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## Plant Species for Enhancing Ecosystem Functions of the Reclamation Program on Ex-Mining Areas in South Kalimantan

*Jenis Tanaman untuk Meningkatkan Fungsi Ekosistem pada Program Reklamasi Lahan Bekas Tambang di Provinsi Kalimantan Selatan*

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### RESEARCH ARTICLE

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### ABSTRACT

Mined reclamation failure could lead to land degradation, ecosystem instability, community poverty, and loss of environmental services. Previous research linked reclamation success to the selection of suitable plants. This study aimed to identify the best species for reclamation and ecosystem services, measured by ecosystem conditions, plant growth, and soil fertility. *Angsana* (*Pterocarpus indicus* Willd.), *waru* (*Hibiscus tiliaceus* L.), *cashew* (*Anacardium occidentale* L.), *segon* (*Paraserianthes falcataria* (L.) Nielsen), and *mahogany* (*Swietenia mahagoni* (L.) Jacq.) were selected as the highest number of species planted in PT Kalimantan Energi Lestari (KEL) reclamation area. Mean annual increment (MAI) was measured using a 10% sampling intensity for all plant stages. Soil quality (C-organic, N, C/N, P, K) was sampled at 5% around the tree root zone using a purposive sampling method. The five species showed positive impacts on soil nutrients, increasing by 14.6% in five-year-old plants, except for K-exchange, which decreased by 3.4% to 71.4%. In addition, *P. falcataria* improved significantly in three macro parameters, namely C-organic 121.2%, N-total 100%, and P-avail 156%, and had the highest MAI for total height of 252.5 cm/year. This research concluded that *P. falcataria* was the most appropriate revegetation plant species for the reclamation program in coal-mined areas.

### INTISARI

Keberhasilan reklamasi lahan bekas tambang sangat penting, karena kegagalan dapat menyebabkan degradasi lahan, ketidakstabilan ekosistem, kemiskinan masyarakat, dan hilangnya layanan lingkungan. Penelitian sebelumnya menghubungkan keberhasilan reklamasi dengan pemilihan tanaman yang sesuai. Penelitian ini bertujuan untuk mengidentifikasi spesies terbaik untuk reklamasi dan layanan ekosistem, diukur dengan kondisi ekosistem, pertumbuhan tanaman, dan kesuburan tanah. *Angsana* (*Pterocarpus indicus* Willd.), *waru* (*Hibiscus tiliaceus* L.), *jambu mete* (*Anacardium occidentale* L.), *segon* (*Paraserianthes falcataria* (L.) Nielsen), dan *mahoni* (*Swietenia mahagoni* (L.) Jacq.) dipilih sebagai spesies dengan jumlah penanaman terbanyak di area reklamasi PT Kalimantan Energi Lestari (KEL). Riap tahunan rata-rata (MAI) diukur menggunakan intensitas sampling 10% untuk semua tahapan tanaman. Kualitas tanah (C-organik, N, C/N, P, K) diambil sampelnya sebesar 5% di sekitar zona akar pohon menggunakan metode purposive sampling. Kelima spesies tersebut menunjukkan dampak positif terhadap hara tanah sebesar 14,6% pada tanaman umur lima tahun, kecuali untuk pertukaran K yang menurun sebesar 3,4%-71,4%. Selain itu, *segon* berkontribusi pada peningkatan yang signifikan pada C-organik 121,2%, N-total 100%, dan P-tds 156%, serta memiliki MAI tertinggi untuk tinggi total, yaitu 252,5 cm/tahun. Penelitian ini menyimpulkan bahwa *segon* merupakan spesies tanaman revegetasi yang paling tepat untuk program reklamasi lahan bekas tambang batubara.

## Introduction

Based on the Decree of the Minister of Energy and Mineral Resources 1827 K/30/MEM/2018 concerning Guidelines for the Implementation of Good Mining Engineering Principles, the mining process begins with land clearing. It continues through the transportation of mining commodities to the final stockpile location. Coal mining using the open-pit mining method begins with tree felling, land clearing, topsoil and subsoil stripping, soil stockpiling, or direct spreading for ex-mining land reclamation activities. After topsoil and subsoil stripping, layers of rock, which are overburden or coal seams, are exposed for exploration. The overburden is treated differently from topsoil and subsoil that have been stripped previously. The topsoil and subsoil are separated from the stockpiled material and can be reused in mine reclamation activities, while the overburden is piled and rehabilitated after mining.

The process of stripping topsoil and subsoil in the mining process often alters the structure, texture, and biology of the soil. Lawing (2021) identified that the coal exposure process altered the physical and textural properties of the soil by stripping it, reversing its profile during the loading and unloading process, and causing soil compaction during land reclamation preparation. The degraded soil conditions resulting from mining activities have also been confirmed by Kusdarini et al. (2022) and Thakur et al. (2024). Changes in soil chemistry that initially provided nutrients for plant growth have been altered and reduced due to the influence of acid mine drainage (AMD), a common phenomenon in coal mines (Maulida & Purwanti 2023). The biological condition of the soil, which is strongly influenced by the activity of microorganisms, becomes hollow, primarily because most of the soil microorganisms that are beneficial to fertility die due to the process of opening the forest canopy, turning over the soil, and the influence of AMD. Consequently, management of the soil and area is required to prevent severe land degradation caused by mining activities (Thakur et al. 2024).

