Original Paper

Carbon Sequestration Dynamics in The Above Ground Biomass on Reclaimed Land: a Coupled Ecological-Economic Assessment in Indonesia

Zainal Arifin*[1], Yudhi Harini Bertham[2], Wiryono[3], Agus Martono H. Putranto[4], Guswarni Anwar[3], Agus Susatya[3]

[1]*Bengkulu University, Faculty of Agriculture, Natural Resources Doctoral Study Program, Supratman, Kandang Limun, Bengkulu, Indonesia*
[2]*Bengkulu University, Faculty of Agriculture, Soil Science Study Program, Supratman, Kandang Limun, Bengkulu, Indonesia*
[3]*Bengkulu University, Faculty of Agriculture, Department of Forestry, Supratman, Kandang Limun, Bengkulu, Indonesia*
[4]*Bengkulu University, Chemistry Department of Natural Science and Mathematics, Supratman, Kandang Limun, Bengkulu, Indonesia*

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Land degradation due to coal mining causes loss of vegetation and soil degradation, thus greatly reducing carbon stocks. This loss inhibits carbon sequestration and reduces organic carbon storage, releasing carbon dioxide into the atmosphere, exacerbating greenhouse gas levels and climate change. Reclamation of post-mining land by replanting and soil improvement is essential to restore carbon stocks and mitigate the adverse impacts of coal mining on the environment. This study aims to analyze carbon stocks in post-mining land that has been reclaimed by PT Inti Bara Perdana. The study was conducted in January 2024 on the post-mining land of PT Inti Bara Perdana, Central Bengkulu Regency, Bengkulu Province. This study uses a method of measuring the potential for vegetation carbon storage at several sampling points on post-mining reclamation land aged 4 years, 7 years, and 11 years. The research method used is to create a 20 × 20 m plot to measure tree biomass and wood necromass. Measurement of understory biomass and litter necromass using a 1 × 1 m sub-plot. The results of the study showed that carbon sequestration on post-coal mining land increases significantly with reclamation age, rising from 99.71 t.ha^{-1} at 4 years to 234.66 t.ha^{-1} at 11 years. Correspondingly, the economic valuation based on the carbon market grew from IDR 5,683,470 mil.ha^{-1} to IDR 13,375,620 mil.ha^{-1} (342.26–805.48 USD). These findings highlight the effectiveness of long-term land reclamation in restoring ecosystem functions and contributing to climate change mitigation through carbon market integration. The study also provides valuable insights for policymakers and stakeholders in promoting sustainable post-mining land management.

Keywords: carbon stock, reclamation plant, coal mining post

1 Introduction

Post-coal mining land reclamation represents one of the most pressing environmental management challenges in Indonesia, a country where coal remains a dominant energy resource and a major contributor to the national economy. However, the ecological costs of coal extraction are severe and long lasting, with large expanses of land left in a degraded state following intensive mining operations. These areas are often characterized by substantial deterioration of physical, chemical, and biological soil properties, which severely limit the land's natural capacity for recovery (Saidy et al., 2024). The degradation process is primarily driven by large scale excavation and the stripping of surface soil layers, resulting in the irreversible loss of fertile topsoil, disruption of natural soil horizons, and a decline in soil structural stability. Moreover, the removal of the organic rich upper layer leads to nutrient depletion, reduced cation exchange capacity, and weakened water holding potential, thereby creating conditions hostile

***Corresponding Author:** Zainal Arifin, Bengkulu University, Faculty of Agriculture, Natural resources doctoral study program, Jl. WR, Supratman, Kandang Limun, Bengkulu 3837, Indonesia
e-mail: zainal.unib@yahoocom ORCID: https://orcid.org/0000-0002-3723-2281

to vegetation regrowth (Chandra et al., 2024). Without intervention, such areas face chronic erosion, reduced biodiversity, and long term ecological stagnation.

In this context, reclamation activities become a pivotal environmental management strategy aimed at reversing the adverse impacts of mining. Their role extends far beyond the mere restoration of vegetation cover, encompassing the rehabilitation of soil health, hydrological stability, and the reestablishment of ecological processes essential for long term sustainability. Importantly, reclamation also plays a role in mitigating global climate change by facilitating the sequestration of CO_2 emissions previously released through mining operations (Pambudi et al., 2023).

