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Regeneration status and floristic composition at pioneer stands on reclaimed ex-coal mine sites in South Sumatra, Indonesia

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Abstract. *Juniarto A, Hardiwinoto S, Faridah E, Mansur I. 2025. Regeneration status and floristic composition at pioneer stands on reclaimed ex-coal mine sites in South Sumatra, Indonesia. Biodiversitas 26: 3446-3459.* Understanding the role of pioneer species is crucial for optimizing post-mining reclamation and supporting biodiversity. Therefore, this study aimed to evaluate and compare the regeneration status and floristic composition of pioneer stands at different ages within a reclaimed coal mine site in Tanjung Enim, South Sumatra. By using nested plot sampling, diversity was assessed through Important Value Index (IVI), species richness, Shannon-Wiener Index (H'), and Pielou Evenness Index (J'). The results showed regeneration patterns: *Melaleuca cajuputi* dominated seedling (IVI: 93.3-200.0%) and sapling stages (IVI: 141.3-200.0%) in all stands, while *E. cyclocarpum* dominated pole (IVI: 70.4-273.5%) and tree stages (IVI: 229.7-252.5%) in older stands. *M. cajuputi* supported 10 naturally regenerating species, slightly more than the 9 found in *E. cyclocarpum* stands. Across both stands, *Acacia mangium* and *Pterospermum javanicum* dominated sapling, pole, and tree stages, whereas *Commersonia bartramia* dominated exclusively in *M. cajuputi* stands. The community exhibits low to moderate diversity and moderate uniformity (H’: 0.57-1.34; J’: 0.46-0.69). The complementary roles of *M. cajuputi* in early recruitment and *E. cyclocarpum* in structural growth promoted ecosystem recovery. Regeneration is successful, but ecological recovery is limited by low diversity and dominance of a few species.

Keywords: Diversity index, *Enterolobium cyclocarpum*, *Melaleuca cajuputi*, reclamation, regeneration status

Abbreviations: D: Density, DO: Dominance, F: Frequency, IVI: Important Value Index, RD: Relative Density, RDO: Relative Dominance, RF: Relative Frequency

INTRODUCTION

The environmental consequences of coal mining include damage to soil structure, nutrient-poor soil, acidic soil pH levels, acid mine drainage, biodiversity loss, susceptibility to erosion, and heavy metal pollution (Sevilla-Perea and Mingorance 2015; de Quadros et al. 2016; Li et al. 2019). Consequently, mining enterprises are legally obligated to undertake the reclamation of their post-mining areas (Pemerintah Republik Indonesia 2010). According to Regulation No. 07/2014 by the Minister of Energy and Mineral Resources, reclamation is defined as an initiative to restore, rehabilitate, and enhance environmental quality and ecosystem functionality to a pre-mining state (Kementerian ESDM 2014). This process uses a comprehensive method, including land reshaping, revegetation, and water resource management, to mitigate erosion and pollution risks (Kodir et al. 2017; Pratiwi et al. 2021).

A critical reclamation stage involves selecting and planting pioneer species resilient to degraded soil conditions. As these pioneer species mature, local vegetation is interplanted according to the prescribed reclamation guidelines. The successful establishment of pioneer species plays an essential role in fostering diverse natural vegetation, serving as an indicator of reclamation success (Oktavia et al. 2015; Gebeyehu et al. 2019; Iskandar et al. 2022). The growth of these species also improves microclimatic conditions, such as temperature reduction and increased air humidity, creating favorable environments for late-successional species with more demanding ecological requirements (Gwenzi 2021; Putra et al. 2024).

Mine reclamation programs frequently prioritize pioneer species with rapid growth rates. For instance, PT Bukit Asam (PTBA) has long used *Enterolobium cyclocarpum* (Jacq.) Griseb. (a legume) and *Melaleuca cajuputi* Powell (a non-legume) as pioneer species in reclamation areas across Tanjung Enim, South Sumatra. Existing studies in this field have primarily compared species composition, structural attributes (basal area), and ecosystem functional attributes (diversity) between unmined and rehabilitated mined areas (Suyono et al. 2023). However, there are no studies that specifically compare ecosystem biodiversity profiles among pioneer species stands. Only a few investigations have analyzed the regeneration dynamics of legume and non-legume pioneer species in Indonesia.

The absence of species-specific and age-stratified analyses represents a critical knowledge gap. Generally, legumes and non-legumes differ fundamentally in their interactions with the recruitment of native flora, soil biota, nutrient contributions, and microclimatic modifications (da Silva et al. 2022; Zedníková et al. 2023). For instance, legumes like *E. cyclocarpum* enhance nitrogen fixation, potentially accelerating soil fertility restoration, while non-legumes such as *M. cajuputi* can excel in stabilizing water-logged soils lacking nutrient-enriching symbionts (Daws et al. 2015; Maiti and Prasad 2016). To address this gap, PTBA's initial revegetation species, namely *E. cyclocarpum* (legume) and *M. cajuputi* (non-legume), were selected as focal subjects. Despite their widespread use, there is no study on how these functional differences influence biodiversity trajectories across varying stand ages or support the spontaneous regeneration of indigenous species. The divergent pathways likely lead to distinct biodiversity profiles, yet no studies have quantified these effects in post-mining areas.

The temporal dimension of rehabilitation serves to observe how pioneer stands evolve structurally and functionally over time. Additionally, the "regeneration status" of rehabilitated areas, defined by density and health of naturally regenerating species, remains poorly quantified (Malik and Bhatt 2016; Singh et al. 2016; Gebeyehu et al. 2019). Regeneration status indicates whether pioneer stands can transition to self-sustaining forests (Kassahun et al. 2024). In this context, current data focus on planted vegetation rather than spontaneous regeneration, limiting insights into ecological autonomy.

Recent studies, such as those by Corrêa et al. (2015) and Inniss (2021), highlight the importance of floristic diversity in post-mining restoration and tropical secondary succession. Therefore, floristic comparison aids biodiversity recovery by identifying key species and traits, assessing restoration success, and guiding strategies to ensure restored lands provide essential ecosystem services (Sherilyn Jeanette Inniss 2021; Garate-Quispe et al. 2024; Xu et al. 2024).

This study aimed to address the knowledge gap by analyzing the floristic composition and regeneration status between *E. cyclocarpum* (legume) and *M. cajuputi* (non-legume) stands at several age classes. By mapping biodiversity profiles and regeneration patterns across chronosequences, the results will show how pioneer identity and stand age jointly shape ecological recovery. Ecologically, this study provides a framework for evaluating rehabilitation success beyond vegetation cover, emphasizing the restoration of functional ecosystems capable of autonomous regeneration.

MATERIALS AND METHODS

Study area

This study was conducted in August 2023 in the revegetation area of PTBA Tbk in Tanjung Enim, South Sumatra, Indonesia. As shown in Figure 1, the reclamation area was selected in the Mining Business License of Tambang Air Laya (IUP TAL) and West Banko (IUP BB). The plants evaluated were selected from the different categories, namely legumes, *Enterolobium cyclocarpum* (locally known as *sengon buto*), and non-legumes, *Melaleuca cajuputi* (cajuput; locally known as *kayu putih*).

Enterolobium cyclocarpum study areas were positioned at 3°45'20.9"S, 103°46'57.8"E (3 years old), 3°42'43.1"S, 103°45'27.7"E (7 years old), and 3°42'43.1"S, 103°45'27.7"E (9 years old); while *M. cajuputi* was located at 3°44'49.4"S, 103°48'54.9"E (2 years old), 3°44'14.5"S, 103°49'04.9"E (6 years old), and 3°43'56.7"S, 103°49'52.3"E (9 years old). These pioneer species were selected due to their adaptability to the reclamation area (Kodir et al. 2017; Pratiwi et al. 2021), showing adaptive growth (Kodir et al. 2017) and wide application across different revegetation areas at PTBA (PT Bukit Asam 2022).

