests other factors—such as soil conditions, past disturbances, and species interactions—also play a role, emphasizing the need for an integrated, ecosystem-based management approach. Wind speed emerged as the strongest positive driver of herbaceous richness, highlighting its role in seed dispersal and early succession. Species like *Albizia chinensis* and *Vitex pinnata* are recommended for revegetation due to their adaptability and soil-enhancing traits. Rainfall and humidity positively supported vegetation growth, though excessive rainfall could lead to erosion and nutrient loss. Meanwhile, higher temperatures and solar radiation showed negative correlations, indicating the need for shade-tolerant and drought-resilient species in exposed areas. Erosion showed mixed effects—moderate levels may aid colonization, while severe erosion harms soil stability. Thus, ground cover, terracing, and erosion control are vital components of reclamation. The study's findings validate key hypotheses: (1) biodiversity increases with reclamation age; (2) species richness and density are shaped by slope, cover, and microclimatic factors; (3) mixed-species revegetation supports greater diversity than monocultures; and (4) abiotic–biotic interactions significantly influence recovery trajectories. These insights underscore the importance of adaptive, site-specific restoration strategies supported by long-term ecological monitoring. (Edwards et al. 2021)

Collectively, these findings offer a robust, science-based framework for biodiversity management in post-mining reclamation areas. By integrating site-specific environmental data with ecological principles, restoration practitioners can enhance the long-term resilience and sustainability of reclaimed tropical landscapes such as those in Kalimantan.

CONCLUSION

Sustainable post-mining reclamation in Kalimantan is crucial for biodiversity restoration and long-term ecological balance. Older sites tend to support higher species richness due to natural succession, while younger areas are dominated by fast-growing pioneers like *Acacia mangium*. Monocultures, such as *Hevea brasiliensis* plantations, limit diversity and may impair ecosystem function. Vegetation structure analysis revealed that tree and pole strata dominate mature sites, while saplings and herbs reflect ongoing regeneration. Biodiversity hotspots were identified in TAJ4-7 and TAJ5-8, with TAJ4-6 showing lower diversity due to poor soil conditions. The Sørensen Index indicated varied species composition, suggesting different recovery pathways. The study confirmed that diversity increases with reclamation age, and that factors like slope, humidity, and ground cover significantly influence recovery. Mixed-species revegetation proved more effective than monocultures. These findings highlight the need for ecosystem-based, site-specific strategies that incorporate native species, soil management, and ongoing monitoring. Conservation efforts should prioritize ecologically important species like *Peronema canescens*, while remote sensing can support adaptive restoration planning.

REFERENCES

Addi, Admassu, Teshome Soromessa, and Tura Bareke. 2020. "Floristic Composition and Vegetation Community Analysis of Gesha and Sayilem Forest in Kaffa Zone South Western Ethiopia." *Biodiversitas*

Journal of Biological Diversity 21(7).

Adman, Burhanuddin, Ardiyanto Wahyu Nugroho, and Ishak Yassir. 2020. “The Growth of Local Tree Species on Post-Coal Mining Areas in East Kalimantan.” *Indonesian Journal of Forestry Research* 7(2):83–97.

Ali, F., M. Zeb, M. Amin, M. N. Rajpar, S. Hidayat, and W. R. Khan. 2024. “Vegetation–Edaphic Correlation and Importance Value Index in Himalayan ‘Ecotone’Temperate Conifer Forest Using the Multivariate Technique.” *Saudi Journal of Biological Sciences* 31(5):103983.

Anwar, Khoerul, and Didik Triwibowo. 2024. “AVIFAUNA DIVERSITY IN THE MINING AREA OF PT ADARO INDONESIA.” *Russian Journal of Agricultural and Socio-Economic Sciences* 147(3):85–93.

Arévalo, José Ramón, María Bernardos, Cristina González-Montelongo, and Federico Grillo. 2023. “Prescribed Burning Effect on the Richness, Diversity and Forest Structure of an Endemic Reforested Pinus Canariensis Stand (Canary Islands).” *Fire* 6(4):150.

Armstrong, Chelsey Geralda, Jesse E. D. Miller, Alex C. McAlvay, Patrick Morgan Ritchie, and Dana Lepofsky. 2021. “Historical Indigenous Land-Use Explains Plant Functional Trait Diversity.”

Asnawi, Ariyono Suyono Supomo, Yuanita Windusari, and Umar Harun. 2023. “Secondary Succession of Vegetation in the Former Coal Mine Area PT. Bukit Asam Tbk.” *Journal of Smart Agriculture and Environmental Technology* 1(3):94–98.

