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Biodiversity and Carbon Stock as Indicators of Mine Reclamation Success at PT Indocement Tunggal Prakarsa, Tarjun, South Kalimantan, Indonesia

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ABSTRACT

This study evaluated the success of post-mining reclamation at PT Indocement Tunggal Prakarsa Tbk., Tarjun Unit, South Kalimantan, Indonesia, using biodiversity (flora and fauna) and carbon stocks as environmental performance indicators aligned with the Green PROPER criteria (PROPER Hijau). We assessed four reclaimed land types—limestone, clay, laterite, and silica—using stratified plot analysis for vegetation, and line-transect plus point-count methods for fauna. Above-ground biomass and carbon stocks were estimated with Brown's (1997) allometric model, applying a carbon fraction of 0.47. Results show significant ecological recovery across all reclaimed areas, indicated by increased vegetation cover, multilayered stand structure, and the presence of indicator species. Laterite plots stored the highest carbon (56.47 t ha^{-1}) and exhibited the greatest plant diversity (H′ = 2.69), whereas clay plots had the lowest carbon stock (0.67 t ha^{-1}; H′ = 1.02). We recorded 41 bird species, 6 mammals, and 5 herpetofauna species, with an overall fauna diversity index of H′ = 2.21 (moderate–high). Total biodiversity (flora + fauna) correlated positively with carbon stocks (r = 0.82), indicating that increasing ecosystem complexity parallels greater carbon sequestration capacity. Overall, reclamation at PT Indocement has effectively restored ecosystem functions and supported climate-change mitigation, consistent with Green PROPER parameters, particularly those related to biodiversity, land rehabilitation, and sustainable carbon management.

Keywords: post-mining reclamation; plant diversity; faunal diversity; carbon stocks; green PROPER; PT Indocement Tarjun

INTRODUCTION

Mining of cement raw materials (e.g., limestone) alters landscapes, removes vegetation cover, and disrupts wildlife habitats and the balance of soil carbon. These conditions diminish the land's ecological functions, particularly its capacity to sequester and store carbon in biomass and soils. Ecosystem regeneration on post-mining lands is a strategic measure to ensure the continuity of ecological functions and to stabilize microclimates in tropical regions. Post-mining reclamation is therefore required so that disturbed lands can return to productivity, support biodiversity, and contribute to climate-change mitigation (Bandyopadhyay et al., 2022; Zine et al., 2024).

Effective reclamation goes beyond re-shaping landforms; it must also restore ecological structure, composition, and function. This recovery is pursued by enhancing biodiversity and carbon-uptake capacity—two key indicators of successful ecosystem rehabilitation (Wos et al., 2024). Floral diversity helps re-establish vegetation layers that resist erosion, improve soil structure, and increase biomass through atmospheric carbon uptake. Faunal diversity—especially birds, mammals, and herpetofauna—signals ecosystem stability, as these taxa act as pollinators, seed dispersers, and natural population regulators. The linkage between biological diversity and carbon stocks indicates that highly complex ecosystems are better able to maintain ecological balance and support climate-change mitigation (Peng et al., 2020; Yang et al., 2024).

Ecosystem recovery on reclaimed mine lands also has significant moral and social value. Revegetation and the restoration of wildlife habitats not only fulfill corporate environmental responsibility but also represent a long-term ecological investment in natural-resource sustainability and the well-being of future generations. These efforts advance the Sustainable Development Goals—especially Goal 13 (Climate Action) and Goal 15 (Life on Land)—and align with Indonesia's Green PROPER principles under the Ministry of Environment and Forestry (Zine et al., 2024).

This study systematically evaluates the success of land reclamation at PT Indocement Tunggal Prakarsa Tbk., Tarjun Unit, South Kalimantan, using biodiversity (flora and fauna) and carbon stocks as environmental performance indicators consistent with the Green PROPER criteria. The study has three objectives: (1) to analyze floral and faunal diversity as indicators of ecological recovery on Indocement Tarjun's reclaimed sites; (2) to quantify carbon stocks in reclaimed vegetation as a parameter of reclamation effectiveness and its contribution to climate-change mitigation; and (3) to assess the relationship between biodiversity and carbon stocks as the basis for evaluating reclamation success in supporting Green PROPER performance and ecosystem sustainability.