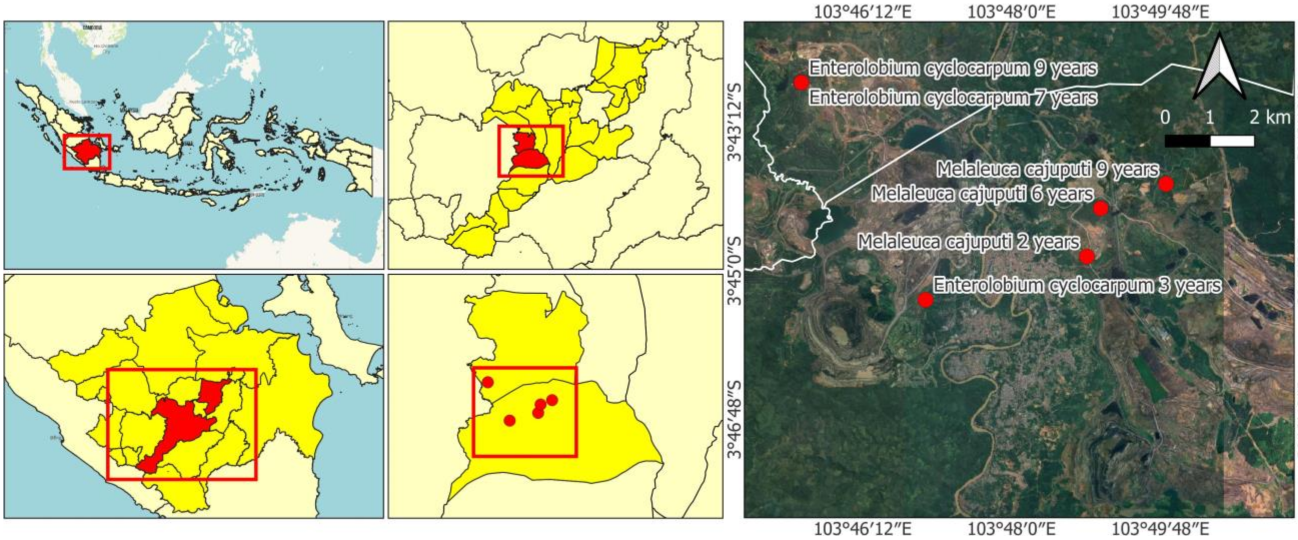

Figure 1. Tanjung Enim Village, Muara Enim District, South Sumatra Province, Indonesia, indicates the sampling areas of *E. cyclocarpum* and *M. cajuputi* planted (PT Bukit Asam 2022)

Procedures

Stands selection

The criteria for sample selection were based on planting age category and pioneer species, namely *E. cyclocarpum* and *M. cajuputi*. The reclamation area included stands of *E. cyclocarpum* and *M. cajuputi*, categorized by plant age as young (2-4 years old), intermediate (5-7 years old), and old (8-10 years old). This led to the selection of 6 stands, and observation areas were located using purposive sampling, focusing on areas where *E. cyclocarpum* and *M. cajuputi* were dominant, as shown in Figure 2. It was observed that *E. cyclocarpum* stands were heterogeneous in some areas (planted alongside other species during initial cultivation) and grouped in the Tambang Air Laya area. Consequently, grouped stands were selected for observation. At the West Banko site, some of the planted *M. cajuputi* stands were monocultures (2 years old), while others (6 and 9 years old) were partially mixed with enrichment plants. However, some species were distributed and dominant in the area, as shown in Figure 2. Since 2019, the company has implemented a reclamation design at the Banko Barat area, specifically for cultivating *M. cajuputi* to produce cajuput oil. Implemented uniform silvicultural practices include 3×1 m spacing, initial fertilization with 5 kg/tree of Bokashi fertilizer, and follow-up fertilization with up to 125 g of urea or NPK per plant until the age of 3 years (Kodir et al. 2017).

Microclimate measurement

The measurement of microclimate parameters included the assessment of temperature and relative humidity, which was conducted using a thermohygrometer. Measurements were taken at each observation area once a week in the morning (between 8.00-10.00 a.m.) for 4 weeks. Each area took three microclimate measurement points in three different vegetation observation sample plots (Putri et al. 2018).

Plant growth response measurement

Based on selected *M. cajuputi,* reclamation areas are relatively uniform at a young age, but become enriched with plants such as *Adenanthera pavonina*, *Pterocarpus indicus*, *Reutealis trisperma,* and *Intsia palembanica* as they mature (PT Bukit Asam 2022). Observation of *E. cyclocarpum* stands in reclamation areas is frequently mixed with 2 or 3 other legume species, including *A. pavonina*, *P. indicus, Samanea saman,* and *Senna siamea* (PT Bukit Asam 2022). Consequently, the selection of sample plots is determined by purposive sampling, based on the dominance of *E. cyclocarpum* species present in the reclamation area. We used a purposive sampling technique with two parallel criteria: (i) stands dominated by *E. cyclocarpum* (approximately >75% of the community), and (ii) stands dominated by *M. cajuputi* (approximately >75% of the community), both with similar criteria (Gris et al. 2020).

The plot method was used to set up nested quadrat plots (Rusolono et al. 2015; Murdjoko et al. 2021). The measuring plot were 20×20 m in size, with 10-15 plots perstand, covering a total area of 0.4-0.60 hectares in area. The plot is 20×20 m and subdivided into four subplots, each measuring 2×2 m (for seedling and understory measurement), 5×5 m (for sapling measurement), 10×10 m (for pole measurement), and 20×20 m (for tree measurements). Vegetations are categorized into the following levels: (i) The understory comprises of shrubs, bushes, lianas, herbs, and ferns; (ii) Seedlings are small trees with a height of <1.5 m and a diameter of <5cm; (iii) Saplings are woody plants with a height of ≥1.5 m and a diameter of 5cm≤Ø<10cm; (iv) Poles are woody plants with a diameter of 10 cm to Ø<20 cm; (v) Trees are woody plants with a diameter of at least 20 cm (Rusolono et al. 2015; Murdjoko et al. 2021).

The data collected for trees and poles included the number of individuals, diameter, total height, and branch-free height. For saplings, seedlings, and understory, the data collected were the number of individuals. Other naturally occurring vegetation was also inventoried, and data were obtained by comparing the history of the main plant species planted at age 0 (null) years with age *-n*. Furthermore, the method for species identification uses morphological methods and is assisted by botanists.

Data analysis

The vegetation data were analyzed in Microsoft Excel to obtain significant values describing stand characteristics such as density (stems ha^{-1}), dominance (m^2 ha^{-1}), frequency, relative density, relative dominance, relative frequency, and Important Value Index (IVI). Specifically, IVI combines each species' relative density, relative dominance, and relative frequency.


A B C D E F

Figure 2. Image view of *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands. A. *E. cyclocarpum* 3-years old, B. *E. cyclocarpum* 7-years old, C. *E. cyclocarpum* 9-years old, D. *M. cajuputi* 3-years old, E. *M. cajuputi* 7-years old, F. *M. cajuputi* 9-years old

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

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

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

Important Value Index (IVI) = RD + RF + RDO (%)

According to Malik and Bhatt (2016) and Gebeyehu et al. (2019), the regeneration status of species was determined based on the population size of seedlings, saplings, and adult trees (dbh>10 or pole and tree levels) as described in: (i) "good" regeneration if seedlings>saplings>adults, and (ii) "fair" regeneration when seedlings>saplings≤adults. Also, the regeneration status was categorized as (iii) 'poor' for species represented exclusively by the sapling stage (though saplings may be less, more, or equal to adults), (iv) 'none' when only adult trees represent a species (absent in sapling and seedling stages), and (v) 'new' if a species has no adults, but only saplings and/or seedlings. We analyzed differences in regeneration status using the Kruskal-Wallis test, followed by further analysis with the Mann-Whitney U test to distinguish specific groups. This is because the observation of stands with two other species (independent) was conducted simultaneously. Shannon-Wiener Index (H’) and Pielou Index (J’) were also applied to measure species diversity and evenness/equality, respectively, based on the method of Chen et al. (2018) as follows:

$$H' = \sum (p . \ln pi) \qquad J' = \sum \frac{H'}{\ln S}$$

Where:

H’ : Shannon-Wiener Index

pi : Proportion of individuals of species *i*

J’ : Evenness Index

S : Total number of species (species richness)

RESULTS AND DISCUSSION

Microclimate condition

Microclimate characteristics observed in *E. cyclocarpum* and *M. cajuputi* stands varied depending on the vegetation age. In *E. cyclocarpum* stands, the average temperature ranges from 33°C at age 3 to 31°C at age 9, but relative humidity increases from 55% to 63% (Table 1). Similarly, in *M. cajuputi,* the average temperature declines from 35°C at age 2 to 29°C at age 9. Relative humidity increases from 51% at age 2 to 61% at age 7, followed by a slight decrease to 60% at age 9 (Table 1). These results show changes in microclimatic conditions associated with increasing pioneer species age.

