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# Dynamics of vegetation diversity and arbuscular mycorrhizal fungi in post-coal mining revegetation land in Sawahlunto, West Sumatra, Indonesia

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**Abstract.** *Herman W, Iskandar, Budi SW, Pulunggono HB, Kurniati, Milantara N. 2024. Dynamics of vegetation diversity and arbuscular mycorrhizal fungi in post-coal mining revegetation land in Sawahlunto, West Sumatra, Indonesia. Biodiversitas 25: 4627-4641.* Post-coal mining causes significant changes in vegetation, soil, and landscape, necessitating reclamation to increase land area through revegetation activities as per government policy. Revegetation is expected to accelerate the recovery of ecosystem functions and reduce the impact of coal mining activities. Therefore, this study aims to analyze the dynamics of vegetation diversity and Arbuscular Mycorrhizal Fungi (AMF) on post-coal mining revegetation land in Sawahlunto, West Sumatra, Indonesia. Vegetation samples were obtained using the purposive sampling method, and AMF analysis was carried out using the wet-sieving decanting method. The results showed an increase in vegetation diversity along with the increasing age of the revegetation plants. The highest control of plant species was *Acacia mangium* with INP values ranging from 100-300%. Vegetation diversity and vegetation dominance index were positively correlated with spore density with correlation coefficient values of 0.083 and 0.029. However, the relationship between diversity and vegetation dominance index in influencing spore density had a small effect; the highest spore density was found in revegetation in 2006, with a total of 555 spores per 25 g of soil$^{-1}$. It can be concluded that natural succession land materials and revegetation in post-coal mining land up to 32 years of age can improve vegetation growth but still cannot match natural forests, both in terms of the number of species growing and the level of vegetation diversity achieved. However, it is important to note that this study has limitations, such as the focus on a specific region and the need for further research to understand the long-term effects of revegetation.

**Keywords:** Arbuscular mycorrhizal fungi, coal, natural succession, revegetation, vegetation

## INTRODUCTION

Coal is a biogenic sedimentary rock formed from plant remains through coalification. It contains high carbon, dark in color, has little mineral association, and is characterized by a solid polymer of aromatic as well as polycyclic groups, which are used as energy sources (Zhu 2014; Wei et al. 2015; Voncken 2019). Indonesia has coal reserves of around 3.7% and is one of the largest coal producing countries in the Asia-Pacific region. The International Energy Agency (IEA) stated that the global coal export volume would reach 1.47 billion tons in 2023, showing an increase of 6.6% compared to 2022 (year-on-year/yoy). Therefore, Indonesia is still the largest coal-exporting country, with an export volume of 500 million tons or 34.1% of the total global supply (Yasin et al. 2021; Ahdiat 2023).

Although coal mining businesses can significantly boost the economy and national development, the impact of mining activities is significant in changing the environmental conditions (Kementerian ESDM 2021). In open mining systems, activities are carried out directly on the surface of the ground conventionally. During this process, long periods and large-scale mining have a significant impact on the ecosystem by disrupting ecological functions as well as damaging topography and vegetation (Eugene et al. 2016; Xu et al. 2018; Di Carlo et al. 2019; Altiti et al. 2020; Zhang and Sun 2020; Zhang et al. 2020). The exploration, development, and beneficiation process of open pit mining areas results in deforestation, handling, and accumulation, significantly altering vegetation, soil, and landscape (Chen et al. 2018; Xiao et al. 2022). Therefore, the urgency and importance of post-coal mining land improvement efforts such as revegetation activities are needed to restore damaged land.

Revegetation is an effort to repair and restore damaged vegetation by planting and maintenance activities on land affected by natural disasters (Permenhut 2011). Revegetation activities in Indonesia are focused on reforestation activities in post-mining areas; around 70.59% of post-mining areas have become secondary forests (Pambudi et al. 2023). Revegetation affects plant growth in terms of stem diameter, plant height, stand structure, density, biomass, and vegetation cover of a land area (Hale et al. 2018; Greet et al. 2020; Iskandar et al. 2022). Additionally, revegetation restores and improves the condition of vegetation, along with a corresponding effect on the habitat of wildlife such as birds. Birds play a crucial role in the revegetation process by dispersing seeds and contributing to the regeneration of plant species. This phenomenon allows mutualistic symbiosis to occur, thereby maintaining the quantity and quality of vegetation on land (Lestari et al. 2017).

Revegetation can affect vegetation diversity; the older the age of revegetation, the higher the density of vegetation species and the greater the diversity of trees that grow naturally. As the age of revegetation increases, the density of plant species also increases along with the diversity of trees that grow naturally so that it is gradually able to form natural forest conditions (Salim et al. 2020). Furthermore, vegetation composition will increase as the revegetation age progresses, regarding the number of species, importance value index and the species diversity index (Tuheteru et al. 2021). Soil microbial diversity can also be improved by enriching Arbuscular Mycorrhizal Fungi (AMF), which increase with the age of revegetation (Bi et al. 2020; et al. 2021).

AMF, through its symbiotic relationships, can significantly influence plant growth, plant community structure and ecosystems through symbiotic relationships, both mutualistic and parasitic. This symbiotic relationship is usually influenced by the characteristics of the host plant, the type of fungus, and abiotic and biotic conditions, which all play a role in this relationship (Hoeksema et al. 2010). AMF forms a symbiotic relationship with plant roots, significantly enhancing growth and productivity, especially under abiotic stress conditions. This is achieved through increased absorption of nutrients, water, and minerals (Wahab et al. 2023). The presence of AMF is crucial in enhancing the resilience of an ecosystem, ensuring plant stability, and promoting biological diversity (Simamora et al. 2015). Moreover, it acts as a natural accelerator in the phytoremediation system, reducing metal toxicity, stimulating plant growth, and altering soil nutrient dynamics (Tiwari et al. 2022).

This study aimed to examine the dynamics of vegetation diversity and AMF development at various stages of post-coal mining land revegetation. We hypothesized that as the age of revegetation increases, there would be significant changes in the composition of vegetation structure. We found that the diversity of AMF indeed increases with the age of revegetation, and the interaction between vegetation and AMF is a key contributor to ecosystem sustainability in post-coal mining revegetation land.

## MATERIALS AND METHODS

### Study area

This study was conducted on post-coal mining land of PT Allied Indo Coal Jaya (PT AICJ) located in Parambahan, Batu Tanjung Village, Talawi Sub-district, Sawahlunto City, West Sumatra Province, Indonesia, as shown in Figure 1. The area is geographically located between 0°35'55"-0°36'50" LS and 100°47'00"-100°48'10" BT, at an altitude of 378 m a.s.l. and has a temperature between 24-33°C and an average rainfall of 2042.27 mm per year. The mining company is located in Parambahan, Batu Tanjung Village, Talawi District, Sawahlunto City, West Sumatra Province, with a mining area of 372.40 ha. PT Allied Indo Coal Jaya carries out mining through two methods, namely open pit and underground mining. The company has been mining since 1985, with revegetation carried out for approximately 34 years starting from 1990.

