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Plant diversity and vegetation structure across reclamation ages in a tropical gold mine landscape, North Sumatra, Indonesia

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Abstract. *Anwar S, Mansor AB, Haris H, Wahyudi R, Hayati QN, Budiman. 2025. Plant diversity and vegetation structure across reclamation ages in a tropical gold mine landscape, North Sumatra, Indonesia. Biodiversitas 26: 6056-6073.* Restoration is essential to recover biodiversity in post-mining landscapes. This study aimed to descriptively compare the plant diversity and vegetation structure in reclamation sites aged 3 to 12 years at the Martabe gold mine, North Sumatra, Indonesia. Vegetation was sampled using nested quadrat methods with 10% sampling intensity (2.36 ha of 22.8 ha total area); species richness (S), Shannon–Wiener diversity (H′), Margalef richness (R), and evenness (E) were calculated. The Morisita index quantified community similarity, and species dominance was assessed using the Importance Value Index (IVI). Density profiles (ind·ha^{-1}) were also constructed to examine stand structure. This research provides novel insights into the trajectories of ecological succession and restoration potential in tropical mining landscapes. Across all age groups, 177 species were recorded, with seedling-stage richness peaking at 58 species in 3-year-old sites. Seedling communities showed high diversity but low evenness, indicating pioneer species dominance. Sapling and pole stages exhibited moderate diversity with balanced species distributions, while tree communities had the lowest richness but increasing evenness with age. Community similarity increased from the seedling to the tree stage, suggesting convergence toward a mature assemblage. *Falcataria falcata* dominated the tree layer, while *Samanea saman* and *Hibiscus tiliaceus* prevailed in sapling and pole layers. Pioneer plants like *Melastoma malabathricum* and *Asystasia gangetica* were common among the young seedlings. The vegetation density displayed an inverted J-shaped pattern, indicating healthy regrowth. These findings reveal changes in species composition, dominance, and structure over a decade of reclamation, providing valuable information to enhance mine-land restoration strategies in tropical regions.

Keywords: Ecological indices, *Falcataria falcata*, post-mining, regeneration, succession

INTRODUCTION

Gold mining has profound ecological impacts, including habitat fragmentation, soil disturbance, water impairment, and significant biodiversity loss (Sonter et al. 2018; Boldy et al. 2021; Feng et al. 2024). These effects are especially severe in tropical regions such as Indonesia, where mining activities often overlap with globally recognized biodiversity hotspots (Sonter et al. 2017; Von Rintelen et al. 2017; Timsina et al. 2022). The environmental degradation caused by mining disrupts natural regeneration processes, resulting in long-lasting damage to ecosystem functions and services. Such disturbances necessitate the development and implementation of effective ecological restoration strategies that consider the complex interplay of multiple ecological factors to rehabilitate these damaged landscapes (Nie et al. 2021; Washburn et al. 2021; Giljum et al. 2022; Maus et al. 2022; Rillig et al. 2023).

Ecological restoration in tropical regions is critical for rebuilding ecosystem functions, conserving biodiversity, and ensuring the sustainability of natural resources. The unique characteristics of tropical ecosystems, including high species richness and complex successional dynamics, require restoration approaches that integrate an understanding of species interactions, successional trajectories, and structural development of vegetation over time (Holl 2020; Zhu et al. 2022; Luo et al. 2025; Nakadai and Suzuki 2025). Restoration efforts must aim not only to reestablish plant communities but also to recover ecosystem resilience and functional redundancy, which are essential for maintaining ecosystem stability in the face of environmental change (Chazdon 2017; Xu et al. 2023).

Restoration success is heavily assessed using biodiversity and structural metrics that reflect the recovery of ecosystems. Plant diversity indicators, such as species richness, evenness, and the Shannon–Wiener index, provide quantitative measures of community composition and biodiversity recovery (Londe et al. 2017; Shaw 2018; Kitikidou et al. 2024). These metrics help evaluate the extent to which restored sites approximate natural reference conditions in terms of species variety and relative abundance. In addition to diversity metrics, structural characteristics—such as vertical layering patterns, spatial distribution, and stand density—offer insights into the complexity and maturity of vegetation communities, which are closely linked to ecological processes, including nutrient cycling, habitat provision, and microclimate regulation (Maua et al. 2020). Together, diversity and structure metrics form a comprehensive framework for monitoring restoration trajectories and guiding adaptive management.

Despite advances in tropical restoration science and numerous studies on post-mining vegetation recovery, significant knowledge gaps remain, particularly in the context in Indonesia. While many tropical post-mining studies have documented vegetation recovery, there is a notable scarcity of long-term, multi-stage assessments that track changes in plant diversity and structural development over extended reclamation periods. This lack of longitudinal data limits understanding of successional pathways and the effectiveness of restoration interventions under Indonesian tropical conditions. Furthermore, although the Martabe gold mine in North Sumatra has been engaged in reclamation efforts for over a decade, no published studies have yet analyzed its vegetation diversity or structural development across different reclamation ages. This absence of empirical data restricts the ability to evaluate restoration progress, understand species composition dynamics, and refine restoration strategies tailored to the site's specific ecological and management contexts.

Addressing these gaps, the present study aims to compare plant diversity and vegetation structure across reclamation sites aged 3 to 12 years at the Martabe gold mine. Employing a descriptive-comparative approach, this research examines sites with similar environmental conditions and management histories to provide an initial assessment of species composition, dominance patterns, and structural development throughout the reclamation timeline. Although baseline vegetation data are unavailable, limiting precise inference of successional sequences, the findings of this study offer valuable empirical insights that can inform adaptive restoration planning. By elucidating vegetation recovery patterns in a tropical post-mining landscape, this study contributes to the improvement of restoration practices and supports biodiversity conservation in Indonesia's ecologically sensitive mining regions.

MATERIALS AND METHODS

Study area description

The research was conducted in Martabe gold mine, North Sumatra, Indonesia, from January 2024 to July 2024 in a post-mining area that has been reclaimed actively for 3-12 years (Figure 1). The Martabe gold mine is located in a tropical rainforest zone, characterized by high annual rainfall (3500-4000 mm), average temperatures ranging from 21 to 31°C, and predominantly Podzol, Ultisol, and Inceptisol soil types. The site has an average slope of 20%. Reclamation activities included land management by adjusting the drainage system and slope, placing acidic and non-acidic materials, and spreading topsoil. Cover crops based on legumes and local pioneer plants were then planted for up to two years. Once the canopy is deemed to have integrated well and covered the reclaimed land, other local plant species were planted, reflecting the initial plant diversity. Reclamation activities utilized various plant stands, including 19 tree species, 21 sapling species, 21 pole species, and 21 seedling species.

Sampling design

Vegetation sampling was conducted across reclamation blocks established between 2012 and 2021. A total of 59 sampling plots, representing 10% (2.36 ha) of the total sampled area, were distributed across various locations based on revegetation ages. These plots were allocated using a stratified sampling approach where each reclamation block was treated as a stratum, and the number of plots per block was adjusted proportionally to its area (Table 1). The number of plots for each reclamation age was as follows: 6 plots (12 years), 10 plots (11 years), 8 plots (10 years), 8 plots (9 years), 5 plots (5 years), 4 plots (4 years), and 18 plots (3 years). Within each block, plots were placed randomly, with a minimum inter-plot distance of 100 m applied where the block area allowed; for smaller blocks, the number of plots was adjusted to ensure adequate representation of the area.

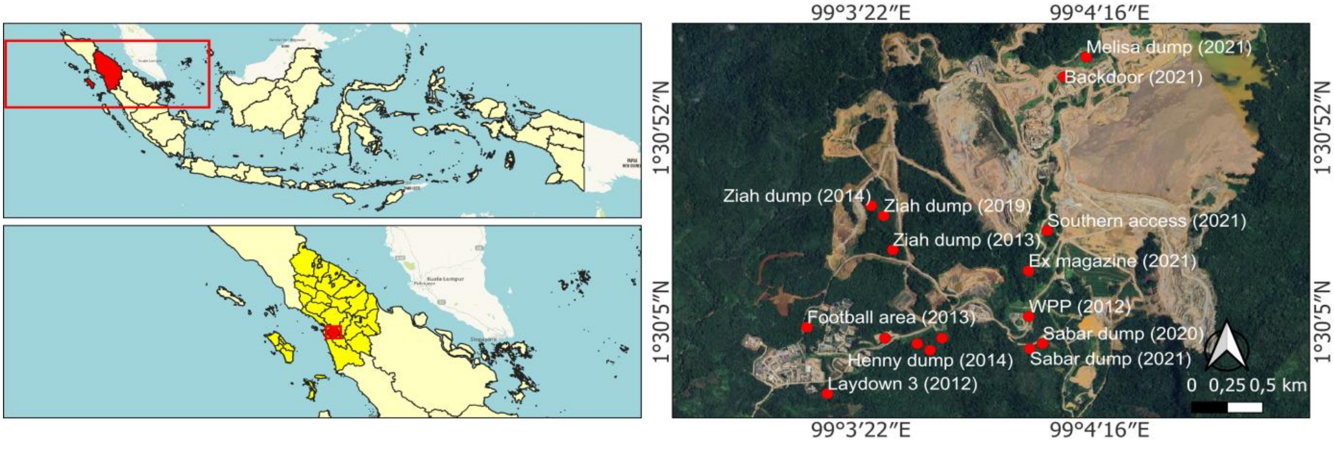

Figure 1. Map of the reclamation sites in Martabe gold mine, North Sumatra, Indonesia

Table 1. The sampling area in the reclamation sites of Martabe gold mine, North Sumatra, Indonesia

