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Plant adaptability and species diversity after coal mining reclamation in South Borneo

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Abstract

Reclamation is an important activity to support ecosystem recovery after mine closure. The success of this effort depends on plant adaptability to environmental pressure, primarily related to high-acidity soil. However, more information about plant adaptability in reclamation sites is needed, although it is required to determine the alternative species for supporting revegetation efforts. Our study investigated the adaptability of multiple tree species used for coal mining reclamation and assessed their essential role in enhancing biodiversity in the degraded ecosystem. An ecological survey was conducted using a transect line method with a sampling plot size of 20×20 m and an interval from each 50 m. This study found that seven species were used to support the reclamation efforts, i.e., *Aleurites moluccana*, *Archindendron pauciflorum*, *Artocarpus heterophyllus*, *A. integer*, *Durio zibethinus*, *Hevea brasiliensis*, and *Mangifera casturi*. The survival across species was 78.60−89.39 %, with a height of 64.75−133.94 cm and a diameter of 0.59−1.39 cm. The species diversity was low, with a richness of 0.98 and a heterogeneity of 0.84. These species also had an unbalanced distribution pattern with an evenness index of 0.43. These findings showed that the selected plant species had good adaptability to the environmental conditions of the reclamation site. Although their contribution to biodiversity improvement was still low, there was a positive contribution from these species to biodiversity recovery after the mine closure. Further investigation is still required to monitor the long-term benefits of these species on ecosystem recovery in the reclamation area.

Key words: biodiversity, degraded ecosystem, environmental pressure, mine closure, revegetation.

Introduction

Coal mining is one of Indonesia's most important industries contributing to the gross domestic product (Nugroho et al. 2022, Supandi et al. 2023). However, it also has negative impacts on the environment in the future. Coal mining exploitation using an open-cut system changes the landscape (Nugroho et al. 2021), increases runoff and erosion (Jiang et al. 2022), reduces biodiversity (Sasaki et al. 2015), and causes soil contamination (Mourinha et al. 2022). This circumstance creates degraded land after mine closure (Worlanyo and Jiangfeng 2021). To minimize the impact, reclamation effort is necessary to support land recovery. It is conducted by closing mining holes, returning soil, and establishing vegetation (Buta et al. 2019). This effort is expected to accelerate vegetation succession and minimize land degradation in the following periods.

Nevertheless, coal mining reclamation takes work and time to implement. This effort has many challenges, primarily related to soil characteristics. After the mine closure, the soil had high acidity and contained heavy metals due to the impact of chemical contamination (Li et al. 2018). This stimulates the high mortality of plants during coal mining reclamation. Soil with high acidity causes Al toxicity, inhibiting root growth and development (Hajiboland et al. 2022). At the same time, the excessive content of heavy metals is also toxic for plants (Chibuike and Obiora 2014). Consequently, the plant cannot grow well and has a high mortality risk. To tackle these constraints, selecting adaptive plant species is necessary to support coal mining reclamation (Stojnić et al. 2021). It can be conducted by planting several species to evaluate their adaptability in the reclamation area.

Until now, many reclamation activities have been implemented by coal mining managers. One of them is PT Borneo Indobara (BIB), a coal mining enterprise that has a concession area in South Borneo. BIB has conducted reclamation effort in its site by establishing several plant species. Unfortunately, information about adaptive plant species for coal mining reclamation in this area is rarely published, although it is required as basis information to support mining reclamation in the future. On another side, the current challenge of coal mining reclamation in BIB is not only about revegetation but also should consider biodiversity conservation through reclamation. Coal mining exploration with open-pit systems causes biodiversity loss, especially for native species. These plants have low natural regeneration; thus, artificial regeneration is required to conserve them. In this context, the result of the reclamation can also accelerate biodiversity recovery, primarily related to local species from the reclamation area (Trimanto and Shofiah 2018). Considering these explanations, there are two critical questions related to the reclamation effort in this site:

1. What kind of alternative plant species can facilitate coal mining reclamation?

2. How is the contribution of these species in recovering biodiversity at the reclamation site?

In order to address those questions, this study aims to evaluate the adaptability of multiple tree species used for coal mining reclamation and to assess their essential role in improving biodiversity. Results will deliver sufficient information for BIB managers related to the list of adaptive plant species for reclamation and their contribution to biodiversity recovery in the land.