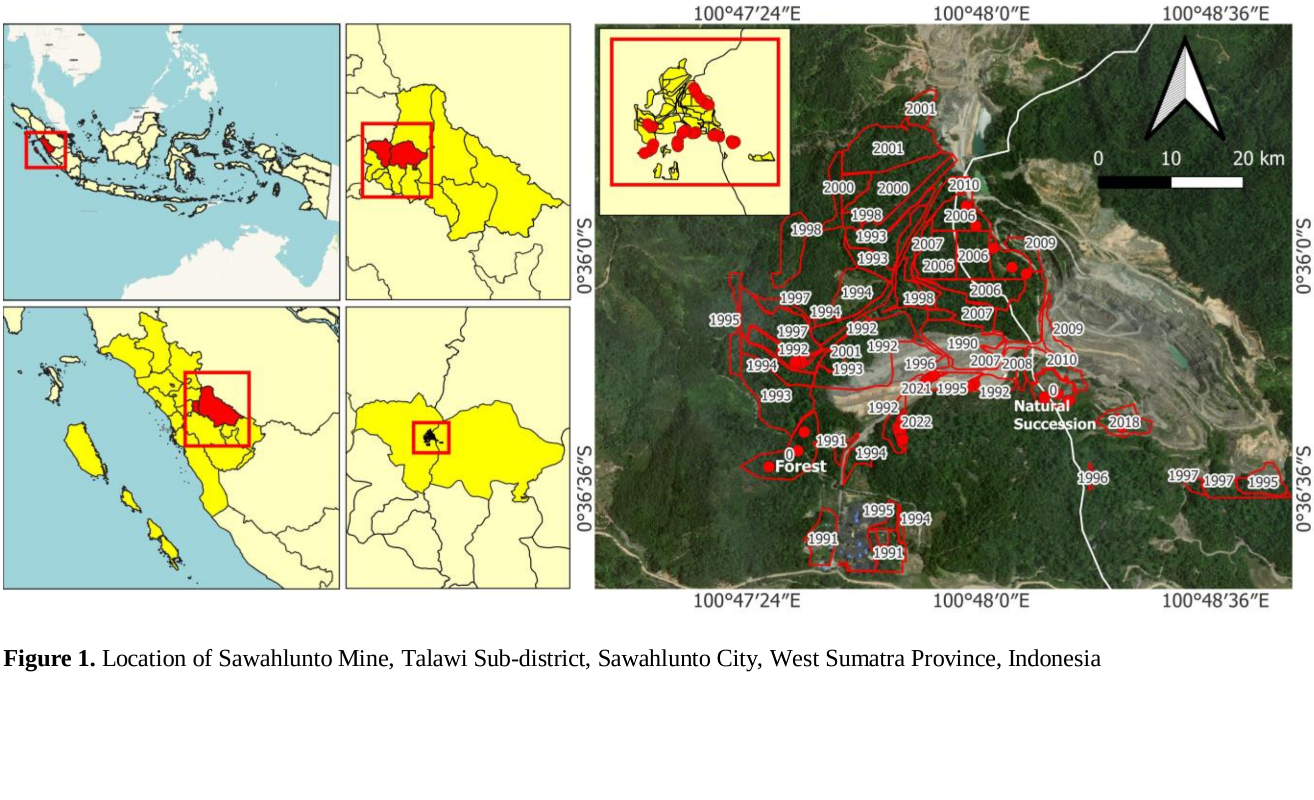


**Figure 1.** Location of Sawahlunto Mine, Talawi Sub-district, Sawahlunto City, West Sumatra Province, Indonesia

**Data collection procedure**

Data collection was carried out at the location points for natural forests, succession (filling in 2008 and without planting), and revegetation with different planting years (1992, 1995, 2006, 2008, 2018, 2021, and 2022), as shown in Figure 1. These locations were selected at various ages of revegetation, from the early stages to the advanced age, with the specific aim of providing an overview of the revegetation process. This overview can later be compared with natural forests to evaluate the success of revegetation in approaching natural forest conditions, both in terms of species composition and ecosystem function.

**Vegetation diversity**

Vegetation data were collected using an exploratory method through direct collection in the field. Samples were collected using the purposive sampling method by considering the density of each revegetation age class. Quantitative observation of the vegetation community was carried out using the double plot method (Kusmana 2017) with a plot measuring 20 × 20 m, comprising 3 plots per location, as shown in Figure 2. After obtaining the density class per revegetation age and the location of the sampling plot, vegetation analysis was carried out and the results were recorded from both tree and non-tree species.

**Diversity of AMF**

Data collection was carried out using vegetation analysis observation locations and plots. Each location consisted of 3 plots measuring 20 m × 20 m comprising 5 observation samples. Soil samples were taken around the plant rhizosphere with a depth of 0-20 cm to check for AMF spores. Subsequently, the samples were analyzed at the LRI Advanced Technology Biotechnology Center, Institut Pertanian Bogor, Bogor, Indonesia, which includes:

*Isolation of AMF spores and density of AMF spore samples*

AMF spores were isolated from soil using the wet sieving decanting method by Brundrett et al. (1996). A 25 g soil sub-sample was taken and put into a measuring cup, added with 500 mL of water. The soil was stirred and left for 10 minutes to form a precipitate. This was followed by filtration using a graduated sieve with a size of 710 µm, 425 µm, and 45 µm under running tap water. The filtering results were placed in a Petri dish and observed under a microscope to count the number of spores in each field of observation. The criteria for counting were spores that settled in the Petri dish and were still intact.

*Identification of AMF spores*

Grouping and identification of AMF were carried out based on morphological characteristics of spores found at the morpho species level (https://invam.ku.edu/classification). The identified spores were prepared on a glass object and placed on both sides of the glass object given PVLG. Each spore was observed based on the microscopic characteristics of the genus, such as color, size, ornamentation, and shape of the hyphae attached to the hyphae spores (Brundrett et al. 1996). The preparation was observed under a microscope with a magnification of 40 times.

**Data analysis**

Vegetation data obtained was analyzed quantitatively by calculating several variables, including the Importance Value Index (IVI), which identified the level of dominance (level of control) of species in the vegetation community. The calculation of the IVI value was done using the formula:

$$IVI = KR + FR + DR$$

With the different terms meaning:

$$RelativeDensity(KR) = \frac{species\ specific\ density}{all\ speciesd\ ensity} x100\%$$

$$RelativeFrequency(FR) = \frac{species\ specific\ frequency}{all\ speciesf\ requency} x100\%$$

$$RelativeDominance(DR) = \frac{species\ specific\ dominance}{allspecies\ dominance} x100\%$$

The calculation of the dominance index is written using the formula:

$$C = -\sum(n.i/N)$$

Grade C Criteria:

0< C ≤0.5 : Low dominance
0.5< C ≤0.75 : Moderate dominance
0.75< C ≤1 : High dominance

The vegetation diversity index was determined using the Shannon species diversity index formula (H') through the equation:

$$H' = -\sum \frac{ni}{N} \ln \frac{ni}{N}$$

H' Value Criteria:
H'>3: High diversity
1<H'>3: Moderate diversity
H'<1: Low diversity

The community similarity index was calculated to compare the similarity of the species composition of two communities. Calculations were done using Jaccaed's Presence-Community Coefficient through the formula:

$$ISJ = [C/(A + B + C]x100\%$$

Where :
A : ∑ types in community 1
B : ∑ types in community 2
C : ∑ species in two communities

ISJ Value Criteria: Approaching 1 = The level of similarity between habitats is high, Approaching 0 = The level of similarity between habitats is low.

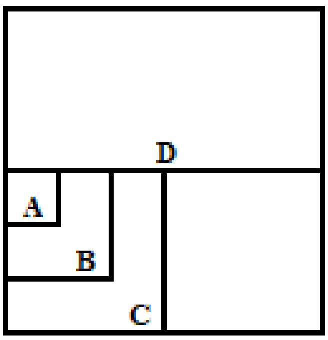


**Figure 2.** Design of sample plots for collecting vegetation data at the mining location using the multiple plot method. Note: Package A: Observation of seedlings and understory (2 m × 2 m); Package B: Sapling observation (5 m × 5 m); Package C: Observation pole (10 m × 10 m); Package D: Tree observation (20 m × 20 m)

**Density of AMF spores**

Analysis of AMF spores density was carried out by counting and observing the shape, size, and color using a light microscope with 40× magnification for 25 g of soil$^{-1}$. The data were analyzed destructively and continued with a correlation test to determine the relationship between vegetation diversity index, dominance, and the number of spore densities using the Pearson correlation test.

## RESULTS AND DISCUSSION

**Importance value index (IVI) in post-coal mining revegetation**

IVI describes the role of species in a community, showing the ability to adapt to the habitat and high tolerance to environmental conditions. Table 1 shows IVI values for the three highest plant species in the tree, pole, sapling, and seedling strata.

The highest IVI in natural forests in seedling, pole, and tree strata was *Eugenia sprengelii* DC., and sapling was dominated by *Archidendron ellipticum* (Blume) I.C.Nielsen. Natural succession land and several revegetation activities in 2018, 2021, and 2022 showed no vegetation at the tree and pole levels. *Acacia mangium* Willd. was a dominant species that appeared with very high IVI values, particularly in revegetation with older ages (1992, 1995, 2006, 2008).

The IVI values are crucial for plants in the different strata of seedlings, saplings, poles, trees, and understory. Understanding these values is essential as they indicate the relative importance of a species in a community. Understory plants are often an important component of forest ecosystems, dominating areas with high IVI values in the early years of succession.

Natural forests showed that *Dicranopteris linearis* (Burm.fil.) Underw. had a high IVI value of approximately 200%. Based on the results, the understory of *D. linearis* (Burm.fil.) Underw. was very dominant, and only one species was found in natural forests. *D. linearis* was a type of fern that dominated the 1992 revegetation with an IVI value of approximately 32.36%. This plant has a high adaptability to natural forests and the 1992 revegetation. Natural forests have a dense and shaded canopy, making them a preferred habitat for *D. linearis*. In contrast to the 1992 revegetation land, which has a canopy that is not so dense and has lots of light, it turns out that this plant is also able to grow well. However, *Cajanus scarabaeoides* (L.) Thouars dominated natural succession with IVI values ranging from 36-37%.