Regeneration status

Based on the results, there are still different regeneration statuses of pioneer species at various ages in Table 2. In *E. cyclocarpum*, adult density increases significantly from 25 stems ha^{-1} at age 3 to 540 stems ha^{-1} at age 9. An age of 3 years is sufficient for a few species of *E. cyclocarpum* (25 stem ha^{-1}) to reach a diameter of more than 10 cm. At *E. cyclocarpum* 3-year-old, sapling density is 3,400 stems ha^{-1} but decreases to 160 stems ha^{-1} at 9. Seedling density also decreases from 14,063 stems ha^{-1} at age 3 to 250 stems ha^{-1} at age 9. The regeneration status shifts from "good" at 3 to "fair" at ages 7 and 9. *E. cyclocarpum* 3-year-old shows regeneration status as "good" because of the density of seedling>sapling>adult.

In *M. cajuputi*, adult density increases from 0 stem ha^{-1} at age 2 to 426 stem ha^{-1} at age 6 before slightly declining to 294 stem ha^{-1} at age 9 (Table 2). Sapling and seedling density at age 2 of *M. cajuputi* are the highest, with 16,309 stem ha^{-1} and 5,796 stem ha^{-1}, respectively, but show a significant decrease at ages 6 and 9. Despite these changes, the regeneration status remains "good" at ages 6 and 9, which is categorized as new at age 2. *M. cajuputi* 6- and 9-year-old showed regeneration in "good" status because of seedling density>sapling density>adult density. Furthermore, *M. cajuputi* 2-year-old stand was considered a young stand due to the absence of the adult stage (adult = 0). *E. cyclocarpum* 3-year-old has shown "good" status because of seedling density>sapling density>adult density.

The results of the differential analysis revealed significant differences (p-value<0.01) in seedling density, sapling density, and adult density. *E. cyclocarpum* 3-year-old seedlings had a significantly higher density than all other sites. At *M. cajuputi*, 2-year-olds had a significantly higher density than *E. cyclocarpum* at ages 7 and 9 but were not different from *M. cajuputi* at ages 6 and 9. At the sapling level, *M. cajuputi* at age 2 had the highest density, significantly exceeding all other sites. *E. cyclocarpum* 3-year-olds had a significantly higher density than *E. cyclocarpum* at ages 7 and 9 and *M. cajuputi* at ages 6 and 9, but a lower density than *M. cajuputi* 2-year-olds. At the adult level, no significant differences were observed among *E. cyclocarpum* 7 and 9-year-olds and *M. cajuputi* 6 and 9-year-olds.

Table 1. Average microclimate on each stand of *Enterolobium cyclocarpum* and *Melaleuca cajuputi*

Parameter	***Enterolobium cyclocarpum***			***Melaleuca cajuputi***		
	Age 3	**Age 6**	**Age 9**	**Age 2**	**Age 7**	**Age 9**
Average temperature (°C)	33	32	31	35	30	29
Relative humidity (%)	55	58	63	51	61	60

Table 2. The regeneration status of pioneer species planted between *Enterolobium cyclocarpum* and *Melaleuca cajuputi* in ex-coal mine land

Sites	**Mean±SE** **Median (Min-Max)**			**Regeneration status**
	Seedling density	**Sapling density**	**Adult density**	
Enterolobium cyclocarpum 3-year-old	14063±3533.5^{a}	3400±595.2^{a}	25±16.4^{a}	Good
	11250 (2500-27500)	3600 (1200-6400)	0 (0-100)	
Enterolobium cyclocarpum 7-year-old	0^{b}	150±73.2^{b}	359±125.8^{b}	Fair
	0	0 (0-400)	300 (50-975)	
Enterolobium cyclocarpum 9-year-old	250±250.0^{b}	160±88.4^{b}	540±129.2^{b}	Fair
	0 (0-2500)	0 (0-800)	600 (0-975)	
Melaleuca cajuputi 2-year-old	5795±1360.3^{c}	16309±603.6^{c}	0^{a}	New
	3750 (0-25000)	16000 (10000-23600)	0	
Melaleuca cajuputi 6-year-old	4457±1295.7^{b,c}	817±126.9^{d}	426±72.6^{b}	Good
	0 (0-20000)	800 (0-2400)	300 (0-1400)	
Melaleuca cajuputi 9-year-old	6471±3307.6^{b,c}	871±124.8^{d}	294±56.5^{b}	Good
	0 (0-52500)	800 (0-1600)	300 (0-800)	
p-value	<0.01*	<0.01*	<0.01*	

Note: *: Significantly different, $^{a, b, c, d}$: Different letters in the same column showed significant differences among sites

Table 3. IVI of understory species in *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands (in descending order of density). For all pioneer stands in Tables (3-7), D: Density (stem ha^{-1}), DO: Dominance (m^{2} ha^{-1}), F: Frequency, RD: Relative Density (%), RDO: Relative Dominance (%), RF: Relative Frequency (%), and IVI: Important Value Index (%)

Species	**D**	**F**	**RD (%)**	**RF (%)**	**IVI (%)**
Enterolobium cyclocarpum 3-year-old					
Imperata cylindrica (L.) Raeusch.	24,375	0.38	100.0	100.0	200.0
Enterolobium cyclocarpum 7-year-old					
Imperata cylindrica (L.) Raeusch.	146,875	0.25	97.9	66.7	164.6
Melastoma malabathricum L.	3,125	0.13	2.1	33.3	35.4
Enterolobium cyclocarpum 9-year-old					
Melastoma malabathricum L.	6,500	0.30	100.0	100.0	200.0
Melaleuca cajuputi 2-year-old					
Imperata cylindrica (L.) Raeusch.	25,000	0.27	100.0	100.0	200.0
Melaleuca cajuputi 6-year-old					
Imperata cylindrica (L.) Raeusch.	17,826	0.13	88.2	42.9	131.0
Chromolaena odorata (L.) R.M.King & H.Rob.	1,196	0.04	5.9	14.3	20.2
Melastoma sp.	1,087	0.04	5.4	14.3	19.7
Clidemia hirta (L.) D.Don	109	0.09	0.5	28.6	29.1
Melaleuca cajuputi 9-year-old					
Imperata cylindrica (L.) Raeusch.	102,206	0.41	96.0	43.8	139.7
Melastoma sp.	1,912	0.18	1.8	18.8	20.6
Chromolaena odorata (L.) R.M.King & H.Rob.	1,618	0.18	1.5	18.8	20.3
Clidemia hirta (L.) D.Don	588	0.12	0.6	12.5	13.1

Stand structure

Understory species

Understory species identified in all ages of *E. cyclocarpum* were *Melastoma malabathricum* and *Imperata cylindrica*. As shown in Table 3, *I. cylindrica* dominated *E. cyclocarpum* 3-year-old stand, with IVI of 200%, indicating dominance in relative density (100%) and relative frequency (100%). Then, *I. cylindrica* also dominated *E. cyclocarpum* 7-year-old, with IVI of 164.6% and very high density (D 146,785), while *M. malabathricum* appeared as a secondary species with IVI of 35.4%. In *E. cyclocarpum* 9-year-old stand, *M. malabathricum* was the highest with IVI of 200%, displacing *I. cylindrica.*

Similar conditions were found in all *M. cajuputi* stands. *I. cylindrica* was the most dominant understorey with a high IVI. The 2-year-old species was completely dominated by *I. cylindrica*, with IVI of 200%. This was followed by *I. cylindrica* dominating 6-year-old stand, with IVI of 131.0%. Meanwhile, secondary species like *Chromolaena odorata* (IVI 20.2%) and *Clidemia hirta* (IVI 29.1%) are observed. The *I. cylindrica* dominated *M. cajuputi* 9-year-old stand with IVI of 139.7%, while *Melastoma* sp. (IVI 20.6%), *C. odorata* (IVI 20.3%), and *C. hirta* (IVI 13.1%) contributed to enhanced understory species variety. These results showed that IVI of understory species changed with age in *E. cyclocarpum* and *M. cajuputi* stands.

