Volume 20 Nomor 2, Desember 2025, Halaman 263–273
Jurnal Hutan Tropika
Laman: https://e-journal.upr.ac.id/index.php/JHT
DOI: https://doi.org/10.36873/jht.v20i2.24002
e-ISSN: 2656–9736
p-ISSN: 1693–7643

Evaluating the Growth Performance of Three Fast-Growing Species in Coal Mine Reclaimation in Aceh

(Evaluasi Kinerja Pertumbuhan Tiga Spesies Pohon Cepat Tumbuh pada Lahan Reklamasi Tambang Batu Bara di Aceh)

Yosie Syadza Kusuma[1*], Yuni Septia Riharja[1], Tuti Arlita[1], Ida Rosita[1], Laila Wijaya[2]
[1] Department of Forestry, Faculty of Agriculture, Syiah Kuala University, Jl. Teuku Nyak Arief Darussalam, Banda Aceh, 23111, Indonesia
[2] Department of Soil science, Faculty of Agriculture, Syiah Kuala University, Jl. Teuku Nyak Arief Darussalam, Banda Aceh, 23111, Indonesia
* *Corresponding Author: yosiesyadza@usk.ac.id*

Article History
Received : December 14, 2025
Revised : December 18, 2025
Approved : December 22, 2025

Keywords: *Fast-growing tree species, Land rehabilitation, post-mining reclamation, Reclamation strategies, Revegetation*

ABSTRACT

Coal mining plays a crucial role in global energy production and regional development, including in Aceh, Indonesia, where operations such as PT. Mifa Bersaudara contribute to energy supply and employment. This study evaluated the revegetation success of three fast-growing species (Falcataria moluccana, Enterolobium cyclocarpum, and Gmelina arborea) in post-mining reclamation areas planted in 2017 and 2018. Planting was performed at a uniform spacing of 4 × 4 m across 27 plots (8 in 2017, 19 in 2018), each measuring 20 × 20 m and containing 25 trees per plot, with a sampling intensity of 3%. Analyzed using descriptive statistics, two-way ANOVA with Tukey HSD, t-test, and Wilcoxon rank-sum tests. Results showed F. moluccana achieved the highest height (17.53 ± 24.75 m in 2017; 10.73 ± 2.88 m in 2018) and diameter (22.25 ± 8.12 cm in 2017; 31.84 ± 11.59 cm in 2018), followed by E. cyclocarpum, while G. arborea grew more slowly. Survival rates of the planted trees remained relatively high in both planting years, with 80.0 ± 19.0% in 2017 and 70.2 ± 16.9% in 2018, and statistical analysis indicated no significant difference between the two years. Fast-growing species enhanced canopy cover, soil stabilization, and microhabitats, supporting slower-growing species, and their combination is recommended to optimize short-term revegetation success and long-term ecosystem resilience in degraded areas.

Sejarah Artikel
Diterima : 14 Desember 2025
Direvisi : 18 Desember 2025
Disetujui : 22 Desember 2025

Kata Kunci: Spesies pohon cepat tumbuh, Rehabilitasi lahan, Reklamasi pasca tambang, Strategi reklamasi, Revegetasi