Revegetation land showed similarity in the control of understory plant species, such as *Axonopus compressus* (Sw.) P.Beauv. with a high IVI value in revegetation in 1995 and 1992 (Figure 3). *Eleusine indica* (L.) Gaertn. had high IVI values in 1992, 2006, and 2018, while *Solanum jamaicense* Mill. dominated revegetation in 1995 and 2006. New revegetation carried out 2-3 years after planting showed that the dominant plant species were more different from previous years. Understory plants that dominated the new revegetation land were from the Fabaceae and Poaceae families.

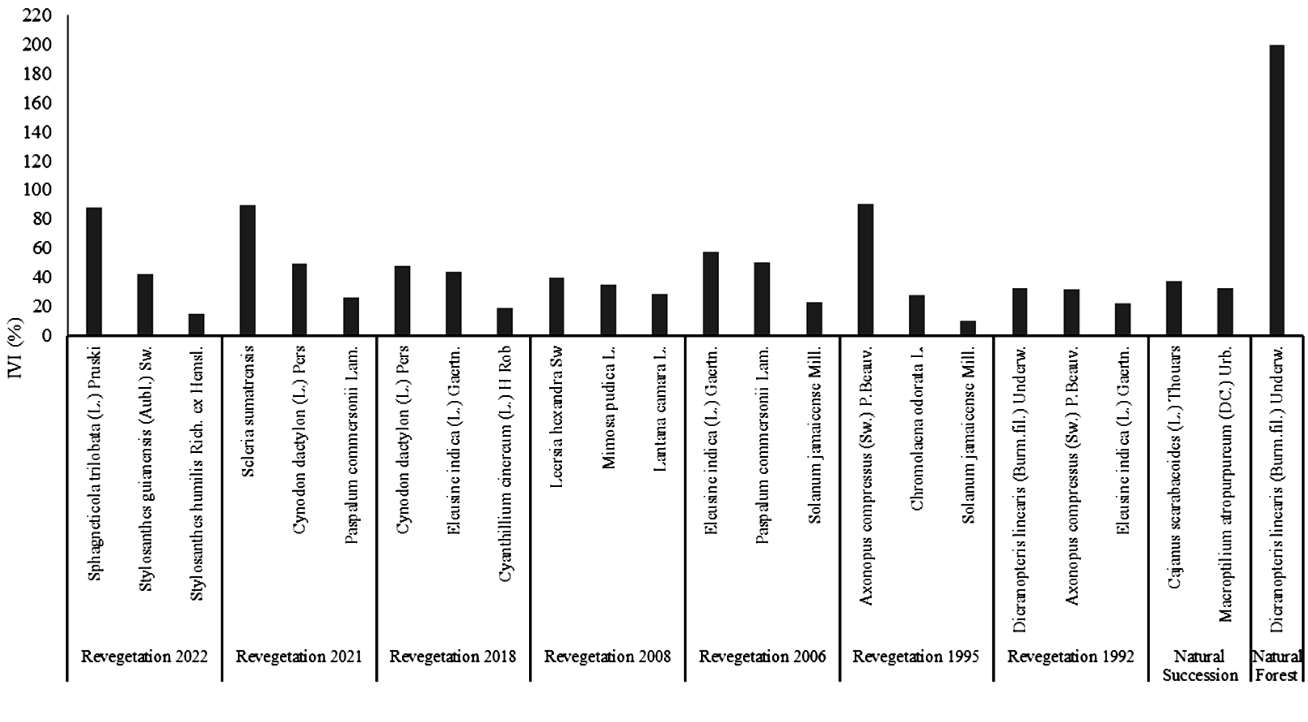


**Figure 3.** IVI at the understory level in post-coal mining land

**Table 1.** IVI at the tree, pole, sapling, and seedling strata on post-coal mining land

| Strata | Revegetation year | | | | | | | Natural succession | Natural forest |
|---|---|---|---|---|---|---|---|---|---|
| | 2022 | 2021 | 2018 | 2008 | 2006 | 1995 | 1992 | | |
| **Seedling** | *Paraserianthes falcataria* (L.) I.C.Nielsen 200,00 | *Muntingia calabura* L. 116.67 | *Toona sinensis* Roem 100.00 | *Acacia mangium* Willd. 200.00 | *Murraya koenigii* (L.) Spreng 133.33 | *Murraya koenigii* (L.) Spreng. 200.00 | *Murraya koenigii* (L.) Spreng. 135.71 | *Acacia mangium* Willd. 100.00 | *Eugenia* sprengelii DC. 33.83 |
| | × | *Leucaena leucocephala* (Lam.) de Wit 83.33 | *Leucaena leucocephala* (Lam.) de Wit 100.00 | × | *Acacia mangium* Willd. 66.67 | × | *Acacia mangium* Willd. 64.29 | *Swietenia mahagoni* (L.) Jacq 100.00 | *Alstonia scholaris* (L.) R.Br. 33.83 |
| | × | × | × | × | × | × | × | × | *Dipterocarpus gracilis* Blume 16.83 |
| **Sapling** | *Swietenia mahagoni* (L.) Jacq 196,43 | *Acacia mangium* Willd. 140.75 | *Leucaena leucocephala* (Lam.) de Wit 169.73 | × | *Acacia mangium* Willd. 207.62 | *Mallotus macrostachyus* (Miq.) Müll.Arg. 300.00 | × | *Acacia mangium* Willd. 300.00 | *Archidendron ellipticum* (Blume) I.C.Nielsen 56.32 |
| | × | *Paraserianthes falcataria* (L.) I.C.Nielsen 126.46 | *Swietenia mahagoni* (L.) Jacq 49.63 | × | *Mallotus macrostachyus* (Miq.) Müll.Arg. 51.11 | × | × | × | *Cinnamomum iners* Wight 39.29 |
| | × | *Psidium guajava* L. 32.79 | *Ceiba pentandra* 45.65 | × | *Toona ciliata* M.Roem. 41.27 | × | × | × | *Schima wallichii* (DC.) Korth. 33.50 |
| **Pole** | × | × | × | *Acacia mangium* Willd. 160.68 | *Acacia mangium* Willd. 249.74 | × | *Grewia bicolor* Juss. 130.65 | × | *Eugenia* sprengelii DC. 57.61 |
| | × | × | × | *Eusideroxylon zwageri* Teijsm. and Binn. 139.32 | *Toona ciliata* M.Roem. 50.26 | × | *Acacia mangium* Willd. 89.30 | × | *Microcos sumatrana* (Baker) Burret 53.64 |
| | × | × | × | × | × | × | *Eusideroxylon zwageri* Teijsm. and Binn. 80.04 | × | *Melanorrhoea wallichi* Hook.fil. 34.72 |
| **Tree** | × | × | × | *Acacia mangium* Willd. 166.22 | *Acacia mangium* Willd. 300.00 | *Acacia mangium* Willd. 200.00 | *Acacia mangium* Willd. 300.00 | × | *Eugenia* sprengelii DC. 134.49 |
| | × | × | × | *Paraserianthes falcataria* (L.) *I.C.Nielsen* 69.88 | × | × | × | × | *Dipterocarpus grandifloras* Blanco 35.50 |
| | × | × | × | *Tectona grandis* L.f. 63.90 | × | × | × | × | *Schima wallichii* (DC.) Korth. 33.89 |

Description: ×: No vegetation

**Dominance index in post-coal mining revegetation**

The dominance index shows the level of concentration of species control in communities and the amount of space used by each species in a unit area (Yuningsih et al. 2021). Based on its categorization, the dominance index value is divided into three classes: low, moderate, and high. When the value is less than 1, the dominance pattern is centered on several species; meanwhile, a value of 1 shows that one species dominates a stand.

Based on the results, natural forests had a low to moderate dominance index in the tree, pole, sapling, and seedling strata. The understory had a high dominance index with a value of 1, indicating centralized control by *D. linearis*. This highlights the need for further research and understanding of this species. Natural succession had a high dominance index in the sapling strata, moderate in seedlings, and low in the understory. This showed that trees are starting to grow and several dominant species have successfully been adapted.

In 1995, a high dominance was observed at the sapling and seedling levels, indicating a successful plant recovery (Figure 4). This success is a clear indication of the effectiveness of the revegetation efforts. The 2006 revegetation dominance index was evenly distributed across all vegetation strata, from high to low categories. This showed that some species were very dominant, as indicated by their stabilization and not being disturbed. In 1992, the tree and seedling strata had a high dominance index, showing that the species grown began to dominate. A high dominance was observed at the sapling and seedling levels in 1995, suggesting success in plant recovery. Revegetation was only carried out for approximately 2-3 years (2022 and 2021) planting, with varying dominance indices in poles, saplings, and seedlings. This showed that there were continuous changes in plant species as the age of revegetation increased.