Planting year	Area	Total area (ha)	Number of plots	Sampling area (ha)	Age	Coordinate (N, E)
2012	Laydown 3	1.2	5	0.2	12	1°29'47.528"N, 99°3'13.989"E
	WPP	0.3	1	0.04		1°30'6.366"N, 99°3'59.831"E
2013	Ziah dump	1.2	3	0.12	11	1°30'22.658"N, 99°3'28.89"E
	Football area	0.4	3	0.12		1°30'3.746"N, 99°3'9.313"E
	Henny dump	1.8	4	0.16		1°29'59.738"N, 99°3 '34.452"E
2014	Ziah dump	2.8	4	0.16	10	1°30'33.409"N, 99°3' 23.964"E
	Henny dump	1.5	4	0.16		1°29'58.132"N, 99°3' 37.355"E
2015	Ziah dump	2.02	4	0.16	9	1°30'1.08"N, 99°3'27.115"E
	Henny dump	0.63	4	0.16		1°30'1.08"N, 99°3'40.106"E
2019	Ziah dump	2.54	5	0.2	5	1°30'30.967"N, 99°3' 26.806"E
2020	Sabar dump	1	4	0.16	4	1°29'59.754"N, 99°4' 2.967"E
2021	Southern access	1.88	5	0.2	3	1°30'27.334"N, 99°4' 4.033"E
	Sabar dump	2	4	0.16		1°29'58.503"N, 99°4' 0.068"E
	Melisa dump	2.6	5	0.2		1°31'9.743"N, 99°4'12.912"E
	Ex magazine	0.46	2	0.08		1°30'17.52"N, 99°3'59.757"E
	Backdoor	0.47	2	0.08		1°31'4.86"N, 99°4'7.867"E
Total		22.80	59	2.36		

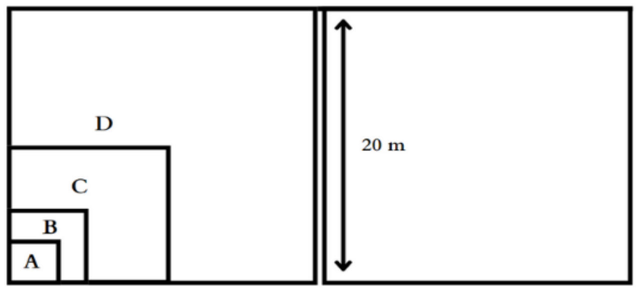

Figure 2. Quadratic method design for vegetation sampling across reclamation ages

Plot establishment

The plant communities for each growth stage (seedlings, saplings, poles, and mature trees) were observed using a quadratic method with random sampling for vegetation analysis across reclamation ages (Figure 2). Seedlings, including understorey plants (shrubs, bushes, lianas, herbs, and ferns), are small trees with a height of less than 1.5 m and a diameter (Ø) of less than 5 cm. Saplings are woody plants with a height of ≥ 1.5 m and a diameter of 5 cm ≤ Ø < 10 cm. Poles are woody plants with a diameter of 10 cm ≤ Ø < 20 cm. Trees are woody plants with Ø ≥ 20 cm (Septiawan et al. 2017).

Tree communities were measured in plots with a size of 20 x 20 m (Figure 2.D). Smaller plot sizes are used to store poles (10 x 10 m; Figure 2.C), saplings (5 x 5 m; Figure 2.B), and seedlings (1 x 1 m; Figure 2.A; Brandt et al. 2017). To ensure these plot sizes were appropriate for the post-mining terrain at Martabe, preliminary field surveys were conducted, which showed that the selected plot sizes were sufficient to capture local heterogeneity in vegetation structure and density, even in areas with steep slopes and disturbed soils.

Species identification

Plant species were identified by local botanical experts and standard taxonomic references, including "Tree Flora of Indonesia: Checklist for Sumatra" (Sidiyasa et al. 1986). Scientific names were then cross-validated using the Global Biodiversity Information Facility (GBIF) and Plant of the World Online (POWO) to ensure the accuracy of current classifications. Complete species lists for each growth stage are provided in Tables S1-S4.

Data analysis

The floristic diversity for seedlings, saplings, poles, and trees across reclamation ages was determined using several ecological indices (Table S5): species richness (S; Kitikidou et al. 2024); Shannon-Wiener diversity index (H'; Daly et al. 2018); Margalef richness index (R; Thukral 2017); evenness index (E; Fedor and Zvaríková 2019); and Importance Value Index (IVI; Osipov 2021). The importance value index for trees and poles was obtained by combining Relative Frequency (RF), Relative Dominance (RDo), and Relative Density (RDe), and produces a value between 0 and 300%. However, the important value index for seedlings and saplings is obtained by combining RF and RDe, with a maximum value of 200%.

The similarity of plant communities among reclamation ages was determined using the Morisita index (Morisita 1961) embedded in the software PAST 4.16 (Hammer 2024). The density of trees, poles, saplings, and seedlings for each reclamation age was also calculated to determine the regeneration status of the vegetation in each selected site. A good regeneration was indicated by the density of seedlings > saplings > poles > trees (Maua et al. 2020). Descriptive data analyses were conducted to compare plant community profiles across reclamation ages.

RESULTS AND DISCUSSION

Profile plant diversity across the gold mine reclamation ages

A total of 177 plant species were found across the varying ages of the Martabe gold mine reclamation areas in South Tapanuli, North Sumatra, Indonesia, of which 18 species belong to the tree stage, 36 species to the pole stage, 54 species to the sapling stage, and 153 species to the seedling stage (Tables S1-S4). The species richness of those plant communities also varied among the reclamation ages (Table 2). At the seedling stage, species richness ranged widely from 19 to 58 species, with the highest richness observed at 3 years of reclamation (58 species) and generally decreasing with increasing reclamation age. The sapling and pole stages also showed a decline in richness with age, although both exhibited fluctuations, with temporary increases at certain ages (e.g., saplings at 11 years). In contrast, the number of tree species tended to increase from 3 to 10-11 years, reaching a plateau of 8 species, followed by a slight decline at 12 years.

The Shannon-Wienner diversity index similarly declined through the stages. At the seedling stage, diversity values ranged from 2.2 to 3.2, indicating moderate to high diversity. In the sapling stage, the index decreased to a range of 1.3 to 2.9. The pole stage maintained moderate diversity with values between 1.0 and 2.5. The tree stage showed the lowest diversity, with values from 0.3 to 1.6. The Margalef index values follow a comparable pattern. At the seedling stage, values ranged from 4.0 to 10.2, peaking at younger reclamation ages. The sapling stage showed lower richness indices between 1.3 and 5.3. The pole stage ranged from 0.7 to 3.8, while the tree stage exhibited the lowest values, from 0.3 to 1.7. Furthermore, the evenness index values varied across stages. At the seedling stage, evenness fluctuated between 0.4 and 0.8, whereas the sapling stage showed consistently high evenness, mostly around 0.8 to 1.0. The pole stage maintained high evenness values, generally between 0.8 and 1.0. At the tree stage, evenness varied more widely from 0.4 to 1.0 (Table 2).

Plant communities' structure and similarity across the gold mine reclamation ages

The similarity of plant communities for each growth stage (seedling, sapling, pole, and tree) across reclamation ages (3-12 years) is shown in Figure 3. At the seedling stage, similarity values were generally low, mostly below 0.6. Similarity increased at the sapling and pole stages, and the tree stage showed the highest similarity values, reaching up to 0.9 across some reclamation ages.

Figure 4 shows the Importance Value Index (IVI) of dominant plant species across four growth stages (tree, pole, sapling, and seedling) and reclamation ages (3 to 12 years). The IVI combines Relative Density (RDe), Relative Frequency (RF), and Relative Dominance (RDo) to reflect species dominance. IVI values varied across stages and reclamation ages with species composition and dominance.

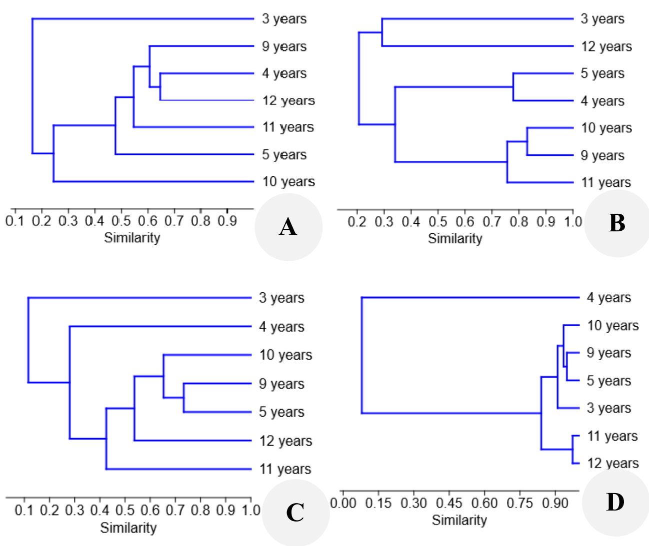

Figure 3. The similarity patterns of plant communities across different reclamation ages at the Martabe gold mine area in North Sumatra, Indonesia. A. Seedling, B. Sapling, C. Pole, D. Tree

Table 2. The ecological indices of plant communities across different reclamation ages at the Martabe gold mine area in North Sumatra, Indonesia