ABSTRAK

Pertambangan batu bara memainkan peran penting dalam produksi energi global dan pengembangan regional, termasuk di Aceh, Indonesia, di mana operasi seperti PT. Mifa Bersaudara berkontribusi pada pasokan energi dan penciptaan lapangan kerja. Studi ini mengevaluasi keberhasilan revegetasi tiga spesies cepat tumbuh (*Falcataria moluccana, Enterolobium cyclocarpum*, dan *Gmelina arborea*) di area reklamasi pasca-pertambangan yang ditanam pada tahun 2017 dan 2018. Penanaman dilakukan dengan jarak tanam seragam 4 × 4 m di 27 petak (8 petak pada tahun 2017, 19 petak pada tahun 2018), masing-masing berukuran 20 × 20 m dan berisi 25 pohon per petak, dengan intensitas sampling 3%. Analisis dilakukan menggunakan statistik deskriptif, uji ANOVA dua arah dengan Tukey HSD, uji t, dan uji Wilcoxon rank-sum. Hasil menunjukkan *F. moluccana* mencapai tinggi tertinggi (17,53 ± 24,75 m pada tahun 2017; 10,73 ± 2,88 m pada 2018) dan diameter (22,25 ± 8,12 cm pada 2017; 31,84 ± 11,59 cm pada 2018), diikuti oleh *E. cyclocarpum*, sementara *G. arborea* tumbuh lebih lambat. Tingkat kelangsungan hidup pohon yang ditanam tetap relatif tinggi pada kedua tahun penanaman, dengan 80,0 ± 19,0% pada tahun 2017 dan 70,2 ± 16,9% pada tahun 2018, dan analisis statistik menunjukkan tidak ada perbedaan yang signifikan antara kedua tahun tersebut. Spesies yang tumbuh cepat meningkatkan tutupan kanopi, stabilisasi tanah, dan mikrohabitat, mendukung spesies yang tumbuh lebih lambat, dan kombinasi keduanya direkomendasikan untuk mengoptimalkan keberhasilan revegetasi jangka pendek dan ketahanan ekosistem jangka panjang di area yang terdegradasi.

1. Introduction

Mining activities, particularly coal mining, play a crucial role in global energy production by making a significant contribution to energy production and supporting economic development in many countries (McHugh 2017; Stecuła & Brodny 2018; Betz et al. 2015), including Indonesia (Ordonez et al. 2022; Ministry of Energy and Mineral Resources 2021). In Indonesia, coal mining has a history of over 160 years, beginning with colonial-era exploration, and the modern industry is concentrated mainly in the large Cenozoic sedimentary basins of Sumatra and Kalimantan, where thick coal seams enable low-cost mining (Friederich & Van Leeuwen 2017). At the regional level, coal mining activities contribute to local development through revenue generation, tax and royalty contributions, infrastructure improvement, and community empowerment. This includes local job creation and corporate social responsibility (CSR) programs that support education, health, and environmental sustainability initiatives (Aceh Energy and Mineral Resources Service 2019).

Despite its economic importance, coal mining often causes extensive soil degradation, loss of vegetation cover, and disruption of ecological processes, leading to long-term negative impacts on land productivity and ecosystem services (Pandey et al. 2022; Goswami 2015; Huang et al. 2015). Consequently, post-mining reclamation is essential to restore soil fertility, re-establish vegetation, and restore biodiversity (Tibbett 2024; Maiti et al. 2021; Islam et al. 2024; Rana et al. 2024). To ensure responsible mining, the Indonesian Ministry of Forestry Regulation No. P.4/Menhut-II/2011 on Post-Mining Reclamation in Forest Areas requires every mining and energy company to reclaim post-mining areas within forest land. Furthermore, according to the Ministerial Decree No. 146/Kpts-II/99, post-mining reclamation is an effort to restore land and vegetation in forest areas degraded by mining and energy activities so that these areas can optimally function according to their designated use.

One of the most widely adopted strategies in land reclamation is the use of fast-growing tree species (Hong et al., 2020; Yunanto et al. 2021). These species are preferred because of their rapid establishment, high biomass production, and ability to enhance soil structure and nutrient cycling (Alaejos et al. 2023; Madejón et al. 2016). Fast-growing trees also help stabilize the soil, reduce erosion, and create microclimatic benefits that facilitate the succession of native species (Minotta et al. 2025; Maiti et al. 2021). In Indonesia, post-mining reclamation programs have increasingly utilized these species to accelerate ecosystem recovery. However, the success of such efforts largely depends on a comprehensive understanding of species-specific growth patterns, planting density, and local environmental conditions.

Nevertheless, the success of reclamation efforts is primarily determined by species-specific growth responses and local environmental conditions, which remain poorly documented in many mining regions, including Aceh. To address this knowledge gap, the present study evaluates the growth performance of fast-growing tree species planted in two consecutive years (2017 and 2018) in post-mining reclamation areas of PT. Mifa Bersaudara, West Aceh, Indonesia. Specifically, the study assesses tree survival, height, and diameter to provide empirical evidence to inform future species selection and enhance reclamation management strategies for sustainable ecosystem recovery.