**Vegetation diversity index in post-coal mining revegetation**

Land with diverse plant species would affect the vegetation diversity index due to the complexity of interactions between species. A high or low diversity index in a community depends on the number of species and individuals of each type, as shown in Figure 5.

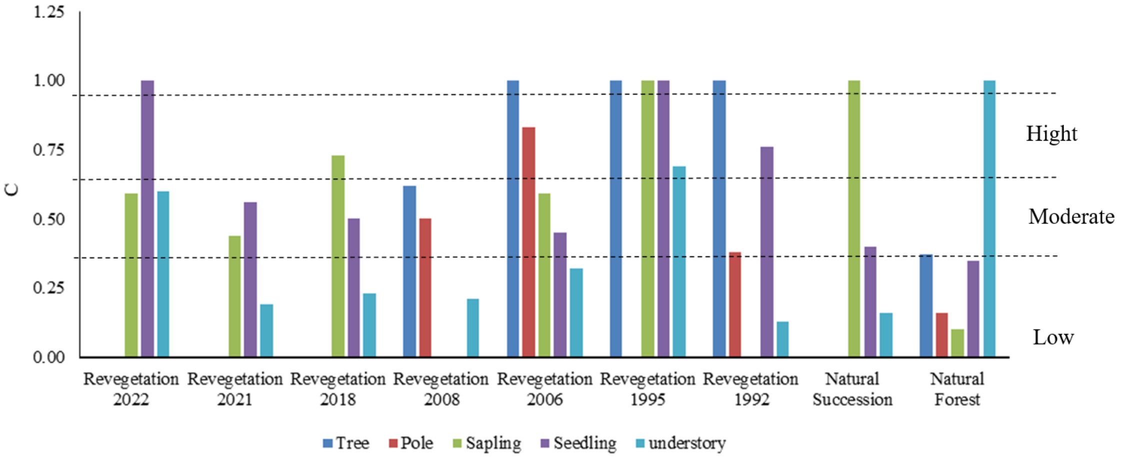


**Figure 4.** Vegetation dominance index on post-coal mining land

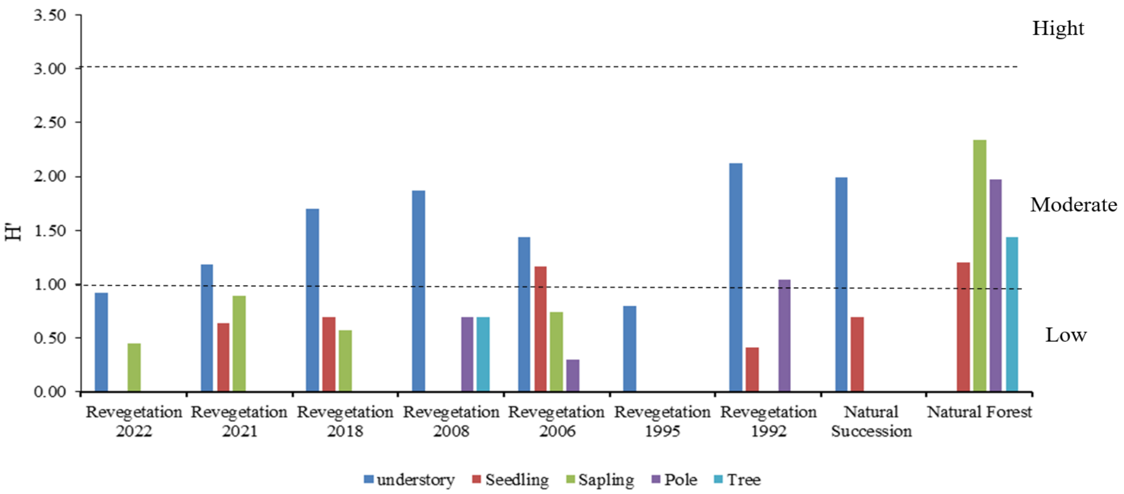


**Figure 5.** Vegetation diversity index on post-coal mining land

Natural forests had a higher diversity index compared to natural succession and revegetation land at both tree, pole, sapling, and seedling levels but not at the understory level, showing greater species diversity. Low diversity in natural succession and revegetation land showed low vegetation diversity at the tree, pole, sapling, and seedling levels in terms of understory, revegetation, and natural succession, which had a higher diversity index compared to natural forests with low to medium categories. At several ages, revegetation carried out in 1992 had a higher understory diversity index (H' = 2.12) compared to others. The diversity index varied depending on the age and type of vegetation, as the tree and understory levels tended to show higher diversity at higher revegetation ages.

**Vegetation diversity in post-coal mining revegetation**

The number of species affected the composition and structure of vegetation at the tree growth stage. The results in Figure 6 showed that natural forests and natural succession tend to produce more diverse vegetation structures compared to revegetation.

Revegetation showed higher numbers of species in the understory, poles, and trees as the age of revegetation increased. However, the seedling strata had low numbers in revegetation and natural succession but natural forests show higher numbers. The continued growth of plants could increase the number of plants in the sapling, pole, and tree strata. The number of trees was observed to be high in older revegetation (1995 and 2006) but not comparable to natural forests.

Plant species at the tree, pole, sapling, and seedling levels comprised 34 species grouped into 17 families. Natural forests had the largest number of plant species compared to natural succession and revegetation areas, as shown in Table 2. Natural forests had 31 plant species, with the most dominant family being Lauraceae. Dipterocarpaceae and Lauraceae showed good adaptability in natural forests, particularly in tropical forests. Both families played an important role in forming the structure and function of the ecosystem and were able to develop properly. Specifically, Lauraceae is the most dominant plant family that grows in the tropical forests of Southeast Asia, particularly Indonesia (Tamin et al. 2018). Natural succession and revegetation land found plant species spread from the families Fabaceae, Meliaceae, Leguminoceae, Myrtaceae, Muntingiaceae, Malvaceae, Verbenaceae, Lauraceae, and Euphorbiaceae.

Table 3 revealed the novel findings of our research on understory plants, which found 40 species grouped into 19 families. This discovery that revegetation and natural succession land had more understory plant species than natural forests is a significant contribution to the field of plant ecology and restoration. The abundance of understory plants in natural succession and revegetation areas, ranging from 5 to 13 species, is a new insight that adds to our understanding of these ecosystems. Natural succession areas were dominated by the Fabaceae and Poaceae families, comprising approximately 9 species. In comparison, revegetation areas showed an increasing trend in the number of understory plant species as the age of revegetation increased. In the 1992 revegetation, the most understory plant species were found, including those from the Gleicheniaceae, Solanaceae, Asclepiadaceae, Melastomataceae, Fabaceae, Apiaceae, Poaceae, Lythraceae, and Oxalidaceae families. The abundance of understory plants in natural succession and revegetation was due to adaptation to environmental conditions, abundant sunlight, and minimal competition with undeveloped trees. Most understory plant species were included in the category of pioneer plants that grew quickly and could adapt to changing soil conditions, such as species from the Fabaceae and Poaceae families.

**Community similarity post-coal mining revegetation**

The community similarity index was used to assess the extent to which two vegetation communities have similarities in their species composition. Based on the results, the community similarity index between natural forests, natural successional land, and revegetation ranged from 0 to 0.83 (Table 4).