MATERIALS & METHODS

Study Area

This research was conducted within the reclamation area of PT Indocement Tunggal Prakarsa Tbk., Tarjun Unit, located in Kotabaru Regency, South Kalimantan Province, Indonesia. The study site comprised four major substrate types—limestone, clay, laterite, and silica—each representing variations in soil characteristics, reclamation age, and revegetation success. The sites were selected purposively, based on the company's map of active reclamation zones. Field data collection was carried out in September 2025.

Tools and Materials

The equipment used in this study included a Global Positioning System (GPS) device to determine the coordinates of observation points, a compass, measuring tape, clinometer, and tree caliper (phi-band) for measuring stem diameter. Additional tools consisted of stationery and field data sheets, as well as a digital camera and binoculars for documenting fauna.

The materials included primary data obtained from direct field observations of flora and fauna, and secondary data comprising reclamation maps, planting age records, and the 2025 environmental monitoring report of PT Indocement Tunggal Prakarsa Tbk.

RESEARCH PROCEDURE

This study employed a descriptive–quantitative ecological approach using a field survey method. Data were collected through direct field observations following standardized sampling techniques on three major components: vegetation (flora), fauna, and above-ground carbon stock (AGB).

Vegetation Observation (Flora)

Vegetation analysis was performed using the nested plot method to assess the structure and composition of plant stands. Sampling plots measured 20 × 20 m for trees (diameter ≥ 10 cm), 10 × 10 m for poles (diameter 5–9.9 cm), and 5 × 5 m for saplings (diameter 2–4.9 cm).

Each individual plant was recorded by species, diameter at breast height (DBH), height, and density. These data were used to calculate density (D), frequency (F), dominance (Do), and the Importance Value Index (IVI).

The Shannon–Wiener diversity index (H′) was applied to determine the species diversity for each reclamation land type.

Faunal Inventory

The faunal inventory focused on three main groups: birds, mammals, and herpetofauna. Observations were conducted using the point count and line transect methods, with sampling points spaced 50–100 m apart. Observation sessions were carried out during 06:00–09:00 and 15:00–17:30 local time (WITA) to coincide with peak activity periods of most species.

Fauna was identified through direct observations and indirect signs such as tracks, droppings, and vocalizations. All species encountered were recorded by their scientific names, individual counts, and ecological behaviors.

The Shannon–Wiener diversity index (H′), evenness index (E), and relative abundance (D) were calculated to assess faunal community stability across different reclamation land types.

Carbon Stock Estimation

Above-ground carbon stock was estimated based on tree diameter and height measurements, following the model proposed by Chauve et al. (2014):

$$B = 0{,}0673 \times (\rho \times DBH^2 \times H)^{0{,}976}$$

where B is the biomass (kg/tree), ρ is wood density (g/cm³), DBH is stem diameter (cm), and H is tree height (m).

The resulting biomass values were converted to total carbon stock (ton/ha) using a conversion factor of 0.47. Carbon stock was then compared among reclamation land types to evaluate the effectiveness of carbon sequestration across different substrate conditions.

Data Analysis

Vegetation, fauna, and carbon data were analyzed using a descriptive–quantitative approach, supported by statistical software and ecological index calculations. The Shannon–Wiener diversity index (H′) was employed to evaluate flora and fauna diversity, while the relationship between biodiversity and carbon stock was examined using Pearson's correlation coefficient (r).

Interpretation of the results referred to the Green PROPER criteria, emphasizing indicators of biodiversity conservation, land rehabilitation, and sustainable carbon management.

RESULT AND DISCUSSION

The results indicate clear variation in flora diversity, fauna diversity, and carbon stocks across the different reclamation land types. The following analysis outlines the ecological patterns that have emerged, the key factors shaping differences among locations, and their implications for evaluating reclamation success based on ecological parameters and PROPER Green performance. The variation in vegetation diversity among land types is illustrated in Figure 1, which presents the Shannon–Wiener diversity index (H′) for each structural level of the vegetation community.

