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The regulatory role of mine soil properties in the growth of revegetation plants in the post-mine landscape of East Kalimantan

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ABSTRACT

The growth of revegetation plants in post-mining areas is determined by the mine soil quality, which strongly depends on the physical and chemical properties of the original soil. Visual observation of revegetation plants in two ex-coal mining areas in East Kalimantan, i.e. Lati and Sambarata sites, showed a clear difference in plants growth. This research aims to study the role of the physical and chemical properties of mine soil on the growth rate of revegetation plants so that it can be used to develop a sustainable ex-mining land reclamation strategy. The observation plots on each ex-mining land were grouped into (0–2), (2–4), (4–6), (6–8), (8–10), and (10–12) years since revegetation. In each group, soil sampling was carried out at a depth of 0–30 cm for analysis of soil physical and chemical properties. Observations were also made on the development of plant growth. The better revegetation plant growth at Sambarata site compared to those at Lati site was indicated by the composition of the stand structure, stem diameter, and plant height. Both sites have a similar texture, which is dominated by silt, and slightly higher bulk densities at Sambarata site compared to those at Lati site. Hence, not soil physical properties but soil chemistry played a regulatory role in the growth of revegetation plants. Here, the exchangeable cations at Sambarata site were dominated by Ca^{2+} and Mg^{2+}, whereas those at Lati site were dominated by Al^{3+}. Linked with a high base saturation, the pH, organic C, total N, and available P_2O_5 mine soil quality of the Sambarata site were more favourable for plants growth. Thus, in reclamation activities in post-mining areas, soil quality improvement using lime, rock phosphate, and compost is indispensable to increase soil fertility and establish fast revegetation.

1. Introduction

It is widely accepted that open-pit coal mining activities induce the risk of land degradation by changing the shape of the landscape, the loss of vegetation and soil horizons with favourable aggregation and organic matter accumulation conditions and the presence of available plant nutrients (Ghose, 2004; Ussiri and Lal, 2005; Zvomuya et al., 2006). Moreover, mining activities can cause on site and nearby environmental pollution by the formation of acid mine drainage due to the oxidation of sulfide minerals (Haigh, 1995; Kim and Chon, 2001). To avoid the above negative impacts, governmental regulations require mining entrepreneurs to carry out reclamation so that ex-mining lands can be again transferred to land use, whereby different concepts are possible (Skousen and Zipper, 2014; Mborah et al., 2016; Pratiwi et al., 2021). Thomas et al. (2015) suggested that reclamation can be achieved by restoring the landscape shape close to the original contour, using the former topsoil as a substrate for plants by spreading atop the overburden and revegetating the area with trees and herbaceous plants under the planned post-mining land use design. Plans for the use of post-mining land can be diverse. For land reclamation sites in the USA, Skousen and Zipper (2014) suggested that land use could occur in the form of (1) prime farmland, (2) hay land and pastures, (3) biofuel crops, (4) forestry, (5) wildlife habitats, and (6) building site development. However, independent of the post-mining land use chosen, ex-mining land must be

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replanted, especially with fast-growing pioneer plants adapted to the local climatic conditions.

The term mine soil refers in general to mine spoil materials, whether or not mixed with soil materials spread across the surface of land that has been reclaimed to function as a plant substrate and support plant growth (Daniels and Zipper, 1997; Sencindiver and Ammons, 2000; Zipper et al., 2013). Here, the most suitable material used as a plant substrate is soil material (Skousen et al., 2011). When mining begins, soil horizons O, A, E, B, C, and R can be collected with a dozer, whereby the bedrock containing large rock fragments is undesired. In Indonesia, based on governmental regulation SNI 6621:2016, soil materials that can be used as planting media on reclaimed surfaces should consist of materials derived from the A and B horizons and, if the properties are suitable, from the C horizon (Pratiwi et al., 2021; Iskandar et al., 2022). As the soil materials derived from these different horizons exhibit different shares in mechanical mixtures, the resulting mine soil materials may possess very different qualities compared to the original soil.

Overall, mine soils tend to be poor. In general, mine soils contain very low levels of organic C, poor nutrient availability (N and P), acidic pH, signs of compaction, poor structure, low water holding capacity, and low biomass productivity, whereby all these properties limit the quality, ability, and function of mine soils as a plant substrate (Haigh, 1995; Sheoran et al., 2010; Mushia et al., 2016).