Seedling species

As shown presented in Table 4, *E. cyclocarpum* and *M. cajuputi* seedling levels show significant patterns of species dominance and diversity at various ages. *E. cyclocarpum* had the highest IVI (91.0%) and density (14,063 stem ha^{-1}) among 3-year-old stand, followed by *A. pavonina* (41.7%) and *Acacia mangium* (34.9%). *A. mangium* became the single dominating species at 7 years old. *Bridelia tomentosa* had the highest IVI of 9-year-old stand, at 125.0%, followed by *Vitex pinnata* (43.8%) and *E. cyclocarpum* (31.3%). The seedling at *E. cyclocarpum* 9-year-old was dominated by *B. tomentosa* and *V. pinnata,* with IVI 125.0% and 43.8%, respectively.

The seedlings of pioneer species, namely *M. cajuputi,* are greatly dominant in all ages. *M. cajuputi* (IVI 200%) is completely dominant at 2-year-old, including at 6-year-old stand (IVI 93.3%), sharing space with *A. mangium* (45.2%) and *V. pinnata* (30.2%). *M. cajuputi* (IVI 97.6%) and *Schima wallichii* (IVI 71.9%) dominate at 9 years old, with other species, such as *Syzygium* sp. and *Bridelia monoica*, having significantly lower IVI. This suggests increasing variety while the dominance decreases significantly.

Table 4 shows several seedlings that naturally grow and have high IVI values in all age *E. cyclocarpum* stands, including *A. mangium* and *B. tomentosa*. Meanwhile, on the same criteria (natural seedling and IVI value) in *M. cajuputi* stands, the species *A. mangium* and *S. wallichii* are dominant. The results show that the level of natural seedlings in *E. cyclocarpum* and *M. cajuputi* stands has a high IVI value in *A. mangium*, particularly in *E. cyclocarpum* 7-year-old stand.

Sapling species

The sapling levels of *E. cyclocarpum* and *M. cajuputi* show significant variations in species dominance and diversity at different ages, as presented in Table 5. High species diversity is shown in *E. cyclocarpum* 3-year-old and *M. cajuputi* 6-year-old, where the number of saplings found is 7-8. Meanwhile, Table 6 shows that the highest IVI at the sapling level for various ages is still dominated by pioneer species, namely *E. cyclocarpum* and *M. cajuputi*. *E. cyclocarpum* had the highest IVI at ages 3, 7, and 9 with IVI of 76.2%, 76.2%, and 90.0%, respectively. *Melaleuca cajuputi* had the highest IVI at ages 2, 6, and 9 with IVI of 200%, 141.3%, and 142.9%, respectively.

Table 5 shows that *A. mangium* is the natural species with the second-highest IVI value, except *E. cyclocarpum* 9-year-old stand. *Acacia mangium* had the second highest IVI at ages 3 and 7 of *E. cyclocarpum* with an IVI of 50.3% and 50.8%, respectively, also the second highest IVI at ages 6 and 9 of *M. cajuputi* with IVI of 28.8% and 25.4%. However, other natural species, such as *P. indicus* and *I. palembanica,* significantly contribute to the diversity of the ecosystem, as shown by their high IVI values. *Pterocarpus indicus* had the highest density and second highest IVI at age 7 of *E. cyclocarpum* with an IVI of 73.0%. Then, *I. palembanica* had the second highest IVI at age 9 of *E. cyclocarpum* with an IVI of 73.0%.

Pole species

As shown in Table 6, *E. cyclocarpum* stands at various ages were dominated by *E. cyclocarpum* and *A. mangium*, while *M. cajuputi* stands were dominated by *M. cajuputi* and *A. mangium*. In *E. cyclocarpum* 7- and 9-year-old stand*, E. cyclocarpum* had the highest IVI (273.5%; 226.1%), followed by *A. mangium* (26.5%; 53.3%). In line with the results, *A. mangium* had the highest IVI (194.5%), followed by *E. cyclocarpum* (70.4%) at *E. cyclocarpum* 3-year-old stand. Similarly, in the ages 7 and 9 *M. cajuputi* stands*, M. cajuputi* exhibited the highest IVI (237.9% and 210.7%, respectively), followed by *A. mangium* (40.7% and 38.1%).

Tree

Based on the results in Table 7, *E. cyclocarpum* still dominated at 7- and 9- year-old, while *M. cajuputi* was not attended at older *M. cajuputi* stands (ages 6 and 9). *E. cyclocarpum* had the highest IVI, with 252.5% and 229.7% at ages 7 and 9, respectively, followed by *A. mangium*, with 47.5% and 70.3%, respectively. By comparing ages 7 and 9, *E. cyclocarpum* stands, the Density (D) at both ages is the same, with 122 and 120 stem ha^{-1}, respectively. However, the Dominance (DO) value differs, with 3.94 and 2.69 m^2 ha^{-1}, respectively.

The absence of *M. cajuputi* at tree level in stands is dominated by *A. mangium* in all ages (Table 7). *A. mangium* had the highest IVI, with 300% and 287% at ages 6 and 9 of *M. cajuputi* stands, respectively. Meanwhile, in *E. cyclocarpum* 7- and 9-year-old stands*, A. mangium* had the second-highest IVI. This indicates that *A. mangium* occupancy is dominant in *M. cajuputi* stands but low in *E. cyclocarpum* revegetation stands.

Species composition

The species composition is classified as trees or understory vegetation (Figure 3). In both *E. cyclocarpum* and *M. cajuputi* stands, the distribution between trees and understory varies over time. In the 3-year-old *E. cyclocarpum* stand, there are 7 tree species and 1 understory species. At 7 years old, the number of tree species decreases to 3, while the understory species increase to 2. In the 9-year-old stand, tree species increase to 5, with only 1 understory species remaining. For *M. cajuputi*, at 2 years old, both trees and understory show equal representation, with 1 species each. At 6 years old, the number of tree species increases significantly to 10, while the understory comprises 4 species. Similarly, at 9 years old, there are 9 tree species and 4 understory species.

Ages 3, 7, and 9 of *E. cyclocarpum* showed species richness that differed based on the growth level. At *E. cyclocarpum* 3-year-old stand was dominated by the number of seedlings and saplings, with 5 and 7 species, respectively. At *E. cyclocarpum* 7-year-old stand, no seedlings were observed, but there were 3 saplings and 2 poles. In 9-year-old, there were an equal number of seedlings, saplings, and pole species, with 3 species.

There was one species of understory, seedling, and sapling at *M. cajuputi* 2-year-old. Furthermore, 6-year-old *M. cajuputi* had the highest number of understories, seedlings, and saplings of all ages, with 4, 7, and 8, respectively. *M. cajuputi* 9-year-old stand had the highest number of understories and poles of all ages, with 4 and 7, respectively.

Diversity and similarity in species composition

Shannon-Wiener Diversity Index is a quantitative measure of species variety in a community, as shown in Figure 4. The diversity index was observed to be high in *E. cyclocarpum* 3- and 9-years-old stands, with values of 1.34 and 1.02, respectively. Similarly, high diversity indices were recorded in *M. cajuputi* 6- and 9-year-old stands, with values of 1.06 and 1.15, respectively. A low diversity index was found in 9-year-old stand, including the Evenness value, which is used to determine how evenly species are distributed within a community. As shown in Figure 4, the Evenness index in the all-ages *M. cajuputi* stands is moderate (0.46-0.69), except for *M. cajuputi* 3 years-old. There is no diversity and similarity value in 3-years-old *M. cajuputi* because only *M. cajuputi* occupies the area.