A crucial dimension in measuring the success of post-mining land reclamation is the systematic assessment of carbon stocks, a metric closely linked to both ecosystem recovery and international climate change mitigation commitments. Carbon stocks act as a tangible indicator of ecosystem functionality, as the land's ability to absorb and retain atmospheric carbon reflects the effectiveness of restoration interventions (Zheng & Zheng, 2023). Such evaluations typically cover two main carbon pools: soil organic carbon, which represents long term below ground storage (Gao et al., 2024), and above-ground biomass carbon, which is stored in vegetation components such as trunks, branches, foliage, and roots (Machado et al., 2025). The monitoring of these carbon pools over time provides critical feedback for adaptive management, allowing adjustments to be made in species selection, planting density, or soil management practices to optimize carbon sequestration outcomes (Shangguan et al., 2025).

The role of vegetation in CO_2 sequestration within reclaimed mining areas is especially critical, as plants function as primary agents in transforming atmospheric carbon into stable biomass pools (Kusumaningrum et al., 2024). Mining induced deforestation and land clearance drastically reduce this carbon sink capacity, leading to heightened atmospheric CO_2 concentrations and exacerbating global warming. Strategic revegetation guided by ecological restoration principles can counteract these impacts by promoting rapid biomass accumulation and enhancing soil organic matter through litterfall and root turnover (Somprasong, 2024). In post-mining landscapes, carefully planned species composition not only improves carbon storage but also supports biodiversity recovery, enhances microclimate regulation, and facilitates the reestablishment of trophic interactions within the ecosystem (Mante & Cadiz, 2024).

To evaluate these impacts within the carbon cycle, accurate estimation of carbon stocks is essential. The carbon sequestration potential is generally measured based on the total carbon stored in forest biomass organic material comprising tree trunks, branches, leaves, and roots, with approximately half of this dry biomass representing carbon. Reclamation and revegetation activities aim to enhance biodiversity, canopy cover, and forest stratification, all of which contribute to increased carbon storage. Such estimations are particularly important in tropical forests, which possess a significant capacity to store carbon and mitigate atmospheric CO_2 levels. Therefore, integrating carbon stock estimation into post-mining land management is a vital step in ensuring sustainable reclamation, supporting atmospheric CO_2 reduction, and facilitating the restoration of healthier and more productive ecosystems.

2 Material and Methods

2.1 Study Site and Period

This study was conducted in January 2024 at the post-coal mining reclamation site of PT Inti Bara Perdana, located in Central Bengkulu Regency, Bengkulu Province, Indonesia. The research focused on evaluating above ground carbon stock in reclamation areas that had been revegetated for 4, 7, and 11 years. Sampling was conducted across selected plots to estimate carbon stored in standing vegetation, litter, understory plants, and necromass.

The study site is located at an elevation of 347 m above sea level. The site is situated in a humid tropical climate, with an average annual precipitation of about 2,000 mm and a mean temperature of 27 °C. The soil at the site is classified as cambisol, characterized by moderate weathering, well-defined illuvial processes, brown to reddish coloration, sandy loam texture, slightly acidic to neutral pH, and low to moderate organic matter content. The land represents a formerly exploited coal mining area that has been reclaimed to restore ecological functions and productivity. The reclamation program began with land contouring and surface stabilization to minimize erosion and improve site conditions. As an initial step, the cover crop *Mucuna bracteata* was introduced to enhance soil organic matter, control erosion, and improve soil fertility. Following this stage, *Paraserianthes falcataria* was selected and planted as the primary revegetation species. Sengon was chosen due to its fast growth, adaptability to degraded soils, nitrogen-fixing ability, and high potential for biomass accumulation, which collectively contribute to enhanced carbon sequestration.