At the end of 2021, there were over 260 mineral and coal mining companies in the Kalimantan Island region. These companies held Forest Area Borrowing

Permits (IPPKH) for more than 286,000 ha of forest, as released by the Forest Area Borrowing Information System (SIPPKH) of the Ministry of Environment and Forestry in 2022. South Kalimantan Province hosts 86 companies that mine coal and minerals. These companies operate in a total area of 46,892.37 ha. By the end of 2019, they should have restored 44,724.59 ha of land that they had mined, which is approximately 95.4% of their IPPKH area (KLHK RI 2022). Reclamation of ex-mining land is an essential part of mining activities that must not be overlooked (Kusdarini et al. 2022). This step helps control the adverse effects of mining and can even turn the site into a beneficial area after the mineral deposits have been extracted. Based on Decree of the Minister of Energy and Mineral Resources 1827 K/30/MEM/2018, reclamation of ex-mining land is carried out in two stages. The first stage involves land management, including soil spreading and erosion control construction, while the second stage focuses on revegetation. The stage separation was to ensure the reclamation process works properly (Kementerian ESDM Republik Indonesia 2018). Failures in one of the stages can have detrimental effects on the entire program, impacting the company, its surrounding community, and the environment.

This research focuses on revegetation activities as the second stage of reclamation, assuming that the first-stage activities, namely land management, have been carried out correctly. The primary issue with revegetation activities is the role of plants in restoring land conditions and ensuring that natural succession occurs. PT Kalimantan Energi Lestari (KEL) has selected several types of legume plants and MPTS (multi-purpose tree species) for its reclamation program, expecting that these plant types can restore the ecosystem conditions of ex-mining land. The research conducted by Izza et al. (2022) concluded that the types of plants selected by PT KEL were appropriate. Izza et al. (2022) shared similar view on determining the most suitable plants for a revegetation program on mine reclamation areas. The novelty of this research lies in its focus on examining plants that have proven effective in the revegetation program, in terms of their progressive growing rate and improvement of soil fertility within five years of planting. Therefore, this research aimed to determine

suitable revegetation plants that support the reclamation program and ecosystem services. Plant growth and soil fertility were selected as key indicators following a study conducted by Azhar et al. (2023) in a coal mine situated in South Kalimantan. The study found that these indicators represent the success criteria for mine reclamation, which align with the evaluation of the revegetation program in the ex-mining area in this research. Ecosystem conditions would express the healthy and sustainable ecosystem of reclamation mined lands. Yanti et al. (2025) used this indicator to evaluate coal mine reclamation activities in Aceh Province.

## Methods

### Research Location

PT KEL is a coal mining company located in Gendang Timburu Village, Sungai Durian District, Kotabaru Regency, South Kalimantan Province, which was part of the Barito Watershed (*Daerah Aliran Sungai - DAS*). The revegetation area in this research, covering 122.90 ha, was located in the central pit reclamation area of PT KEL (Figure 1). Based on the

company procedure number (KEL-EFOR-001-SOP 2023) concerning the Rehabilitation of Disturbed Land, the revegetation activities for ex-mining land involved replanting the land located within the Coal Contract of Work (CCoW) area. The planting activities employed a 4 m × 4 m spacing, or approximately 625 trees/ha, and planting holes measuring 30 cm × 30 cm × 30 cm. Cow dung compost fertilizer was applied at a dose of 2 kg/planting hole. The plant species for the revegetation included 60% pioneer plants and 40% multi-purpose tree species (MPTS) seedlings, at least three months old, with an average height of between 40 and 90 cm. The legume cover crop (LCC) seeds were spread after the seedlings were planted. This approach facilitates the establishment of the LCC without impeding the growth of the seedlings.

### Data Collection

Data collection employed a 100% census for the 2023, 2021 and 2018 planting years, data were obtained from the KEL reclamation plant maintenance results report, detail will describe in Result and Discussion section. Natural revegetation, which enriched the diversity of the reclamation area, was not recorded