Discussion

Regeneration status and IVI of pioneer species

In summary, the data obtained from the status regeneration shows several things. At the seedling stage, *E. cyclocarpum* 3-year-olds showed the highest recruitment, while at the sapling stage, *M. cajuputi* 2-year-olds dominated. Adult density levels indicated that all sites, except *E. cyclocarpum* at age 3 and *M. cajuputi* at age 2, had established adult populations. These findings highlight that *M. cajuputi* maintains "Good" regeneration due to consistent seedling and sapling recruitment, but *E. cyclocarpum* shows a concerning decline in recruitment.

Furthermore, the different regeneration statuses of *E. cyclocarpum* and *M. cajuputi* show species-specific growth strategies. *M. cajuputi* maintained high seedling densities (4,457 stems ha^{-1} at age 6; 6,471 stems ha^{-1} at age 9), far exceeding *E. cyclocarpum*, which showed no regeneration at age 7 and only 250 stems ha^{-1} at age 9. *M. cajuputi* stands had more seedlings and saplings than *E. cyclocarpum* at comparable ages. *E. cyclocarpum* regeneration declines with stand age due to its nature as an obligate pioneer species that requires more open conditions without dense shade. As stands mature (7-9 years), canopy closure reduces understory light and eliminates canopy gaps, limiting light at the forest floor (Yunanto et al. 2021). Low light conditions limit the photosynthesis and growth of light-demanding species. However, shade-tolerant species gain an advantage, as seen in *V. pinnata* and *B. tomentosa*, which dominate the seedling level in older *E. cyclocarpum* stands.

Table 4. IVI of seedling levels in *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands (in descending order of density)

Species	D	F	RD (%)	RF (%)	IVI (%)
Enterolobium cyclocarpum 3-year-old					
*Enterolobium cyclocarpum**	14,063	1.00	57.7	33.3	91.0
*Adenanthera pavonina***	4,063	0.75	16.7	25	41.7
Acacia mangium	3,438	0.63	14.1	20.8	34.9
Commersonia bartramia (L.) Merr.	1,563	0.38	6.4	12.5	18.9
Pterospermum javanicum Jungh.	1,250	0.25	5.1	8.3	13.5
Enterolobium cyclocarpum 7-year-old					
Acacia mangium	625	0.13	100.0	100.0	200.0
Enterolobium cyclocarpum 9-year-old					
Bridelia tomentosa	3,000	0.20	75.0	50.0	125.0
Vitex pinnata	750	0.10	18.8	25.0	43.8
*Enterolobium cyclocarpum**	250	0.10	6.3	25.0	31.3
Melaleuca cajuputi 2-year-old					
*Melaleuca cajuputi**	5,795	0.82	100.0	100.0	200.0
Melaleuca cajuputi 6-year-old					
*Melaleuca cajuputi**	4,457	0.48	52.6	40.7	93.3
Acacia mangium	1,630	0.30	19.2	25.9	45.2
Vitex pinnata	1,304	0.17	15.4	14.8	30.2
*Pterocarpus indicus****	652	0.09	7.7	7.4	15.1
Hibiscus tiliaceus L.	217	0.04	2.6	3.7	6.3
Bridelia tomentosa	109	0.04	1.3	3.7	5.0
Schima wallichii	109	0.04	1.3	3.7	5.0
Melaleuca cajuputi 9-year-old					
*Melaleuca cajuputi**	6,471	0.47	59.5	38.1	97.6
Schima wallichii	3,676	0.47	33.8	38.1	71.9
Syzygium sp.	294	0.12	2.7	9.5	12.2
Cratoxylum sp.	147	0.06	1.4	4.8	6.1
Adinandra sp.	147	0.06	1.4	4.8	6.1
Bridelia monoica	147	0.06	1.4	4.8	6.1

Note: *: Pioneer species, **: Enrichment planting, ***: Natural seedling from enrichment planting

Table 5. IVI of sapling levels in *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands (in descending order of density)

Species	D	F	RD (%)	RF (%)	IVI (%)
Enterolobium cyclocarpum 3-year-old					
*Enterolobium cyclocarpum**	3,400	1.00	50.4	25.8	76.2
Acacia mangium	1,650	1.00	24.4	25.8	50.3
Commersonia bartramia	900	0.88	13.3	22.6	35.9
Pterospermum javanicum	450	0.38	6.7	9.7	16.3
*Adenanthera pavonina***	250	0.38	3.7	9.7	13.4
Clidemia hirta	50	0.13	0.7	3.2	4.0
Terminalia catappa L.	50	0.13	0.7	3.2	4.0
Enterolobium cyclocarpum 7-year-old					
Pterocarpus indicus	200	0.25	44.4	28.6	73.0
*Enterolobium cyclocarpum**	150	0.38	33.3	42.9	76.2
Acacia mangium	100	0.25	22.2	28.6	50.8
Enterolobium cyclocarpum 9-year-old					
*Enterolobium cyclocarpum**	160	0.30	40.0	50.0	90.0
Intsia palembanica	160	0.20	40.0	33.3	73.3
Vitex pinnata	80	0.10	20.0	16.7	36.7
Melaleuca cajuputi 2-year-old					
*Melaleuca cajuputi**	16,309	1.00	100.0	100.0	200.0
Melaleuca cajuputi 6-year-old					
*Melaleuca cajuputi**	817	0.83	73.4	67.9	141.3
Acacia mangium	122	0.22	10.9	17.9	28.8
Commersonia bartramia	70	0.13	6.3	10.7	17.0
Hibiscus tiliaceus	35	0.09	3.1	7.1	10.3
*Pterocarpus indicus****	17	0.04	1.6	3.6	5.1
Anacardium occidentale	17	0.04	1.6	3.6	5.1
Vitex pinnata	17	0.04	1.6	3.6	5.1
Peronema canescens	17	0.04	1.6	3.6	5.1
Melaleuca cajuputi 9-year-old					
*Melaleuca cajuputi**	871	0.88	80.4	62.5	142.9
Acacia mangium	94	0.24	8.7	16.7	25.4
Commersonia bartramia	71	0.18	6.5	12.5	19.0
*Adenanthera pavonina****	47	0.12	4.3	8.3	12.7

Note: *pioneer species; **enrichment planting; ***natural sapling from enrichment planting

Table 6. IVI of pole levels in *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands (in descending order of density)

Species	D	F	DO	RD (%)	RF (%)	RDO (%)	IVI (%)
Enterolobium cyclocarpum 3-year-old							
Acacia mangium	125	0.25	0.11	76.9	40.0	77.6	194.5
*Enterolobium cyclocarpum**	25	0.25	0.02	15.4	40.0	15.0	70.4
Pterospermum javanicum	13	0.13	0.01	7.7	20.0	7.4	35.1
Enterolobium cyclocarpum 7-year-old							
*Enterolobium cyclocarpum**	238	0.75	0.28	95.0	85.7	92.7	273.5
Acacia mangium	13	0.13	0.02	5.0	14.3	7.3	26.5
Enterolobium cyclocarpum 9-year-old							
*Enterolobium cyclocarpum**	420	0.90	0.84	76.4	69.2	80.5	226.1
Acacia mangium	90	0.30	0.15	16.4	23.1	13.9	53.3
*Intsia palembanica***	40	0.10	0.06	7.3	7.7	5.6	20.5
Melaleuca cajuputi 6-year-old							
*Melaleuca cajuputi**	426	0.87	1.24	86.0	71.4	80.5	237.9
Acacia mangium	39	0.22	0.23	7.9	17.9	14.9	40.7
*Pterocarpus indicus***	26	0.09	0.06	5.3	7.1	3.9	16.3
Commersonia bartramia	4	0.04	0.01	0.9	3.6	0.7	5.1
Melaleuca cajuputi 9-year-old							
*Melaleuca cajuputi**	294	0.76	0.54	80.6	54.2	75.9	210.7
Acacia mangium	29	0.24	0.10	8.1	16.7	13.3	38.1
Commersonia bartramia	18	0.18	0.03	4.8	12.5	4.3	21.6
Pterospermum javanicum	6	0.06	0.01	1.6	4.2	1.6	7.4
Vitex pinnata	6	0.06	0.01	1.6	4.2	1.2	7.0
*Adenanthera pavonina***	6	0.06	0.02	1.6	4.2	2.3	8.1