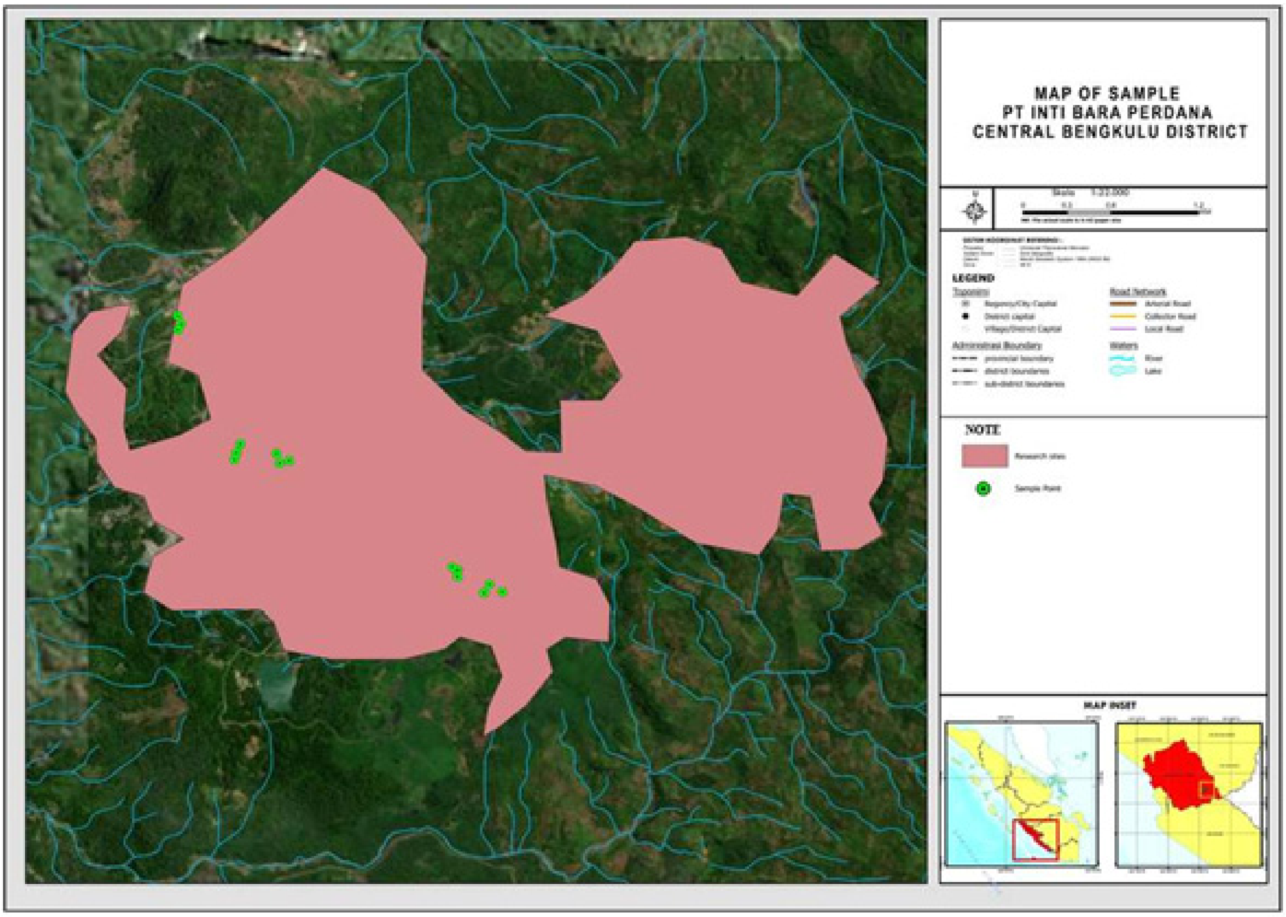

Figure 1 Research sampling location

2.2 Plot Establishment

Square shaped plots measuring 20 × 20 m were established to assess above ground biomass. In each main plot, four 1 × 1 m subplots were constructed at the corners for sampling litter and necromass.

2.3 Estimation of Tree Biomass

Tree biomass was estimated using field measurements of stem diameter and species specific allometric equations. For mature trees, the diameter at breast height (DBH) was measured at 1.3 m above ground level, while for younger trees, poles, and seedlings, the diameter was measured at 2 cm above the ground. For Sengon (*Paraserianthes falcataria* L.), the procedure involved:

a) wrapping a measuring tape around the tree trunk at the appropriate height to obtain the circumference (*k*),
b) recording the measured circumference,
c) calculating the diameter (*D*) as:

$$D = \frac{k}{\pi} \tag{1}$$

where: *D* – the tree diameter (cm); *k* – the tree circumference (cm); π\piπ is 3.14