2. Materials and Method

2.1. Study Site and Experimental Design

The study was conducted in post-mining reclamation areas planted in 2017 and 2018 within the reclamation site of PT. Mifa Bersaudara, Meureubo District, West Aceh Regency, Indonesia (**Figure 1**). The total reclamation area was 9.8 ha for the 2017 planting and 25.87 ha for the 2018 planting. Data collection was carried out from January to May 2024. Planting was conducted using a uniform spacing of 4 × 4 m. A 3% sampling intensity was applied, with each plot measuring 20 × 20 m (400 m² = 0.04 ha), and each plot containing 25 trees. Based on the sampling calculation, 27 sampling plots were established, including eight plots in the 2017 planting area and 19 plots in the 2018 planting area. The study targeted three dominant species, *Gmelina arborea, Enterolobium cyclocarpum*, and *Falcataria moluccana*.

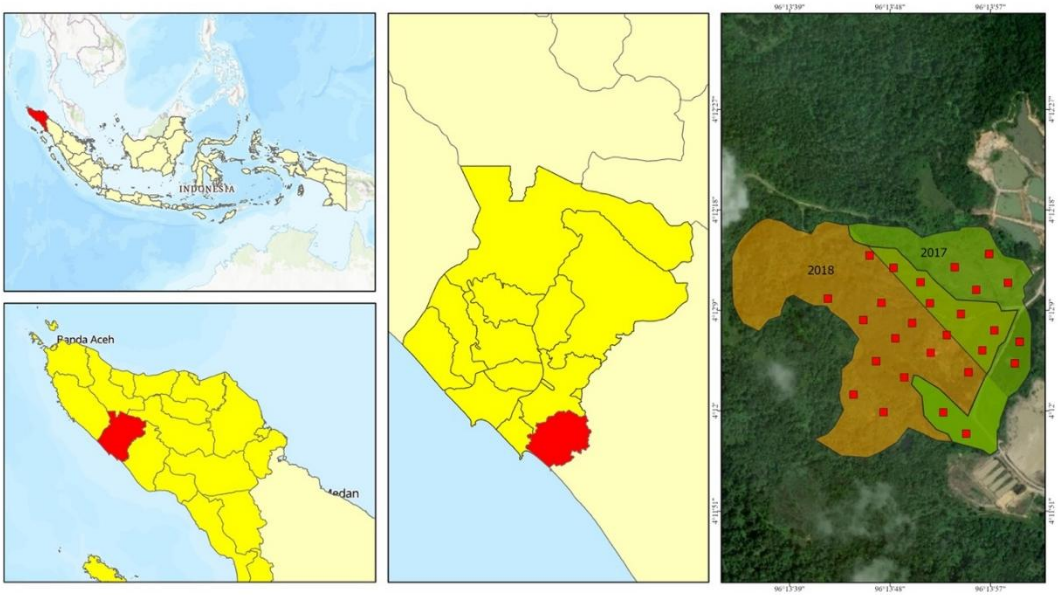

Figure 1. Maps of the study site in Meureubo District, West Aceh Regency, Indonesia, showing the locations of the 2017 and 2018 planting plots

2.2. Data Analysis

Data analysis was conducted using descriptive statistics, including mean, standard deviation (SD), range, 95% confidence interval (CI), and several key parameters for evaluating revegetation success, as summarised in **Table 1**. The key parameters comprised the Mean Annual Increment of stem diameter (MAId) and tree height (MAIh), along with the survival rate (SR), which together provide a quantitative basis for evaluating growth performance and seedling persistence in post-mining reclamation areas.

Table 1. The parameters used to evaluate tree growth and survival in post-mining reclamation areas

Equation	Definition
$MAI_d = \frac{D}{A}$	MAI_d (cm year⁻¹), calculated as D / A, where D (cm) is the mean stem diameter at the time of measurement and A (years) is the stand age or number of years since planting.
$MAI_h = \frac{H}{A}$	MAI_h (m year⁻¹), calculated as H / A, where H (m) is the mean tree height at the time of measurement and A (years) is the stand age or number of years since planting.
$SR = \frac{N_s}{N_t} \times 100\%$	SR (%) represents the proportion of surviving plants (N_s) relative to the total number of plants initially planted (N_t).