Ecological indices	Reclamation ages (years)						
	12	11	10	9	5	4	3
Seedling stage							
Species Richness_S	21	43	26	27	19	23	58
Shannon-Wienner Diversity Index_H'	2.2	3.2	3.0	2.7	2.7	2.3	3.2
Margalef Richness Index_R	4.0	7.6	5.5	5.0	4.1	4.5	10.2
Evenness Index_E	0.4	0.5	0.8	0.5	0.8	0.4	0.4
Sapling stage							
Species Richness_S	14	24	19	13	8	5	21
Shannon-Wienner Diversity Index_H'	2.7	2.9	2.6	2.4	2.0	1.3	2.6
Margalef Richness Index_R	3.7	5.3	4.5	3.2	2.5	1.3	4.1
Evenness Index_E	1.0	0.9	0.9	0.9	0.9	0.8	0.9
Pole stage							
Species Richness_S	9	13	12	12	9	3	15
Shannon-Wienner Diversity Index_H'	2.1	2.4	2.5	2.0	2.1	1.0	2.3
Margalef Richness Index_R	2.7	3.0	3.2	2.9	2.3	0.7	3.8
Evenness Index_E	1.0	1.0	1.0	0.8	0.9	0.9	0.9
Tree stage							
Species Richness_S	7	8	8	6	3	2	2
Shannon-Wienner Diversity Index_H'	1.6	1.5	1.1	1.0	0.3	0.6	0.7
Margalef Richness Index_R	1.5	1.6	1.7	1.3	0.6	0.3	0.7
Evenness Index_E	0.7	0.6	0.4	0.5	0.5	0.9	1.0

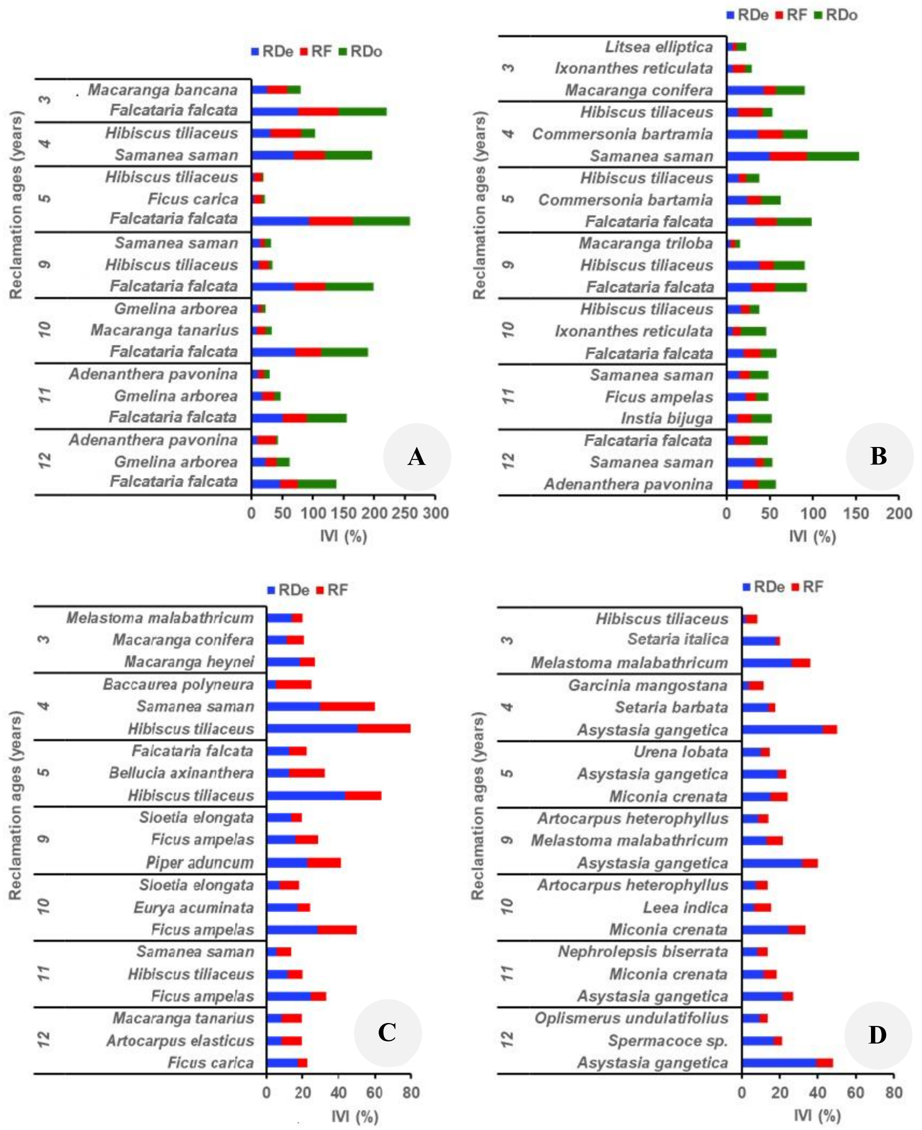

Figure 4. The Importance Value Index (IVI) of dominant plant species across varying reclamation ages at the Martabe gold mine area in North Sumatra, Indonesia. A. Tree, B. Pole, C. Sapling, D. Seedling

At the tree stage, *Falcataria falcata* (L) Greuter & R. Rankin exhibited high IVI values across multiple reclamation ages, particularly at 5 years (IVI 259%), 3 years (IVI 220%), and 9 years (IVI 199%). Meanwhile, *Samanea saman* (Jacq.) Merr. and *Hibiscus tiliaceus* L. were dominant during the early stages of reclamation, with *S. saman* and *H. tiliaceus* reaching IVI values of 196% and 104% (4 years). Other species, such as *Gmelina arborea* Roxb. ex Sm. and *Adenanthera pavonina* L., emerged in later reclamation stages, with IVI values of 23-62% and 29-42%, respectively, particularly at ages 10-12 years. Moreover, *F. falcata* consistently exhibited mid to later pole importance across various ages, achieving a high IVI value of 98% (5 years), while *H. tiliaceus* was predominant between 4 and 10 years, and *S. saman* dominated during the early (4 years) and late (11-12 years) stages of reclamation. At the sapling stage, *H. tiliaceus* and *S. saman* were dominant during the early and late reclamation stages. *Ficus* spp. took precedence from 9 to 12 years. At the seedling stage, *Asystasia gangetica* (L.) T. Anderson became prominent across early to later reclamation ages, with high IVI values of 50% (4 years). *Melastoma malabathricum* L. and *Setaria italica* (L.) P. Beauv. dominated the early stages, with IVI values of 36% and 20% at 3 years. The presence of forest-regenerating species, including *Artocarpus heterophyllus* Lam. (14% at 9-10 years) and *Leea indica* (Burm.fil.) Merr. (15% at 10 years), increased during the later stages of reclamation.

Vegetation density across reclamation ages

The density profile, expressed as individuals per hectare, for four structural layers (seedlings, saplings, poles, and trees) of vegetation under varying reclamation ages is provided in Figure 5. Seedling density ranged from 30,000 to 90,000 ind·ha^{-1} across all sites, followed by successively lower densities in the sapling, pole, and tree layers. All sites exhibited an inverted J-shaped distribution of stand.

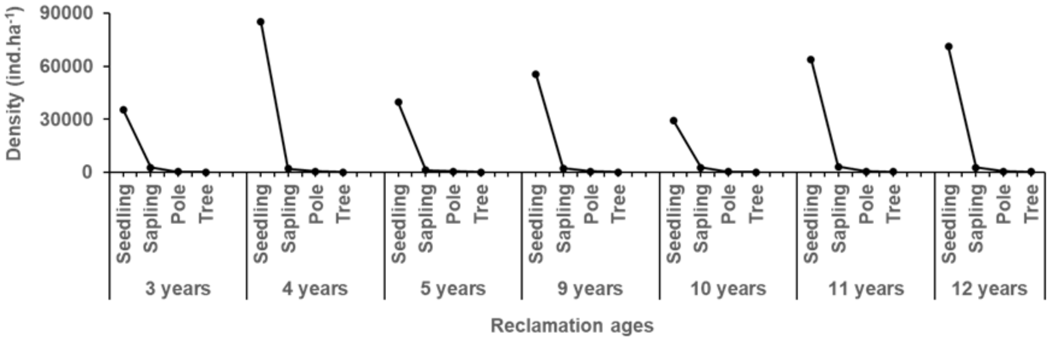

Figure 5. Vegetation density profile across varying ages of reclamation at the Martabe gold mine area in North Sumatra, Indonesia

Discussion

The findings presented the dynamics of plant diversity in the reclaimed areas of Martabe over time. The quality of plant diversity varied among growth stages (seedlings, saplings, poles, and trees). Plant communities at the seedling stage exhibited high diversity quality, characterized by a distinctive pioneer structure across reclamation ages. At three years of reclamation age, the seedling communities were driven by the rapid colonization of pioneer species (e.g., *A. gangetica, Miconia crenata* (Vahl) Michelang, and *M. malabathricum*), but declined by 12 years. Pioneer species, whether native or non-native, can rapidly colonize disturbed areas, providing initial ground cover and stabilizing the soil. These species are often adapted to harsh conditions. They can help ameliorate the site and improve microclimate conditions for later-successional species; however, this may come at the cost of potential trade-offs, as some non-native species can become invasive and hinder natural succession (Cavieres 2021).

The seedlings' species composition shifted steadily to decline with increasing reclamation age, which is likely associated with canopy closure that progressively limits light availability (Xu et al. 2023; Nakadai and Suzuki 2025). The seedling layer is critical for predicting future forest composition, canopy structure, and regeneration (Xu et al. 2023). The presence of native and economically valuable species in later stages, e.g., *Garcinia mangostana* L., *L. indica*, and *A. heterophyllus*, suggests potential recruitment of species beyond early pioneers, although the low evenness at most ages indicates that a few taxa still dominate early regeneration, with more balanced distributions emerging only in mid-successional ages.

Furthermore, plant diversity decreased from seedlings to saplings and poles, but remained relatively stable, except at the four-year reclamation age, where a low diversity was observed due to dominance by *H. tiliaceus* and *S. saman*. Evenness remained uniformly high across all ages, indicating that once seedlings recruit into higher strata, competitive suppression by single species becomes less pronounced. A mix of pioneers and early-successional trees (e.g., *H. tiliaceus*, *Ficus* spp., and *Macaranga* spp.) emerged, suggesting successful recruitment and vertical stratification. Temporary drops in richness, such as at four years, may reflect transitional phases such as cohort thinning rather than long-term regression.