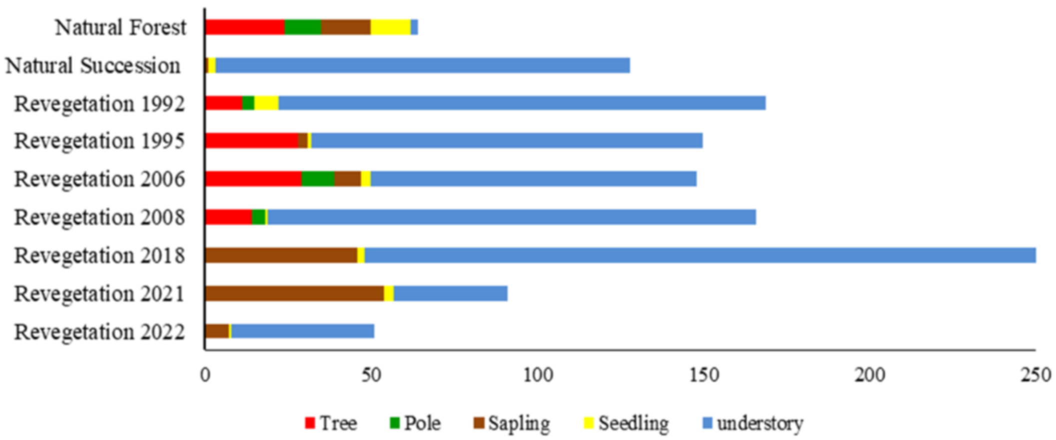


**Figure 6.** Number of plant species in the understory, seedling, sapling, pole, and tree on post-coal mining land

**Table 2.** Plant species in seedling, sapling, pole, and tree strata in revegetation on post-coal mining land

| Strata | Family | Species | Revegetation year | | | | | | | Natural succession | Natural forest |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 2022 | 2021 | 2018 | 2008 | 2006 | 1995 | 1992 | | |
| Seedling | Apocynaceae | *Alstonia scholaris* (L.) R.Br. | × | × | × | × | × | × | × | × | ● |
| | Dipterocarpaceae | *Dipterocarpus gracilis* Blume | × | × | × | × | × | × | × | × | ● |
| | Fabaceae | *Acacia mangium* Willd. | × | ● | × | ● | ● | × | ● | ● | × |
| | Fabaceae | *Leucaena leucocephala* (Lam.) de Wit | × | ● | ● | × | × | × | × | × | × |
| | Leguminoceae | *Paraserianthes falcataria* (L.) I.C.Nielsen | ● | × | × | × | × | × | × | × | × |
| | Meliaceae | *Swietenia mahagoni* (L.) Jacq | × | × | × | × | × | × | × | ● | × |
| | Meliaceae | *Toona sinensis* (A.Juss.) M.Roem. | × | × | ● | × | × | ● | × | × | × |
| | Muntingiaceae | *Muntingia calabura* L. | × | ● | × | × | × | × | × | × | × |
| | Myrtaceae | *Eugenia* sprengelii DC. | × | × | × | × | × | × | × | × | ● |
| | Rutaceae | *Murraya koenigii* (L.) Spreng. | × | × | × | × | ● | × | ● | × | × |
| | Theaceae | *Schima wallichii* (DC.) Korth. | × | × | × | × | × | × | × | × | ● |
| Sapling | Anacardiaceae | *Melanorrhoea wallichi* Hook.fil. | × | × | × | × | × | × | × | × | ● |
| | Caesalpiniaceae | *Sindora bruggemanii* de Wit | × | × | × | × | × | × | × | × | ● |
| | Dipterocarpaceae | *Shorea sumatrana* (Slooten) Desch | × | × | × | × | × | × | × | × | ● |
| | Euphorbiaceae | *Mallotus macrostachyus* (Miq.) Müll.Arg. | × | × | × | × | ● | × | × | × | × |
| | Fabaceae | *Acacia mangium* Willd. | × | ● | × | × | ● | × | × | ● | × |
| | Fabaceae | *Archidendron ellipticum* (Blume) I.C.Nielsen | × | × | × | × | × | × | × | × | ● |
| | Fabaceae | *Leucaena leucocephala* (Lam.) de Wit | × | × | ● | × | × | × | × | × | × |
| | Fagaceae | *Quercus* L. | × | × | × | × | × | × | × | × | ● |
| | Lauraceae | *Cinnamomum iners* (Reinw. ex Nees & T.Nees) Blume | × | × | × | × | × | × | × | × | ● |
| | Lauraceae | *Cryptocarya strictifolia* Kosterm. | × | × | × | × | × | × | × | × | ● |
| | Lauraceae | *Mezzetti parviflora* Becc. | × | × | × | × | × | × | × | × | ● |
| | Lauraceae | *Phoebe canescens* (Blume) Miq. | × | × | × | × | × | × | × | × | ● |
| | Leguminoceae | *Paraserianthes falcataria* (L.) I.C.Nielsen | ● | ● | × | × | × | × | × | × | × |
| | Malvaceae | *Ceiba pentandra* (L.) Gaertn. | × | × | ● | × | × | × | × | × | × |
| | Malvaceae | *Microcos sumatrana* (Baker) Burret | × | × | × | × | × | × | × | × | ● |
| | Meliaceae | *Swietenia mahagoni* (L.) Jacq | ● | × | × | × | × | × | × | × | × |
| | Meliaceae | *Toona sinensis* (A.Juss.) M.Roem. | × | × | ● | × | × | × | × | × | × |
| | Myrtaceae | *Eugenia* sprengelii DC. | × | × | × | × | × | × | × | × | ● |
| | Myrtaceae | *Psidium guajava* L. | × | ● | × | × | × | × | × | × | × |
| | Theaceae | *Schima wallichii* (DC.) Korth. | × | × | × | × | × | × | × | × | ● |
| Pole | Anacardiaceae | *Melanorrhoea wallichi* Hook.fil. | × | × | × | × | × | × | × | × | ● |
| | Burseraceae | *Canarium indicum* L. | × | × | × | × | × | × | × | × | ● |
| | Euphorbiaceae | *Mallotus macrostachyus* (Miq.) Müll.Arg. | × | × | × | × | × | ● | × | × | × |
| | Fabaceae | *Acacia mangium* Willd. | × | × | × | ● | ● | × | ● | × | × |
| | Lauraceae | *Cinnamomum iners* (Reinw. ex Nees & T.Nees) Blume | × | × | × | × | × | × | × | × | ● |
| | Lauraceae | *Eusideroxylon zwageri* Teijsm. & Binn. | × | × | × | ● | × | × | ● | × | × |
| | Lauraceae | *Litsea* (Kosterm.) Kosterm. | × | × | × | × | × | × | × | × | ● |
| | Lauraceae | *Mezzetti parviflora* Becc. | × | × | × | × | × | × | × | × | ● |
| | Malvaceae | *Grewia bicolor* Juss. | × | × | × | × | × | × | ● | × | × |
| | Malvaceae | *Microcos sumatrana* (Baker) Burret | × | × | × | × | × | × | × | × | ● |
| | Meliaceae | *Toona ciliata* M.Roem. | × | × | × | × | ● | × | × | × | × |
| | Myrtaceae | *Eugenia* sprengelii DC. | × | × | × | × | × | × | × | × | ● |
| | Theaceae | *Schima wallichii* (DC.) Korth. | × | × | × | × | × | × | × | × | ● |
| Tree | Anacardiaceae | *Melanorrhoea wallichi* Hook.fil. | × | × | × | × | × | × | × | × | ● |
| | Dipterocarpaceae | *Dipterocarpus crinitus* Dyer | × | × | × | × | × | × | × | × | ● |
| | Dipterocarpaceae | *Dipterocarpus grandifloras* (Blanco) Blanco | × | × | × | × | × | × | × | × | ● |
| | Dipterocarpaceae | *Shorea* Roxb. | × | × | × | × | × | × | × | × | ● |
| | Fabaceae | *Acacia mangium* Willd. | × | × | × | ● | ● | ● | ● | × | × |
| | Leguminoceae | *Paraserianthes falcataria* (L.) I.C.Nielsen. | × | × | × | ● | ● | × | × | × | × |
| | Myrtaceae | *Eugenia* sprengelii DC. | × | × | × | × | × | × | × | × | ● |
| | Myrtaceae | *Syzygium palembanicum* Miq. | × | × | × | × | × | × | × | × | ● |
| | Theaceae | *Schima wallichii* (DC.) Korth. | × | × | × | × | × | × | × | × | ● |
| | Verbenaceae | *Tectona grandis* L.f. | × | × | × | ● | × | × | × | × | × |
| Total | | | 3 | 6 | 5 | 6 | 8 | 3 | 6 | 3 | 31 |