2.3. *Statistical Analysis*

All statistical analyses were conducted using R software (version 4.5.0). Descriptive statistics, including sample size (n), mean ± SD, minimum–maximum, and 95% confidence intervals (CI), were computed. Growth performance, measured as mean annual increment of height (MAI_h) and diameter (MAI_d) per species and planting year, was analysed using two-way ANOVA, followed by Tukey's HSD test for pairwise comparisons whenever significant differences were observed ($p < 0.05$). Comparisons between years for percentage-based variables were performed using Student's t-test and Wilcoxon rank-sum test, as appropriate based on data distribution, with effect sizes calculated as Cohen's d with 95% confidence interval (CI). Graphical representations consisted of bar plots with error bars (mean ± standard error, SE), with letters above the bars indicating significant differences according to Tukey HSD at α = 0.05. This approach comprehensively evaluated growth differences among species, planting years, and other measured variables.

3. Result and Discussion

3.1. *Survival Rate*

Figure 2 shows tree survival in post-mining reclamation areas varied across planting years and plots. The 2017 planting area comprised eight plots; in 2018, there were nineteen plots. **Table 2** presents the survival rates of tree seedlings in post-mining reclamation areas by planting year, including mean ± SD, range, 95% CI, and statistical test results with effect size. The data provide an overview of seedling persistence and differences between the 2017 and 2018 planting areas.

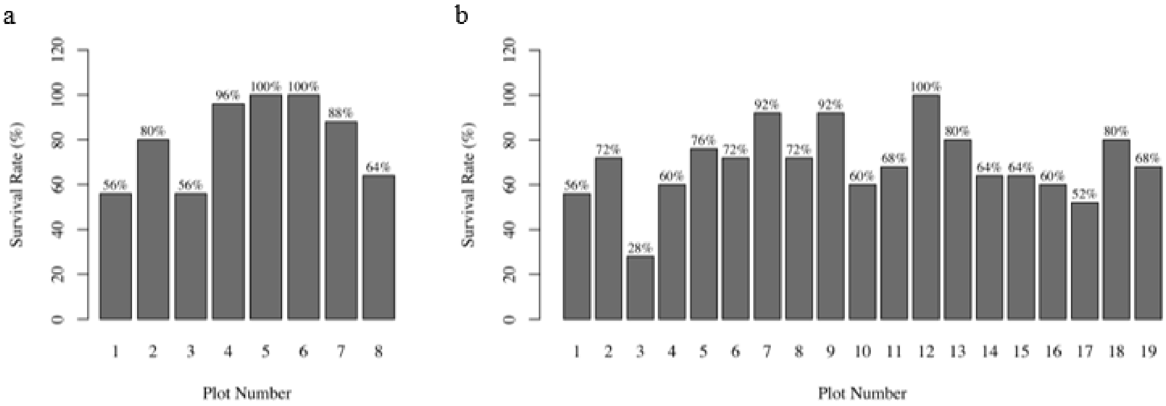

Figure 2. Survival of trees in post-mining reclamation areas: (a) after 7 years of planting (2017 area) and (b) after 6 years of planting (2018 area)

The survival rate of revegetated plots in the 2017 planting year varied from 56% to 100%, with the highest values recorded in Plots 5 and 6, and the lowest in Plots 1 and 3. In contrast, the 2018 planting year, comprising 19 plots, showed survival rates ranging from 28% to 100%, with only Plot 12 achieving 100% survival and the lowest recorded in Plot 3 (Figure 2). Overall, the mean survival rate in 2017 was 80.0%, classified as “good”, whereas the 2018 planting year recorded a mean survival rate of 70.2%, classified as “moderate”, in accordance with national regulations (Ministry of Forestry Regulation No. P.60 of 2009; Decree of the Minister of Energy and Mineral Resources No. 1827 of 2018).

The 100% survival rate observed in several plots was likely partially influenced by gap filling, a practice in which dead seedlings were replaced during the early establishment phase. This practice helps maintain plot density and promotes uniform growth, per post-mining reclamation guidelines recommending a minimum revegetation success rate of 80% to indicate satisfactory performance (Decree of the Minister of Energy and Mineral Resources No. 1827 of 2018). Similar findings have been reported in various post-mining reclamation areas in Indonesia, with survival rates generally ranging from 70% to 90%, including PT Baramarta, South Kalimantan, 70.97% (Rizal et al. 2020), PT Gunung Bale, East Java, 80–89% (Wicaksono et al. 2020), and PT Kitadin Site Embalut, East Kalimantan, 77.7–88% (Budiana 2017). These findings indicated survival rates above 80% are generally considered satisfactory and reflect successful revegetation management in post-mining areas.