However, exceptions exist to this general rule. The properties of mine soils are not in all cases much poorer than those of the original topsoil. Iskandar et al. (2022) observed for the 0–30 cm mine soil layer in the post-mining landscape of open cast mine coal at the Lati Site, Berau, East Kalimantan, that the potential reserves of P and K, exchangeable K, Ca, and Mg, cation exchange capacity (CEC), and base saturation (BS) percentage were higher than those in the original soil, i.e., Typic Dystrudepts, at the same depth.

Research on the relationship between the mine soil quality and revegetation plant growth can be generally grouped into two different approaches. In the first type, the impact of revegetation on the quality of mine soil is directly determined in the field over a period up to 12 years starting with the newly planted mine soil (Mummey et al., 2002; Sourková et al., 2005; Iskandar et al., 2019). In the second type of research, the improvement in mine soil quality through the addition of ameliorant materials is determined using revegetation plants as an indicator. This approach requires less time, as it can be implemented either in a greenhouse or directly at reclamation sites (Larney and Angers, 2012; Liu and Lal, 2014; Mushia et al., 2016). One exception is the work of Bendfeldt et al. (1999), who investigated the effect of native soil, sawdust, and sludge addition on the mine soil quality and plant growth over a period up to 16 years. Long-term studies on the effect of the mine soil quality on the development of revegetation plants are rarely performed, although the soil quality, either natural or mine soil, can greatly affect plant growth and productivity (Passioura, 2002; Prinzenberg et al., 2010; Schjoerring et al., 2019).

Visual observations during a monitoring campaign of the environment at the Lati and Sambarata coal mine sites in East Kalimantan revealed that there were differences in the growth performance of revegetation plants between the two sites. This encouraged us to study the relationship between the growth performance and mine soil quality as affected by the properties of the natural soil. In particular, we wanted to clarify the following:

(i) Does the observed difference in growth rate between revegetation plants depend on soil physical and/or chemical properties?
(ii) How did the parameters of the plant growth rate change during the growth period from 0 to 12 years since revegetation at the two study sites?
(iii) Is there a single parameter with the highest impact on the growth of revegetation plants?
(iv) Based on the results of this study, which outcomes should be considered in improving the quality of mine soil so that revegetation plants grow better?

To answer these questions, plant growth rate and mine soil quality in the observation plot of 0–2 years since revegetation were compared with the other older observation plots using an interval of 2 years, up to the observation plot of 10–12 years after revegetation. Hereby, monitoring and sampling with a temporal resolution of 2 years allowed fine-scaled tracking of changes over time.

2. Materials and methods

2.1. Description of the study area

The study was conducted during the 2014–2017 period at the Lati and Sambarata open coal mine sites, Berau Regency, East Kalimantan Province (Fig. 1). The closest straight distance between these two sites is approximately 15 km. Based on a semi-detailed soil map of Berau Sheet Regency 1918-12 with a scale of 1:50,000 (IAARD, 2016), the original soils dominating the Sambarata mine site include Typic Eutrudepts and Typic Hapludalfs. Both soils exhibit a deep solum, good drainage, fine texture, and neutral pH. Whereas Typic Eutrudepts exhibit a moderate CEC and high BS, Typic Hapludalfs exhibit a high CEC and high BS close to 100%. Both soils developed from calcareous sandstone as the parent material on small structural hills with gradients ranging from 25 to 40%. The original soils at the Lati mine site, located east of the Sambarata mine site, are dominated by Typic Dystrudepts, based on a semi-detailed soil map of Berau Sheet District 1918-23, with a scale of 1:50,000. The soils are characterised by a deep solum with good drainage, fine texture, acidic pH, moderate CEC, and low BS and developed from sandstone as the parent material on small structural hills (25–40% slope) (IAARD, 2016). In all soil profiles, the sandstone is completely decomposed, and rock fragments are absent.

The study location experienced an average annual rainfall of 2,247 mm with an average monthly rainfall of 187.3 mm during the 2014–2017 period of observation. The lowest monthly rainfall of 120.3 mm occurred in August, and the highest monthly rainfall of 259.6 mm occurred in October. The average recorded minimum air temperature reached 26.4 °C, with a maximum temperature of 27.5 °C and an average temperature of 27.0 °C, while the humidity ranged from 82.3 to 88.5%.