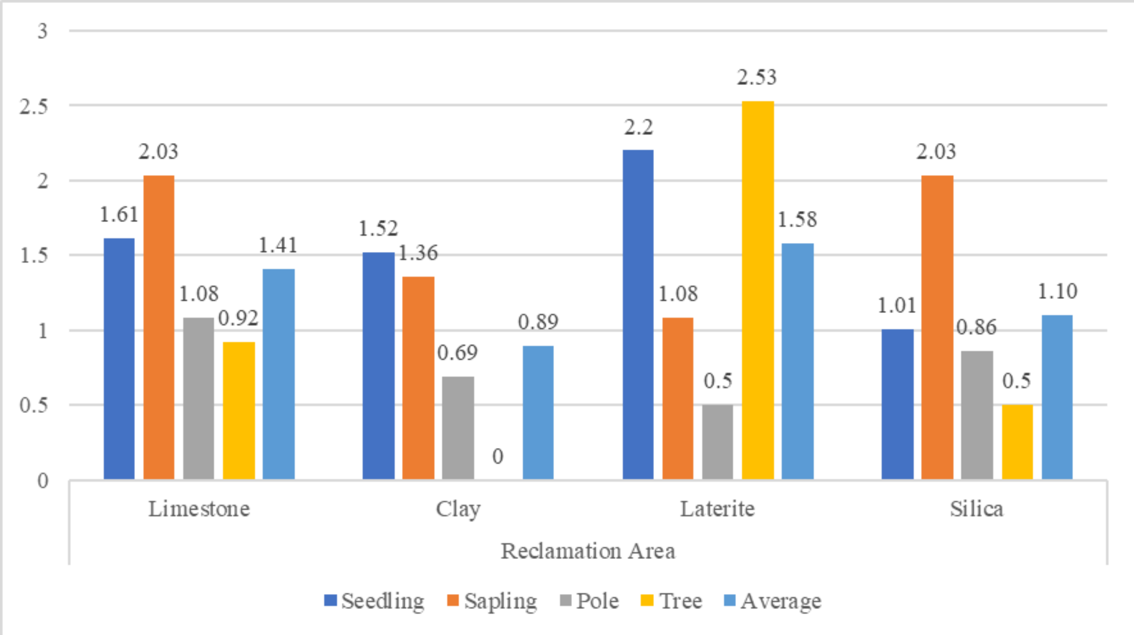

Figure 1. Diversity Index of each Vegetation Level across Reclamation Land Types at PT Indocement Tarjun, South Kalimantan

Figure 1 illustrates the variation in Shannon–Wiener diversity index (H′) across the vegetation strata—saplings, poles, and trees—within the four reclamation land types. Overall, the pattern indicates that vegetation diversity tends to increase in areas with more stable substrates that support the development of layered stand structures.

The laterite site exhibits the highest H′ values across nearly all vegetation levels, indicating that succession has progressed toward a more complex community structure. This pattern is consistent with the characteristics of lateritic soils, which have good drainage and relatively high mineral content, enabling the growth of diverse hardwood species that contribute to the formation of multistrata canopies. The consistently high H′ values at all structural levels reinforce that the laterite area represents the most ecologically advanced stage of reclamation.

In contrast, the clay site shows the lowest H′ values across all vegetation levels. Its compact soil texture, poor aeration, and limited drainage restrict root development and hinder successful species colonization. The dominance of pioneer species at the sapling and pole levels reflects that this site remains in the early stages of ecological succession.

The limestone and silica sites display moderate H′ values, with a clear increasing trend from sapling to tree strata. The rocky, alkaline limestone substrate supports adaptive vegetation that tolerates dry conditions, while the porous, nutrient-poor silica substrates sustain a more limited plant community that nevertheless shows gradual recovery. The upward trend in H′ from saplings to trees in both sites indicates that stand structure is beginning to form, although it has not yet reached the complexity observed in the laterite area.

Overall, Figure 1 demonstrates that reclamation success is strongly influenced by substrate conditions and the capacity of vegetation to develop multilayered stand structures. Higher H′ values at the tree level reflect emerging ecosystem stability and serve as a key indicator of successful vegetation recovery. To further understand the species composition and ecological factors that shape the variation in H′ across land types, the dominant vegetation species and their characteristics are presented in Table 1.

Table 1. Dominant Vegetation Types and Shannon–Wiener Diversity Index (H′) across Reclamation Land Types at PT Indocement Tarjun, South Kalimantan