Note: ●: Presence of vegetation; ×: No vegetation

**Table 3.** Understory plant species in revegetation on post-coal mining land

| Family | Species | Revegetation year | | | | | | | Natural succession | Natural forest |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 2022 | 2021 | 2018 | 2008 | 2006 | 1995 | 1992 | | |
| Acanthaceae | *Asystasia gangetica* (L.) T.Anderson | × | × | × | × | × | ● | × | × | × |
| Apiaceae | *Centella asiatica* (L.) Urb. | × | × | × | × | × | × | ● | × | × |
| Asclepiadaceae | *Cynanchum acutum* L. | ● | × | × | × | × | × | ● | × | × |
| Asteraceae | *Ageratum conyzoides* L. | × | × | × | × | × | ● | × | × | × |
| Asteraceae | *Chromolaena odorata* (L.) R.M.King & H.Rob. | × | ● | ● | ● | ● | ● | ● | × | × |
| Asteraceae | *Cyanthillium cinereum* (L.) H.Rob. | × | × | ● | × | × | × | × | × | × |
| Asteraceae | *Sphagneticola trilobata* (L.) Pruski | ● | × | × | × | × | × | × | × | × |
| Cypereceae | *Scleria sumatrensis* Retz. | ● | ● | × | × | × | × | × | × | × |
| Fabaceae | *Alysicarpus vaginalis* (L.) DC. | × | × | × | × | × | × | × | ● | × |
| Fabaceae | *Cajanus scarabaeoides* (L.) Thouars | × | × | × | × | × | × | × | ● | × |
| Fabaceae | *Calopogonium mucunoides* Desv. | × | × | ● | × | × | × | × | × | × |
| Fabaceae | *Centrosema pubescens* Benth. | × | × | × | ● | ● | × | ● | × | × |
| Fabaceae | *Crotalaria pallida* Aiton | × | × | × | × | × | × | × | ● | × |
| Fabaceae | *Macroptilium atropurpureum* (DC.) Urb. | × | × | ● | ● | × | × | × | ● | × |
| Fabaceae | *Mimosa pudica* L. | × | × | ● | ● | × | × | ● | ● | × |
| Fabaceae | *Stylosanthes humilis* Kunth | ● | × | × | × | × | × | × | × | × |
| Fabaceae | *Stylosanthes guianensis* (Aubl.) Sw. | ● | × | × | × | × | × | × | ● | × |
| Gleicheniaceae | *Dicranopteris linearis* (Burm.fil.) Underw. | × | × | × | × | × | × | ● | × | ● |
| Lamiaceae | *Hyptis capitata* Jacq. | × | × | × | × | × | ● | × | × | × |
| Lygodiaceae | *Lygodium volubile* Sw. | × | × | × | × | × | ● | × | × | × |
| Lythraceae | *Cuphea elliptica* Koehne ex Engl. | × | × | × | × | × | × | ● | × | × |
| Mavaceae | *Urena lobata* L. | × | × | × | ● | × | × | × | × | × |
| Melastomataceae | *Melastoma malabathricum* L. | × | × | × | ● | × | × | ● | × | × |
| Melastomataceae | *Clidemia hirta* (L.) D.Don | × | × | × | ● | × | × | × | × | × |
| Oxalidaceae | *Oxalis corniculate* L. | × | × | × | × | × | × | ● | × | × |
| Piperaceae | *Piper aduncum* L. | × | × | × | × | × | ● | × | × | × |
| Poaceae | *Axonopus compressus* (Sw.) P.Beauv. | ● | ● | × | × | × | ● | ● | × | × |
| Poaceae | *Cynodon dactylon* (L.) Pers | × | ● | ● | × | × | × | × | × | × |
| Poaceae | *Eleusine indica* (L.) Gaertn. | × | × | ● | × | ● | × | ● | ● | × |
| Poaceae | *Leersia hexandra* Sw. | × | × | × | ● | × | ● | × | × | × |
| Poaceae | *Leersia virginica* Willd. | × | × | × | × | × | × | ● | × | × |
| Poaceae | *Paspalum commersonii* Zuccagni, 1806 | × | ● | × | × | ● | × | × | × | × |
| Poaceae | *Pennisetum purpureum* Schumach. | × | × | ● | × | × | × | × | ● | × |
| Polygonaceae | *Fallopia dumetorum* (L.) Holub | × | × | × | × | × | ● | × | × | × |
| Rubiaceae | *Hexasepalum teres* (Walter) J.H.Kirkbr. | × | × | × | × | × | × | × | ● | × |
| Rubiaceae | *Mitracarpus hirtus* (L.) DC. | × | × | × | × | ● | × | × | × | × |
| Rubiaceae | *Spermacoce alata* Aubl. | × | × | × | × | ● | × | × | × | × |
| Solanaceae | *Solanum jamaicense* Mill. | ● | × | × | ● | ● | ● | ● | × | × |
| Verbenaceae | *Lantana camara* L. | × | × | × | ● | ● | ● | × | × | × |
| Verbenaceae | *Stachytarpheta jamaicensis* (L.) Vahl | × | × | ● | ● | ● | × | × | × | × |
| Total | | 7 | 5 | 9 | 11 | 9 | 11 | 13 | 9 | 1 |

Note: ●: Presence of vegetation; ×: No vegetation

The community similarity index between natural forests and natural succession and revegetation land had a value of 0, indicating no common species. This reliable data provides a solid foundation for our research. Natural succession land showed a low community similarity index to revegetation ranging from 0.04 to 0.14. The low community similarity index was due to the very small similarity of plant species between natural succession and revegetation. The 1992 revegetation showed the highest similarity with the 2022, which was demonstrated by a community similarity index value of 0.83. This high community similarity suggests that the planted plant species were thriving in both locations. The community similarity index also appeared moderate in 2006 (0.24) and 2008 (0.28), which was lower compared to other years. However, revegetation land tended to be more similar to each other in relation to natural forests and natural succession, further reinforcing the reliability of our data.

## Density and genus of AMF spores post-coal mining revegetation

The density of spores 25 g of soil$^{-1}$ showed different amounts at each location due to the influence of environmental conditions and the impact of mining activities (Table 5). As presented in Table 5, the 2006 revegetation had the highest spore density, while natural succession showed the lowest spore density with AMF genera found. The spore density decreased after the peak in 2006 but remained higher compared to several previous years. The 2006 revegetation showed that the AMF spore density had a high number of 540 spores in 25 g soil$^{-1}$. This was due to the even distribution of vegetation diversity in various vegetation strata, which significantly influenced the overall revegetation development. Good vegetation conditions would create a proper and more productive growing habitat for AMF. The spore density was also high in 2022, showing that the land was overgrown with vegetation characterized by fine and young roots. Importantly, the influence of revegetation practices, such as the application of manure, was evident, highlighting the practical implications of this finding. In natural forests, natural succession, and revegetation land, four genera of AMF spores were found; this is presented in Figure 7.

Figure 7 illustrates the genus of AMF found in natural forests, natural succession land, and revegetation. The results, which are of great significance, show that natural succession land and revegetation in 1995 were home to four genera of AMF: *Glomus* sp., *Scutellospora* sp., *Acaulospora* sp., and *Gigaspora* sp. This discovery has profound implications for our understanding of AMF diversity in different ecological settings. In other natural forests and revegetation, three genera of AMF were identified, namely *Glomus* sp., *Gigaspora* sp., and *Acaulospora* sp.

**Correlation between vegetation structure and density of AMF**

The results of the relationship between vegetation diversity index, dominance index, and number of mycorrhizal spores were tested using Pearson correlation to determine the association between variables, as shown in Figure 8. This figure shows a significant negative relationship between vegetation diversity and the dominance index with a correlation coefficient value of -0.930. The results showed that the linear relationship pattern formed was negative, as indicated by clustered observation points following a straight line with a negative slope. The vegetation diversity index decreased in line with the increasing dominance index and increasing diversity of plants tending to have lower species dominance.

The relationship between the number of AMF spores with diversity and dominance index had a correlation coefficient of 0.083 and 0.029. Positive values indicate that when vegetation diversity increases, spore density tends to increase as well, although the relationship is weak. The positive correlation indicates a directional pattern. However, correlation values below 0.3 indicate that the relationship between vegetation and spore density could be stronger, or there is almost no significant linear relationship. This illustrates that vegetation diversity can indeed affect spore density, but the effect is small, and other factors are more dominant in influencing AMF spore density, such as soil conditions, humidity, and age of the host plant.