After coal excavation, the mine sites were immediately reclaimed and revegetated. Reclamation typically begins with structuring the shape and slope of the waste rock material. As a substrate for revegetation plants, soil material was spread atop waste rock with a thickness of approximately 125 cm. A planting hole of 40x40x40 cm was prepared for planting seedlings of fast-growing pioneer plants, such as *Anthocephalus cadamba*, *Acacia mangium*, *Cassia siamea, Falcataria moluccana*, *Melaleuca leucadendron*, and *Entorolobium cyclocarpum*. Then, 5 kg of compost originating from plant remains was added to each planting hole to improve the nutrient supply. The planting distance was 4x4 m, resulting in a population density of 625 trees ha^{-1}. When the seedlings were still small, the soil surface between the revegetation plants was planted with herbaceous cover crops, such as *Centrosema pubescens*, *Pueraria javanica*, *Calopogonium mucunoides, Axonopus compressus*, and *Chrysopogon aciculata*, to reduce the increase in soil erosion.

2.2. Observation and collection of plant growth data

To study the effect of the mine soil quality on plant growth, in a combined approach, soil samples were analysed, and plant parameters were determined at the Lati and Sambarata sites. In both reclaimed land areas, the observation plots were divided into six groups, namely, (0–2), (2–4), (4–6), (6–8), (8–10), and (10–12) years since revegetation. Collection of plant data was carried out with a minimum sampling

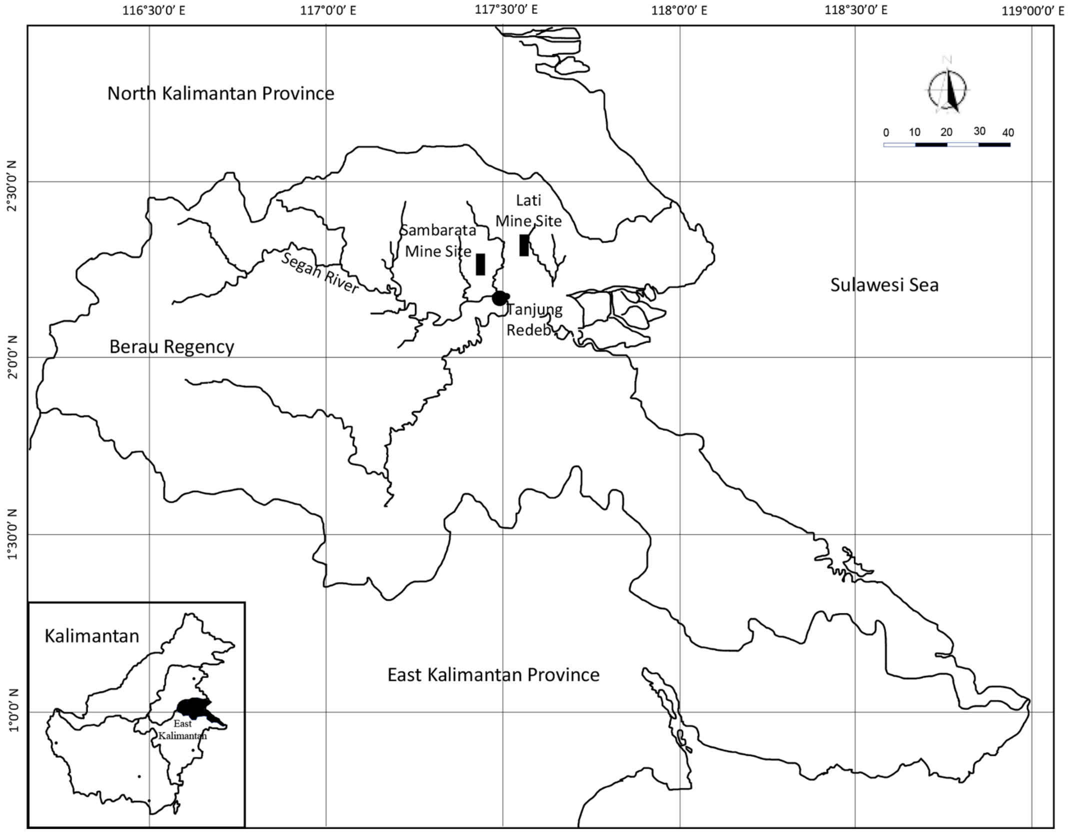

Fig. 1. Location of the Sambarata and Lati coal mine sites in the Berau Regency, East Kalimantan.

amount of 5% of the total land area using the line transect method with a size of 40 × 25 m or one line transect every 1000 m^2 (Soerianegara and Indrawan, 1988). The total area of observation was 116.3 ha at the Lati site and 74.7 ha at the Sambarata site (Table 1). The types of data recorded included the number of species and the number of individuals of each species in all six age groups determined in a sampling area, which is 5% from the total area.