Reclamation Land Type	Dominant Vegetation Species	Ecological Group	Growth/ Adaptation Level	Shannon–Wiener Diversity Index (H′)	Ecological Description
Limestone	*Acacia mangium, Albizia chinensis, Swietenia macrophylla, Alstonia scholaris, Terminalia catappa*	Fast-growing species tolerant to high pH	Moderate	1.41	Rocky and dry soil conditions; vegetation grows well with strong root systems and moderate–high biomass.
Clay	*Macaranga gigantea, Paraserianthes falcataria, Melaleuca leucadendra, Gliricidia sepium*	Pioneer and nitrogen-fixing species	Low–Moderate	0.89	Compact and poorly drained soil; supports only pioneer and shrub species. Vegetation growth is slow with low biomass accumulation.
Laterite	*Swietenia macrophylla, Acacia mangium, Albizia chinensis, Macaranga hypoleuca, Cassia siamea, Artocarpus elasticus*	Hardy and adaptive hardwood species	Moderate	1.51	Stable soil with good drainage and slightly acidic to neutral pH. High biomass and multilayered canopy indicate successful reclamation progress.
Silika	*Terminalia catappa, Albizia chinensis, Melaleuca cajuputi, Acacia auriculiformis, Paraserianthes falcataria*	Drought- and light-tolerant species	Moderate	1.19	Porous and nutrient-poor substrate; vegetation grows sparsely with dominance of shrubs and medium-sized trees. Carbon stock is moderate.

The Shannon–Wiener diversity index (H′) serves as an important indicator for assessing the stability and complexity of vegetation communities on reclaimed lands. This index reflects not only the number of species present but also the evenness of their distribution; a higher H′ value indicates a more diverse and stable ecosystem (Yang et al., 2024). Conversely, a lower H′ value suggests that the ecosystem is still in the early stage of succession and has yet to reach optimal ecological balance (Li et al., 2024).

The results showed that the laterite site had the highest H′ value (1.51), indicating that the reclamation process in this area has successfully established a stable, heterogeneous, and semi-natural ecosystem. The stable structure of lateritic soil, characterized by good drainage and slightly acidic to neutral pH, supports the growth of hardwood species such as Swietenia macrophylla, Acacia mangium, and Albizia chinensis. These species play a key role in forming multilayered vegetation stands, which contribute to higher biomass and carbon stock. The high H′ value in the laterite site demonstrates that PT Indocement Tunggal Prakarsa Tbk. has effectively restored the ecological functions of post-mining land into a productive and functional vegetation system—a strong indicator of successful ecological reclamation. Meta-analytical studies further support that reclamation success is strongly influenced by vegetation diversity and complex stand structure (Yang et al., 2024; Isworo et al., 2025).

In contrast, the clay site exhibited the lowest H′ value (0.89), suggesting that the area remains in an early successional phase, dominated by pioneer species such as Macaranga gigantea and Paraserianthes falcataria. The compact, poorly aerated soil with inadequate drainage poses major constraints on the development of more complex vegetation. The low species diversity also indicates that reclamation in this area has not yet achieved optimal outcomes in terms of species richness and ecological functionality. Recent studies highlight that post-mining lands with poor soil conditions require intensive interventions, including soil structure improvement, introduction of adaptive native species, and the addition of organic matter to accelerate vegetation succession (Li et al., 2024).

The limestone site showed a moderate H′ value (1.41), reflecting a balanced level of vegetation diversity. Although the rocky, nutrient-poor substrate presents challenging growing conditions, the presence of fast-growing species such as Acacia mangium and Swietenia macrophylla demonstrates strong adaptation to extreme environments. These species contribute to improving soil structure and increasing organic matter content, indicating that the reclamation process has progressed from the pioneer to the intermediate successional stage. This finding is consistent with international studies indicating that Acacia mangium, as a fast-growing pioneer species, is widely used in the rehabilitation of degraded lands due to its ability to improve soil fertility, accelerate vegetation cover, and promote the regeneration of secondary plant communities, although it carries a potential risk of invasiveness (Koutika & Richardson, 2019). In addition, research conducted in the Tropical Karst Forest of Gunung Sewu adopted a strategy that balances carbon sequestration and biodiversity objectives to restore land cover and vegetation structure while supporting ecological functions on limestone substrates (Putri et al., 2025).

Meanwhile, the silica site recorded an H′ value of 1.19, dominated by drought-tolerant species such as Melaleuca cajuputi and Acacia auriculiformis. The sandy, porous soil leads to sparse vegetation cover; however, the persistence of adaptive species indicates that ecosystem recovery is progressing, albeit slowly toward greater structural complexity. Post-mining revegetation literature emphasizes that nutrient-poor, well-drained substrates require the use of fast-growing pioneer species, such as Acacia spp., to support successful ecosystem recovery (Pratiwi et al., 2021).