Table 2. Survival rate of tree seedlings in post-mining reclamation by planting year, showing mean ± SD, range, 95% CI, and results of statistical tests (t-test, Wilcoxon) with effect size (Cohen's **d**)

Year	n	Mean ± SD (%)	Min–Max (%)	95% CI for Mean	t-test (p)	Wilcoxon (p)	Cohen's d (95% CI)
2017	8	80.0 ± 19.0	56–100	64.1 – 95.9			
2018	18	70.2 ± 16.9	28–100	61.9 – 78.6			
Comparison					0.22(ns)	0.27(ns)	0.57 (–0.31 – 1.46)

Statistical analysis of the survival rate revealed no significant difference between the 2017 and 2018 planting years, as indicated by both parametric (t-test, p = 0.22) and non-parametric (Wilcoxon, p = 0.27) tests (**Table 2**). However, the effect size, measured using Cohen's d, was 0.57 (95% CI: –0.31–1.46), indicating a moderate effect. These results suggest that, although the difference was not statistically significant, a moderate ecological variation in revegetation success existed between planting years, likely influenced by variations in local environmental conditions and seedling quality across planting periods.

3.2. Growth in Stem Diameter and Height

The mean stem diameter of the fast-growing species varied among species and planting years (**Table 3**). *E. cyclocarpum* exhibited the highest mean diameters in 2017 and 2018 (28.03 ± 13.40 cm and 28.09 ± 10.52 cm, respectively), indicating stable radial growth and good adaptability to post-mining land conditions. This species also dominated the plantation regarding the number of individuals, with 96 trees in 2017 and 269 trees in 2018. A similar study reported that E. cyclocarpum dominated more than >75% of the community in coal mine plantations in South Sumatra (Juniarto et al. 2025), highlighting its consistent establishment success in post-mining reclamation areas. The widespread use of *E. cyclocarpum* in post-mining reclamation is supported by the high macronutrient content of its leaves, which can improve the physical properties of degraded soils, such as enhancing bulk density, increasing porosity, and improving soil texture to become more friable and fertile (Sukariyan et al. 2019).

F. moluccana exhibited notably larger stem diameters in the 2018 planting year (31.84 ± 11.59 cm) than in 2017 (22.25 ± 8.12 cm), reflecting a differential growth response likely influenced by local environmental conditions. In contrast, *G. arborea* showed a smaller in stem diameter between the two planting years (14.59 ± 3.64 cm in 2018 compared to 13.57 ± 4.83 cm in 2017), consistent with its characteristically slower radial growth rate. Despite uniform management across all plots, these results indicate that site quality and species-specific characteristics influence growth performance.

Table 3. Mean (± standard deviation) of tree height and diameter of three fast-growing species across two planting years in the post-mining revegetation area.

Species	**Year**	**n**	**Diameter (cm) (Mean ± SD)**	**Height (m) (Mean ± SD)**
Gmelina arborea	2017	25	13.57 ± 4.83	7.76 ± 1.76
Gmelina arborea	2018	27	14.59 ± 3.64	7.09 ± 1.12
Enterolobium cyclocarpum	2017	96	28.03 ± 13.40	11.96 ± 4.34
Enterolobium cyclocarpum	2018	269	28.09 ± 10.52	10.52 ± 9.63
Falcataria moluccana	2017	38	22.25 ± 8.12	17.53 ± 24.75
Falcataria moluccana	2018	26	31.84 ±11.59	10.73 ± 2.88

Tree height also varied among species and planting years. In 2017, F. moluccana exhibited the highest mean height (17.53 ± 24.75 m), followed by E. cyclocarpum (11.96 ± 4.34 m) and G. arborea (7.76 ± 1.76 m). In 2018, average tree heights were generally lower, with *F. moluccana* reaching 10.73 ± 2.88 m, *E. cyclocarpum* at 10.52 ± 9.63 m, and *G. arborea* at 7.09 ± 1.12 m, reflecting inter-annual variation and species-specific growth responses to post-mining site conditions.