Regarding the determination of the growth rate of poles and trees, the trunk diameter at breast height (~130 cm from the ground level) and the total tree height were quantified. The plant height was measured with a hagameter, while the plant diameter was measured with callipers. Data for the measurements conducted in 2017 were evaluated for the total plant diameter and height combined with the annual growth rate. As the composition and number of revegetation plants in each reclamation area are not always homogeneous, only the same species of plants in each group were considered. The level of vegetation growth was divided into a) seedlings, namely, saplings < 1.5 m in height and $<$ 3 cm in trunk diameter; b) saplings, namely, vegetation measuring trunk diameter < 10 cm and height > 1.5 m; c) poles, namely, vegetation with a trunk diameter of 10–19 cm at chest height; and d) trees, namely, vegetation with a trunk diameter of > 20 cm at breast height (Soerianegara and Indrawan, 1988).

Table 1
Total and minimum sampling area for plant data collection at the Lati and Sambarata sites.

Plant group since revegetation (year)	Sampling area (m^2)		Total area (ha)	
	Lati site	Sambarata site	Lati site	Sambarata site
0–2	2,935	1,250	5.9	2.5
2–4	12,240	14,200	24.5	28.4
4–6	16,560	3,250	33.1	6.5
6–8	7,835	4,225	15.7	8.5
8–10	5,445	1,995	10.9	4.0
10–12	10,800	12,425	21.6	24.9
Total area	55,815	37,345	111.6	74.7

2.3. Soil sampling and analysis

Soil sampling was carried out annually during the period from 2014 to 2017. In each observation plot, regarding analysis of the soil chemical properties, composite topsoil samples were obtained in the middle between plants at a depth from 0 to 30 cm. Soil samples were dried at room temperature, sieved through a < 2 mm mesh and analysed according to Van Reeuwijk (2002). The soil pH was determined in deionized H_2O at a soil:water ratio of 1:5, the organic C content was measured with the Walkley and Black method using chromic acid wet oxidation, the total N was determined via the Kjeldahl method, and the available P was obtained with the Bray I and Olsen method. The exchangeable Al was quantified using 1 N KCl and the exchangeable base cations Na, K, Ca, and Mg, combined with the CEC via extraction with 1 N NH_4OAc at pH 7.0. The levels of the potential P and K reserves were determined through extraction with 25% HCl (Eviati and Sulaeman, 2009). The soil texture was determined in 3 fractions, sand (0.05–2.0 mm), silt (0.002–0.05 mm), and clay ($<$0.002 mm), by sieving and sedimentation according to Van Reeuwijk (2002). Analysis of the bulk density was performed by collecting undisturbed soil samples approximately 5 cm below the mine soil surface using a ring sampler measuring 7.5 cm in diameter and 4 cm in height. The bulk density was determined gravimetrically (Wilke, 2005).

2.4. Soil quality index analysis

Parameters in the soil quality index (SQI) were determined using factor analysis, which was based on principal component analysis to evaluate the effect of the two mine soils developed from different parent materials. For this purpose, methodologies used by Karlen and Stott (1994), Brejda et al. (2000) and Cavalcante et al. (2021) were adapted. The soil parameters used for factor analysis were pH, organic C, total N, potential reserved P_2O_5, potential reserved K_2O, available P_2O_5, exchangeable–Ca, –Mg, –K, –Na; CEC, base saturation, Al-saturation, percent of sand, silt and clay, and bulk density. Principal component analysis was used as a method for extracting the weighting factors. Only factors with eigenvalues ≥ 1.0 were selected for SQI analysis. In total 7 factors with eigenvalues ≥ 1.0 and a cumulative value of 80.57% were obtained (Table 2). Based on factor analysis, only parameters with factor loadings > 0.700 were retained. They included pH, exchangeable Ca, base saturation, Al saturation, percent of clay, organic C, total N, potential reserved K_2O, exchangeable K, percent of sand and silt, bulk density, and exchangeable Na (Table 2).