**Table 4.** Community similarity index between natural forest, natural succession, and revegetation land

| Location | Rev. 2022 | Rev. 2021 | Rev. 2018 | Rev. 2008 | Rev. 2006 | Rev. 1995 | Rev. 1992 | Natural succession | Natural forest |
|---|---|---|---|---|---|---|---|---|---|
| Rev. 2022 | 1 | 0.12 | 0.05 | 0.09 | 0.45 | 0.45 | 0.83 | 0.11 | 0.00 |
| Rev. 2021 | | 1 | 0.14 | 0.14 | 0.15 | 0.14 | 0.13 | 0.05 | 0.00 |
| Rev. 2018 | | | 1 | 0.16 | 0.12 | 0.04 | 0.11 | 0.14 | 0.00 |
| Rev. 2008 | | | | 1 | 0.32 | 0.21 | 0.28 | 0.08 | 0.00 |
| Rev. 2006 | | | | | 1 | 0.27 | 0.24 | 0.09 | 0.00 |
| Rev. 1995 | | | | | | 1 | 0.19 | 0.04 | 0.00 |
| Rev. 1992 | | | | | | | 1 | 0.12 | 0.03 |
| Natural succession | | | | | | | | 1 | 0.00 |
| Natural Forest | | | | | | | | | 1 |

Note: Rev.: Revegetation

**Table 5.** Number, density, and distribution of AMF genera in post-coal mining land

| Location | AMF spore density (25 g soil$^{-1}$) | Genus spore | | | |
|---|---|---|---|---|---|
| | | ***Glomus* sp.** | ***Gigaspora* sp.** | ***Acaulospora* sp.** | ***Scutellospora* sp.** |
| Natural forest | 276 | 263 | 6 | 7 | 0 |
| Natural succession | 28 | 22 | 1 | 4 | 1 |
| Revegetation 1992 | 279 | 275 | 1 | 3 | 0 |
| Revegetation 1995 | 215 | 212 | 1 | 1 | 1 |
| Revegetation 2006 | 555 | 540 | 4 | 11 | 0 |
| Revegetation 2008 | 223 | 192 | 2 | 29 | 0 |
| Revegetation 2018 | 55 | 51 | 3 | 1 | 0 |
| Revegetation 2021 | 78 | 68 | 3 | 7 | 0 |
| Revegetation 2022 | 499 | 491 | 2 | 6 | 0 |

## Discussion

*Dominance of post-mining land vegetation*

Natural forests showed a low dominance index in all vegetation strata, including seedlings, saplings, poles, and trees. This suggested that no plant species were dominating the ecosystem, although high dominance was observed in the understory of natural forests. The dominance index had a value of 1, which described centralized control by *D. linearis*. Specifically, *D. linearis* is a type of fern that commonly grows in tropical and subtropical areas, with special branches forming a single species dominant community due to rapid reproduction and allelopathy. This species can also form dense thickets and often dominates the lower part of forests (Yang et al. 2021).

Based on the results, natural succession had a high dominance index in the sapling strata, medium and low for the seedling strata and understory. *A. mangium* dominated this location with an IVI value ranging from 100-300%. *A. mangium* showed significant growth and successful adaptation, dominating several revegetations from 2021 to 1992. This showed that revegetation was carried out with *A. mangium* succeeded in dominating. Therefore, *A. mangium* was widely used for revegetation activities and was included in the fast-growing Fabaceae family, which formed a symbiosis with nitrogen-fixing bacteria. The species also adapted to nutrient-poor soil and was considered drought-resistant, serving as an invasive species in coal mining revegetation areas (Paramitha and Mardji 2015).

Revegetation in 2006 or after 18 years showed an even dominance index in all vegetation strata as an impact of the species that were no longer disturbed. Meanwhile, 29 years after revegetation (1995), the dominance index was very high in the tree, sapling, and seedling strata, with understory being moved to the moderate category. This showed successful plant recovery after revegetation with a species dominance index value close to 1. The value suggested that dominance was centered on one species, which played a very important role in forming the community structure, although their behavior was not uniform (Mujahid et al. 2022). After 32 years of planting, there was another decrease in the dominance index.

Based on the results, revegetation carried out for approximately 2-3 years (2022 and 2021) planting showed a dominance index that varied at the pole, sapling, and seedling levels. This showed that there was a continuous change as plant species started to dominate. Revegetation carried out on post-mining land showed that, at the beginning, several species were dominating at certain vegetation levels. However, as the age of revegetation increased, the dominance of plant species spread to other vegetation levels and decreased with increasing species diversity. This phenomenon showed the complex and competitive dynamics of succession between species on revegetation land.