The above ground biomass (*Y*) of Sengon trees was then estimated using a species-specific allometric equation:

$$Y = 0.0272 \cdot X^{2.831} \tag{2}$$

where: *Y* – the biomass (kg per tree); *X* – the diameter at breast height (cm)

2.4 Estimation of Understory and Litter Biomass

The biomass of understory vegetation and litter was estimated using 1 × 1 m subplots established within each main plot using purposive sampling. All litter within each subplot was completely collected, while understory vegetation was sampled by harvesting the above ground parts of all plants present in the subplot. The collected litter and understory samples were weighed to obtain their fresh weight. If the total sample mass exceeded 200 grams, a 200 g subsample was taken for further analysis. If the total mass was less than 200 grams, the entire sample was used. Subsamples were then oven-dried at 70 °C for 48 hours (2 × 24 hours) to determine their dry weight, which was used for biomass calculation. The resulting dry biomass values were later converted to per hectare estimates for carbon stock analysis.

Under post-mining conditions, the composition of understory vegetation varied with reclamation age. At 4 years, the community was dominated by pioneer herbs such as *Paspalum conjugatum* (Poaceae), *Mikania micrantha* (Asteraceae), *Chromolaena odorata* (Asteraceae), *Cyperus rotundus* (Cyperaceae), *Imperata cylindrica* (Poaceae), and *Mucuna bracteata* (Leguminosae), which provided rapid ground cover on open sites. By 7 years, additional life forms appeared, including lianas and shrubs such as *Lygodium microphyllum* (Lygodiaceae), *Melastoma malabathricum* (Melastomataceae), *Merremia peltata* (Convolvulaceae), and *Ottochloa nodosa* (Poaceae), contributing to greater structural diversity and higher vegetation coverage. At 11 years, the understory community became more complex, with pioneer species still prevalent but complemented by an increased presence of lianas and shrubs, resulting in enhanced vegetation cover and indicating progressive ecosystem recovery.

2.5 Estimation of Standing Dead Tree Necromass (Snags and Dead Poles)

The necromass of dead standing trees, poles, and saplings was estimated using a correction factor based on the level of tree decomposition. The method followed the guidelines from Indonesian National Standard (SNI) 7724-2019, and the necromass (*N*) was calculated as:

$$Ni = Bi \cdot f \qquad (3)$$

where: Ni – the necromass (kg); Bi – the estimated biomass of the tree (kg); f – the decomposition correction factor. The value of the correction factor in calculating the biomass of dead trees was based on Indonesian National Standard (SNI) measurements according to carbon stock:

- f = 0.9 for trees without leaves,
- f = 0.8 for trees without leaves and small branches,
- f = 0.7 for trees without leaves, branches, and large limbs.

2.6 Estimation of Deadwood Necromass Biomass

The necromass potential of deadwood was estimated using the Brereton volume from Indonesian National Standard (SNI) 7724-2019, which was then multiplied by the wood density to obtain biomass. The calculation involved two steps: first, estimating the deadwood volume (V_{km}), and second, converting the volume into biomass (N_{km}). The formulas are:

$$V_{km} = 0.25\pi \frac{d_p + d_u}{2 \cdot 100} \cdot p \qquad (4)$$

$$N_{km} = V_{km} \cdot \rho \qquad (5)$$

where: V_{km} – the volume of deadwood (m^3); d_p – the base diameter of the deadwood (cm); d_u – the top diameter of the deadwood (cm); p – the length of the deadwood (m); N_{km} – the deadwood necromass (kg); ρ – the wood density (kg.m^{-3})

2.7 Carbon Stock Calculation per Hectare for Aboveground Biomass

All biomass estimates obtained from each plot were then extrapolated to a per hectare basis. The carbon content per hectare (C_n) for each carbon pool in each plot was calculated using the following formula:

$$C_n = \frac{C_x}{1{,}000} \cdot \frac{10{,}000}{L_{plot}} \qquad (6)$$

where: C_n – the carbon content per hectare for each carbon pool in each plot (t.ha^{-1}); C_x – the total carbon content in each carbon pool in each plot (kg); L_{plot} – the plot area for each carbon pool (m^2)