In contrast, the tree communities were similar in plant structure across most reclamation ages, except at four years. The quality of tree diversity remained low in all sites. A dominant tree, e.g., *F. falcata*, consistently outcompeted others for space and resources. However, the gradual increase in tree diversity with age indicates a possible trend toward greater structural complexity, although the dominance of *F. falcata* persists. Importantly, this interpretation is further supported by independent soil data from the same reclamation sites showing significant recovery of soil chemical properties (e.g., pH, organic carbon, total nitrogen, C/N ratio, available phosphorus, and Cation Exchange Capacity (CEC) within a decade, with strong correlation to natural forest soils (R^2 = 0.87). Such soil recovery indicates an improvement in substrate quality, which reinforces the observed vegetation regeneration and supports the “trajectory toward natural forest” interpretation (Anwar et al. 2025).

The consistent presence of native pioneers, such as *Ficus* spp., *Macaranga* spp., and *F. falcata*, suggested successful early successional dynamics; however, the absence of late-successional species highlights the need for extended long-term observation before inferring convergence toward mature forest composition. Thus, diversity indices remain useful indicators for comparing forest stand structure, ecological characteristics, and richness. Although the species composition remains distinct from that of natural forests, the functional patterns observed here are broadly consistent with those of early- to mid-successional stages, indicating partial ecological recovery. This highlights the potential of Martabe’s restoration model as a replicable framework for post-mining reclamation in tropical landscapes.

The vegetation density profile showed an inverted J-shaped curve across all reclamation ages. This structural pattern, characterized by high seedling density followed by progressively lower densities in saplings, poles, and trees, is consistent with commonly reported regeneration structures in recovering tropical forests (Ao et al. 2024). The increasing number of seedlings across sites reflects the availability of early regeneration stages, while the progression to sapling and pole layers illustrates increasing structural layering without implying full equivalence to natural forest conditions (Asmara et al. 2022; da Costa Gonçalves et al. 2023). Furthermore, vegetation structure likely contributes to microclimate amelioration and soil improvement, creating feedbacks that support continued regeneration. Varied stand conditions may also enhance habitat heterogeneity, potentially benefiting fauna associated with regenerating forests (Gastauer et al. 2021).

The overall pattern, high seedling richness dominated by light-demanding pioneers, declining seedling richness with canopy closure, stable mid-story diversity, and a gradual rise in tree-layer similarity with age, generally aligns with established successional models, where pioneer colonization is followed by thinning and compositional stabilization (Maua et al. 2020; Poorter et al. 2023). However, the chronosequence design and unmeasured biotic drivers (e.g., soil microbiota, fine-scale nutrient heterogeneity) limit the strength of mechanistic inferences. Published soil data from the same sites provide useful external validation, but long-term monitoring and permanent plots would be required to confirm the successional trajectories suggested here.

Based on the findings, several sustainability implications and recommendations can be made. For early reclamation (0-5 years), fast-growing native pioneers such as *F. falcata*, *S. saman*, and *H. tiliaceus* should be prioritized for rapid ground cover and soil stabilization. Between 5 and 8 years, enrichment planting with native mid-successional species (e.g., *G. mangostana*, *A. heterophyllus*, *L. indica*) is recommended to enhance vertical and taxonomic diversity. Where *F. falcata* forms dense monospecific patches, selective thinning may be necessary to prevent competitive exclusion of slower-growing native species. Long-term monitoring should include periodic IVI assessment, seedling recruitment surveys, and soil–microbe indicators to evaluate ecological stability. While the Martabe reclamation program demonstrates promising structural and floristic recovery, the observed declines in evenness and richness at later stages indicate the need for adaptive management interventions to maintain balanced regeneration. Integrating diverse native species, promoting biotic interactions, and maintaining habitat heterogeneity will be essential for supporting long-term ecological resilience in post-mining restoration.

In conclusion, the Martabe gold mine reclamation areas exhibit clear successional dynamics over 3-12 years, with 177 plant species recorded. Seedling stages had the highest species richness, dominated by pioneers such as *A. gangetica*, *M. crenata*, and *M. malabathricum*. In contrast, tree richness increased with age, plateauing in mid-aged sites, and was dominated by *F. falcata*. Diversity indices were higher at early stages and lower in the tree layer, whereas evenness was greater in the sapling and pole layers, indicating relatively balanced species distribution. Community similarity increased with growth stage, from low values in seedlings to high values in trees, and IVI analysis revealed dynamic shifts in species dominance from pioneers to mid- and late-successional trees. Vegetation density followed an inverted J-shaped pattern typical of regenerating tropical forests, supporting vertical stratification, soil stabilization, and ongoing recruitment. These findings indicate partial ecological recovery driven by successful pioneer succession, yet the persistent dominance of fast-growing species highlights the need for adaptive management. Enrichment planting, selective thinning, and long-term monitoring are recommended to enhance structural and taxonomic diversity, thereby supporting sustainable forest development. Overall, the Martabe reclamation model proves effective for tropical post-mining restoration, while continued interventions remain essential to achieve mature forest composition.

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REFERENCES

Anwar S, Mansor AB, Haris H, Dharsono M, Lubis A, Wahyudi R, Fathiya N. 2025. Assessment of soil quality changes following land reclamation at the Martabe gold mine, South Tapanuli, Indonesia. Asian J Agric 9 (2): 623-628. DOI: 10.13057/asianjagric/g090229.

Ao A, Changkija S, Tripathi SK. 2024. Patterns of forest community diversity, regeneration potential, and carbon storage along an altitudinal gradient in Eastern Himalaya, India. Environ Sustain Indic 22: 100399. DOI: 10.1016/j.indic.2024.100399.

Asmara DH, Allaire S, van Noordwijk M, Khasa DP. 2022. Tree establishment on post-mining waste soils: Species, density, and mixture effects. Can J For Res 52 (1): 79-89. DOI: 10.1139/cjfr-2021-0044.

Boldy R, Santini T, Annandale M, Erskine PD, Sonter LJ. 2021. Understanding the impacts of mining on ecosystem services through a systematic review. Extr Ind Soc 8 (1): 457-466. DOI: 10.1016/j.exis.2020.12.005.

Brandt JS, Allendorf T, Radeloff V, Brooks J. 2017. Effects of national forest-management regimes on unprotected forests of the Himalaya. Conserv Biol 31 (6): 1271-1282. DOI: 10.1111/cobi.12927.

Cavieres LA. 2021. Facilitation and the invasibility of plant communities. J Ecol 109 (5): 2019-2028. DOI: 10.1111/1365-2745.13627.

Chazdon RL. 2017. Landscape restoration, natural regeneration, and the forests of the future. Ann Mo Bot Gard 102 (2): 251-257. DOI: 10.3417/2016035.

da Costa Gonçalves LF, Balestra CET, Gil MAR. 2023. Evaluation of mechanical, physical and chemical properties of ecological modular soil-alkali activated bricks without Portland cement. Environmental Development 48: 100932. DOI: 10.1016/j.envdev.2023.100932.

Daly AJ, Baetens JM, De Baets B. 2018. Ecological diversity: Measuring the unmeasurable. Mathematics 6 (7): 119. DOI: 10.3390/math6070119.

Fedor P, Zvaríková M. 2019. Biodiversity Indices. In: Fath B (eds). Encyclopedia of Ecology. Elsevier, Amsterdam. DOI: 10.1016/B978-0-12-409548-9.10558-5.

Feng Y, Wang J, Bai Z, Reading L. 2024. Effects of surface coal mining and land reclamation on soil properties: A review. Earth-Sci Rev 191: 12-15. DOI: 10.1016/j.earscirev.2019.02.015.

Gastauer M, Ramos SJ, Caldeira CF, Siqueira JO. 2021. Reintroduction of native plants indicates the return of ecosystem services after iron mining at the Urucum Massif. Ecosphere 12 (11): e03762. DOI: 10.1002/ecs2.3762.

Giljum S, Maus V, Kuschnig N, Luckeneder S, Tost M, Sonter LJ, Bebbington AJ. 2022. A pantropical assessment of deforestation caused by industrial mining. Proc Natl Acad Sci USA 119 (38): e2118273119. DOI: 10.1073/pnas.2118273119.

Hammer Ø. 2024. PAST (Paleontological Statistics) 4.16. Natural History Museum, University of Oslo, Oslo.

Holl KD. 2020. Primer of Ecological Restoration. Island Press, Washington, D.C.

Kitikidou K, Milios E, Stampoulidis A, Pipinis E, Radoglou K 2024. Using biodiversity indices effectively: Considerations for forest management. Ecologies 51 (1): 42-51. DOI: 10.3390/ecologies5010003.

Londe V, de Sousa HC, Kozovits AR. 2017. Key plant indicators for monitoring areas undergoing restoration: A case study at the Das Velhas River, southeast Brazil. Ecol Eng 103: 191-197. DOI: 10.1016/j.ecoleng.2017.04.012.

Luo Y, Cheng J, Mahmood M, Wei S, Peng L, Zhang C, Zhang M, Zhang J, Yang H, Wang J, Hao Z, Yan X. 2025. Plant community restoration time is a key factor affecting plant nutrient and species richness. Sci Rep 15 (1): 15752. DOI: 10.1038/s41598-025-00326-6.

Maua JO, MugatsiaTsingalia H, Cheboiwo J, Odee D. 2020. Population structure and regeneration status of woody species in a remnant tropical forest: A case study of South Nandi forest, Kenya. Glob Ecol Conserv 21: e00820. DOI: 10.1016/j.gecco.2019.e00820.

Maus V, Giljum S, da Silva DM, Gutschlhofer J, da Rosa RP, Luckeneder S, Gass SLB, Lieber M, Mccallum I. 2022. An update on global mining land use. Sci Data 9: 433. DOI: 10.1038/s41597-022-01547-4.