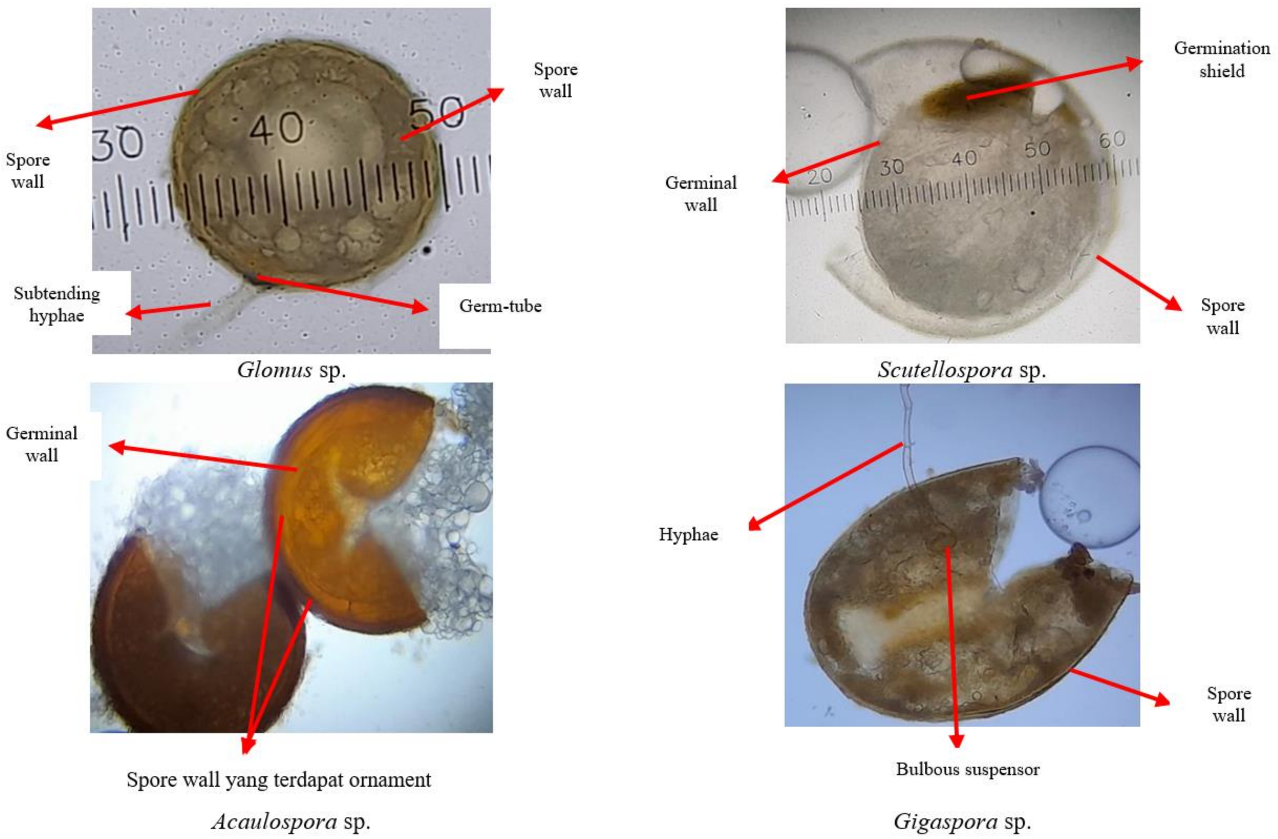


**Figure 7.** AMF genera found in post-coal mining land

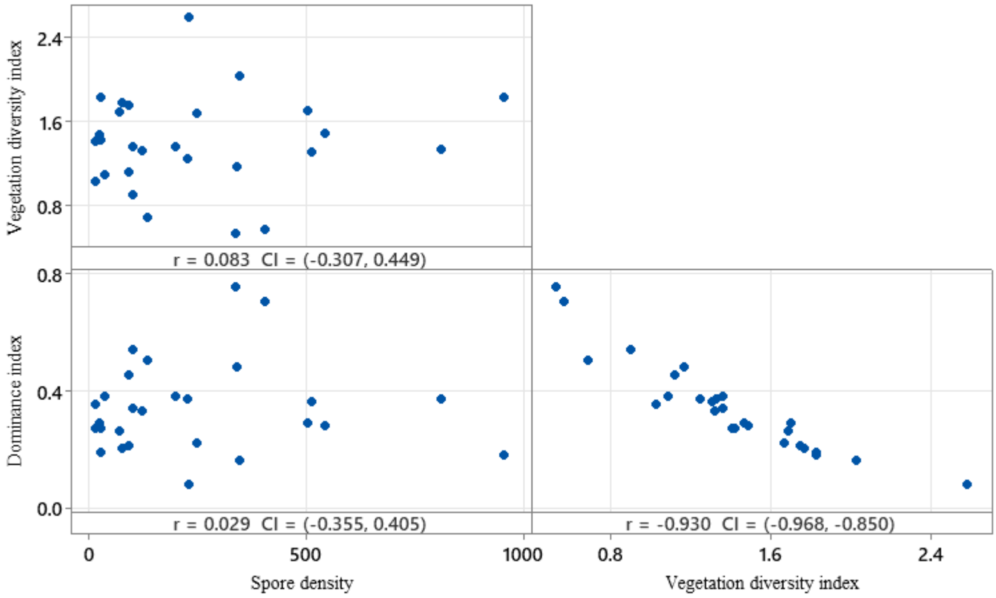


**Figure 8.** Correlation between vegetation diversity index, dominance index, and spore density

*Diversity of post-mining land vegetation*

The dynamics of vegetation diversity development and AMF at several ages of post-coal mining land revegetation were important to restore the ecosystem, develop a more effective strategy, and maintain the ecosystem for the long term. High diversity in natural forests showed a stable ecosystem with various native species that had long adapted to the environment. The species found in natural forests were very different from those in natural succession and revegetation land. A revegetation process that prioritized non-native species to accelerate ecosystem recovery was considered quite successful. However, the diversity of species planted was still relatively low, as shown from 2022 to 1992, when compared to natural forests (Table 2). The plant species used for revegetation were *A. mangium* and *Paraserianthes falcataria* (L.) I.C.Nielsen, which had very good adaptability to disturbed land conditions. However, *A. mangium* Willd. was found to be a plant species that could survive growing for approximately 32 years after revegetation.

The higher diversity of tree-level plant species was found in natural forests compared to others. This occurred because the plants in natural forests reached their climax faster than natural succession and revegetation land. Furthermore, land cover in natural forests affected the existence of native plants, which increased and maintained the species to achieve diverse vegetation structures with distinctive characteristics (Pan et al. 2021; Nugroho et al. 2022). After 32 years of revegetation, the number of species that correlated with natural forests did not increase. Plant species found in revegetation and natural succession areas were different from those found in natural forests due to the distance to the seed source.

In addition to the diversity of tree strata, poles, saplings, and seedlings, understory plants also play an important role that can be used as an indicator in assessing the success of revegetation activities. The density and height of the land stand could affect the understory community as a form of excessive intraspecific competition (Zhang et al. 2023) and canopy density (Sun et al. 2022). Understory is the initial process of succession that describes successful reforestation. For forests, understory will occur when environmental conditions such as soil are not eroded. The succession process is a major component in assessing the success of the reclamation of the ecosystem on post-mining land. Undergrowth is a group of vegetation that grows in the early stages of succession (Nasihin et al. 2021). In this study, the high diversity index of understory in revegetation land was due to elevated understory diversity. The species of plants that grow spontaneously vary based on location and monitoring period, where the seed dispersal mechanism is assisted by natural activities (Soendjoto et al. 2023).

The diversity of understory plant species was influenced by the time since disturbance occurred in a field, the availability of light (Kumar et al. 2018), and the availability of nutrients (Yu et al. 2022). Understory plants in natural succession and revegetation areas were considered important vegetation components in accelerating ecosystem formation. Deng et al. (2023) stated that understory plants played a very significant role in plant diversity, providing ecosystem functions and services such as nutrient cycles, decomposing organic matter, and ecosystem regeneration. The high species diversity of understory plants in natural succession and revegetation could be used as an indicator to assess the success or failure of revegetation carried out on coal mining land.

The growing understory would help the land gradually recover, although some did not develop because the appearance of the plants only changed slightly and remained near the ground surface, functioning as parent trees. Others gradually developed from seedlings, saplings, poles, or trees as parent trees, which affected the vegetation diversity index (Lefi and Soendjoto 2024). This showed that 2006 revegetation had better diversity at several levels of vegetation (seedlings, saplings) compared to others. Based on the highest diversity index value, 1992 revegetation did show the highest value. However, the 2006 revegetation had a more even distribution in various vegetation strata, showing better development.

The development of vegetation diversity in post-coal mining revegetation land showed that understory plants played an important role in initiating the ecosystem recovery process. Although species diversity had not fully correlated with natural forests, the longer revegetation age in 2006 and 1992 showed an increase in diversity and better distribution in various vegetation strata. The regeneration process began with the formation of understory plants, which could be used as an indicator of the success of revegetation in restoring disturbed ecosystem functions.

*Comparison of plant species composition*

The similarity index of natural forest communities with natural succession and revegetation land had a value of 0. This showed that the plant species found in natural forests were very different from those in natural succession and revegetation land. Natural forests still had a very different species composition from disturbed or managed land, suggesting the complexity and uniqueness of forest ecosystems. Moreover, Christopher (2020) explored two types of forests and obtained community similarity index results of approximately 42.66%, which showed a greater diversity of plant species in forest areas.

Natural succession land showed a low community similarity index for all revegetation years, ranging from 0.04 to 0.14. This was due to the very small similarity of several species between natural succession land and revegetation. The 1992 revegetation land showed the highest similarity with the 2022, as indicated by the community similarity index value of 0.83. The high similarity was due to the plant species planted growing well in both locations. The community similarity index also appeared moderate with 2006 (0.24) and 2008 (0.28), while others were lower.

The community similarity index in revegetation areas tended to be more similar to each other compared to natural forests and succession due to the application of the same plant species. According to Sidabukke et al. (2022) changes in forests have impacted changes in the similarity of plant species caused by differences in environmental factors such as air humidity and temperature, sunlight intensity, as well as different management patterns.

The community similarity index value showed the significant differences between natural forests, natural succession, and revegetation land. Although revegetation was able to support the growth of several planted species, it did not fully replicate the diversity and complexity of species found in natural forests. The low community similarity between natural successional land and revegetation showed that environmental and management factors played an important role in determining the species composition of an area. Therefore, revegetation efforts should consider native ecological conditions and increase species diversity to reach the level of complexity of natural forests.

*Density and distribution of AMF spores at various revegetation ages*

High species diversity can affect the density and genus of AMF. The high diversity index in poles, saplings, seedlings and undergrowth affects AMF habitat so that many spores are found. Plant roots are good habitats for AMF, especially vegetation that has many fine fibrous roots as habitats for AMF. This was observed in the 2006 revegetation land, which had a high diversity index and spread across various strata. Revegetation in 2022 also showed spores density because the age of the plants was still new and many young fine roots were serving as habitat for AMF growth. Revegetation carried out was still under monitoring, which influenced the application of fertilizers during revegetation practices, such as the use of manure.

Young and fine roots of plants can increase the effectiveness of AMF to colonize, thereby affecting the number of spores. Fine roots on plants facilitate easy colonization, which affects the density of AMF spores (Prayoga and Prasetya 2021). The addition of new species in 2006 and 2022 revegetations, along with significant changes in the type of vegetation planted, also affects the growth of AMF. In this study, spores densities showed significant fluctuations over time, with several peaks and decreases due to changes in various factors such as vegetation, soil conditions, or interactions with plants. The high spore densities in 1992 and 2006 revegetations show that the increasing age of revegetation affects the presence of AMF.

The genus *Glomus* sp. dominated the distribution of the AMF genus due to its good growth ability in post-mining land and its ability to adapt to the rhizosphere of weeds growing on acidic soil types (Prayoga and Prasetya 2021). *Glomus* sp., *Gigaspora* sp., and *Acaulospora* sp. were genera found in every location, while *Scutellospora* sp. was found only in natural succession and revegetation land in 1995. This suggested species diversity and root conditions of plants affected the density and distribution of AMF genera in revegetation land. Plant age and vegetation type also affected spores fluctuations, with *Glomus* sp. as the dominant genus. Therefore, regevetation management, including proper fertilizer use, was considered important to support AMF colonization and the sustainability of restored ecosystems.

In conclusion, this study shows that revegetation of post-coal mining land exhibits complex ecosystem recovery dynamics. At the beginning of revegetation, the dominance of certain species, such as *A. mangium*, is quite high, but as the age increases, this dominance tends to spread more evenly, increasing diversity in several vegetation strata, especially in seedlings and saplings. However, the diversity of vegetation in revegetation and natural succession is still much lower than in natural forests, which have unique and more complex species compositions. Community similarity indices indicate that the species composition of revegetation and natural succession is significantly different from natural forests, emphasizing the need for revegetation with native species to approach natural ecosystem conditions. In addition, the presence of Arbuscular Mycorrhizal Fungi (AMF), dominated by the genus *Glomus*, plays an important role in the recovery of ecosystem functions, with higher spore densities in older revegetation. Overall, although not yet fully resembling natural forests, revegetation has made an important contribution to ecosystem recovery, with long-term sustainability depending on management that considers native species, microecosystems, and soil conditions.

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