Note: *pioneer species; **enrichment planting

Table 7. IVI of tree levels in *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands (in descending order of density)

Species	D	F	DO	RD (%)	RF (%)	RDO (%)	IVI (%)
Enterolobium cyclocarpum 7-year-old							
*Enterolobium cyclocarpum**	122	1.00	3.94	86.7	66.7	99.2	252.5
Acacia mangium	19	0.50	0.03	13.3	33.3	0.8	47.5
Enterolobium cyclocarpum 9-year-old							
*Enterolobium cyclocarpum**	120	0.80	2.69	84.2	61.5	83.9	229.7
Acacia mangium	23	0.50	0.52	15.8	38.5	16.1	70.3
Melaleuca cajuputi 6-year-old							
Acacia mangium	5	0.24	0.24	100.0	100.0	100.0	300.0
Melaleuca cajuputi 9-year-old							
Acacia mangium	37	0.71	1.57	96.2	92.3	98.5	287.0
Pterospermum javanicum	1	0.06	0.02	3.8	7.7	1.5	13.0

Note: *pioneer species

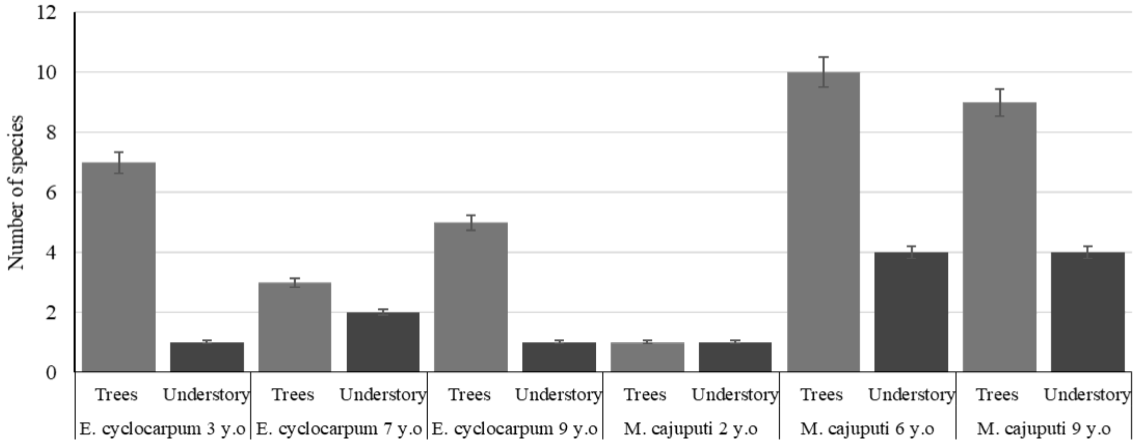

Figure 3. The number of species grouped by life forms in *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands

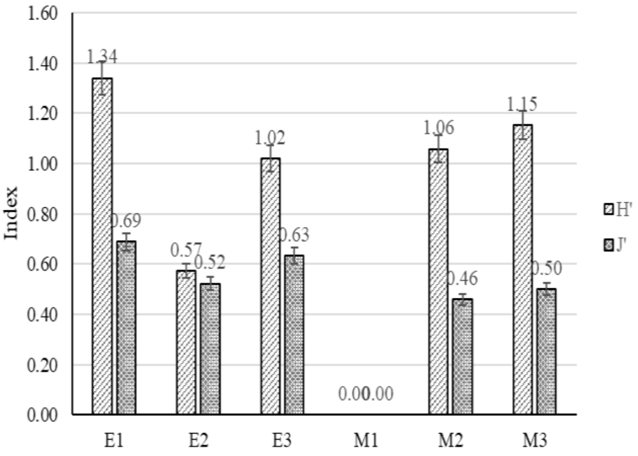

Figure 4. Diversity and similarity indices in species composition of *Enterolobium cyclocarpum* and *Melaleuca cajuputi* stands. E1: *Enterolobium cyclocarpum* 3-year-old; E2: *Enterolobium cyclocarpum* 6-year-old E3: *Enterolobium cyclocarpum* 9-year-old; M1: *Melaleuca cajuputi* 2-year-old; M2: *Melaleuca cajuputi* 7-year-old; and M3: *Melaleuca cajuputi* 9-year-old

In comparison, the "good" regeneration status of *M. cajuputi* in mature age suggests the capacity to establish and maintain continuous regeneration. At age 2 (“new”), regeneration status indicates an early establishment stage for revegetation, with significant seedling and sapling densities. *M. cajuputi* has demonstrated its ability to establish itself in various types of land use, such as peatland, swamp areas, ex-coal mine land, and heavy metal contaminated soil (Wibisono et al. 2023). Besides occurring at PTBA, *M. cajuputi* has shown adaptability on post-coal mining land at the Binungan site of PT Berau Coal, Kalimantan (Farosandi et al. 2024). *M. cajuputi* is also a potential peatland restoration species, naturally widespread across South Sumatra and thriving in various swamp ecologies, from intertidal zones to submerged peat swamp forests (Wibisono et al. 2023).

Overall, this study highlights the role of pioneer species in early-stage revegetation and the significance of monitoring long-term regeneration patterns to ensure the sustainability of reclamation (Kumari and Maiti 2019). The dynamics of successional progress in restored ex-coal mine stands will differ between pioneer species. *E. cyclocarpum* is a fast-growing, nitrogen-fixing species that promotes the establishment of late-successional species through rapid canopy formation, which creates shade conditions favorable for their growth (Yunanto et al. 2021; da Silva et al. 2022). In contrast, *M. cajuputi* thrives in acidic, waterlogged post-mining landscapes, showing high survival and adaptability but slower growth, which results in a slower progression toward late-successional forest (Kodir et al. 2017). These contrasting growth traits influence the restoration trajectory: *E. cyclocarpum* promotes faster structural development (basal area, biomass, canopy closure), while *M. cajuputi* regenerates rapidly and is resistant to environmental stress, but its slow growth delays canopy closure.

Melaleuca cajuputi showed high dominance at seedling level in all stand ages, with the highest density recorded in 6- and 9-year-old stands, reaching 4,457 and 6,471 stems ha^{-1}, respectively. This density was similar to the initial planting design, indicating that *M. cajuputi* had a strong regeneration rate over time. In comparison, *E. cyclocarpum* showed restricted seedling recruitment, with no observation in 7-year-old stand and 250 stem ha^{-1} in 9-year-old stand. The difference in density suggests that *M. cajuputi* can recover more naturally in revegetation areas, while *E. cyclocarpum* regenerates more slowly or inconsistently. At the saplings level, *M. cajuputi* maintained greater densities and IVI values than *E. cyclocarpum*, strengthening dominance in the revegetation area. The sapling density was consistent across stand ages, reaching around 800 stems ha^{-1} at 6 and 9 years. IVI values showed disparity, with *M. cajuputi* saplings in 6- and 9-year-old stands recording 141.3% and 142.6%, respectively, significantly outperforming *E. cyclocarpum* saplings, which had IVI values of 76.2% and 90% at the same ages. These results showed better regeneration potential of *M. cajuputi* and flexibility in post-mining revegetation, distinguishing it as a more resilient pioneer species than *E. cyclocarpum*.