Overall, the observed diversity pattern indicates that reclamation success at PT Indocement is positively correlated with vegetation diversity and soil quality. Sites with higher H′ values exhibit more stable and productive environmental conditions, while lower H′ values reflect physical soil constraints and ongoing early succession stages. This finding reinforces the positive relationship between species diversity and ecosystem functioning, wherein increased vegetation diversity directly enhances biomass accumulation and carbon sequestration capacity (Chen et al., 2024).

The outstanding performance of the laterite site provides tangible evidence that reclamation based on ecological principles can effectively restore both vegetation structure and ecological function in a sustainable manner. Implementing biodiversity-based revegetation techniques not only accelerates land recovery but also enhances carbon storage capacity, maintains hydrological balance, and creates new habitats for fauna. Therefore, the Shannon–Wiener diversity index (H′) can serve as a quantitative indicator of reclamation success at PT Indocement Tarjun, reflecting not merely vegetative cover restoration but also the recovery of ecological functions in line with the Green PROPER criteria of the Indonesian Ministry of Environment and Forestry (Isworo et al., 2025).

Table 2. Faunal Diversity across Reclamation Land Types at PT Indocement Tarjun, South Kalimantan

Reclamation Land Type	Faunal Group	Shannon–Wiener Diversity Index (H′)	Common Species Observed	Ecological Description
Limestone	Aves	3.26	*Geopelia striata*	High avian diversity, indicating a relatively stable habitat that provides abundant food sources for common bird species.
	Mammals	1.10	*Macaca fascicularis, Callosciurus notatus, Nannosciurus melanotis, Tupaia minor*	Moderate mammal diversity; the presence of omnivorous and herbivorous species reflects adaptation to reclaimed habitats.
	Herpetofauna	0.90	*Ahaetulla mycterizans, Eutropis multifasciata, Varanus salvator, Fejervarya cancrivora*	Fairly diverse herpetofauna community, suggesting vegetation that provides adequate shelter and feeding grounds.
Clay	Aves	3.25	*Stigmatopelia chinensis, Treron vernans*	Relatively high bird diversity, indicating a semi-open habitat with sufficient food supply for granivorous species.
	Mammals	0.69	*Callosciurus notatus, Tupaia minor*	Low mammal diversity, likely due to soil and substrate conditions that limit faunal richness.
	Herpetofauna	0.69	*Ahaetulla mycterizans, Eutropis multifasciata, Varanus salvator, Fejervarya cancrivora, Hylarana nicobariensis*	Moderate herpetofaunal diversity, associated with moderately humid habitats and the presence of temporary water pools.
Laterite	Aves	3.25	*Orthotomus ruficeps*	High avian diversity, reflecting complex habitat structures and stable substrates that support multiple ecological guilds.
	Mammals	1.10	*Callosciurus notatus, Tupaia minor, Mydaus Javanensis*	Diverse mammal community, including nocturnal species, indicating well-developed and sustainable reclaimed habitats.
	Herpetofauna	0.69	*Takydromus sexlineatus, Eutropis multifasciata, Fejervarya cancrivora, Hylarana nicobariensis*	Moderately diverse herpetofauna, found in moist areas with heterogeneous substrates.
Silika	Aves	3.06	*Stigmatopelia chinensis*	Medium bird diversity, suggesting a habitat capable of supporting seed- and insect-dispersing species.
	Mammals	0.69	*Callosciurus notatus, Tupaia minor*	Low mammal diversity dominated by small, adaptable species that tolerate sandy environments.
	Herpetofauna	1	*Oligodon octolineatus, Ahaetulla mycterizans, Takydromus sexlineatus, Fajervarya cancrivora, Hylarana nicobariensis*	Moderate herpetofaunal diversity in relatively dry habitats with limited amphibian populations.

Faunal diversity in post-mining reclamation sites serves as a vital indicator of how effectively revegetated ecosystems can provide habitat and resources for wildlife. The Shannon–Wiener Diversity Index (H′) for faunal groups such as birds, mammals, and herpetofauna reflects the ecological balance achieved after revegetation. A high H′ value indicates that reclaimed habitats can support multiple species with different ecological functions, whereas lower values suggest that habitat structure remains simplified and suboptimal for sustaining diverse wildlife communities (Isworo et al., 2025).