Material and Methods

Study area

This study was conducted in a coal mining reclamation site managed by PT Borneo Indobara with a size of 6 ha. This area is part of the Riam Kanan Watershed in Artain Village, Banjar District, South Borneo. The study site has geographic coordinates 114°55’−115°15’ E and 3°21’−3°40’ S. It is situated in the lowland with topography predominantly hilly areas. Annual rainfall ranges from 2000 to 3000 mm·yr^{-1} over the last ten years. The highest rainfall is recorded in December, while the lowest is in May. Dry periods occur for five months, from June to October. The average daily temperature is 25 °C with a minimum of 19 °C and a maximum of 35 °C. The reclamation effort on this site was conducted in 2020 by planting several alternative species in an open area. These species were planted by a spacing of 3×3 m. However, species distribution was irregular and not arranged in zonation.

Data collection

A field survey was undertaken by a systematic sampling method with a sampling intensity of 5%. The entire sampling plot in this study reached 40 units. The shape of each plot was square, with a size of 20×20 m (Alam et al. 2022). The plot was distributed systematically with a distance between plots of 50 m (Sadono et al. 2020b). It was expected to cover the variation of vegetation from the reclamation area.

Several parameters were recorded from each plot, i.e. species name, number of species, plant height, and plant diameter. The plants' name was determined using the guidance of plant species identification in the tropics (Suyanto et al. 2022). Plant height was measured using a pole from aboveground to the top crown (Wirabuana et al. 2021a). The measurement of plant diameter was undertaken by a caliper at 30 cm from aboveground (Wirabuana et al. 2019). It was conducted since most plants in the reclamation site were still categorised into seedlings and saplings although it has been 3 years post-reclamation.

In parallel, soil samples were also collected in every sampling plot at a depth of 0−10 cm (Nugroho et al. 2022). These samples were composited and brought to the laboratory for quality analysis. Six attributes were used to quantify the soil quality, namely soil acidity (pH H_2O), soil organic carbon (SOC), total nitrogen (TN), total phosphorus (TP), total potassium (TK), and cation exchange capacity (CEC) (Alam et al. 2022). Soil pH was determined using a pH meter while SOC was quantified using the Walkley−Black method. TN was analysed using Kjeldahl method. The ammonium acetate NH_4OAc 1 M, pH 7.0 extraction was applied to determine TK while for TP, Bray method was used. The ammonium acetate method was used to quantify the CEC. Soil analysis protocols were conducted following Estefan et al. (2013).

Data analysis

Three indicators were used to evaluate the adaptability of plant species in the study site: survival rate, average height, and average diameter. The survival rate for each species was calculated as the ratio between actual plant density and the initial planting density and is stated in percentage units (Wirabuana et al. 2021a). Meanwhile, the average height and diameter were computed based on the arithmetic mean of plant dimensions from every species (Wirabuana et al. 2022). The equations (1, 2 and 3) for quantifying those parameters are presented below:

$$SR = \frac{AD}{ID} \cdot 100, \quad (1)$$

$$H = \frac{h_1 + h_2 + h_3 + \ldots}{n}, \quad (2)$$

$$D = \frac{d_1 + d_2 + d_3 + \ldots}{n}, \quad (3)$$

where: *SR* is survival rate, %; *AD* is actual species density; *ID* is initial planting density; *n* is the number of species abundance; *H* indicates average plant height, m; *D* is average plant diameter, cm; $h_{1,2,3}$,… are the heights of plants, m; and $d_{1,2,3,}$… indicate diameters of plants, cm.

The important value index (IVI) was also calculated to assess the essential role of each species in improving biodiversity in the reclamation site. It is an indicator commonly used in ecological studies to understand the bargaining position of certain species in communities (Matatula et al. 2021). This parameter was computed by summing the relative density and frequency owned by certain species (Sadono et al. 2020a). Only two parameters were considered for counting IVI because the size of plant species was in seedling and sapling stage (Purwanto et al. 2022). Detail equations (4, 5 and 6) for quantifying IVI are expressed below:

$$RD = \frac{SD}{TPD} \cdot 100, \tag{4}$$

$$RF = \frac{SF}{TF} \cdot 100, \tag{5}$$

$$IVI = RD + RF, \tag{6}$$

where: *RD* is relative density, *SD* indicates species density, *TPD* shows total population density, *RF* is relative frequency, *SF* is species frequency, and *TF* is total frequency.