2.8 Estimation of Carbon Stock and CO_2 Sequestration Potential

The total carbon stock stored in aboveground biomass, including stand trees, understory vegetation, litter, and necromass, was estimated using the following equation:

$$C = biomass\ (\text{kg.ha}^{-1}) \cdot 0.46 \qquad (7)$$

where: C – the estimated carbon content (kg.ha^{-1}); 0.46 – the carbon fraction in dry biomass from IPCC standard value (Hiraishi et al., 2014)

Furthermore, the potential amount of CO_2 sequestered by vegetation was estimated by converting the carbon stock to its equivalent CO_2 value using the atomic weight ratio of carbon in CO_2 molecules:

$$CO_2 = C \cdot 3.67 \qquad (8)$$

where: CO_2 – the amount of carbon dioxide equivalent (kg.ha^{-1}); 3.67 – the molecular weight ratio of CO_2 to C

2.9 Carbon Sequestration Valuation Approach

The economic valuation of carbon sequestration in post-coal mining lands was conducted to quantify the contribution of rehabilitated ecosystems in mitigating greenhouse gas emissions. This approach integrates ecological measurements of CO_2 uptake with a market based valuation framework using nationally recognized carbon pricing. To determine the economic value of the sequestered carbon, the amount of CO_2 absorbed (t.ha^{-1}) at each reclamation age was multiplied by the market price of carbon credits.

The carbon price used in this study was obtained from the official listing on the Indonesian Carbon Exchange (IDXCarbon) as of January 8, 2025 (IDXCarbon, n.d.), which was IDR 57,000 per ton of CO_2 equivalent. The economic valuation per hectare was calculated as follows:

$$\textit{carbon value}\ (\text{IDR.ha}^{-1}) = CO_2\ \textit{sequestered}\ (\text{t.ha}^{-1}) \cdot \textit{carbon price}\ (\text{IDR.t}^{-1}) \qquad (9)$$

where: *carbon value* represents the estimated monetary value of CO_2 sequestration per hectare; CO_2 *sequestered* – the total amount of CO_2 absorbed by vegetation (t.ha^{-1}); *carbon price* – the unit price of CO_2 equivalent (IDR.t^{-1})

3 Results and Discussion

Rehabilitation of post-coal mining lands through revegetation using *Falcataria moluccana* (sengon) demonstrated a consistent and substantial increase in biomass, carbon stock, and CO_2 sequestration potential over time. As shown in Table 1, aboveground biomass storage increased significantly with stand age, from 49.51 t.ha^{-1} at 4 years to 89.99 t.ha^{-1} at 7 years, and reached 109.13 t.ha^{-1} at 11 years. This growth was predominantly driven by tree biomass expansion, which rose markedly from 5.79 t.ha^{-1} to 59.30 t.ha^{-1}. The most substantial gain occurred between years 4 and 7, indicating a rapid early growth phase typical of pioneer species on degraded lands, consistent with earlier findings in tropical restoration contexts (Indrajaya et al., 2022).

In addition to tree biomass, pole and sapling components also contributed significantly. Pole biomass increased steadily from 21.36 t.ha^{-1} to 33.51 t.ha^{-1}, while sapling (stake) biomass declined between years 4 and 7, then slightly increased by year 11 (Table 1). This reflects competitive thinning and canopy closure processes as the stand matures.

Litter and understory biomass also increased with stand age (Table 2). Total biomass from these components rose from 7.05 t.ha^{-1} at 4 years to 21.27 t.ha^{-1} at 11 years. Understory vegetation, in particular, showed the most prominent rise, from 2.36 t.ha^{-1} to 12.34 t.ha^{-1}, suggesting improving microclimatic conditions and soil quality, likely driven by increasing litter input and decomposition from overstory sengon trees, which enhanced soil organic matter and nutrient availability. This development underscores the role of ground vegetation in maintaining biodiversity and stabilizing reclaimed ecosystems.

The significant increase in understory biomass highlights the progressive recovery of ecological functions, particularly in nutrient retention, water regulation, and habitat provision for various fauna (Akter et al., 2025). As plant litter accumulates over time, it contributes to the formation of humus, thereby enhancing soil structure and microbial activity, which are critical for sustaining ecosystem productivity. However, the rate and quality of humus formation are influenced by several environmental and biological factors. Soil type and texture play a key role in stabilizing organic matter, with clay-rich soils promoting longer-term humus accumulation, while sandy soils accelerate decomposition but retain less humus (Li et al., 2020). Soil moisture, pH, and temperature strongly affect microbial activity and enzymatic processes that drive the transformation of litter into stable humus, whereas unfavorable conditions such as drought or extreme pH can slow decomposition (Bogati et al., 2025).