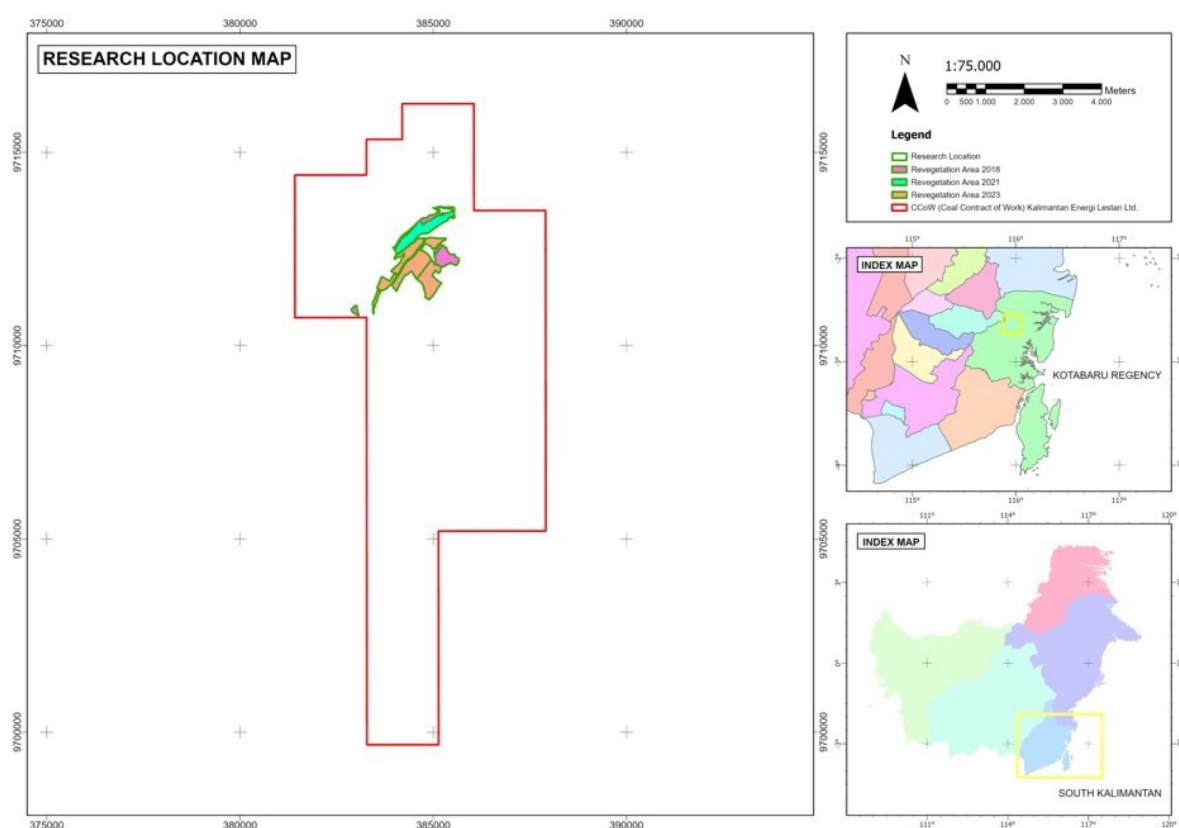


Figure 1. Research location at PT Kalimantan Energi Lestari mine site

quantitatively, but it was observed visually. This research selected five species for further study based on the assumption that seedlings of the same species would have the same height and diameter when planted. The selection criteria considered similar species planted in the reclamation area in 2018, 2021, and 2023, focusing on those with the highest number of individuals of each planting year.

A purposive sampling method was employed for diameter and height measurements. This approach considered the morphological conditions of the plants. The measurement included diameter at breast height (dbh) and the total height of the sample trees. Approximately 1 kg of soil samples were collected from the root zone of plants, at a depth of 10–20 cm, from 5% of the observed plants (Figure 2). The sampling techniques for data collection is summarized in Figure 3.

## Data Analysis

Improving soil fertility became one of the key factors in recovering ecosystem functions in ex-mining areas. According to the Balai Pengujian Standar Intrumen Tanah dan Pupuk (BPSITP 2023) Appendix 3 on the Criteria for Assessment of Soil Analysis Results, the criteria is generally used as an empirical guide to soil quality, the level of soil fertility was determined by several parameters, as summarized in Table 1. This research selected the C/N ratio, C-organic, and Nitrogen (N), phosphorus availability, and K-exchange as macronutrient parameters that were easily absorbed by plant roots (Salam 2020). Plants require four macronutrients (C, N, P, and K) to grow, and these become key parameters for determining the level of soil fertility (Salam 2020). By comparing the soil nutrient levels in this study with the standard, this research could determine the level



Figure 2. Soil sampling around the tree root zone

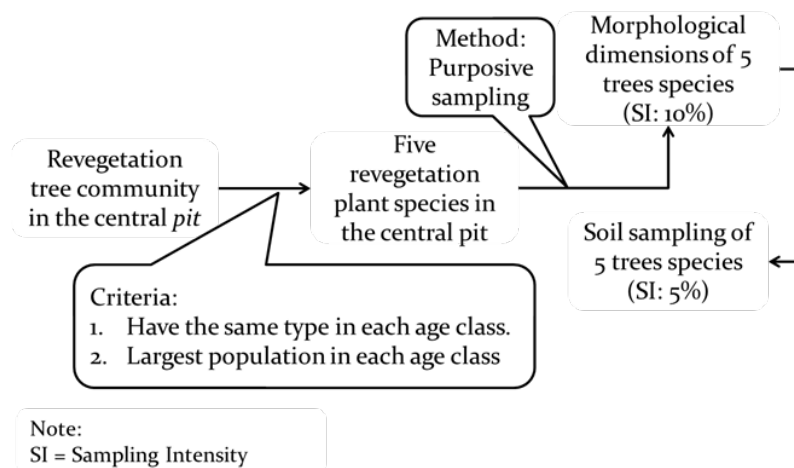


Figure 3. The sampling techniques for data collection

**Table 1.** Criteria for several soil parameters tested based on the *Balai Pengujian Standar Instrumen Tanah dan Pupuk* (2023)

| Parameter | Unit        | VL        | L           |
|-----------|-------------|-----------|-------------|
| C-Org     | %           | <1        | 1-2         |
| N-Total   | %           | <0.1      | 0.1-0.2     |
| C/N ratio |             | <5        | 5-10        |
| P-avail   | ppm         | <4        | 5-7         |
| K-exch    | cmol (+)/kg | <0.1      | 0.1-0.3     |
| pH        |             | <4.5 (VA) | 4.5-5.5 (A) |

Remarks: VL= very low; L= low; VA = very acidic; A= acidic

$$\text{NC Change (\%)} = \frac{(\text{NC}_{2018} - \text{NC}_{2023})}{\text{NC}_{2023}} \times 100\% \dots \text{Equation 1}$$

Notes: NC Change = Nutrient Concentration Change;  
NC 2018 = Nutrient Concentration of planting year 2018;  
NC 2023 = Nutrient Concentration of planting year 2023.

of soil fertility in the research area. The increase (or decrease) in each soil nutrient as a parameter was calculated using Equation 1.

Soil samples were sent to the laboratory of the Agricultural Instrument Standardization Agency (BSIP) of Swamp Land, Banjarbaru, South Kalimantan Province. The soil chemical analysis included C/N ratio, C-organic, Nitrogen (N), Available Phosphorus (P-avail), and Exchangeable Potassium (K-exchange) (BPSITP 2023). The measurement of soil pH was conducted in the initial soil condition in the field (Table 2), in which the topsoil was then used for reclamation and revegetation.