The height of *G. arborea* recorded in this study was slightly higher than previously reported for a six-year-old stand in Bongohuwala Village, Bakti Village, and Haya-Haya Village, Gorontalo Province, with mean heights of 5.6, 5.5, and 6.2 m, indicating satisfactory vertical growth under post-mining site conditions. The mean stem diameter of *G. arborea* in the 2017 and 2018 planting areas was similar to that reported in Bongohuwala (≈14 cm), but smaller than that reported in Bakti and Haya-Haya (≈17 and 18.5 cm) (Sandalayuk et al. 2018; Ruslim et al. 2021), indicating relatively limited radial growth under post-mining site conditions. These results confirm that although *G. arborea* exhibits good height performance, its diameter growth remains limited compared to other fast-growing species, such as *F. moluccana* and *E. cyclocarpum*, demonstrating comparatively more efficient adaptation to post-mining environments.

3.3. Mean Annual Increment of Diameter and Height

Figure 3 and **Table 4** show the mean annual increment of MAIh and MAId for three tree species, G. arborea, E. cyclocarpum, and F.moluccana, planted in two different years. While the standard deviations varied considerably across species and years, partly due to gap-filling activities, the overall differences in growth performance largely reflect inherent genetic potential and site heterogeneity.

Table 4. Mean annual increment of height (MAI_h) and diameter (MAI_d) of three tree species under two different planting years.

Species	Planting Year	MAI_d (cm year^{-1})	MAI_h (cm year^{-1})
Gmelina arborea	2017	1.94 ± 0.69^{c}	1.11 ± 0.25^{b}
Gmelina arborea	2018	2.43 ± 0.61^{c}	1.18 ± 0.18^{b}
Enterolobium cyclocarpum	2017	4.00 ± 1.91^{b}	1.71 ± 0.62^{a}
Enterolobium cyclocarpum	2018	4.68 ± 1.75^{a}	1.75 ± 1.60^{a}
Falcataria moluccana	2017	3.18 ± 1.16^{b}	2.50 ± 3.54^{a}
Falcataria moluccana	2018	5.31 ± 1.93^{a}	1.79 ± 0.48^{a}

Note: Different letters within the same column indicate significant differences (Tukey's HSD, $\alpha = 0.05$):
a = highest, significantly different, b = lowest, significantly different, ab = not significanly different from a or b.

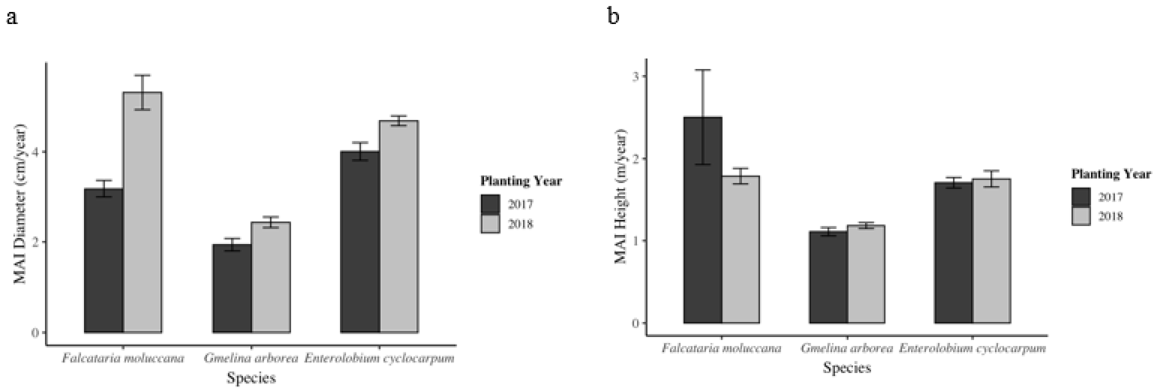

Figure 3. Mean annual increment in diameter (MAI_d) (a) and mean annual increment in height (MAI_h); (b) of 6 and 7-year-old fast growing tree species planted (n = 481; df = 475)