The diversity and density of understory plant species further influence humus dynamics by providing litter with varied nutrient content, which supports a more diverse and active microbial community. The expansion of herbaceous and shrub layers in older reclamation stands enhances successional processes, facilitates seedling recruitment, reduces

Table 1 Biomass storage of revegetation stands

Observation parameters	Biomass weight (t.ha^{-1})		
	4 years	7 years	11 years old
Tree	5.79	45.34	59.30
Pole	21.36	29.35	33.51
Stake	22.36	15.30	16.32
Total	49.51	89.99	109.13

Table 2 Litter and understory biomass storage

Observation parameters	Biomass weight (t.ha^{-1})		
	4 years	7 years	11 years old
Litter	4.69	7.68	8.93
Understory plants	2.36	4.67	12.34
Total	7.05	12.35	21.27

surface runoff, and increases carbon input into the soil pool (Kauffman et al., 2025). Consequently, areas with favorable combinations of soil properties, moisture regime, and plant diversity tend to accumulate humus more efficiently, reinforcing soil fertility, microbial diversity, and overall ecosystem resilience. This pattern aligns with previous findings indicating that older reclamation sites support more complex understory structures, which are essential for sustaining long-term ecosystem functions (Puspitaloka et al., 2021).

In addition, increasing biomass of litter and understory components plays a pivotal role in enhancing belowground biodiversity, including soil fungi, bacteria, and detritivores, which are instrumental in nutrient mineralization and organic matter decomposition (Iqbal et al., 2025). The continual development of ground vegetation layers also acts as a protective barrier against soil erosion and supports the reestablishment of native species, making it a key indicator of successful post-mining land rehabilitation (Du et al., 2025). Therefore, monitoring the trajectory of litter and understory biomass offers valuable insights into the trajectory of ecological succession and the sustainability of ecosystem functions in reclaimed landscapes.

Necromass accumulation, comprising dead trees, poles, stakes, and woody debris, also exhibited an upward trend over time, rising from 2.50 t.ha^{-1} to 8.60 t.ha^{-1} (Table 3). The increase in coarse woody debris (0 to 2.89 t.ha^{-1}) and dead tree biomass reflects ongoing natural mortality and self-thinning processes, which are essential components of forest succession and nutrient.This gradual accumulation of necromass not only serves as a reservoir of nutrients, particularly carbon and nitrogen, but also contributes to habitat complexity, promoting the presence of fungi, invertebrates, and saproxylic organisms. As decomposition advances, the necromass releases nutrients back into the soil, enhancing microbial activity and influencing the biogeochemical cycling within the recovering ecosystem dynamics (Yang et al., 2025).

Moreover, the dynamics of necromass are closely linked to stand development stages and are indicative of the ecological maturity of reclaimed sites. In early successional stages, low necromass is expected due to limited woody biomass input, but as stands age, self thinning and tree mortality contribute significantly to deadwood pools. The presence of necromass not only supports biodiversity but also moderates microclimatic conditions, such as soil temperature and moisture retention, which are critical in post-mining land restoration. These functions underscore the importance of monitoring necromass as a key ecological indicator of forest recovery, particularly in disturbed or reclaimed ecosystems, where structural complexity and organic matter accumulation are critical benchmarks of success (Komonen et al., 2024).

When all biomass compartments (trees, litter, understory, and necromass) are combined, the total storage increased from 59.06 t.ha^{-1} at 4 years to 139.00 t.ha^{-1} at 11 years (Table 4). The majority of this increase was attributed to trees, poles, and understory vegetation, while necromass components contributed to structural complexity and long term ecosystem functioning. This overall growth indicates a positive trajectory of ecological recovery, suggesting that post-mining reclamation efforts have fostered not only biomass accumulation

Table 3 Necromass biomass storage

Observation parameters	Biomass weight (t.ha^{-1})		
	4 years	7 years	11 years old
Dead tree	0.37	1.48	2.68
Dead pole	0.78	2.08	1.87
Dead stake	1.35	1.38	1.16
Dead wood	0.00	0.47	2.89
Total	2.50	5.41	8.60