**Table 2.** Initial pH soil condition in the revegetation land

| Soil Samples         | pH        |
|----------------------|-----------|
| Soil in-situ site #1 | 4.70      |
| Soil in-situ site #2 | 4.80      |
| Topsoil Bank         | 4.23      |
| Average              | 4.58±0.30 |

$$H' = -\sum_{i=1}^s \frac{n_i}{N} \times \ln \frac{n_i}{N} \dots \dots \dots \text{Equation 2}$$

Where: H' = species diversity index; s = number of species in the research plot; n<sub>i</sub> = number of individuals of the i-th species; N = total number of individuals in all research plots

The Shannon-Wiener index, calculated according to Equation 2 (Riswan et al. 2015), was used to identify the H' value of the area. The results of the Shannon-Wiener diversity index calculation would be verified by senior-experienced personnel conducted visual

observations on tree species surrounding the five-year-old trees selected for this research. Additionally, natural ingrowth species were recorded and considered in evaluating the area's richness.

## Result and Discussion

### Ecosystem Condition

Data on the number of plants that thrived in the revegetation areas from the 2018 and 2021 planting years were obtained from the trees' maintenance report by PT KEL for the fourth quarter of 2023. The plants from 2018 were five years old, and those from 2021 were two years old at the time of data collection. Meanwhile, data on the number of plants that thrived in the revegetation areas from the 2023 planting year were obtained from the planting report provided by the PT KEL in the fourth quarter of 2023. Table 3 summarizes the reports of those three planting years.

Revegetation by KEL was carried out according to the company's SOP and government regulations through Kementerian ESDM Republik Indonesia (2018), which required the composition of revegetation plant types to consist of 60% pioneer species and 40% MPTS. This could be seen and was implemented by KEL at 0 years of planting or during revegetation of ex-mining land in 2023 (Table 3). Over time, this composition changed, and according to its nature, the ratio of pioneer plants decreased, and MTPS plants increased. MTPS plants in the KEL reclamation area had taken over the role of pioneer plants in creating a microclimate of reclaimed land. This was an indication of the success of revegetation or forest succession in a positive direction. A similar phenomenon was found in the research by Riswan et al. (2015), where on old reclaimed mining land, only MTPS species such as *Tectona grandis* L.f. and *Eucalyptus deglupta* Blume were found to be dominant, and there were almost no more pioneer plants. The ecological implications of changes in species composition were the stability of the ecosystem, an increase in flora-fauna diversity, a reduction in erosion rate, restoration of a simple hydrological system (Damiti et al. 2025), and improved microclimate (Karyati et al. 2018).

The density and number of revegetation plant individuals also decreased over time. These figures

**Table 3.** Summary of PT KEL revegetation data of 2018, 2021, and 2023 planting years

| Species Name                                                         | Planting Year      |                    |                    | Pioneer/<br>MPTS |
|----------------------------------------------------------------------|--------------------|--------------------|--------------------|------------------|
|                                                                      | 2023<br>(44.90 ha) | 2021<br>(41.40 ha) | 2018<br>(36.60 ha) |                  |
| Laban ( <i>Vitex pinnata</i> L.)                                     | 0                  | 2,166              | 1,525              | P                |
| Sengon ( <i>Paraserianthes falcataria</i> (L.) Nielsen)              | 9,000              | 3,212              | 3,860              | P                |
| Galam ( <i>Melaleuca cajuputi</i> Maton & Sm. ex R.Powell)           | 0                  | 2,900              | 157                | MPTS             |
| Waru ( <i>Hibiscus tiliaceus</i> L.)                                 | 5,010              | 1,977              | 1,054              | P                |
| Jabon ( <i>Neolamarckia cadamba</i> (Roxb.) Bosser)                  | 0                  | 3,273              | 998                | P                |
| Gamal ( <i>Gliricidia sepium</i> (Jacq.) Kunth)                      | 0                  | 2,260              | 0                  | P                |
| Kayu putih ( <i>Melaleuca leucadendra</i> (L.)L.)                    | 869                | 0                  | 858                | MPTS             |
| Cashew ( <i>Anacardium occidentale</i> L.)                           | 3,027              | 518                | 739                | MPTS             |
| Meranti ( <i>Shorea</i> sp.)                                         | 0                  | 1,209              | 0                  | MPTS             |
| Johar ( <i>Cassia siamea</i> Lamk.)                                  | 2,210              | 125                | 500                | P                |
| Durian ( <i>Durio zibethinus</i> L.)                                 | 130                | 0                  | 0                  | MPTS             |
| Salam ( <i>Syzygium polyanthum</i> (Wight) Walpers)                  | 620                | 17                 | 0                  | MPTS             |
| Angsana ( <i>Pterocarpus indicus</i> Willd.)                         | 2,490              | 2,647              | 927                | P                |
| Simpur ( <i>Dillenia eximia</i> Miq.)                                | 0                  | 35                 | 0                  | P                |
| Gempol ( <i>Nauclea orientalis</i> (L.) L.)                          | 820                | 0                  | 0                  | P                |
| Rubber ( <i>Hevea brasiliensis</i> (Willd. ex A.Juss.) Müll.Arg.)    | 0                  | 0                  | 245                | MPTS             |
| Kemiri ( <i>Aleurites moluccana</i> (L.) Willd.)                     | 0                  | 0                  | 615                | MPTS             |
| Jengkol ( <i>Archidendron pauciflorum</i> (Benth.) I.C.Nielsen)      | 200                | 0                  | 4                  | MPTS             |
| Mahogany ( <i>Swietenia mahagoni</i> (L.) Jacq.)                     | 750                | 1,425              | 1,369              | MPTS             |
| Pulai ( <i>Alstonia scholaris</i> (L.) R.Br.)                        | 245                | 0                  | 12                 | P                |
| Binuang laki ( <i>Duabanga moluccana</i> Blume)                      | 0                  | 2                  | 5                  | P                |
| Manggo ( <i>Mangifera indica</i> L.)                                 | 0                  | 0                  | 13                 | MPTS             |
| Kapuk ( <i>Ceiba pentandra</i> (L.) Gaertn.)                         | 1,050              | 25                 | 422                | MPTS             |
| Jackfruit ( <i>Artocarpus heterophyllus</i> Lamk.)                   | 0                  | 0                  | 180                | MPTS             |
| Ketapang ( <i>Terminalia catappa</i> L.)                             | 0                  | 805                | 550                | P                |
| Gmelina ( <i>Gmelina arborea</i> Roxb.)                              | 0                  | 0                  | 205                | P                |
| Sungkai ( <i>Peronema canescens</i> Jack)                            | 1,100              | 0                  | 105                | P                |
| Trembesi ( <i>Samanea saman</i> (Jacq.) Merr.)                       | 510                | 0                  | 0                  | P                |
| Tabebuaya ( <i>Handroanthus chrysotrichus</i> (Mart. ex DC.) Mattos) | 10                 | 0                  | 0                  | P                |
| <b>Number of Individuals</b>                                         | <b>28,041</b>      | <b>22,596</b>      | <b>14,343</b>      |                  |
| <b>Density (tree/ha)</b>                                             | <b>625</b>         | <b>546</b>         | <b>392</b>         |                  |
| <b>Number of Species</b>                                             | <b>16</b>          | <b>16</b>          | <b>21</b>          |                  |
| <b>Plant Type Ratio (P/MPTS)</b>                                     | <b>60%:40%</b>     | <b>42%:58%</b>     | <b>40%:60%</b>     |                  |
| <b>Shannon-Wiener Index (H')</b>                                     | <b>2.2</b>         | <b>1.7</b>         | <b>1.8</b>         |                  |