The MAI_d differed significantly among species and planting years (**Table 4**). *G. arborea* showed the lowest growth, with 1.94 ± 0.69 cm yr^{-1} in 2017 and 2.43 ± 0.61 cm yr^{-1} in 2018, comparable to the 1.73 ± 0.01 cm yr^{-1} reported for *G. arborea* in Nigerian plantations (Osundun et al. 2021), but lower than that of the other species in this study. *E. cyclocarpum* showed moderate to high MAI_d values, ranging from 4.00 ± 1.91 cm year^{-1} in 2017 to 4.68 ± 1.75 cm year^{-1} in 2018, while *F. moluccana* exhibited the highest MAI_d in 2018 (5.31 ± 1.93 cm year^{-1}). However, the 2017 value (3.18 ± 1.16 cm year^{-1}) was slightly lower than that of *E. cyclocarpum*, reflecting species-specific growth differences. The MAI_d of *E. cyclocarpum* and *F. moluccana* exhibited higher MAI_d values than *G. arborea*, indicating better adaptability and radial growth performance under post-mining site conditions. The increase in *F. moluccana* MAI_d over the years reflects a positive response to improving site conditions. Conversely, the consistently lower MAI_d of *G. arborea* underscores its slower growth and sensitivity to environmental variability.

The MAI_h values exhibited significant variations among species and planting years (**Table 4**). F. moluccana exhibited the highest height MAI_h in height among the studied species, reaching 2.50 ± 3.54 m in the 2017 planting year, substantially higher than in 2018 (1.79 ± 0.48 m). *E. cyclocarpum* exhibited moderate MAI_h values across both planting years, with 1.71 ± 0.62 m in 2017 and 1.75 ± 1.60 m in 2018, while *G. arborea* recorded the lowest MAI_h values, at 1.11 ± 0.25 m in 2017 and 1.18 ± 0.18 m in 2018. These trends are consistent with Sitepu et al. (2023), who reported high annual height growth for *F. moluccana* (≈2.1 m) and moderate growth for *E. cyclocarpum* (0.8–2.0 m) on reclaimed mining sites in East Kalimantan, Indonesia.

Previous studies reported MAI_d and MAI_h for *F. moluccana* as 2.90 cm/yr and 2.06 cm/yr, respectively (Santoso & Syafrudin 2020). In the present study, MAI_d for the 2017 and 2018 planting years and MAI_h for 2017 exhibited higher values than previously reported, whereas MAI_h for 2018 was slightly lower. Meanwhile, Dendang & Sudomo (2020) reported an MAI_h of 3.31 cm/yr and an MAI_d of 2.77 cm/yr, indicating that their MAI_d was lower than in both planting years of the present study, whereas MAI_h was higher than that observed in this study.

The growth of *G. arborea* in this study exhibited a distinct pattern in diameter and height increments compared to previous reports. MAI_d in 2017 and 2018 exceeded the 1.42 cm/yr reported by Santoso & Syafrudin (2020), indicating relatively rapid radial growth. In contrast, MAI_h in both years was slightly lower than the 1.25 cm/yr reported in the same study, reflecting slower height growth. These findings suggest that *G. arborea* stands at the study site and tends to increase in diameter more rapidly than in height, likely in response to local environmental conditions and management practices.

Overall, *F. moluccana* and *E. cyclocarpum* demonstrate strong potential for rapid site stabilization and early canopy development during the initial y phases of revegetation. Meanwhile, *G. arborea* contributes to structural diversity and the development of longer-term stands.

3.4. Soil pH as an Indicator of Site Recovery

After seven years of planting on the 2017 site and six years on the 2018 site, soil pH was measured at 6.1 and 5.9, respectively, indicating that the soils were approaching neutral conditions.. This indicates substantial progress in post-mining land recovery through revegetation. These results are consistent with Chen et al. (2023), who reported that revegetation can alter soil physical and chemical properties, including reductions in pH and electrical conductivity, decreases in bulk density, and increases in moisture content, organic carbon, nitrogen, phosphorus, and potassium. Thus, the observed improvements in soil quality reflect the effectiveness of revegetation in restoring post-mining ecosystems.