Each data obtained was further provided with a score. The score of each parameter was determined based on the expert judgment with high, medium, and low criteria based on ICSR (1983), Brady (1984), Dierolf et al. (2001), Daniels and Zipper (1997), and Arshad et al. (1996). Parameters of percent sand, silt and clay were expressed in soil texture class according to Arsyad (2010) and Ritung et al. (2011). The scores of each data were then summed for each year of revegetation to obtain the SQI, based on the equation proposed by Amacher et al. (2007). The parameters of the physical and chemical properties of the soil and the score values used are presented in Table 3.

3. Results and discussions

3.1. Mine soil properties

Despite the fact that the mine soils under investigation are derived from different parent materials and soil types, the particle size distribution was dominated in general by silt (41.3–51.2% and 29.2–48.4%), followed by clay (28.7–38.0% and 22.2–35.5%, respectively) and sand (10.8–29.5% and 16.3–31.1%, respectively) at the Lati and Sambarata sites, respectively (Fig. 2a). The particle size distribution at the Lati site with a higher clay content was classified as silty clay loam and clay loam, while at the Sambarata site, the soil was classified as clay loam, except for the observation plot of 10–12 year since revegetation with a higher sand content (48.6%), resulting in a loam textural class.

The bulk densities of the mine soils at the Sambarata site with a slightly higher share of sand ranged from 1.54 to 1.60 g cm^{-3}, relatively higher than the bulk densities at the mine soil Lati site, which ranged from 1.42 to 1.64 g cm^{-3} (Fig. 2b). If the two mine sites are compared in terms of their respective original soils (1.34 g cm^{-3} at Sambarata and 1.47 g cm^{-3} at Lati), it can be concluded that the Sambarata mine soils experienced higher compaction than those of the Lati site. However, all these values occur within the bulk density range rated as productive soils, namely, natural soils typically exhibit a bulk density from 1.1 to 1.5 g cm^{-3} (Daniels and Zipper, 1997). If mine soils attain a bulk density > 1.7 g cm^{-3} with a thickness of the soil material spread as a planting substrate smaller than 0.6 m, the available water needs for plant growth are not fulfilled, especially during the dry season.

Chemical analysis revealed that the pH values of the mine soils at the Sambarata site ranged from 4.7 to 5.6 and are higher than those of the mine soils at the Lati site, which ranged from 3.9 to 4.3 (Fig. 3a). This difference in pH is closely related to the amount of exchangeable Al^{3+} in the topsoil samples from the Lati site (2.6–8.3 $cmol_c$ kg^{-1}), which was larger than that at the Sambarata site (0.2–3.1 $cmol_c$ kg^{-1}) (Fig. 3b). The difference in soil pH between the two sites reflects the pH of the respective natural soils. The Typic Dystrudepts near the Lati site typically exhibit a strongly acidic pH, while the Typic Eutrudepts and Typic Hapludalfs near the Sambarata site typically indicate a slightly acidic pH (IAARD, 2016).

In addition to the higher pH of the mine soil, the Sambarata site exhibited higher levels of organic C, total N and available P than those at the Lati site. The organic C and total N levels at the Sambarata site ranged from 0.66 to 2.09% and 0.08–0.19%, respectively, while at the Lati site, the values ranged from 0.53 to 1.44% and 0.05–0.13% (Fig. 4a and 4b, respectively). With increasing time since revegetation, the organic C and total N levels increased at both mine soil locations. The Sambarata site attained available P_2O_5 levels ranging from 3.0 to 12.2 mg kg^{-1}, higher than the available P_2O_5 at the Lati site, which ranged from 2.4 to 4.4 mg kg^{-1} (Fig. 4c). The available P_2O_5 levels at the Lati and Sambarata sites also increased with increasing time since revegetation. The observed trend, increasing levels of soil organic C, total N and available P_2O_5 with increasing time since revegetation, agrees with the results in other studies (Pietrzykowski, 2008; Fu et al., 2010; Mukhopadhyay et al., 2014).