Remarks: P= pioneer; MPTS = Multi Purposes Tree Species

were calculated only in planting holes that had been provided at the beginning of planting, which amounted to approximately 625 holes/ha. Although the number of plants planted decreased and the density also decreased (Harsono et al. 2024), this did not mean that revegetation in this land was unsuccessful. Apart from planting holes, natural revegetation had occurred and grown native plants from around the revegetation location, which functioned as a source of seeds for the revegetation land. Research on the revegetation land of a coal mining company in East Kalimantan Province by Harsono et al. (2024) found that no revegetation plants survived at the age of 22 years. However, local species were found that were not planted during revegetation activities, such as *Durio zibethinus*, *Peronema canescens* Jack, *Pterospermum javanicum* Jungh., and *Lansium domesticum* Corrêa. Natural

revegetation was not measured in this research, but was found visually in the field, such as *Aquilaria malaccensis* Lamk., *Acacia mangium* Willd., *Dillenia grandifolia* Wall. and *Bridelia tomentosa* Blume., found growth well naturally in surrounding revegetation areas, see Figure 4. It was suspected that their presence was due to the dispersion of seeds or grains blown by the wind or accidentally carried by birds originating from the native forest around the mining site. Seeds could be flown or carried by animals, specifically those that were animal feed, which were around the revegetation site (Karmini et al. 2021). Revegetation that occurred naturally and used local species could accelerate the restoration process of ex-mining land (Xu et al. 2023).

The Shannon-Wiener index (H') measures species diversity based on the number of individuals of each species. The results showed that all revegetation ages

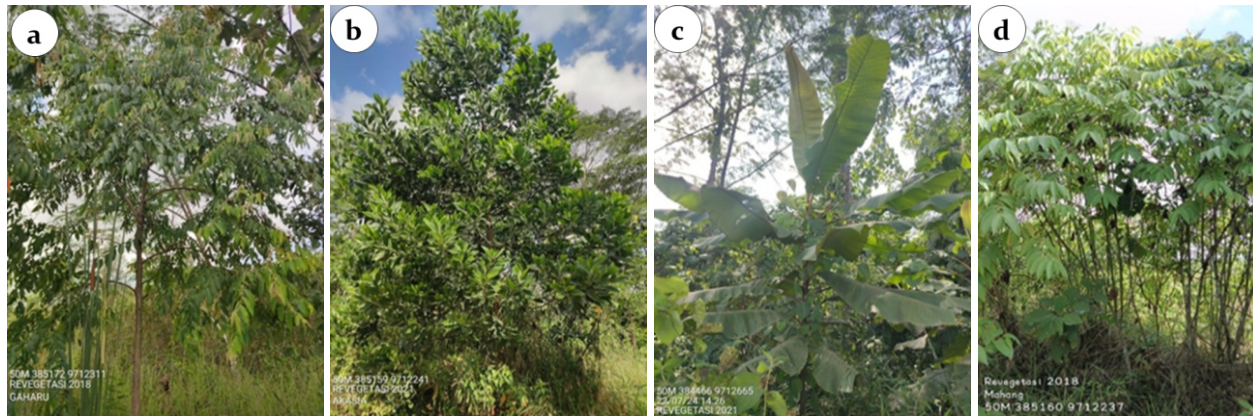


**Figure 4.** An observation: Natural succession of local species found in KEL's Revegetation Area Planting Year 2018 and 2021, (a) agarwood (*Aquilaria malaccensis* Lamk.) in revegetation area 2018, (b) acacia (*Acacia mangium* Willd.) in revegetation area 2021, (c) simpur or simpoh (*Dillenia grandifolia* Wall.) in revegetation area 2021, and (d) kenidai (*Bridelia tomentosa* Blume.) in revegetation area 2018

had an index value ranging from 1.7 to 2.2 (Table 3). The index range was similar to the research results of Riswan et al. (2015), which reported an index ranging from 1.3 to 2.0 for the growth rate of seedlings and saplings at ages of one and 10 years after planting. However, it was much better than Triwanto et al. (2023), which ranged between 0.6 and 1.0 for seedling and sapling growth rate. The difference in these index values might be due to the variation in media and source rocks between lime-cement mines (Triwanto et al. 2023) and coal mines (Riswan et al. 2015; Harsono et al. 2024), including this research. As vegetation ages, plant density decreases, apart from decreasing the number of pioneer plants. Initially, there are 625 stems/ha, but after five years, this number decreases to 392 stems/ha.