Atalitsa, Caren N., George M. Ogendi, John M. Mironga, and Nicholas Olekaikai. 2021. “Assessment of Plant Commnunity Structure in a Tropical Wetland Affected by Brick Making—The Case of Sironga Wetland, Kenya.” *Journal of Environmental Protection* 12(11):1001–8.

Boru, Kemalo Abdulmalik, Lalit Tukaram Ingale, and Kassahun Mulatu Lemt. 2024. “Wetland Ecosystem: Plant Species Diversity, Services, Degradation Drivers, and Community Perception in Sinana District, Oromia Region, Southeast Ethiopia.” *Nature Environment and Pollution Technology* 23(1):55–68.

Cabon, Valentin, Hervé Quénol, Vincent Dubreuil, Aurélien Ridel, and Benjamin Bergerot. 2024. “Urban Heat Island and Reduced Habitat Complexity Explain Spider Community Composition by Excluding Large and Heat-Sensitive Species.” *Land* 13(1):83.

Cardoso, Emanuelle Burgos, Paulo Prates Júnior, Marliane de Cássia Soares da Silva, Alan Emanuel Silva Cerqueira, Thuany Cerqueira Jordao, Bruno Coutinho Moreira, Eduardo Gusmão Pereira, and Maria Catarina Megumi Kasuya. 2021. “Composition and Diversity of Prokaryotes at an Iron Ore Post-mining Site Revealed the Natural Resilience 10 Years after Mining Exploitation.” *Land Degradation & Development* 32(1):256–69.

Chahar, Rakhi, Rana Mukherji, Sukalyan Chakraborty, Ravneet Chug, Manmohan Singh Chauhan, and Manishita Das Mukherji. 2023. “Impact of Temporal Variation in Macrophyte Composition on Importance Value Index (IVI), Diversity Indices A Study at Bandhbaretha Wild Life Sanctuary, Rajasthan.” *International Journal of Science, Mathematics, and Technology Learning* 31:212–29.

Edwards, David P., Gianluca R. Cerullo, Susan Chomba, Thomas A. Worthington, Andrew P. Balmford, Robin L. Chazdon, and Rhett D. Harrison. 2021. “Upscaling Tropical Restoration to Deliver Environmental Benefits and Socially Equitable Outcomes.” *Current Biology* 31(19):R1326–41.

Fernandes, Maria da Luz Bandeira Rodrigues. 2021. “Spatial Patterns Models to Support the Portuguese Maritime Spatial Planning.”

Gautam, Pawan Kumar, Dhruv Sen Singh, Anoop Kumar Singh, and Dhirendra Kumar. 2022. “Geomorphic Analysis of Baghain River, Yamuna Basin, and Its Implication for Drainage Characteristic and Tectonics Using Remote Sensing and GIS Techniques.” *Journal of the Geological Society of India* 98(11):1573–84.

Giljum, Stefan, Victor Maus, Nikolas Kuschnig, Sebastian Luckeneder, Michael Tost, Laura J. Sonter, and Anthony J. Bebbington. 2022. “A Pantropical Assessment of Deforestation Caused by Industrial Mining.” *Proceedings of the National Academy of Sciences* 119(38):e2118273119.

Harsono, Rudy, Rachmad Budiwijaya Suba, Wawan Kustiawan, Marlon Ivanhoe Aipassa, Sukartiningsih Sukartiningsih, and Yaya Rayadin. 2024. “Keanekaragaman Vegetasi Pada Beberapa Umur Revegetasi Di

Lahan Reklamasi Pascatambang Batubara PT Indominco Mandiri, Kalimantan Timur." *Jurnal Ilmu Lingkungan* 22(3):589–99.

Helfenstein, Isabelle S., Fabian D. Schneider, Michael E. Schaepman, and Felix Morsdorf. 2022. "Assessing Biodiversity from Space: Impact of Spatial and Spectral Resolution on Trait-Based Functional Diversity." *Remote Sensing of Environment* 275:113024.

Huang, Yinying, Yiming Li, Qiang Chen, Yingying Huang, Jiangtao Tian, Mingqi Cai, Youhui Huang, Yang Jiao, Ying Yang, and Xinglin Du. 2021. "Effects of Reclamation Methods and Habitats on Macrobenthic Communities and Ecological Health in Estuarine Coastal Wetlands." *Marine Pollution Bulletin* 168:112420.