The ability of *M. cajuputi* to maintain high seedling and sapling densities across stand ages suggests strong natural recruitment and establishment capacity, which is crucial for long-term vegetation recovery. This species is well-suited to harsh or disturbed conditions due to its rapid growth, high light tolerance, and competitive ability. This demonstrates that *M. cajuputi* is highly efficient at utilizing resources in degraded land. Furthermore, mature *M. cajuputi* trees produce very large quantities of seeds within their capsules. Although seed viability varies between species and conditions, this mass production statistically increases the likelihood that a significant number of seeds will germinate (Nakmee et al. 2023). *M. cajuputi* is the plant that adapts and thrives in various conditions on ex-coal mined land in East Kalimantan, such as at the sites of PT Berau Coal and PT Bara Tabang (Adman et al. 2023; Farosandi et al. 2024). Kissinger et al. (2020) reported a similar result that *M. cajuputi* is the most dominant species found in High Conservation Values (HCV) swamp habitats at all growth stages (seedlings, saplings, poles, and trees). The sapling-stage performance of *M. cajuputi* further reinforces its ecological advantage in post-mining revegetation. Its steady number of saplings at various ages and high IVI values indicate that it not only successfully grows from seedlings to saplings but also lasts a long time in recovering forest areas.

Regarding dominance value at pole level, *E. cyclocarpum* dominates in *E. cyclocarpon* stands, specifically in older stands, while *M. cajuputi* dominates across all ages. *E. cyclocarpum* shows significant RD and RF values in older stands but decreases in younger stands. Meanwhile, *M. cajuputi* consistently shows high RD and RF values in all ages. Furthermore, at the tree levels, dominance value of *E. cyclocarpum* was large, indicating greater basal area of *E. cyclocarpum* and capable of reaching the tree level in 7 years. As shown in Table 7, tree levels also support that no *M. cajuputi* reach the tree level despite being 9 years old. It grows small in diameter but dense (high density). It is suspected that *M. cajuputi* grows new branches directly from the ground. Additionally, previous studies have shown that *M. cajuputi* has not yet reached the tree level at PTBA area after 9 months (diameter above 20 cm) (Suyono et al. 2023).

Floristic composition and natural species

In pioneer stands, natural species increased, except in *M. cajuputi* 2-year-old stand (Table 8). Species richness at the seedling and sapling levels was highest in *E. cyclocarpum* 3-year-old stand and *M. cajuputi* 6-year-old stand compared to others. Furthermore, species richness at the pole level was greater in *M. cajuputi* 6- and 9-year-old than in *E. cyclocarpum* 7- and 9-year-old stands. Pioneer at various ages have provided valuable insights into the development of natural species richness and their crucial role in rehabilitating post-mining land. Fields planted with pioneer species showed a greater presence of natural species compared to *E. cyclocarpum*. However, both pioneer stands supported understory and tree species that thrived.

The spacing between *E. cyclocarpum* trees, regardless of age, is consistently 4 × 4 m. However, trees of different ages show different levels of species diversity. Mature *E. cyclocarpum* stands show high dominance, while younger stands are characterized by greater species richness, especially at the seedling and sapling stages. Other species, particularly light-demanding pioneer species, are more likely to grow up themselves in younger areas with increased canopy openness. Pioneer species such as *A. mangium*, *C. bartramia*, and *C. hirta* have been recorded in these young revegetated sites, with some of them identified as invasive. Meanwhile, mature-age stands exhibit lower species richness. Between seven and nine years old, *E. cyclocarpum* reaches the same establishment stage, exhibiting high density and dominance at both pole and tree levels, and covering the area with a dense canopy. This data indicates that young pioneer stands generally have lower canopy cover, which in turn leads to increased species diversity (seedling and sapling layer). This is under the finding that the abundance of species increased as the availability of light increased (Márialigeti et al. 2016). Gaps promote the recruitment of new species by increasing light and space, enhancing seed germination and seedling growth, which can gradually shift species composition (Margreiter et al. 2021).

The adaptability of plant species that regenerate naturally is also supported by their seed dispersal mechanisms, which contribute to the imminance in certain stands and support biodiversity in post-coal mining lands (Suyono et al. 2023). For example, *P. javanicum* is relatively abundant in the 9-year-old *M. cajuputi* stand at the tree and pole levels, as well as in the 3-year-old *E. cyclocarpum* stand at the pole, sapling, and seedling levels. *Pterospermum javanicum* disperses seeds widely across coal mine areas through explosive dehiscence, where mechanical stress within the seed pods triggers bursting to propel seeds (Baethke et al. 2020). According to the seed dispersal mode, namely autochory (self-dispersal), *P. javanicum* has a certain predictive power because it is positively correlated with succession age (Horáčková et al. 2016).

Understory plants identified in all areas were *I. cylindrica* and *M. malabathricum*. *I. cylindrica* is an adaptive plant, pioneer in post-mining environments, and a problematic weed capable of growing in various soil types (Albasri et al. 2021; Pratiwi et al. 2021). This weed thrives in soils with acidic pH, low fertility, and limited organic matter, showing high efficiency in nutrient absorption (Wang et al. 2023). The density value of *I. cylindrica* is very high because it grows through rhizomes and produces large amounts of seed that are easily carried by the wind, thereby expanding spread (Estrada and Flory 2015). *I. cylindrica* is a highly invasive plant whose advancing front reduces native species abundance over time, although it remains unclear whether it serves as the primary driver of changes in plant communities (Estrada and Flory 2015).

The natural species in all-age *E. cyclocarpum* stands, including *A. mangium, A. occidentale, B. tomentosa, C. hirta, C. bartramia, P. canescens, P. javanicum, T. catappa, and V. pinnata.* The dominant natural species are identified as *A. mangium* and *P. javanicum.* Meanwhile, older *M. cajuputi* stands (ages 6 and 9), naturally growing species include *A. mangium, A. occidentale, B. tomentosa, H. tiliaceus, C. bartramia, P. javanicum, P. canescens, S. wallichii, Syzygium* sp., and *V. pinnata.* The dominant natural species in the all-ages *M. cajuputi* stands are *A. mangium, P. javanicum, and C. bartramia.* The number of natural species growing in *M. cajuputi* stands was slightly higher than in *E. cyclocarpum* stands. These results confirm several species found to be dominant on Tanjung Enim's coal mine sites, but in the other revegetation sites, including *A. mangium*, *I. cylindrica*, and *V. pinnata* (Yuningsih et al. 2021). A similar finding was reported in Iskandar's et al. (2022) research, which revealed that *A. mangium* thrives alongside the pioneer legume, *Falcataria moluccana.* In addition, Yunanto's research findings report that there is a relationship between fast-growing species and natural regeneration at ex-mine sites. A multivariate analysis showed that the naturally regenerating species *P. javanicum* was grouped with the pioneer species *Paraserianthes falcataria* instead of *E. cyclocarpum*. Nevertheless, this species was still grouped with a pioneer legume (Yunanto et al. 2021).

The presence of *A. mangium* in all ages of pioneer stands suggests that the species is highly adaptable and has significant growth potential on ex-mining sites. At pole levels, *A. mangium* had the highest IVI (194.50%) at *E. cyclocarpum* 3-year-old stand, and the second-largest in all-ages *E. cyclocarpum* and *M. cajuputi* stands. The results also indicate that species such as *A. mangium* play secondary roles in these ecosystems, with high density and dominance values. *A. mangium* is well adapted to post-mining soil with acidic to slightly acidic pH (Pratiwi et al. 2021). A similar study was reported at a coal mine site in East Kalimantan, where pioneer species with high survival rates included *A. mangium*, *P. falcataria*, and *Hevea brasiliensis* (Yunanto et al. 2021). Moreover, *A. mangium* showed the highest IVI values (100-300%) and was present across all development stages—from seedlings and saplings in sites revegetated in 1992, 2006, 2008, and through natural succession, to poles and mature trees in areas planted in 1992, 1995, 2006, and 2008—on post-coal mining revegetation land in Sawahlunto, West Sumatra (Herman et al. 2024). However, the presence raises concerns about its potential as an invasive species in the later stages of post-mining land reclamation. While invasive species can thrive in new environments of a pioneer stand, their establishment may cause ecological disruptions, such as the extinction of native species and the change of ecosystem functioning. This is evident in the *E. cyclocarpum* stands aged 7 and 9 years, which have native species at the pole level but do not show recruitment at the seedling level. This is different from the invasive species *A. mangium*, which appears at the seedling-to-tree levels in mature stands.