### Plant Growth

The plant growth observation involved only five selected dominant species, as presented in Table 4. The diameter of trees planted in 2023 was measured at 10 cm above the root neck or soil surface. The average and standard deviation of the height and diameter of the measured species were presented in Table 5 and plotted in Figure 5.

In terms of height growth rate, only *P. falcataria* showed a significantly faster growth rate compared to the other plants. This result was consistent with the findings of research conducted by Izza et al. (2022), which suggested that the sengon plant type is suitable for use as a revegetation plant in copper mining, coal mining, and andesite mining. The height growth rate of *P. falcataria* in this research was much slower

**Table 4.** Selected species for growth measurement from each planting years

| Species Code | Species Type                                | Planting Year |       |       |
|--------------|---------------------------------------------|---------------|-------|-------|
|              |                                             | 2018          | 2021  | 2023  |
| V1           | Angsana ( <i>Pterocarpus indicus</i> )      | 927           | 2,647 | 2,490 |
| V2           | Waru ( <i>Hibiscus tiliaceus</i> )          | 1,054         | 1,977 | 5,010 |
| V3           | Cashew ( <i>Anacardium occidentale</i> )    | 739           | 518   | 3,027 |
| V4           | Sengon ( <i>Paraserianthes falcataria</i> ) | 3,860         | 3,212 | 9,000 |
| V5           | Mahogany ( <i>Swietenia mahagoni</i> )      | 1,369         | 1,425 | 750   |

**Table 5.** Average and standard deviation of the height and diameter (dbh) of measured species

| Revegetation Age (Year) | <i>P. indicus</i> |               | <i>H. tiliaceus</i> |               | <i>A. occidentale</i> |               | <i>P. falcataria</i> |               | <i>S. mahagoni</i> |               |
|-------------------------|-------------------|---------------|---------------------|---------------|-----------------------|---------------|----------------------|---------------|--------------------|---------------|
|                         | h±s<br>(cm)       | dbh±s<br>(cm) | h±s<br>(cm)         | dbh±s<br>(cm) | h±s<br>(cm)           | dbh±s<br>(cm) | h±s<br>(cm)          | dbh±s<br>(cm) | h±s<br>(cm)        | dbh±s<br>(cm) |
| 0*                      | 80.2±28.3         | 1.2±0.6       | 106.4±21.3          | 0.9±0.2       | 87.6±15.6             | 0.6±0.2       | 106.0±24.1           | 0.7±0.1       | 52.8±1.9           | 0.3±0.1       |
| 2                       | 208.3±106.2       | 53.5±53.4     | 209.7±80.3          | 26.9±26.3     | 245.2±124.9           | 59.3±54.8     | 705.9±507.3          | 12.8±12.6     | 248.0±120.0        | 8.1±6.6       |
| 5                       | 239.0±68.6        | 72.5±68.6     | 269.1±119.2         | 61.3±53.5     | 303.9±170.9           | 96.9±101.8    | 1368.6±893.0         | 63.0±54.6     | 303.4±186.8        | 11.8±10.3     |

Remarks: h = height; dbh = diameter at breast height; s = standard deviation; \* = the dbh was measured at 10 cm above soil surface or root neck

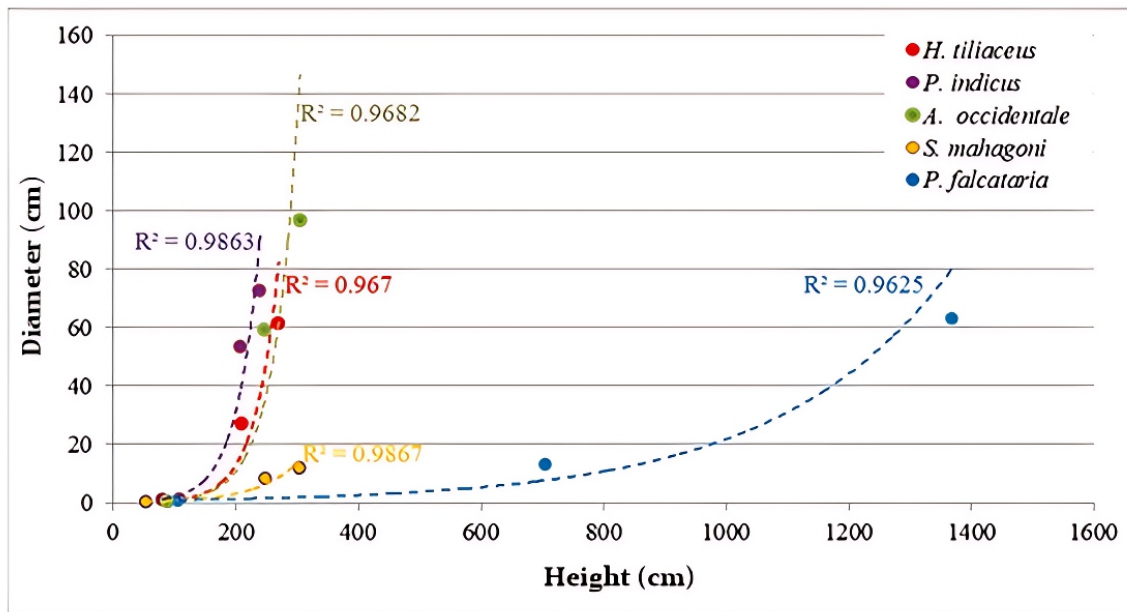


Figure 5. Correlation between the diameter and the height of individual revegetation species