Morisita M. 1961. Mesuring of dispersion of individuals and analysis of the distributional patterns. Jpn J Ecol 11 (6): 252-253.

Nakadai R, Suzuki SN. 2025. Ecological succession revisited from a temporal beta-diversity perspective. For Ecol Manag 580: 122504. DOI: 10.1016/j.foreco.2025.122504.

Nie X, Hu Z, Zhu Q, Ruan M. 2021. Research on temporal and spatial resolution and the driving forces of ecological environment quality in coal mining areas considering topographic correction. Remote Sens 13 (14): 2815. DOI: 10.3390/rs13142815.

Osipov SV. 2021. The importance of a species in a biocoenosis, a class of biocoenoses, and a region: A review of combined indexes. Biol Bull Russ Acad Sci 48: 379-393. DOI: 10.1134/S1062359021030109.

Poorter L, Amissah L, Bongers F, Hordijk I, Kok J, Laurance SGW, Lohbeck M, Martínez-Ramos M, Matsuo T, Meave JA, Muñoz R, Peña-Claros M, van der Sande MT. 2023. Successional theories. Biol Rev Camb Philos Soc 98 (6): 2049-2077. DOI: 10.1111/brv.12995.

Rillig MC, van der Heijden MGA, Berdugo M, Liu YR, Riedo J, Sanz-Lazaro C, Moreno-Jiménez E, Romero F, Tedersoo L, Delgado-Baquerizo M. 2023. Increasing the number of stressors reduces soil ecosystem services worldwide. Nat Clim Chang 13 (5): 478-483. DOI: 10.1038/s41558-023-01627-2.

Septiawan W, Indriyanto I, Duryat D. 2017. Species, density, and canopy stratification of social forestry of the farmers group Rukun Makmur 1 in Register 30 Mount Tanggamus, Lampung. Sylva Lestari 5 (2): 88-110. DOI: 10.23960/jsl2588-101.

Shaw TE. 2018. Species diversity in restoration plantings: Important factors for increasing the diversity of threatened tree species in the restoration of the Araucaria forest ecosystem. Plant Divers 41 (2): 84-93. DOI: 10.1016/j.pld.2018.08.002.

Sidiyasa K, Whitmore TC, Tantra IGM. 1986. The Flora of Indonesia: Check List for Sumatra. Ministry of Forestry, Agency for Forestry Research and Development, Forest Research & Development Centre, Bogor.

Sonter LJ, Ali SH, Watson JEM. 2018. Mining and biodiversity: Key issues and research needs in conservation science. Proc Biol Sci 285: 20181926. DOI: 10.1098/rspb.2018.1926.

Sonter LJ, Herrera D, Barrett DJ, Galford GL, Moran CJ, Soares-Filho BS. 2017. Mining drives extensive deforestation in the Brazilian Amazon. Nat Commun 8: 1013. DOI: 10.1038/s41467-017-00557-w.

Thukral AK. 2017. A review of the measurement of alpha diversity in biology. Agric Res J 54: 1. DOI: 10.5958/2395-146X.2017.00001.1.

Timsina S, Hardy NG, Woodbury DJ, Ashton MS, Cook-Patton SC, Pasternack R, Martin MP. 2022. Tropical surface gold mining: A review of ecological impacts and restoration strategies. Land Degrad Dev 33 (18): 3661-3674. DOI: 10.1002/ldr.4430.

Von Rintelen K, Arida E, Häuser C. 2017. A review of biodiversity-related issues and challenges in megadiverse Indonesia and other Southeast Asian countries. Res Ideas Outcomes 3: e20860. DOI: 10.3897/rio.3.e20860.

Washburn TW, Menot L, Bonifácio P, Pape E, Błażewicz M, Bribiesca-Contreras G, Dahlgren TG, Fukushima T, Glover AG, Ju SJ, Kaiser S. 2021. Patterns of macrofaunal biodiversity across the Clarion-Clipperton zone: An area targeted for seabed mining. Front Mar Sci 8: 626571. DOI: 10.3389/fmars.2021.626571.

Xu C, De Frenne PD, Blondeel H, De Pauw K, Landuyt D, Lorer E, Sanczuk P, Verheyen K, De Lombaerde E. 2023. Light more than warming impacts understory tree seedling growth in a temperate deciduous forest. For Ecol Manag 549: 121496. DOI: 10.1016/j.foreco.2023.121496.

Zhu SC, Zheng HX, Liu WS, Liu C, Guo MN, Huot H, Morel JL, Qiu RL, Chao Y, Tang YT. 2022. Plant-soil feedback for the restoration of degraded mine lands: A review. Front Microbiol 12: 751794. DOI: 10.3389/fmicb.2021.751794.

Table S1. The species richness (S) and Importance Value Index (IVI) of plant species at the tree stage across reclamation ages of the Martabe gold mine, North Sumatra, Indonesia

Species name	IVI (%) across reclamation ages (years)							Reference source	Notes
	12	11	10	9	5	4	3		
Adenanthera pavonina	42	29	0	0	0	0	0	https://www.gbif.org/species/2951846	Verified accepted name
Artocarpus elasticus	0	0	10	0	0	0	0	https://www.gbif.org/species/7425575	Verified accepted name
Bellucia axinanthera	0	0	10	0	0	0	0	https://www.gbif.org/species/3866766	Verified accepted name
Elaeis guineensis	0	0	11	0	0	0	0	https://www.gbif.org/species/2731882	Verified accepted name
Enterolobium cyclocarpum	9	28	0	0	0	0	0	https://www.gbif.org/species/2961150	Verified accepted name
Falcataria falcata	138	155	191	199	259	0	220	https://www.gbif.org/species/10691906	Verified accepted name
Ficus carica	0	0	0	0	22	0	0	https://www.gbif.org/species/5361909	Verified accepted name
Gmelina arborea	62	48	23	0	0	0	0	https://www.gbif.org/species/8247889	Verified accepted name
Hevea brasiliensis	0	0	13	0	0	0	0	https://www.gbif.org/species/3071171	Verified accepted name
Hibiscus tiliaceus	24	13	0	34	20	104	0	https://www.gbif.org/species/3152584	Verified accepted name
Macaranga bancana	0	0	0	0	0	0	80	https://www.gbif.org/species/3074550	Verified accepted name
Macaranga gigantea	0	0	10	11	0	0	0	https://www.gbif.org/species/3074130	Verified accepted name
Macaranga tanarius	0	8	33	0	0	0	0	https://www.gbif.org/species/3074251	Verified accepted name
Macaranga triloba	0	0	0	11	0	0	0	https://www.gbif.org/species/3074333	Verified accepted name
Mallotus paniculatus	12	0	0	0	0	0	0	https://www.gbif.org/species/5378650	Verified accepted name
Samanea saman	12	12	0	32	0	196	0	https://www.gbif.org/species/2972960	Verified accepted name
Syzygium pycnanthum	0	0	0	13	0	0	0	https://www.gbif.org/species/3183498	Verified accepted name
Vitex pinnata	0	6	0	0	0	0	0	https://www.gbif.org/species/7309306	Verified accepted name

Table S2. The species richness (S) and Importance Value Index (IVI) of plant species at the pole stage across reclamation ages of the Martabe gold mine, North Sumatra, Indonesia

Species name	IVI (%) across reclamation ages (years)							Reference source	Notes
	12	11	10	9	5	4	3		
Adenanthera pavonina	57	11	0	0	0	0	14	https://www.gbif.org/species/2951846	Verified accepted name
Areca catechu	0	0	10	0	0	0	0	https://www.gbif.org/species/2736531	Verified accepted name
Artocarpus elasticus	0	0	0	9	0	0	19	https://www.gbif.org/species/7425575	Verified accepted name
Artocarpus integer	0	9	0	10	0	0	10	https://www.gbif.org/species/2984566	Verified accepted name
Baccaurea racemosa	0	0	0	0	16	0	0	https://www.gbif.org/species/3082122	Verified accepted name
Bellucia axinanthera	0	0	0	13	0	0	0	https://www.gbif.org/species/3866766	Verified accepted name
Calamus burckianus	0	0	0	0	0	0	11	https://www.gbif.org/species/5294109	Verified accepted name
Commersonia bartramia	0	16	0	0	62	94	13	https://www.gbif.org/species/7323037	Verified accepted name
Enterolobium cyclocarpum	22	10	0	0	0	0	0	https://www.gbif.org/species/2961150	Verified accepted name
Falcataria falcata	48	21	58	93	98	0	0	https://www.gbif.org/species/10691906	Verified accepted name
Ficus ampelas	0	49	22	0	0	0	0	https://www.gbif.org/species/8042954	Verified accepted name
Ficus carica	0	0	0	0	0	0	10	https://www.gbif.org/species/5361909	Verified accepted name
Gmelina arborea	0	11	24	0	17	0	0	https://www.gbif.org/species/8247889	Verified accepted name
Hevea brasiliensis	0	0	10	0	0	0	0	https://www.gbif.org/species/3071171	Verified accepted name
Hibiscus tiliaceus	36	24	38	91	38	53	0	https://www.gbif.org/species/3152584	Verified accepted name
Homalanthus populneus	0	0	0	0	17	0	0	https://www.gbif.org/species/3072674	Verified accepted name
Intsia bijuga	20	52	0	0	0	0	0	https://www.gbif.org/species/2963211	Verified accepted name
Ixonanthes reticulata	0	0	46	10	0	0	29	https://www.gbif.org/species/4259197	Verified accepted name
Litsea elliptica	0	0	0	0	0	0	23	https://www.gbif.org/species/4177007	Verified accepted name
Macaranga bancana	0	0	10	0	0	0	0	https://www.gbif.org/species/3074550	Verified accepted name
Macaranga conifera	0	0	21	0	0	0	91	https://www.gbif.org/species/3074156	Verified accepted name
Macaranga heynei	0	0	0	0	16	0	0	https://www.gbif.org/species/3074234	Verified accepted name
Macaranga tanarius	0	0	22	0	17	0	16	https://www.gbif.org/species/3074251	Verified accepted name
Macaranga trichocarpa	0	0	0	0	0	0	11	https://www.gbif.org/species/3074384	Verified accepted name
Macaranga triloba	0	0	0	15	18	0	0	https://www.gbif.org/species/3074333	Verified accepted name
Mallotus paniculatus	27	0	0	10	0	0	0	https://www.gbif.org/species/5378650	Verified accepted name
Nephelium mutabile	0	0	16	0	0	0	0	https://www.gbif.org/species/5421127	Verified accepted name
Piper aduncum	0	0	0	0	0	0	14	https://www.gbif.org/species/3086337	Verified accepted name
Pternandra rostrata	17	11	0	0	0	0	0	https://www.gbif.org/species/3867486	Verified accepted name
Samanea saman	53	48	0	12	0	154	9	https://www.gbif.org/species/2972960	Verified accepted name
Sloetia elongata	0	28	22	15	0	0	0	https://www.gbif.org/species/3763185	Verified accepted name
Swietenia macrophylla	0	0	0	13	0	0	0	https://www.gbif.org/species/3190484	Verified accepted name
Swietenia mahagoni	20	0	0	0	0	0	0	https://www.gbif.org/species/3190485	Verified accepted name
Syzygium pycnanthum	0	0	0	0	0	0	22	https://www.gbif.org/species/3183498	Verified accepted name
Terminalia catappa	0	0	0	0	0	0	9	https://www.gbif.org/species/3189394	Verified accepted name
Vitex pinnata	0	11	0	9	0	0	0	https://www.gbif.org/species/7309306	Verified accepted name