In addition, the diversity of vegetation resulting from reclamation activity was also evaluated using three parameters, i.e. richness, heterogeneity, and evenness (Suyanto et al. 2022). The information is important and required to assess the effectiveness of the reclamation effort to facilitate biodiversity recovery in the long term. Vegetation richness was calculated by Margalef Index (R_1) (Singh 2020), while the heterogeneity of vegetation was assessed by the Shannon-Wienner Index (*H'*) (Naidu and Kumar 2016). The evenness of vegetation was counted using Pielou-Evenness Index (*J*) (Wirabuana et al. 2021b). The detailed equations (7, 8 and 9) for calculating those indicators are shown below:

$$R1 = \frac{S-1}{\ln(N)}, \tag{7}$$

$$H' = -\sum \frac{n_i}{N} \cdot \ln \frac{n_i}{N}, \tag{8}$$

$$J = \frac{H'}{\ln(S)}, \tag{9}$$

where: *S* is the number of species, *N* represents the total plant population, n_i describes the sum of plants from each species.

Results and Discussion

Soil characteristics

Results found that the soil in this site had high acidity with pH = 4.69 (Table 1). It also had low nutrient content like N (0.13 %), P (11.38 mg·100 g^{-1}), and K (10.49 mg·100 g^{-1}). The circumstance was similar to the common post-mining area with low fertility and extreme acidity (Li et al. 2018). However, our study also noted that there were moderate concentrations of SOC (2.40 %) and CEC (24.13 cmolc(+)·kg^{-1}). The coal mining manager added compost as organic matter into the soil during the revegetation process. This effort aimed to provide a better soil condition for establishing plant species.

Organic matter naturally contains nutrients, primarily C as its main component (Alam et al. 2022). When decomposition occurs, these nutrients would release into the soil and increase plant nutrient availability (Nugroho et al. 2022). In the context

Table 1. Soil characteristics in the reclamation site

Soil parameters	Unit	min	max	Mean	Categories
pH H_2O	-	3.86	5.29	4.69	acid
C-organic	%	1.50	3.03	2.40	moderate
N-total	%	0.07	0.17	0.13	low
P_2O_5	$mg\cdot100\ g^{-1}$	3.43	22.45	11.38	low
K_2O	$mg\cdot100\ g^{-1}$	1.11	26.10	10.48	low
CEC	$cmolc(+)\cdot\ kg^{-1}$	19.38	30.39	24.13	moderate

Note: soil attributes classification is determined based on Nandini and Narendra (2012).

of reclamation, adding organic matter can also decrease the absorption of heavy metals by plants since the materials form complex compound and made them immobile (Egli et al. 2010). Supplying organic matter into the soil can also improve soil structure and aggregation (Purwanto and Alam 2020). Therefore, this strategy generally used by mining managers as a site preparation before conducting revegetation.

Plant adaptability

Seven alternative plants supported mining reclamation in this site, i.e. *Artocarpus heterophyllus* Lam., *Artocarpus integer* Merr., *Aleurites moluccana* (L.) Willd., *Mangifera casturi* Kosterm., *Archidendron pauciflorum* (Benth.) I.C.Nielsen, *Durio zibethinus* L., and *Hevea brasiliensis* Müll.Arg. (Table 2). All species exhibited good adaptability with a higher than 70 % survival rate. This finding was relatively similar to another study about the survival rate of plants in the reclamation area by approximately 70−80 % (Adman et al. 2020).

Many studies reported that plant survival was the main challenge of coal mining reclamation since the environmental conditions in post-mining areas had many constraints to facilitate species establishment (Maiti et al. 2007, Kuter et al. 2014, Lestari et al. 2019). Besides having extreme acidity and containing heavy metals (Li et al. 2018), soil mining also had low nutrient availability (Forján et al. 2019). It stimulated plant stress that caused mortality. However, several plant species could survive in this condition. These species naturally could tolerate this environment, but they would result in lower growth performance (Kuter et al. 2014). It directly confirmed why the plant dimension in the study site was still small, although they had been planted for two years.

This study reported that the highest

Table 2. Characteristics of plant species used for supporting mining reclamation.

Species	Survival, %	Height, cm	Diameter, cm
Aleurites moluccana	82.25 ±3.47	81.67 ±7.03	0.80 ±0.13
Archindendron pauciflorum	79.87 ±1.08	133.94 ±17.28	1.39 ±0.17
Artocarpus heterophyllus	81.70 ±2.92	69.82 ±6.26	0.59 ±0.10
Artocarpus integer	89.39 ±10.61	66.00 ±7.02	0.73 ±0.12
Durio zibethinus	79.39 ±0.61	64.75 ±7.62	0.65 ±0.06
Hevea brasiliensis	78.60 ±0.04	70.76 ±1.63	0.69 ±0.02
Mangifera casturi	78.97 ±0.19	77.47 ±4.34	0.99 ±0.07

mean survival rate was recorded for *A. integer* (89.39 ±10.61 %), while the lowest was noted for *H. brasiliensis* (78.60 ±0.04 %). It indicated that *A. integer* was the most adaptive species in the study site. Other literature data also supported that this species could grow well in very acid soil with full sun conditions (Morris 1997). It was similar to the environment in the post-mining area, dominated by bare land with high soil acidity.