compared to the experiment conducted by (Rafly et al. 2022) who planted six-month-old *P. falcataria* seedlings on non-mining land in Gunung Suguh Village, Pesawaran Regency, Lampung Province. In their research, the control treatment at the age of eight months reached a height of 253 cm, which was similar to the results of Tampubolon et al. (2023) on coal mine reclamation land. However, with the provision of a little NPK fertilizer and humic acid, based on the data from this research, a height of 253 cm was achieved at approximately 16 months, almost twice the age. The primary factor contributing to the slower height growth of *P. falcataria* in this research, compared to the experiments of Rafly et al. (2022) and Tampubolon et al. (2023), was the soil. In addition, the soil condition of the ex-mine was significantly worse due to its poor nutrient content, resulting from the mixing and alteration of the original soil (Lawing 2021). The *P. falcataria* had an advantage over other species because it forms root nodules. These nodules established a mutualistic symbiosis between the plant's roots and certain bacteria, known as *Rhizobium* sp., as well as mycorrhiza. This species belongs to the legume family (Prayudyaningsih et al. 2024).

The diameter growth of *P. indicus* saplings or seedlings was faster than the height growth, a physiological trait of the *P. indicus* species. The diameter growth rate of *P. indicus*, a type of legume in this research, was similar to the observation by Husna

et al. (2020). In her research, the growing medium for *P. indicus* consisted of tailings from the gold ore refining process, which had a fertility level similar to that of reclaimed mining land. A mixture of two arbuscular mycorrhizas, namely *Acaulospora delicata* and *Ambispora appendiculata*, was used in this medium. In addition, Husna et al. (2020) confirmed that *P. indicus* significantly relies on mycorrhizae, with the positive effects of mycorrhizal inoculation being as high as 65%. This association enhanced the host plant's ability to absorb nutrients, particularly macronutrients, from the soil. The nutrient-binding mechanism is initiated by microorganisms capable of degrading macronutrients, thereby rendering them available to the host plant. Meanwhile, host plants provided space and energy for microorganism (Prayudyaningsih et al. 2024).

The growth of *H. tiliaceus*, *P. indicus*, and *A. occidentale* exhibited a distinct phenomenon compared to *S. mahagoni* and *P. falcataria*. These three species showed a faster growth in diameter compared to their height growth rate (Figure 5). The growth rate of *H. tiliaceus* was poor because this plant prefers sandy soil (Wirawan et al. 2020). However, the soil in the reclamation area had become compacted and more clayey or loamy (Lawing 2021). Supriyatin et al. (2024) demonstrated that *H. tiliaceus* can exhibit increased transpiration in extreme environmental conditions, such as high exposure times (8,196–9,801

lux) and high temperatures (33.4°C). In conditions of inadequate moisture, particularly evident in reclaimed land, the closure of lenticels and stomata occurs. This physiological response subsequently impedes the uptake of carbon dioxide (CO<sub>2</sub>) and oxygen (O<sub>2</sub>) from the atmosphere, which can adversely affect plant growth processes.

*A. occidentale* planted on reclaimed land showed unhealthy growth (Figure 5). The selection of this species was based on its ability to thrive in less fertile soil conditions and less supportive environments. However, the implication was that this species required relatively large amounts of fertilizer and other additional treatments. In general, the revegetation program applied only 2 kg of organic fertilizer per planting hole. Meanwhile, Ramteke et al. (2022) conducted research by spraying NPK and urea fertilizers through the leaves at a concentration of 2% to accelerate and maintain the growth rate of *A. occidentale*.

The growth of *S. mahagoni* is significantly affected by soil pH (Hutapea et al. 2022). Low pH hinders its growth, and it does not thrive in low pH environments. The reclaimed land, which exhibits a low pH ranging from 4.23 to 4.80 (Table 1), was less suitable for planting *S. mahagoni*. Table 1 indicates that soil acidity increased after the soil was stacked in the temporary storage area from approximately 4.75 to 4.23. This increase was likely due to the influence of AMD from the surroundings or the site itself (Lawing 2021).

## Soil Fertility

The results of the soil chemical analysis were summarized in Table 6. Not all soil parameters were detectable in the laboratory due to their very low concentrations. Table 7 presented the changes in concentration for each parameter. Table 7 shows that there was an increase in soil nutrients, except for potassium (K-exchange), which decreased by between 3.4% and 71.4% across different revegetation species. The nutrient increase indicated a positive trend in the soil quality of reclaimed ex-mining land after five years of revegetation. However, the increase in nutrients did not improve the soil fertility level, which remained at very low (VL) and acidic (A) levels (Table 6). These results aligned with Karyati et al. (2018), which states that the goal of revegetation is to enhance the productivity of former mining areas.

Potassium (K) is classified as a macronutrient essential for plant growth, as it is required in relatively substantial quantities, exceeding 0.1% of the dry weight of the plant. However, the availability of potassium nutrients in the soil has been reported to be restricted (Gunawan et al. 2019; Numba 2024). The concentration of potassium (K) tends to decrease in the absence of mutualistic symbiosis between plants and microorganisms within the soil, paralleling the observed reductions in nitrogen (N) and phosphorus (P). This phenomenon is attributable to the essential roles played by Rhizobium species and mycorrhizal fungi in facilitating nutrient uptake in plant roots.