Table S3. The species richness (S) and Importance Value Index (IVI) of plant species at the sapling stage across reclamation ages of the Martabe gold mine, North Sumatra, Indonesia

Species name	IVI (%) across reclamation ages (years)							Reference source	Notes
	12	11	10	9	5	4	3		
Adenanthera pavonina	17	0	9	0	0	0	9	https://www.gbif.org/species/2951846	Verified accepted name
Alstonia scholaris	14	0	5	0	0	0	0	https://www.gbif.org/species/5414410	Verified accepted name
Aquilaria malaccensis	0	0	5	0	0	0	0	https://www.gbif.org/species/5524063	Verified accepted name
Artocarpus elasticus	20	4	7	0	0	20	9	https://www.gbif.org/species/7425575	Verified accepted name
Artocarpus integer	0	11	0	0	0	0	0	https://www.gbif.org/species/2984566	Verified accepted name
Baccaurea polyneura	0	0	0	0	0	25	5	https://www.gbif.org/species/3082102	Verified accepted name
Baccaurea racemosa	0	0	0	0	16	0	0	https://www.gbif.org/species/3082122	Verified accepted name
Bellucia axinanthera	0	8	13	9	33	0	3	https://www.gbif.org/species/3866766	Verified accepted name
Coffea arabica	0	0	0	9	0	0	0	https://www.gbif.org/species/2895345	Verified accepted name
Commersonia bartramia	0	5	0	0	0	0	19	https://www.gbif.org/species/7323037	Verified accepted name
Enterolobium cyclocarpum	0	4	0	0	0	0	0	https://www.gbif.org/species/2961150	Verified accepted name
Eurya acuminata	8	4	24	13	0	0	5	https://www.gbif.org/species/3591824	Verified accepted name
Falcataria falcata	0	5	7	9	23	15	5	https://www.gbif.org/species/10691906	Verified accepted name
Ficus ampelas	0	33	50	28	0	0	0	https://www.gbif.org/species/8042954	Verified accepted name
Ficus carica	23	0	0	0	0	0	0	https://www.gbif.org/species/5361909	Verified accepted name
Ficus hispida	8	4	0	0	0	0	0	https://www.gbif.org/species/7879404	Verified accepted name
Ficus variegata	0	4	0	0	0	0	0	https://www.gbif.org/species/3234563	Verified accepted name
Gmelina arborea	0	10	0	0	0	0	0	https://www.gbif.org/species/8247889	Verified accepted name
Hevea brasiliensis	0	0	0	0	0	0	4	https://www.gbif.org/species/3071171	Verified accepted name
Hibiscus tiliaceus	8	20	5	18	64	80	3	https://www.gbif.org/species/3152584	Verified accepted name
Intsia bijuga	11	0	5	0	0	0	0	https://www.gbif.org/species/2963211	Verified accepted name
Ixonanthes reticulata	0	0	5	0	16	0	17	https://www.gbif.org/species/4259197	Verified accepted name
Ixora nigricans	0	7	0	0	0	0	0	https://www.gbif.org/species/2905255	Verified accepted name
Leea aculeata	0	7	0	0	0	0	0	https://www.gbif.org/species/7303645	Verified accepted name
Leea indica	14	7	0	0	0	0	0	https://www.gbif.org/species/4160336	Verified accepted name
Leea rubra	0	0	0	11	0	0	0	https://www.gbif.org/species/7714497	Verified accepted name
Litsea elliptica	0	0	0	0	0	0	3	https://www.gbif.org/species/4177007	Verified accepted name
Macaranga bancana	0	0	0	13	0	0	0	https://www.gbif.org/species/3074550	Verified accepted name
Macaranga conifera	0	0	0	0	0	0	21	https://www.gbif.org/species/3074156	Verified accepted name
Macaranga heynei	0	0	5	0	0	0	27	https://www.gbif.org/species/3074234	Verified accepted name
Macaranga tanarius	20	4	0	0	0	0	0	https://www.gbif.org/species/3074251	Verified accepted name
Macaranga triloba	0	5	0	11	16	0	13	https://www.gbif.org/species/3074333	Verified accepted name
Melastoma malabathricum	0	0	0	0	0	0	20	https://www.gbif.org/species/3188511	Verified accepted name
Nephelium mutabile	0	0	7	0	0	0	0	https://www.gbif.org/species/5421127	Verified accepted name
Parkia speciosa	0	0	0	0	0	0	3	https://www.gbif.org/species/5348811	Verified accepted name
Petiveria alliacea	0	0	5	0	0	0	0	https://www.gbif.org/species/3084012	Verified accepted name
Piper aduncum	0	0	0	41	16	0	3	https://www.gbif.org/species/3086337	Verified accepted name
Pometia pinnata	8	0	0	0	0	0	0	https://www.gbif.org/species/5577338	Verified accepted name
Pternandra azurea	0	0	5	0	0	0	0	https://www.gbif.org/species/3867793	Verified accepted name
Pternandra rostrata	0	5	0	0	0	0	0	https://www.gbif.org/species/3867486	Verified accepted name

Samanea saman	0	14	0	0	16	60	18	https://www.gbif.org/species/2972960	Verified accepted name
Senna siamea	0	0	0	0	0	0	8	https://www.gbif.org/species/2956905	Verified accepted name
Shorea platycarpa	0	0	5	0	0	0	0	https://www.gbif.org/species/4097456	Verified accepted name
Sloetia elongata	14	14	18	20	0	0	3	https://www.gbif.org/species/3763185	Verified accepted name
Stachytarpheta sp.	0	0	0	9	0	0	0	https://www.gbif.org/species/2925448	Verified accepted name
Swietenia macrophylla	0	4	0	0	0	0	0	https://www.gbif.org/species/3190484	Verified accepted name
Swietenia mahagoni	17	0	0	0	0	0	0	https://www.gbif.org/species/3190485	Verified accepted name
Syzygium malaccense	0	0	5	0	0	0	0	https://www.gbif.org/species/3184509	Verified accepted name
Syzygium pycnanthum	17	8	0	0	0	0	0	https://www.gbif.org/species/3183498	Verified accepted name
Timonius flavescens	0	7	0	0	0	0	0	https://www.gbif.org/species/2899755	Verified accepted name
Veitchia merrillii	0	0	0	0	0	0	4	https://www.gbif.org/species/5294668	Verified accepted name
Vitex pinnata	0	4	0	0	0	0	0	https://www.gbif.org/species/7309306	Verified accepted name
Vitex pubescens	0	0	9	0	0	0	0	https://www.gbif.org/species/3903460	Verified accepted name
Vitex vestita	0	0	0	11	0	0	0	https://www.gbif.org/species/9153571	Verified accepted name

Table S4. The species richness (S) and Importance Value Index (IVI) of plant species at the seedling stage across reclamation ages of the Martabe gold mine, North Sumatra, Indonesia