Overall, the results show that the limestone area exhibited the highest faunal diversity, with H′ values of 3.26 for birds, 1.10 for mammals, and 0.90 for herpetofauna. These values indicate that the multilayered vegetation and good canopy cover in limestone substrates create abundant food sources, nesting spaces, and sufficient microhabitat protection. The dominance of Geopelia striata in this habitat reflects a stable condition supporting a diverse assemblage of local bird species. Mammals such as Macaca fascicularis and Callosciurus notatus were present as active components of the trophic chain, underscoring the ecological stability of the site. The presence of herpetofaunal species such as Ahaetulla mycterizans and Varanus salvator further suggests that adequate moisture and shelter exist to support semi-aquatic reptiles and amphibians, confirming that the limestone ecosystem has functionally recovered (Yang et al., 2024).

In contrast, the clay area displayed the lowest diversity values, with H′ values of 3.25 for birds, 0.69 for mammals, and 0.69 for herpetofauna. This condition reflects ecological limitations caused by compact soil structure, poor drainage, and limited food availability. Only tolerant and generalist species such as Pycnonotus goiavier and Tupaia minor were able to persist. The presence of waterlogged microhabitats supported a few amphibian species like Fejervarya limnocharis, suggesting that the clay site remains in an early stage of faunal succession. The low H′ values indicate that this habitat has yet to develop sufficient vegetation complexity and microclimatic variability needed to support more complex faunal communities. Previous research has shown that topography and soil porosity strongly influence the pace of faunal recovery in post-mining areas (Vicentini et al., 2020).

The laterite area supported high avian diversity (H′ = 3.25), moderate mammalian diversity (H′ = 1.10), and relatively lower herpetofaunal diversity (H′ = 0.69). Dense vegetation and stable substrates provide ample shelter and food resources for various bird species such as Orthotomus ruficeps, reflecting a structurally complex habitat that supports multicomponent faunal communities. Although variable soil moisture limits herpetofaunal diversity, the overall ecological function of this habitat continues to progress toward stability.

In the silica area, faunal diversity was moderate, with H′ values of 1.91 for birds, 1.03 for mammals, and 0.84 for herpetofauna. The dominance of heat-tolerant birds such as Pycnonotus goiavier and Lonchura punctulata indicates that vegetation in this semi-open habitat supports species adapted to high solar radiation. Low to medium canopy layering accommodates small mammals like Callosciurus notatus and Tupaia glis, though in relatively low numbers. Sandy substrates with low moisture content restrict the presence of amphibians and reptiles to drought-tolerant species such as Eutropis multifasciata and Duttaphrynus melanostictus. These moderate H′ values indicate that reclamation in the silica area has successfully established an adaptive ecological system, though greater vegetation complexity is needed to support broader faunal assemblages (Chen et al., 2024).

Comparative analysis among reclamation types revealed a positive relationship between vegetation diversity and faunal diversity. Sites with high vegetation H′ values, such as the laterite and limestone areas, also exhibited high faunal diversity, highlighting vegetation complexity as a key driver of community stability (Isworo et al., 2025). Layered vegetation creates diverse microhabitats that sustain multiple faunal guilds, including pollinators, seed dispersers, small predators, and detritivores. In contrast, homogeneous vegetation structures such as those found in clay sites tend to support lower diversity due to limited habitat and resource availability.

These findings emphasize that faunal diversity serves as a robust ecological indicator of reclamation success. Reclamation efforts that promote heterogeneous vegetation structures are more capable of restoring food webs, ecological functions, and species interactions naturally. PT Indocement Tarjun has demonstrated notable progress, particularly in the laterite and limestone areas, which have ecologically approached the conditions of secondary natural ecosystems. This success not only reinforces the company's achievement of the Green PROPER standard established by the Ministry of Environment and Forestry but also affirms its commitment to biodiversity-based and sustainable ecosystem reclamation (Wu et al., 2024).

The data presented in Table 3 show the differences in biomass, carbon stocks, and vegetation diversity across the reclamation land types, which are further visualized in Figure 2 to illustrate the proportional contribution of each site to the total carbon stock.