**Table 6.** Results of soil chemical analysis of revegetation land for 2018, 2021, and 2023 planting year

| Parameter | Unit       | <i>P. indicus</i> |      |      | <i>H. tiliaceus</i> |      |      | <i>A. occidentale</i> |      |      | <i>P. falcattaria</i> |      |      | <i>S. mahagoni</i> |      |      | Criteria* |
|-----------|------------|-------------------|------|------|---------------------|------|------|-----------------------|------|------|-----------------------|------|------|--------------------|------|------|-----------|
|           |            | 0 yo              | 2 yo | 5 yo | 0 yo                | 2 yo | 5 yo | 0 yo                  | 2 yo | 5 yo | 0 yo                  | 2 yo | 5 yo | 0 yo               | 2 yo | 5 yo |           |
| C-Org.    | %          | 0.33              | 0.59 | 0.64 | 0.33                | 0.55 | 0.56 | 0.53                  | 0.52 | 0.58 | 0.35                  | 0.35 | 0.77 | 0.28               | 0.56 | 0.47 | VL        |
| N-Total   | %          | 0.07              | 0.09 | 0.10 | 0.08                | 0.07 | 0.09 | 0.07                  | 0.08 | 0.08 | 0.07                  | 0.08 | 0.13 | 0.06               | 0.08 | 0.10 | VL        |
| C/N ratio |            | 4.48              | 6.89 | 6.28 | 4.18                | 9.07 | 6.36 | 8.06                  | 6.15 | 7.00 | 5.39                  | 4.58 | 5.65 | 4.20               | 7.16 | 4.68 | L         |
| P-avail   | ppm        | 0.62              | ND   | 0.97 | ND                  | 0.85 | 0.19 | ND                    | 2.07 | 0.33 | ND                    | 1.34 | 1.56 | ND                 | ND   | 0.64 | VL        |
| K-exch    | cmol(+)/kg | 0.09              | 0.06 | 0.08 | 0.08                | 0.08 | 0.06 | 0.12                  | 0.07 | 0.03 | 0.12                  | 0.09 | 0.08 | 0.10               | 0.07 | 0.09 | VL        |
| pH        |            | 4.58              | 4.82 | 5.25 | 4.58                | 4.82 | 5.25 | 4.58                  | 4.82 | 5.25 | 4.58                  | 4.82 | 5.25 | 4.58               | 4.82 | 5.25 | A         |

Remarks: ND = not detected; VL = Very Low; L = Low; A = Acidic soil; \* = Based on Appendix 3 Research Criteria for Soil Analysis Results p. 234 (BPSITP 2023)

**Table 7.** Percentage of changes in soil nutrient concentration

| Parameter | <i>P. indicus</i> | <i>H. tiliaceus</i> | <i>A. occidentale</i> | <i>P. falcattaria</i> | <i>S. mahagoni</i> |
|-----------|-------------------|---------------------|-----------------------|-----------------------|--------------------|
| C-Org.    | 94.9              | 68.0                | 8.8                   | 121.2                 | 71.1               |
| N-Total   | 36.4              | 8.0                 | 19.0                  | 100.0                 | 52.6               |
| P-avail   | 55.6              | 19.0                | 32.5                  | 156.0                 | 64.0               |
| K-exch    | -11.5             | -25.0               | -71.4                 | -30.6                 | -3.4               |

Gunawan et al. (2019) suggested that potassium ions ( $K^+$ ) be categorized as mobile elements due to their tendency to leach from the soil. This susceptibility arises from the fact that potassium ions are not firmly retained by the surfaces of soil colloids, allowing them to be easily leached from the soil. The nature of K caused its efficiency to be low, as was the case with N elements. In addition, the cause of high and low potassium levels in the soil was influenced by both the parent material and the soil pH. Acidic soil pH led to increased potassium fixation, thereby reducing the soil's potassium availability (Table 6). The biophysicochemical reaction process and the formation of plant cell walls require K nutrients, such as those regulating osmotic and turgor pressure, as well as the mechanism of opening and closing stomata (Numba 2024).

Table 7 indicates that the *P. falcataria* species had the highest increase in C-Org (121.2%), N-total (100.0%), and P-avail (156.0%). These results aligned with research conducted by Handayani & Suryadarma (2022), which explained that *P. falcataria* has relatively small and thin leaves, and its litter decomposes easily on the soil surface due to the presence of mutual symbiosis of *Rhizobium* sp. and micorhiza with the roots of *P. falcataria* (Prayudya-ningsih et al. 2024).

## Conclusion

There is an improvement in the ecological condition of KEL's revegetation land, characterized by a more diverse range of species, increased land productivity, fairly balanced ecosystem conditions, and ecological pressure at a relatively moderate level. In such a situation, natural succession in ex-mining land occurs autonomously. Indications of this natural succession are identified with the arrival of natural ingrowth around the reclamation site. Planting MPTS alongside pioneer species has facilitated this succession process, where the number and density of pioneer plant species decrease over time. However, even after up to five years of revegetation, pioneer species still dominate the reclaimed land.

The *P. falcataria* species shows the fastest growth rate in height and diameter compared to the other four species selected for this research. The ability of *P.*

*falcataria* to outperform other species is due to the nature of this plant, which can form mutualistic symbiosis with microorganisms and fungi. This association has not only succeeded in accelerating the growth of this species but also in maintaining its resistance to the reclaimed land environment, which is often less viable for plant growth. The contribution of *P. falcataria* to increasing soil fertility is due to the association of this plant's roots with microorganisms and fungi that increase the macronutrient content in the soil, except for exchangeable potassium (K). The decrease in potassium in reclaimed soil is attributed to the natural depletion of potassium in the soil. Activities involving the movement and stacking of topsoil, as well as the nature of the potassium element itself, which has high mobility in the soil, such as soil leaching.

It is essential to carefully evaluate the composition of plant types to ensure an appropriate balance between legume species, which serve as pioneer plants, and multi-purpose tree species (MPTS) in relation to the prevailing soil and media conditions when planning revegetation activities. These considerations are crucial to ensure optimum growth of the plants and an increase in soil fertility, leading to natural succession. Given the constraints inherent in the present study, future investigations should explore the relationship between extended plant lifespans and the association of mycorrhiza fungi with macronutrient levels—specifically potassium—in the context of soil fertility in areas affected by mining activities.

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