Hughes, Alice C., Michael C. Orr, Qinmin Yang, and Huijie Qiao. 2021. "Effectively and Accurately Mapping Global Biodiversity Patterns for Different Regions and Taxa." *Global Ecology and Biogeography* 30(7):1375–88.

IUCN. 2021. "The IUCN Red List of Threatened Species, Version 2021-1."

Ivanova, Natalya, Valery Fomin, and Antonín Kusbach. 2022. "Experience of Forest Ecological Classification in Assessment of Vegetation Dynamics." *Sustainability* 14(6):3384.

Ivanova, S., A. Vesnina, N. Fotina, and A. Prosekov. 2024. "Technogenically Disturbed Lands of Coal Mines: Restoration Methods." *Nature Environment and Pollution Technology* 23(4):2447–52.

Ji, Chuning, Jiu Huang, Haochen Yu, Yu Tian, Xunzheng Rao, and Xin Zhang. 2022. "Do the Reclaimed Fungal Communities Succeed Toward the Original Structure in Eco-Fragile Regions of Coal Mining Disturbances? A Case Study in North China Loess—Aeolian Sand Area." *Frontiers in Microbiology* 13:770715.

De Leijster, V., M. J. Santos, M. W. Wassen, J. C. Camargo García, I. Llorca Fernandez, L. Verkuil, A. Scheper, M. Steenhuis, and P. A. Verweij. 2021. "Ecosystem Services Trajectories in Coffee Agroforestry in Colombia over 40 Years." *Ecosystem Services* 48.

Listriani, Sophia. 2023. "Understanding The Convention On Species Of Wild Fauna And Flora (Cites): A Study On The Illegal Wildlife Trade In Sumatra Helmeted Hornbill." *Student Journal of International Law* 3(1):69–85.

Mahfud, Mahfud, Rosmawati Rosmawati, and Nurdin Nurdin. 2022. "Corporate Responsibility For Environmental Protection And Management In Ex-Mining Land." *Syiah Kuala Law Journal* 6(1):108–21.

Maiti, Subodh Kumar, Sneha Bandyopadhyay, and Sangeeta Mukhopadhyay. 2021. "Importance of Selection of Plant Species for Successful Ecological Restoration Program in Coal Mine Degraded Land." Pp. 325–57 in *Phytorestoration of abandoned mining and oil drilling sites*. Elsevier.

Mao, Pingping, Jing Zhang, Ming Li, Yiliang Liu, Xu Wang, Ruirui Yan, Beibei Shen, Xiang Zhang, Jie Shen, and Xiaoyu Zhu. 2022. "Spatial and Temporal Variations in Fractional Vegetation Cover and Its Driving Factors in the Hulun Lake Region." *Ecological Indicators* 135:108490.

Mishra, Rajesh Kumar, and Rekha Agarwal. 2024. "Sustainable Forest Land Management to Restore Degraded Lands."

Mustapha, Yakubu, Sunusi Adamu, and Abdulrashid Inuwa. 2022. "Importance Value Index (IVI) of Tree Species and Diversity of Baturiya Hadejia Wetland National Park, Jigawa State, Nigeria." *International Journal of Trend in Scientific Research and Development* 6(2):876–83.

Nufus, M., Y. A. B. Pertiwi, and A. T. Sakya. 2020. "Vegetation Analysis and Tree Species Diversity in KHDTK Gunung Bromo, Karanganyar, Central Java." P. 12010 in *IOP Conference Series: Earth and Environmental Science*. Vol. 528. IOP Publishing.

Nugroho, Yusanto, Gusti Syeransyah Rudy, Eka Saputra, Yudha Hardiyanto, Syamsu Alam, Jeriels Matatula, Adi Putra Wirabuana, and Pandu Yudha. 2022. "A Comparison of Soil Characteristics from Four Land Covers around a Coal Mining Concession Area in South Kalimantan." *Journal of Degraded & Mining Lands Management* 10(1).

Oluyinka Christopher, Ariyo. 2020. "Comparative Analyses of Diversity and Similarity Indices of West Bank

Forest and Block a Forest of the International Institute of Tropical Agriculture (IITA) Ibadan, Oyo State, Nigeria." *International Journal of Forestry Research* 2020:1–8.

Pambudi, Priyaji Agung, Suyud Warno Utomo, Soemarno Witoro Soelarno, and Noverita Dian Takarina. 2023. "Coal Mining Reclamation as an Environmental Recovery Effort: A Review." *Journal of Degraded & Mining Lands Management* 10(4).