Table 3. Total Biomass, Carbon Stock, and Diversity Index across Reclamation Land Types at PT Indocement Tarjun, South Kalimantan

Reclamation Land Type	Dominant Species (High IVI)	Total Biomass (ton/ha)	Carbon Stock (ton/ha)	Diversity Index (H′)	Ecological Description
Limestone	*Samanea saman, Swietenia macrophylla, Acacia mangium, Albizia chinensis*	15.729	12.534	1.75	Vegetation communities show signs of stabilization; the presence of fast-growing species indicates a mid-successional stage with moderate biomass productivity.
Clay	*Macaranga gigantea, Paraserianthes falcataria, Gliricidia sepium*	1.351	0.669	1.54	Compact soil and poor drainage restrict root development; vegetation dominated by pioneer species; ecosystem remains at an early successional stage.
Laterite	*Swietenia macrophylla, Acacia mangium, Albizia chinensis, Macaranga hypoleuca, Cassia siamea*	120.143	56.467	1.68	Highest biomass and carbon values; multistrata forest structure; stable ecological system indicating optimal reclamation success and balanced ecosystem function.
Silika	*Terminalia catappa, Albizia chinensis, Acacia auriculiformis, Melaleuca cajuputi*	15.667	7.364	1.50	Vegetation adapted to sandy and nutrient-poor substrates; ecological continuity emerging with long-term potential for improvement.

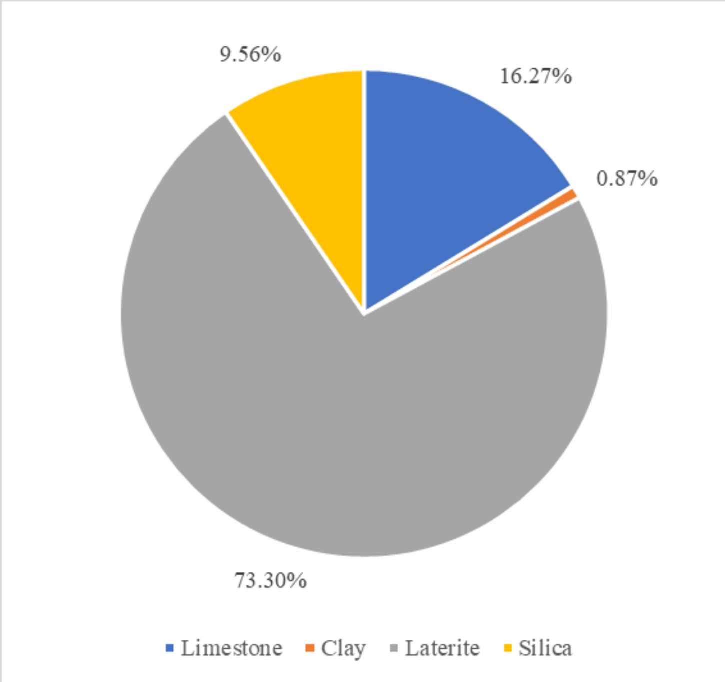

Figure 2. Carbon stock total across reclamation land types at PT Indocement Tarjun, South Kalimantan

Biomass and carbon content serve as key indicators for assessing the ecological success of post-mining reclamation areas, as both parameters reflect the vegetation's capacity for carbon sequestration and organic matter storage. In addition, the Shannon–Wiener diversity index (H′) represents the degree to which the reclaimed vegetation system has developed into a stable and resilient ecosystem. A positive relationship among these three parameters indicates that higher vegetation diversity enhances a system's ability to store carbon and maintain ecological balance (Bandyopadhyay et al., 2022; Li et al., 2024).

The study revealed that the laterite site exhibited the highest total biomass and carbon stock—120.143 ton/ha and 56.467 ton/ha, respectively—with a diversity value of H′ = 2.69. These values indicate that reclamation on laterite soils has reached an advanced secondary-successional stage characterized by a multistrata canopy structure. The presence of hardwood species such as Swietenia macrophylla, Acacia mangium, and Cassia siamea contributes to dense, layered stands with optimal canopy cover and balanced species distribution. This structure significantly enhances biomass accumulation and carbon sequestration capacity (Yang et al., 2024). According to Isworo et al. (2025), reclamation success in Kalimantan's post-mining landscapes strongly depends on integrating fast-growing species with climax trees to establish long-term ecological stability. The high carbon stock in laterite areas thus demonstrates their role as effective carbon sinks, contributing to climate-change mitigation.

In limestone areas, the total biomass (15.729 ton/ha) and carbon stock (12.534 ton/ha) with H′ = 1.94 indicate that vegetation communities are approaching a stable mid-successional stage. The hard calcareous substrate and high soil pH limit root penetration and nutrient uptake; however, the dominance of adaptive species such as Samanea saman and Acacia mangium shows strong ecological adjustment to harsh conditions. These species improve soil structure and increase organic matter through leaf-litter input, consistent with Peng et al. (2020), who found that tree diversity and mycorrhizal associations enhance soil carbon through biological activity and organic decomposition.