Species name	IVI (%) across reclamation ages (years)							Reference source	Notes
	12	11	10	9	5	4	3		
Acalypha indica	0	0	0	0	0	8	0	https://www.gbif.org/species/3056259	Verified accepted name
Acalypha sp.	0	0	0	0	0	0	2	https://www.gbif.org/species/3055964	Verified accepted name
Achyranthes aspera	11	3	0	0	0	0	0	https://www.gbif.org/species/3085168	Verified accepted name
Acrostichum aureum	0	0	0	0	12	0	0	https://www.gbif.org/species/2651706	Verified accepted name
Adiantum latifolium	0	8	0	5	0	0	0	https://www.gbif.org/species/2651837	Verified accepted name
Adenanthera pavonina	6	0	5	0	0	0	0	https://www.gbif.org/species/2951846	Verified accepted name
Ageratum conyzoides	0	0	0	0	0	0	3	https://www.gbif.org/species/5401673	Verified accepted name
Alstonia scholaris	0	0	0	3	8	0	0	https://www.gbif.org/species/5414410	Verified accepted name
Anacardium occidentale	0	0	0	0	0	0	2	https://www.gbif.org/species/5421368	Verified accepted name
Annona squamosa	0	0	0	0	0	0	2	https://www.gbif.org/species/5407099	Verified accepted name
Antiaris toxicaria	0	3	0	0	0	0	0	https://www.gbif.org/species/7262663	Verified accepted name
Aporosa sp.	0	3	0	0	0	0	0	https://www.gbif.org/species/3075057	Verified accepted name
Aquilaria malaccensis	0	0	0	4	0	5	0	https://www.gbif.org/species/5524063	Verified accepted name
Archidendron bubalinum	0	3	0	0	0	0	0	https://www.gbif.org/species/2941202	Verified accepted name
Areca catechu	0	3	0	0	0	0	0	https://www.gbif.org/species/2736531	Verified accepted name
Arenga pinnata	5	0	0	0	0	0	0	https://www.gbif.org/species/2733997	Verified accepted name
Artocarpus elasticus	5	0	6	0	0	0	0	https://www.gbif.org/species/7425575	Verified accepted name
Artocarpus heterophyllus	0	3	14	14	0	5	2	https://www.gbif.org/species/2984565	Verified accepted name
Artocarpus integer	0	8	6	0	0	0	0	https://www.gbif.org/species/2984566	Verified accepted name
Asystasia gangetica	48	27	0	40	24	50	3	https://www.gbif.org/species/3173254	Verified accepted name
Baccaurea polyneura	0	0	0	0	7	0	0	https://www.gbif.org/species/3082102	Verified accepted name
Bellucia axinanthera	0	2	0	0	0	0	0	https://www.gbif.org/species/3866766	Verified accepted name
Breynia androgyna	0	0	5	0	0	0	2	https://www.gbif.org/species/9197670	Verified accepted name
Calamus spp.	0	0	0	0	0	0	2	https://www.gbif.org/species/8494406	Verified accepted name
Calopogonium mucunoides	0	3	0	0	0	0	2	https://www.gbif.org/species/2959433	Verified accepted name
Camellia sinensis	0	3	0	6	0	0	0	https://www.gbif.org/species/3189635	Verified accepted name
Catharanthus roseus	0	0	0	0	0	0	2	https://www.gbif.org/species/3169830	Verified accepted name
Centrosema pubescens	0	0	0	0	0	0	5	https://www.gbif.org/species/2964904	Verified accepted name
Centrosema sp.	0	0	0	0	0	0	2	https://www.gbif.org/species/2964887	Verified accepted name
Centrosema virginianum	6	0	0	0	0	6	2	https://www.gbif.org/species/2964906	Verified accepted name
Ceiba pentandra	0	3	0	0	0	0	0	https://www.gbif.org/species/5406697	Verified accepted name
Cinnamomum verum	0	2	0	0	0	0	0	https://www.gbif.org/species/3033987	Verified accepted name
Citrus maxima	0	0	0	3	0	0	0	https://www.gbif.org/species/3190160	Verified accepted name
Citrus sp.	0	0	0	0	0	0	2	https://www.gbif.org/species/3190155	Verified accepted name
Cladium mariscus	0	0	0	5	0	0	0	https://www.gbif.org/species/2731327	Verified accepted name
Calopogonium sp.	0	0	0	0	0	0	3	https://www.gbif.org/species/2959416	Verified accepted name
Combretum indicum	0	0	0	3	0	0	0	https://www.gbif.org/species/12203608	Verified accepted name
Commersonia bartramia	0	0	0	0	0	0	3	https://www.gbif.org/species/7323037	Verified accepted name
Croton hirtus	0	0	0	0	0	0	2	https://www.gbif.org/species/3058942	Verified accepted name
Costus spiralis	0	3	0	0	0	5	2	https://www.gbif.org/species/2756867	Verified accepted name

Crotalaria pallida	0	0	0	0	0	0	4	https://www.gbif.org/species/7709465	Verified accepted name
Croton tiglium	0	2	0	0	0	0	0	https://www.gbif.org/species/3057656	Verified accepted name
Cyperus sp.	0	0	0	10	0	0	0	https://www.gbif.org/species/2713455	Verified accepted name
Dendrolobium umbellatum	0	0	0	4	0	0	0	https://www.gbif.org/species/2946798	Verified accepted name
Derris elliptica	0	0	0	0	0	5	0	https://www.gbif.org/species/5350305	Verified accepted name
Dimocarpus longan	0	2	0	0	0	0	0	https://www.gbif.org/species/3190008	Verified accepted name
Dryopteris cristata	0	0	0	0	0	9	0	https://www.gbif.org/species/5275110	Verified accepted name
Durio zibethinus	0	0	0	0	0	9	0	https://www.gbif.org/species/3152230	Verified accepted name
Erechtites hieraciifolius	0	0	0	0	0	0	2	https://www.gbif.org/species/3132457	Verified accepted name
Eleusine indica	0	5	0	0	0	0	0	https://www.gbif.org/species/2705953	Verified accepted name
Eurya acuminata	6	0	4	7	8	0	0	https://www.gbif.org/species/3591824	Verified accepted name
Falcataria falcata	0	0	0	0	0	0	2	https://www.gbif.org/species/10691906	Verified accepted name
Ficus ampelas	0	3	7	0	0	0	0	https://www.gbif.org/species/8042954	Verified accepted name
Ficus callosa Willd.	0	2	0	0	0	0	0	https://www.gbif.org/species/5571016	Verified accepted name
Ficus fistulosa	11	0	0	0	0	0	0	https://www.gbif.org/species/7262725	Verified accepted name
Ficus hispida	0	2	0	4	0	0	0	https://www.gbif.org/species/7879404	Verified accepted name
Ficus padana	0	0	0	0	0	0	2	https://www.gbif.org/species/5570157	Verified accepted name
Fissistigma latifolium	0	3	0	0	0	0	0	https://www.gbif.org/species/3157308	Verified accepted name
Garcinia atroviridis	0	2	0	0	0	0	0	https://www.gbif.org/species/3711121	Verified accepted name
Garcinia mangostana	0	0	0	0	6	11	0	https://www.gbif.org/species/3189571	Verified accepted name
Glochidion sp.	0	0	5	0	0	0	0	https://www.gbif.org/species/3080069	Verified accepted name
Gmelina sp.	6	0	0	0	0	0	0	https://www.gbif.org/species/2925650	Verified accepted name
Helianthus divaricatus	0	0	0	0	0	0	2	https://www.gbif.org/species/3119249	Verified accepted name
Helianthus sp.	0	0	0	0	0	0	2	https://www.gbif.org/species/3119134	Verified accepted name
Helianthus tuberosus	0	0	0	0	0	0	2	https://www.gbif.org/species/3119175	Verified accepted name
Hellenia sp.	5	3	0	0	10	0	0	https://www.gbif.org/species/8189889	Verified accepted name
Hevea brasiliensis	0	0	6	0	0	0	0	https://www.gbif.org/species/3071171	Verified accepted name
Hibiscus ovalifolius	0	0	0	0	0	5	4	https://www.gbif.org/species/3935028	Verified accepted name
Hibiscus tiliaceus	0	0	0	7	0	0	8	https://www.gbif.org/species/3152584	Verified accepted name
Ixonanthes reticulata	0	0	0	0	0	0	6	https://www.gbif.org/species/4259197	Verified accepted name
Lantana trifolia	0	0	0	0	0	5	0	https://www.gbif.org/species/2925321	Verified accepted name
Lasiacis divaricata	6	0	0	0	0	0	0	https://www.gbif.org/species/2702852	Verified accepted name
Lasianthus attenuatus	0	0	0	0	0	0	2	https://www.gbif.org/species/5336863	Verified accepted name
Leea aculeata	0	3	0	0	0	0	0	https://www.gbif.org/species/4160310	Verified accepted name
Leea indica	13	3	15	0	10	0	0	https://www.gbif.org/species/4160336	Verified accepted name
Leea rubra	0	0	0	4	0	0	0	https://www.gbif.org/species/7714497	Verified accepted name
Lindsaea ensifolia	0	0	0	4	0	0	0	https://www.gbif.org/species/2650772	Verified accepted name
Litsea elliptica	0	4	0	5	0	0	0	https://www.gbif.org/species/4177007	Verified accepted name
Litsea monopetala	0	0	5	0	0	0	0	https://www.gbif.org/species/4182444	Verified accepted name
Lycopodiella cernua	0	0	0	0	0	0	2	https://www.gbif.org/species/2688348	Verified accepted name
Macaranga bancana	0	0	4	0	0	7	0	https://www.gbif.org/species/3074550	Verified accepted name
Macaranga conifera	0	0	0	0	0	0	4	https://www.gbif.org/species/3074156	Verified accepted name
Macaranga tanarius	5	2	0	0	0	0	0	https://www.gbif.org/species/3074251	Verified accepted name
Macaranga trichocarpa	0	0	0	0	0	0	2	https://www.gbif.org/species/3074384	Verified accepted name
Macrothelypteris torresiana	0	6	0	0	0	0	0	https://www.gbif.org/species/8846035	Verified accepted name
Melaleuca leucadendra	0	0	0	0	0	0	5	https://www.gbif.org/species/5415976	Verified accepted name