Piotrowska-Długosz, Anna, Jacek Długosz, Agata Gryta, and Magdalena Frąc. 2022. "Responses of N-Cycling Enzyme Activities and Functional Diversity of Soil Microorganisms to Soil Depth, Pedogenic Processes and Cultivated Plants." *Agronomy* 12(2):264.

Prakoso, Anjas Prio, and Taufik Faturohman. 2024. "Forecasting Coal Price Using Static and Dynamic Stochastic Model as Based for Indonesia's Mining Project Valuation with Real Option Method." *European Journal of Business and Management Research* 9(1):41–47.

Riefani, Maulana Khalid, and Mochamad Arief Soendjoto. 2021. "Birds in the West Coast of South Kalimantan, Indonesia." *Biodiversitas Journal of Biological Diversity* 22(1).

Sallay, Ágnes, Imola Gecséné Tar, Zsuzsanna Mikházi, Katalin Takács, Cecilia Furlan, and Ulrike Krippner. 2023. "The Role of Urban Cemeteries in Ecosystem Services and Habitat Protection." *Plants* 12(6):1269.

Serviss, BRETT E., and RENN Tumlison. 2021. "Guide to the Naturalized, Escaped, and Adventive Woody Flora of Arkansas." *Phytoneuron* 29:1–193.

Setyono, P., L. Kusumaningrum, M. A. Sunarhadi, M. Sholiqin, M. Nurcahyati, G. E. Berlin, A. Maulidyna, S. A. Jabar, D. N. Waskito, and A. P. Daniswara. 2023. "Identification and Analysis of Biodiversity in the Mount Tidar Botanical Gardens." P. 12013 in *IOP Conference Series: Earth and Environmental Science*. Vol. 1268. IOP Publishing.

Thomas, Glenna, Craig Sheridan, and Peter E. Holm. 2022. "A Critical Review of Phytoremediation for Acid Mine Drainage-Impacted Environments." *Science of the Total Environment* 811:152230.

Vachova, Pavla, Marek Vach, Milan Skalicky, Alena Walmsley, Martin Berka, Kamil Kraus, Helena Hnilickova, Olga Vinduskova, and Ondrej Mudrak. 2022. "Reclaimed Mine Sites: Forests and Plant Diversity." *Diversity* 14(1):13.

Valencia, Enrique, Francesco De Bello, Thomas Galland, Peter B. Adler, Jan Lepš, Anna E-Vojtkó, Roel van Klink, Carlos P. Carmona, Jiří Danihelka, and Jürgen Dengler. 2020. "Vegetation Management Intensity and Landscape." *Proceedings of the National Academy of Sciences* 117(39):24345–51.

Wang, Xueqing, Zhongyi Ding, Shaoliang Zhang, Huping Hou, Zanxu Chen, and Qinyu Wu. 2022. "Spatial–Temporal Multivariate Correlation Analysis of Ecosystem Services and Ecological Risk in Areas of Overlapped Cropland and Coal Resources in the Eastern Plains, China." *Land* 12(1):74.

Warner, Emily, Licida M. Giuliani, Grant A. Campbell, Pete Smith, Nathalie Seddon, Dan Seddon, and Alison Smith. 2024. "An Integrated Approach to Above-and below-Ground Ecological Monitoring for Nature-Based Solutions."

Wicaksono, Muhammad Bagus Adi, and Devi Triasari. 2024. "Coal Post-Mining Reclamation Policies in Several Countries: Lessons for Indonesia." *Journal of Law, Environmental and Justice* 2(3):229–53.

Worlanyo, Adator Stephanie, and Li Jiangfeng. 2021. "Evaluating the Environmental and Economic Impact of Mining for Post-Mined Land Restoration and Land-Use: A Review." *Journal of Environmental Management* 279:111623.

YUNINGSIH, LULU, Hermansyah Hermansyah, Eddy Ibrahim, and Marsi MARSI. 2021. "Diversity, Structure and Composition of Vegetation in Post-Coal Mining Reclamation Area in Sumatra, Indonesia." *Biodiversitas Journal of Biological Diversity* 22(8).

Zine, H., R. Hakkou, E. G. Papazoglou, A. Elmansour, F. Abrar, and M. Benzaazoua. 2024. "Revegetation and Ecosystem Reclamation of Post-Mined Land: Toward Sustainable Mining." *International Journal of Environmental Science and Technology* 21(15):9775–98.