The silica site recorded moderate biomass (15.667 ton/ha), carbon stock (7.364

ton/ha), and H′ = 1.78, reflecting the early stabilization of vegetation despite nutrient-poor and sandy substrates. Drought-tolerant species such as Melaleuca cajuputi and Acacia auriculiformis play a crucial role in maintaining ground cover and preventing erosion. As noted by Zine et al. (2024), the success of revegetation on nutrient-deficient substrates is largely influenced by the selection of leguminous and xerophytic species that form symbiotic relationships with soil microorganisms, thereby enriching nitrogen content and gradually improving soil quality.

Conversely, the clay site showed the lowest biomass (1.351 ton/ha), carbon stock (0.669 ton/ha), and H′ = 1.02, indicating an early-successional ecosystem. The compact soil structure and poor drainage restrict root growth, water infiltration, and nutrient absorption. Vegetation is dominated by pioneer species such as Macaranga gigantea and Paraserianthes falcataria, which initiate ecological processes but have yet to form efficient multistrata canopies for carbon storage. Based on several studies, including Islam et al. (2022), Cotrufo et al. (2013), and Poudel et al. (2024), clay soil texture does not necessarily guarantee high soil carbon stocks. Although clay soils can enhance carbon stabilization through mineral associations and aggregate occlusion, biological processes—such as litter production, microbial activity, and the formation of microbial necromass—remain limited, along with the quantity and quality of organic matter inputs. These constrained biological processes and low organic inputs are largely attributable to the limited range of vegetation capable of surviving under clay soil conditions. Reduced litter production subsequently lowers soil fertility, creating unfavorable conditions for plant establishment and growth, and ultimately results in a limited capacity for carbon storage at the site. Improving ecosystem quality in these areas requires interventions such as soil inversion, organic-matter enrichment, and the introduction of leguminous pioneer species to enhance soil structure and accelerate humus formation.

Correlation analysis revealed a strong positive relationship between vegetation diversity (H′) and carbon stock, indicating that sites with higher diversity store more carbon. This finding supports the theory that structural complexity in vegetation is directly proportional to ecological function and carbon sequestration capacity (Lu et al., 2023). Multilayered vegetation enhances light and water use efficiency, increases photosynthetic productivity, and accelerates above-ground biomass accumulation. Ecologically, this suggests that biodiversity is not only a conservation metric but also a key driver of climate-change mitigation through enhanced carbon retention (Li et al., 2024).

Overall, the results demonstrate that PT Indocement Tarjun has successfully implemented an effective and sustainable reclamation program, with the laterite site showing the highest ecological recovery. The reclamation efforts have produced not only vigorous vegetation growth but also functionally restored ecosystems that support biodiversity and carbon regulation. Through a combination of adaptive species selection, soil management, and ecology-based monitoring, this initiative serves as a national best-practice model for environmentally responsible, low-emission mining reclamation—aligning with Indonesia's Green PROPER standards and the global Sustainable Development Goals (SDG 13 and 15).

CONCLUSION

This study demonstrates that the post-mining reclamation program implemented by PT Indocement Tunggal Prakarsa Tbk., Tarjun Unit, has effectively restored the ecological functions of the degraded land through enhanced biodiversity and increased carbon storage. The analysis revealed that the laterite area exhibited the highest floristic diversity (H′ = 2.69) and carbon stock (56.47 ton/ha), indicating a stable and productive ecosystem condition.

Conversely, the clay area remains in an early successional stage, characterized by low species diversity due to compact soil texture and poor drainage conditions.

Faunal diversity also served as an important indicator of reclamation success. A total of 41 bird species, 6 mammal species, and 5 herpetofauna species were recorded, with an average faunal diversity index (H′ = 2.21) suggesting a moderately to highly stable community structure. The limestone area showed the most balanced faunal community, dominated by pollinating birds, small mammals, and semi-aquatic herpetofauna—reflecting a recovered trophic structure and restored ecological function.

Overall, the strong positive correlation between biodiversity (flora and fauna) and carbon stock (r = 0.82) confirms that increasing ecosystem complexity directly enhances carbon sequestration capacity. These findings affirm that biodiversity-based reclamation strategies adopted by PT Indocement are effective in supporting climate-change mitigation, wildlife conservation, and long-term ecosystem sustainability, in alignment with the Green PROPER criteria of the Ministry of Environment and Forestry and the Sustainable Development Goals (SDG) 13 and 15.

Declaration by Authors

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