As leguminous trees, *F. moluccana* and *E. cyclocarpum* play a crucial role in improving soil fertility and chemical balance through symbiotic nitrogen fixation with Rhizobium, which increases total nitrogen, enhances the C/N ratio, and stimulates microbial activity, contributing to soil pH neutralization (Jhariya et al. 2018; Ramos et al. 2020). Their rapidly decomposing leaf litter, rich in base cations such as calcium and magnesium, helps neutralize acidic soils, increase pH, and improve cation exchange capacity, aggregation, and porosity in nutrient-poor soils (Sukariyan et al. 2019; Roberts et al. 2016; Hu et al. 2021; Xiang et al. 2018). Their extensive root systems, frequently associated with mycorrhizae, further enhance phosphorus and potassium uptake and strengthen soil structure in post-mining areas.

In contrast, *G. arborea* contributes to soil improvement by stabilizing nutrients. The leaf litter of *G. arborea* contributes substantially to the enrichment of organic matter in the upper soil layer. The accumulation of this biomass helps maintain soil moisture and accelerates the release of essential nutrients. The cultivation of *G. arborea* thus plays a vital role in enhancing soil quality by promoting organic matter accumulation through leaf litter deposition, maintaining soil moisture, and accelerating nutrient cycling. Furthermore, the increase in organic matter and humus derived from *G. arborea* litter stimulates soil microbial activity, thereby enhancing the release and availability of water and nutrients to plants, while also contributing to the restoration of degraded lands (Ota et al. 2018).

3.5. Assessment of Revegetation Success Using Fast-Growing Species

Fast-growing species showed varying survival and growth rates across planting years and locations, highlighting the critical role of species selection in facilitating ecosystem recovery. Among the planted species, *F. moluccana* and *E.cyclocarpum* demonstrated superior ability to establish canopy cover and improve microhabitat conditions related to *G. arborea***,** which exhibited relatively slower growth. Rapid canopy formation by *F. moluccana* and *E. cyclocarpum* contributed to increased soil moisture, enhanced nutrient availability, and improved protection against erosion, there by promoting ecosystem stabilization during the early stages of revegetation.

Although exhibiting slower growth, *G. arborea* is crucial in supporting long-term ecological succession. Its organic litter and canopy structure create favourable conditions for establishing understory vegetation and native plant species. A study in the southern Philippines reported that 30 years after planting, *G. arborea* plantations supported greater understory plant diversity compared to plantations of the native species *Nauclea orientalis* (Casas et al., 2025). These findings emphasise that integrating fast-growing pioneer species with slower-growing native species can enhance revegetation success by balancing early-stage stabilisation and the long-term sustainability of ecological succession.

4. Conclusion

The evaluation of fast-growing species in post-mining revegetation revealed distinct growth patterns among species. *F. moluccana* exhibited the highest mean height (17.53 ± 24.75 m in 2017; 10.73 ± 2.88 m in 2018) and diameter (22.25 ± 8.12 cm in 2017; 31.84 ± 11.59 cm in 2018), followed by *E. cyclocarpum* (height: 11.96 ± 4.34 m in 2017, 10.52 ± 9.63 m in 2018; diameter: 28.03 ± 13.40 cm in 2017, 28.09 ± 10.52 cm in 2018). *G. arborea* showed slower growth (height: 7.76 ± 1.76 m in 2017, 7.09 ± 1.12 m in 2018; diameter: 13.57 ± 4.83 cm in 2017, 14.59 ± 3.64 cm in 2018). Survival rates were relatively high in both years (2017: 80.0 ± 19.0%; 2018: 70.2 ± 16.9%) with no statistically significant differences between years (t-test $p = 0.22$, Wilcoxon $p = 0.27$). These results suggest that integrating fast-growing species with slower-growing species like *G. arborea* can optimize rapid canopy formation, enhance soil stabilization, and support long-term ecosystem resilience.

Acknowledgment

The authors would like to express their sincere gratitude to PT. Mifa Bersaudara for granting access to the reclamation sites and for their valuable assistance during fieldwork activities. The support provided by the company's environmental and reclamation teams was essential in facilitating data collection and ensuring the smooth implementation of this research. Appreciation is also extended to all technical staff and field assistants who contributed to the measurement and monitoring of vegetation growth. Their collaboration and commitment greatly contributed to the success of this study

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