Interestingly, this study noted that *A. pauciflorum* demonstrated the highest mean in height and diameter by 133.94 ±17.28 cm and 1.39 ±0.17 cm, respectively. It is indicated that this plant species could absorb water and nutrients more efficiently than other species. Higher resource absorption in plants naturally optimises their metabolism process (Yang et al. 2015). Thus, the plant has a better opportunity to grow and generate more excellent dimensions.

Species diversity

A total of six families were identified from the seven plant species in the study site (Table 3), wherein most alternative species were from Moraceae (2). According to the IUCN status, most plants were classified as Least Concern, except for *M. casturi*, which was grouped into Extinct (Table 4). Surprisingly, this study recorded that *H. brasiliensis* became the most abundant species in the study site. It also had the highest important value index (132.36) since this species showed the first rank in relative density and relative frequency (Table 4). This finding indicated

Table 3. Family categories, IUCN status, and frequency appearance of selected species for mining reclamation.

Family	Species	IUCN status	Frequency
Euphorbiaceae	*Aleurites moluccana*	Least Concern	rare
Fabaceae	*Archindendron pauciflorum*	Least Concern	rare
Moraceae	*Artocarpus heterophyllus*	Least Concern	rare
Moraceae	*Artocarpus integer*	Least Concern	rare
Malvaceae	*Durio zibethinus*	Least Concern	rare
Euphorbiaceae	*Hevea brasiliensis*	Least Concern	abundant
Anacardiaceae	*Mangifera casturi*	Extinct	rare

Table 4. Relative density, relative frequency, and important value index of every plant species.

Species	RD	RF	IVI
Aleurites moluccana	1.32	4.00	5.32
Archindendron pauciflorum	3.75	12.00	15.75
Artocarpus heterophyllus	2.43	8.00	10.43
Artocarpus integer	0.66	1.33	2.00
Durio zibethinus	4.42	9.33	13.75
Hevea brasiliensis	79.03	53.33	132.36
Mangifera casturi	8.39	12.00	20.39
Grand total	100	100	200

Note: *RD* is relative density, *RF* is relative frequency, IVI is important value index.

that *H. brasiliensis* became the most important species for supporting biodiversity recovery in the reclamation site, although this species only occupied the last stage of survival rate (Table 2).

H. brasiliensis could become the most abundant species because it was commonly used by local people on this site. In this case, establishing this species would attract the community to participate in reclamation efforts. Nevertheless, this strategy also affected the vegetation structure in the reclamation site, mainly related to the diversity level. According to the results, vegetation diversity in this site was classified into a low level of richness, heterogeneity, and evenness (Table 5). It could happen since the vegetation resulted from artificial regeneration with a planting design (Nugroho et al. 2021). This statement was supported by the value of the evenness index, which was categorised into an unbalanced distribution (Hussain et al. 2012).

Nevertheless, the reclamation activity still had a positive outcome since it could improve the biodiversity of the plants after the mine closure. Several studies also noted that the biodiversity recovery in the reclamation area occurred step by step over a long-term period (Al-Reza et al. 2016, Pauletto et al. 2016, Lestari et al. 2019, Kuzevic et al. 2022). In this case, the presence of plant species could help a succession process and minimize the risk of degradation.

Table 5. Richness, heterogeneity, and evenness of vegetation communities in the reclamation site.

Parameter	Indices	Value	Categories
Richness	Margalef	0.98	Disturbed
Heterogeneity	Shannon-Wiener	0.84	Bad
Evenness	Pielou	0.43	Unbalanced

Note: the classification of value is determined based on Hussain et al. (2012).

Conclusion

All selected species indicated good adaptability to the environmental conditions in the reclamation site. However, *Artocarpus integer* showed the highest average survival rate than other alternative plant species. *A. integer* became the most adaptive species in the study site. This study revealed that *Hevea brasiliensis* contributed the highest to improving biodiversity in this location. Although the vegetation diversity was low, the reclamation effort showed a prospective outcome to facilitate biodiversity recovery after mine closure. As it is well known, coal mining exploration using open-pit systems has caused biodiversity loss and provided extreme environmental conditions after post-mining. Therefore, only a few species can survive in this condition. In this case, our outcome has delivered important information on what kind of adaptive species to support the reclamation effort in this site.

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