Mallotus sp.	0	0	0	0	7	0	0	https://www.gbif.org/species/3062330	Verified accepted name
Melastoma malabathricum	0	0	5	22	14	0	36	https://www.gbif.org/species/3188511	Verified accepted name
Miconia crenata	0	19	34	10	24	0	0	https://www.gbif.org/species/9404220	Verified accepted name
Mikania micrantha	0	0	0	0	0	0	3	https://www.gbif.org/species/5398421	Verified accepted name
Mimosa pigra	0	0	0	0	0	0	2	https://www.gbif.org/species/2969431	Verified accepted name
Mimosa pudica	0	0	0	4	0	9	4	https://www.gbif.org/species/2969284	Verified accepted name
Mucuna pruriens	0	0	8	0	0	0	0	https://www.gbif.org/species/2951499	Verified accepted name
Mucuna sp.	0	0	0	0	0	0	3	https://www.gbif.org/species/2951351	Verified accepted name
Murraya koenigii	0	0	6	0	8	0	2	https://www.gbif.org/species/3832804	Verified accepted name
Nephelium cuspidatum	0	0	8	0	0	0	0	https://www.gbif.org/species/7264801	Verified accepted name
Nephelium sp.	0	0	0	3	0	0	0	https://www.gbif.org/species/3189978	Verified accepted name
Nepenthes sp.	0	0	0	0	0	0	2	https://www.gbif.org/species/3190711	Verified accepted name
Nephrolepis biserrata	5	14	0	5	0	0	6	https://www.gbif.org/species/12262828	Verified accepted name
Nephrolepis sp.	0	0	9	0	0	0	0	https://www.gbif.org/species/2650926	Verified accepted name
Neustanthus phaseoloides	0	0	0	0	8	0	0	https://www.gbif.org/species/2977687	Verified accepted name
Ocimum sp.	0	0	0	0	0	6	0	https://www.gbif.org/species/2874693	Verified accepted name
Oplismenus compositus	6	3	0	0	0	0	0	https://www.gbif.org/species/2705733	Verified accepted name
Oplismenus undulatifolius	14	0	0	0	0	0	0	https://www.gbif.org/species/7745203	Verified accepted name
Oxalis barrelieri	0	0	0	0	0	5	3	https://www.gbif.org/species/2891750	Verified accepted name
Paraserianthes lophantha	0	0	0	0	0	0	2	https://www.gbif.org/species/2943719	Verified accepted name
Parkia speciosa	0	0	5	0	0	0	0	https://www.gbif.org/species/5348811	Verified accepted name
Persea americana	0	0	0	0	0	0	2	https://www.gbif.org/species/3034046	Verified accepted name
Phegopteris connectilis	0	0	6	0	0	0	0	https://www.gbif.org/species/2651330	Verified accepted name
Phyllanthus reticulatus	0	0	0	0	7	0	0	https://www.gbif.org/species/5382478	Verified accepted name
Phyllanthus sp.	0	0	0	0	0	0	2	https://www.gbif.org/species/3061139	Verified accepted name
Physalis peruviana	0	0	5	0	0	0	0	https://www.gbif.org/species/5341784	Verified accepted name
Piper aduncum	0	0	0	0	12	0	2	https://www.gbif.org/species/3086337	Verified accepted name
Piper betle	0	7	0	0	0	0	0	https://www.gbif.org/species/4187904	Verified accepted name
Piper hispidum	0	0	0	0	0	0	2	https://www.gbif.org/species/3086355	Verified accepted name
Polystichum acrostichoides	0	0	0	4	0	0	0	https://www.gbif.org/species/2651098	Verified accepted name
Pometia pinnata	0	0	0	0	0	5	0	https://www.gbif.org/species/5577338	Verified accepted name
Prunus sp.	0	0	0	0	0	0	3	https://www.gbif.org/species/3020559	Verified accepted name
Psychotria sp.	0	0	0	0	0	5	0	https://www.gbif.org/species/2919963	Verified accepted name
Pternandra azurea	5	0	4	0	0	0	0	https://www.gbif.org/species/3867793	Verified accepted name
Pterocarpus officinalis	0	0	0	0	0	0	2	https://www.gbif.org/species/5349333	Verified accepted name
Pterocarpus santalinus	0	0	0	0	0	5	0	https://www.gbif.org/species/5708628	Verified accepted name
Pueraria montana	0	0	0	6	0	0	0	https://www.gbif.org/species/2977636	Verified accepted name
Pueraria sp.	0	0	0	7	0	0	0	https://www.gbif.org/species/2977604	Verified accepted name
Samanea saman	0	0	0	0	0	0	3	https://www.gbif.org/species/2972960	Verified accepted name
Selaginella willdenowii	0	2	0	0	0	0	0	https://www.gbif.org/species/8688934	Verified accepted name
Senna obtusifolia	0	0	0	0	0	0	2	https://www.gbif.org/species/2957408	Verified accepted name
Senna siamea	0	0	0	0	0	0	2	https://www.gbif.org/species/2956905	Verified accepted name
Setaria barbata	0	0	0	0	0	18	0	https://www.gbif.org/species/5289663	Verified accepted name
Setaria italica	0	0	0	0	0	0	20	https://www.gbif.org/species/5289698	Verified accepted name
Sloetia elongata	0	3	6	0	0	0	0	https://www.gbif.org/species/3763185	Verified accepted name
Spathoglottis sp.	5	0	0	0	0	0	0	https://www.gbif.org/species/2816401	Verified accepted name

Spathoglottis plicata	5	0	0	0	0	0	2	https://www.gbif.org/species/2816456	Verified accepted name
Spermacoce sp.	21	3	0	0	0	0	0	https://www.gbif.org/species/2918053	Verified accepted name
Spondias sp.	0	0	4	0	0	0	0	https://www.gbif.org/species/3190592	Verified accepted name
Stachytarpheta sp.	0	0	0	0	0	7	0	https://www.gbif.org/species/2925448	Verified accepted name
Styrax benzoin	0	0	5	5	7	0	0	https://www.gbif.org/species/5371679	Verified accepted name
Swietenia macrophylla	6	0	0	0	0	0	0	https://www.gbif.org/species/3190484	Verified accepted name
Synedrella nodiflora	0	0	0	0	0	0	2	https://www.gbif.org/species/5404991	Verified accepted name
Syzygium acuminatum	0	0	0	0	0	0	2	https://www.gbif.org/species/3182502	Verified accepted name
Syzygium malaccense	0	0	0	0	6	0	0	https://www.gbif.org/species/3184509	Verified accepted name
Syzygium pycnanthum	0	0	0	0	6	0	2	https://www.gbif.org/species/3183498	Verified accepted name
Syzygium sp.	0	0	0	0	0	0	3	https://www.gbif.org/species/3029010	Verified accepted name
Tamarindus indica	0	0	0	0	0	5	0	https://www.gbif.org/species/2975768	Verified accepted name
Tapeinochilos ananassae	0	3	0	0	0	0	0	https://www.gbif.org/species/2756760	Verified accepted name
Thelypteris dentata	0	5	0	0	0	5	0	https://www.gbif.org/species/5275277	Verified accepted name
Thelypteris sp.	0	8	0	0	0	0	0	https://www.gbif.org/species/5937466	Verified accepted name
Timonius flavescens	0	4	0	0	0	0	0	https://www.gbif.org/species/2899755	Verified accepted name
Trema cannabina	0	5	0	0	0	0	0	https://www.gbif.org/species/2984507	Verified accepted name
Urena lobata	0	0	0	0	15	0	0	https://www.gbif.org/species/3152253	Verified accepted name
Uvaria sp.	0	3	0	7	0	0	0	https://www.gbif.org/species/3154216	Verified accepted name
Vitex pinnata	0	0	9	0	0	0	0	https://www.gbif.org/species/7309306	Verified accepted name
Vitex pubescens	0	4	0	0	0	0	0	https://www.gbif.org/species/3903460	Verified accepted name

Table S5. Summary of six ecological indices use (name, formula, meaning, and reference)

Ecological indices	Formula	Meaning	Reference
Important Value Index (IVI)	**Seedlings & Saplings:** IVI = RDe + RF **Poles & Trees:** IVI = RDe + RF + RDo Density (De) (De): $\frac{\text{Number of Individuals of a particular species}}{\text{Area of the entire sample plot}}$ Relative Density (RDe) (RDe): $\frac{\text{Specific species density}}{\text{Density of all species}}$x 100% Dominance (Do) (Do) : $\frac{\text{Total basal area of a particular species}}{\text{Area of the entire sample plot}}$ Relative Dominance (RDo) (RDo): $\frac{\text{Dominance of a particular species}}{\text{Dominance of all species}}$x 100% Frequency (F) (F): $\frac{\text{The number of sample plots found for a particular species}}{\text{Total number of sample plots}}$ Relative Frequency (RF) (RF): $\frac{\text{Frequency of a particular species}}{\text{Frequency of all species}}$x 100%	The larger the IVI, the greater the dominance of species and its environmental impact.	Osipov (2021)
Species richness (S)	S: Number of species	The larger the S, the greater the diversity.	Kitikidou et al. (2024)
Shannon-Wiener diversity index (H')	H': $-\sum (p_i \times \ln p_i)$, where $p_i = n_i / N$	The larger the H, the greater the diversity. $H' > 3$ (High species diversity) $1 \leq H' \leq 3$ (Medium species diversity) $H' < 1$ (Low species diversity)	Daly et al. (2018)

Margalef richness index (Wealth Index; R)	R = (S - 1) / ln(N)	The larger the R, the greater the diversity. R < 2.5 (Low richness) 2.5 ≤ R ≤ 4 (Medium richness) R > 4 (High richness)	Thukral (2017)
Evenness index (E)	E: H' / ln(S)	0 < E ≤ 0.5 (Low evenness) 0.5 < E ≤ 0.75 (Medium evenness) 0.75 < E ≤ 1 (High evenness)	Fedor and Zvaríková (2019)
Morisita index (ImH)	$\mathrm{ImH} = 2\sum\frac{(\mathrm{Xi} \times \mathrm{Yi})}{(\mathrm{da} + \mathrm{db})\,\mathrm{X} \times \mathrm{Y}}$ Xi: Total number of individuals for species i in community X Yi: Total number of individuals for species i in community Y X, Y: Total number of individuals in sample X and Y, respectively dX : $\sum Xi^2/X^2$ dY : $\sum Yi^2/Y^2$	The index ranges from 0 to 1, where 0 indicates no similarity, and 1 indicates complete similar.	Morisita (1961)