Table 4 Total Biomass and Nechromass Storage

Observation parameters	Biomass weight (t.ha^{-1})		
	4 years	7 years	11 years old
Tree	5.79	45.34	59.30
Pole	21.36	29.35	33.51
Stake	22.36	15.30	16.32
Litter	4.69	7.68	8.93
Understory plants	2.36	4.67	12.34
Dead tree	0.37	1.48	2.68
Dead pole	0.78	2.08	1.87
Dead stake	1.35	1.38	1.16
Dead wood	0.00	0.47	2.89
Total	59.06	107.75	139.00

Table 5 Total carbon storage of revegetation stands

Forest components	Total carbon (t.ha^{-1})		
	4 years	7 years	11 years old
Tree	2.66	20.86	27,28
Pole	9.83	13.50	15.41
Stake	10.29	7.04	7.51
Litter	2.16	3.53	4.11
Understory plants	1.09	2.15	5.68
Necromass	1.15	2.49	3.96
Total	27.17	49.57	63.94

but also the reestablishment of ecosystem services such as carbon sequestration, nutrient cycling, and habitat provisioning (Conrado da Cruz et al., 2020). The integration of various biomass pools demonstrates the holistic progress of forest development stages from establishment and growth to self thinning and maturation thereby reflecting improved site productivity and ecological integrity.

The increasing total biomass also signals enhanced belowground processes, such as soil carbon input from root turnover and litterfall, which support microbial communities and soil fauna essential for nutrient mineralization. The accumulation of living and dead organic matter across strata creates stratified microhabitats, which not only stabilize microclimates but also promote species richness and trophic interactions within the reclaimed ecosystem. In this context, each biomass component plays a distinct but interconnected role trees dominate carbon storage and canopy formation, understory vegetation accelerates soil cover and biodiversity, litter supports decomposition, and necromass enhances habitat and nutrient retention culminating in a resilient and multifunctional landscape (Hao et al., 2025).

Corresponding to biomass gains, total carbon stock also increased significantly from 27.17 t.ha^{-1} to 63.94 t.ha^{-1} (Table 5). Tree biomass was the dominant carbon pool, growing from 2.66 tons ha-1 to 27.28 t.ha^{-1}, consistent with high net primary productivity in early successional stages. Other compartments such as litter, understory, and necromass also showed increasing carbon contributions, reflecting integrated ecosystem recovery (Mgelwa et al., 2025).This upward trend indicates not only enhanced carbon sequestration capacity of the reclaimed land but also the progressive stabilization of the carbon cycle, where both aboveground and belowground biomass pools play crucial roles. Particularly, the increase in necromass and litter carbon stocks implies improvements in detrital pathways, which are vital for sustaining soil organic carbon and microbial food webs (X. Yang et al., 2021).

The accumulation of carbon across all vegetation compartments also suggests that post-mining ecosystems can function as significant carbon sinks when appropriately managed and restored. As tree and understory biomass expand, more atmospheric CO_2 is absorbed through photosynthesis, while the litter and necromass layers contribute to long term carbon storage via slow decomposition and humus formation. The pattern of carbon accumulation observed in this study reinforces the importance of comprehensive biomass accounting in evaluating the effectiveness of reclamation strategies. It also aligns with global findings that even degraded or previously mined lands can recover substantial carbon stocks over time with appropriate revegetation and soil rehabilitation practices (Csillik et al., 2019). Overall, these findings demonstrate the dual ecological and climate mitigation value of post-mining land recovery.

The CO_2 sequestration potential followed this pattern, increasing from 99.71 t.ha^{-1} to 234.66 t.ha^{-1} as the plantation matured (Table 6). This steady rise reflects the accumulation of organic carbon across various biomass components, including living trees, understory vegetation, litter, and necromass. While total CO_2 uptake continued to rise with stand age, the annual sequestration rate per hectare exhibited a declining trend – from 25.99 t.ha^{-1}.year^{-1} during the 4–7 year

Table 6 CO_2 sequestration potential

Reclamation age (years)	CO_2 sequestration potential (t.ha^{-1})	CO_2 sequestration potential (t.ha^{-1}.year^{-1})	Economic valuation (IDR.ha^{-1})
4	99.71	24.93	5,683,470
7	181.90	25.99	10,368,300
11	234.66	21.33	13,375,620

period to 21.33 t.ha^{-1}.year^{-1} during the 7–11 year period. This decline is characteristic of maturing forest systems where growth rates slow as stands approach structural equilibrium and canopy closure limits light availability for new biomass production (Bezerra et al., 2024). Similar patterns have been reported in both natural regrowth and plantation forests, indicating a general shift from rapid biomass accumulation in early successional stages to a phase of biomass maintenance and redistribution in older stands.