A significant indicator of species richness in former mining land is the natural presence of *C. bartramia* (local name *Andilau* or *Nilau*), which is a widespread distribution, ranging from China through Southeast Asia, New Guinea, and Australia (Nhung et al. 2023). *C. bartramia* is a tolerant native species commonly found in fields as disturbances increase (Jambul et al. 2020). Another naturally occurring species, *V. pinnata*, was identified in *E. cyclocarpum* 9-year-old stand and *M. cajuputi* 6-year-old stand, demonstrating adaptability to e-mining land conditions. Another native species found was *S. wallichii* at seedling levels in *M. cajuputi* 9-year-old stand, with a density of 3,676 stems ha^{-1} (Table 4). *Schima wallichii* thrives in well-drained soils with organic content (Thapa and Sharma 2023). This tree species also attracts various fauna, such as birds and insects, thereby accelerating the restoration of the food chain and serving as a habitat for wildlife. The presence of *S. wallichii* indicates an increase in biodiversity in the former mining area. This is in line with a study by Bare and Ashton (2016) that native species can thrive in a variety of soil conditions and exhibit growth rates that are comparable to those of non-native species. Essential criteria for selecting native plant species for reclamation are survival, adaptability, and biomass yield (Chiochetta et al. 2017). The availability of native seeds in the vicinity of restoration sites often limits native recruitment. In Thailand, fifty percent of the adjacent indigenous tree species were missing from restoration plots, demonstrating a dependence on local seed supplies for effective recruitment (Ratanapongsai 2020).

Natural species such as *A. mangium* dominate in *E. cyclocarpum* and *M. cajuputi* stands, showing their importance in early colonization and canopy formation. The appearance of *S. wallichii* and *A. mangium* in older *M. cajuputi* stands suggests that as trees age, species composition becomes more diverse. Species diversity is present in pioneer stands, marking a transition to later successional phases with more permanent community structures (Dechoum et al. 2015). These results show how the maturity of pioneer species influences composition and diversity, which have important implications for successional processes and biodiversity recovery in reclamation zones. Different plant species play distinct roles in enhancing soil structure and fertility (da Silva et al. 2022). For example, natural legumes found in pioneer stands, such as *A. mangium* and *A. pavonina*, show nitrogen-fixing capabilities, which increase soil fertility for other plant species (Daws et al. 2015).

Vegetation communities with changing species composition in degraded land are a sign of ongoing succession (Lestari et al. 2019). Increased species diversity marks one stage of successful succession because species diversity promotes the development of more complex, self-sustaining ecosystems over time (Simanchuk and Sultangazina 2023). Increased species diversity is associated with the development of layered plant canopies, which elevate habitat complexity and support ecological processes, such as nutrient cycling, water retention, and resilience of plant communities (Vasquez and Sheley 2018; Kumari and Maiti 2019; Albasri et al. 2021).

Biodiversity of pioneer stands on rehabilitated ex-coal mine land

Shannon-Wiener Diversity Index in *E. cyclocarpum* and *M. cajuputi* varies significantly with the age of the stands. *E. cyclocarpum* 3-year-old stand retrieved the highest species diversity, with H' value of 1.34, followed by 9-year-old (H' = 1.15) and 7-year-old (H' = 1.06) *M. cajuputi* stands. In comparison, *M. cajuputi* 2-year-old stand showed no species diversity (H' = 0), indicating monospecific dominance during early revegetation. These results showed that species diversity increased with stand age in *M. cajuputi*, indicating progressive habitat maturation.

The progression of stand age in *M. cajuputi* is correlated with higher species diversity and the abundance of naturally occurring species. This contradicted previous studies at PTBA area, where Suyono et al. (2023) found no correlation between species diversity and stand maturity (increasing age). Vegetation indicators remain highly effective for evaluating ecosystem recovery after mining activities (Swain et al. 2023).

Evenness Index, which measured the equitable distribution of individuals among species, was highest in *E. cyclocarpum* 9-year-old stand (J' = 0.63) and *M. cajuputi* 9-year-old stand (J' = 0.50). However, the youngest *M. cajuputi* stand (J' = 0.00) and 7-year-old stand (J' = 0.46) showed the lowest evenness. Evenness Index in *E. cyclocarpum* stands indicated a more uniform distribution of individuals compared to *M. cajuputi* stands across various ages. This pattern suggests that younger stands are dominated by pioneer species, leading to uneven distributions, while older stands develop more balanced ecological communities.

E. cyclocarpum stands show higher species diversity at younger ages compared to *M. cajuputi*. However, as *M. cajuputi* mature, their diversity and evenness values rise, suggesting successful biological succession and habitat complexity. The absence of diversity in *M. cajuputi* 2-year-old stand is due to the management of cajuput oil production (Juliarti et al. 2022). Additionally, two-year-old *M. cajuputi* trees were cultivated to enhance cajuput oil production, leading company management to interplant *M. cajuputi* with existing species. The original planting distance was 3×3 m; however, with the additional planting, the spacing was reduced to 3×1.5 m (PT Bukit Asam 2022). This change has impacted the regeneration of other natural tree species, which struggle to establish due to competition with *I. cylindrica*, a dominant understory species during the early growth stage.

These results emphasize the critical role of stand age in shaping biodiversity and ecological recovery in post-mining restoration efforts. Current biodiversity in post-mining stands has not yet reached levels comparable to tropical forests but is still higher than another reclamation area of PTBA. This was similar to the report by Yuningsih et al. (2021), who stated that Shannon-Wiener Index was 0.99 for 8th-year revegetation. Shannon-Wiener Diversity Index typically ranges from 1.5 to 3.5 in tropical forests (Noweg et al. 2024). However, PTBA revegetation efforts demonstrate progressively improving trends in ecosystem development.

The presence of diverse species contributes to natural nutrient cycling, as each species provides unique nutrient inputs to the soil, ensuring long-term nutrient sustainability. Leguminous species, in particular, play a crucial role in improving soil conditions. Additionally, diverse species composition supports biodiversity restoration on mined land, accelerates the reclamation process, and facilitates ecosystem recovery, allowing stands to achieve optimal ecological functions. Generally, the increase in diversity, density, and species richness of seedlings and saplings over time following rehabilitation indicates sustainable revegetation in ex-mined land (Udayana et al. 2020). The evaluation of *M. cajuputi* and *E. cyclocarpum* pioneer trees of varied ages provides important insights into natural regeneration dynamics and their ability to restore ecological function in coal-mined environments. By contrasting their developmental trajectories—for example, *E. cyclocarpum's* early-stage dominance versus *M. cajuputi's* sustained regeneration in mature stands—this study demonstrates how species-specific traits (e.g., regeneration status, species composition) influence natural species richness and biodiversity recovery.

In conclusion, *E. cyclocarpum* maintained "good" regeneration status in young stands, contrasting with *M. cajuputi,* which retained "good" status in mature stands. *Imperata cylindrica* and *M. malabathricum* were identified as dominant understory plants across all areas. *M. cajuputi* dominated at the seedling stage across all stand ages, with the highest seedling densities observed in 6- and 9-year-old stands. Floristic composition analysis showed 9 naturally occurring species in *E. cyclocarpum* stands and 10 in *M. cajuputi* stands, with *A. mangium* and *P. javanicum* as the most prominent at the pole and tree stages. Furthermore, pioneer stands of *M. cajuputi* and *E. cyclocarpum* at various ages provided critical insights into the development of natural species richness and their role in restoring mined ecosystems. For land reclamation, selecting pioneer species should prioritize their natural regeneration capacity and ability to enhance biodiversity. Long-term studies were needed to analyze regeneration patterns over time, showing the need for further studies to explore interactions between pioneer and native species in supporting ecosystem recovery.

Recommended actions include implementing site-specific interventions through enrichment planting using native species of Sumatra, such as *P. javanicum*, *C. bartramia*, *S. wallichii*, and *I. palembanica*. These species are naturally adapted to the pioneer stand areas of Sumatra. It is crucial to control invasive species that hinder management efforts by contributing to the decline of native species and altering ecosystem functions. Additionally, controlling the spread of *I. cylindrica* (reeds) is important to prevent wildfires during the dry season, which are common in Sumatra.

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