Such temporal dynamics underscore the importance of understanding forest development phases when estimating carbon sequestration potential, especially for inclusion in climate change mitigation programs such as Reducing Emission from Deforestation and forest Degradation (REDD+) and voluntary carbon markets. Younger plantations may exhibit higher annual sequestration rates, but older stands provide long term carbon retention and greater ecosystem stability both of which are essential for achieving sustained mitigation outcomes (Kafy et al., 2023).

From an economic standpoint, the valuation of sequestered carbon based on Indonesia's carbon market price (IDR 57,000 per ton CO_2) illustrates a positive linear trend. On the reclaimed area, the carbon value increased from IDR 5,683,470 mil.ha^{-1} at four years to IDR 13,375,620 mil.ha^{-1} at eleven years (Table 6). This sharp rise highlights not only the carbon capture potential of *Falcataria moluccana*, but also its role as a financially viable species for ecological restoration. The application of economic valuation provides a tangible metric for policymakers and investors, strengthening the argument for integrating revegetation into broader environmental finance frameworks. Furthermore, these results suggest that with appropriate incentives, post-mining landscapes could be transformed into income generating carbon sinks, simultaneously addressing land degradation and rural development goals.

Beyond carbon markets, the sequestration potential of revegetated lands also holds relevance in the context of nationally determined contributions (NDCs) under the Paris Agreement. By quantifying CO_2 removal across reclamation chronosequences, this study offers a data driven basis for tracking progress toward emissions reduction targets. Moreover, the ability to assign a monetary value to ecological services provides a compelling justification for scaling up nature based solutions (NBS) in degraded tropical landscapes (Chazdon & Guariguata, 2016).

Overall, the study confirms that sengon based revegetation of post-mining land not only accelerates ecosystem recovery and improves carbon storage, but also generates measurable economic returns within relatively short timeframes. These findings underscore the multifunctional benefits of forest based restoration linking ecological rehabilitation with climate mitigation and green economic development. Future landscape level planning should consider such integrated outcomes to guide land use transitions that are both environmentally sound and economically sustainable.

4 Conclusions

This study demonstrates that carbon sequestration on post-coal mining land increases significantly with reclamation age, rising from 99.71 t.ha^{-1} at 4 years to 234.66 t.ha^{-1} at 11 years. Correspondingly, the economic valuation based on the carbon market grew from IDR 5,683,470 mil.ha^{-1} to IDR 13,375,620 mil.ha^{-1}. These findings highlight the effectiveness of long term land reclamation in restoring ecosystem functions and contributing to climate change mitigation through carbon market integration. The study also provides valuable insights for policymakers and stakeholders in promoting sustainable post-mining land management.

Conflict of Interest

The authors declare that there is no conflict of interest.

Author Contributions

Zainal Arifin: conceptualization, data curation, formal analysis, investigation, methodology, visualization, writing – original draft, writing – review & editing. Yudhi Harini Bertham: supervision, validation, writing – review & editing, project administration. Wiryono: conceptualization, methodology, supervision, writing – review & editing. Agus Martono H. Putranto: conceptualization, methodology, formal analysis, writing – review & editing. Guswarni Anwar: data curation, investigation, resources, writing – review & editing. Agus Susatya: resources, supervision, validation, funding acquisition.

AI and AI-Assisted Technologies Use Declaration

This manuscript benefited from the use of artificial intelligence (AI)-assisted technologies during its preparation. Specifically, ChatGPT (developed by OpenAI) was employed to improve the readability and linguistic clarity of the text. The authors affirm that all intellectual content, data analysis, interpretation, and scientific arguments were conceived, written, and verified by the authors themselves. The use of AI was limited to language refinement and did not involve any generation of original research content or interpretation of scientific findings.

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