The level of potential P_2O_5 reserves in the Sambarata mine soil, although not very significant at certain locations, was generally higher than the potential P_2O_5 reserves in the Lati mine soil, ranging from 238 to 518 mg kg^{-1} at Sambarata and 128–289 mg kg^{-1} at the Lati site (Fig. 5a). The level of potential K_2O reserves, most likely strongly affected by the texture, did not reveal a regular pattern. At the Sambarata site, the levels ranged from 99 to 206 mg kg^{-1}, while at the Lati site, they ranged from 107 to 169 mg kg^{-1} (Fig. 5b). Iskandar et al. (2022) reported that the levels of potential P and K reserves at the Lati location are mine soil properties mostly inherited from the original soil materials.

The mine soils at the Lati site exhibit a slightly higher CEC range than

Table 2
Factor loadings of the parameters used for soil quality index analysis. Values marked in bold are considered in the analysis.

Parameters	Factor – 1	Factor – 2	Factor – 3	Factor – 4	Factor – 5	Factor – 6	Factor – 7
Year	−0.061	0.046	0.340	−0.132	**0.731**	−0.382	−0.089
Duration	−0.024	0.124	0.384	−0.108	−0.041	0.200	0.691
pH_H_2O	**0.897**	0.084	−0.043	−0.107	−0.074	−0.164	0.011
Organic_C	0.130	0.118	**0.902**	−0.009	−0.040	0.078	0.138
Total_N	0.047	0.060	**0.915**	0.045	0.008	−0.051	0.134
P_2O_5_HCl	0.644	0.091	−0.306	0.000	−0.188	0.362	0.270
K_2O_HCl	0.216	−0.173	−0.040	**0.808**	−0.077	0.315	−0.066
Available_P_2O_5	0.213	0.675	0.323	0.201	0.028	−0.037	0.353
Exchangeable_Ca	**0.879**	0.016	−0.035	0.303	−0.048	0.039	−0.178
Exchangeable_Mg	0.569	0.022	0.233	−0.082	0.422	−0.081	0.060
Exchangeable_K	0.009	−0.182	0.478	**0.706**	0.025	−0.138	0.144
Exchangeable_Na	0.214	0.104	−0.069	0.043	0.130	0.132	**−0.802**
CEC	−0.053	0.247	−0.305	0.079	0.684	0.279	0.328
BS	**0.786**	−0.142	0.283	0.091	−0.272	−0.178	−0.292
Al saturation	**−0.819**	−0.200	−0.172	0.062	−0.083	0.046	0.098
Sand_Percentage	0.072	0.594	0.060	−0.065	**−0.744**	0.037	0.103
Silt_Percentage	−0.044	−0.244	−0.080	−0.057	**0.824**	−0.073	−0.248
Clay_Percentage	−0.076	**−0.821**	0.007	0.228	0.171	0.044	0.198
BD	0.202	0.043	−0.043	0.022	0.102	**−0.886**	0.019

Table 3
Chemical and physical properties of the mine soil and the scores used to calculate the soil quality index.

Parameters	Level					References
pH H_2O	<4.5 (extreme acidity)	4.5–5.5 (strong acidity)	5.5–6.5 (slight acidity)	6.5–7.5 (neutral)	7.5–8.5 (slight alkalinity)	ICSR (1983) Brady (1984)
Score	0	1	2	2	1	
organic C (%)	<1 (very low)	1–2 (low)	2–3 (moderate)	3–5 (high)	>5 (very high)	ICSR (1983)
Score	0	1	1	2	2	
Total N (%)	<0.1 (very low)	0.1–0.2 (low)	0.21–0.50 (moderate)	0.51–0.75 (high)	>0.75 (very high)	ICSR (1983)
Score	0	1	1	2	2	
Pot. Res. K_2O (mg/100 g)	<10 (very low)	10–20 (low)	21–40 (moderate)	41–60 (high)	>60 (very high)	ICSR (1983)
Score	0	1	1	2	2	
exch. Ca (cmol$_c$ kg^{-1})	<2 (very low)	2–5 (low)	6–10 (moderate)	11–20 (high)	>20 (very high)	Dierolf et al. (2001)
Score	0	1	2	2	2	
exch. Na (cmol$_c$ kg^{-1})	<0.1 (very low)	0.1–0.3 (low)	0.4–0.7 (moderate)	0.8–1.0 (high)	>1.0 (very high)	ICSR (1983)
Score	0	1	2	2	2	
exch. K (cmol$_c$ kg^{-1})	<0.1 (very low)	0.1–0.3 (low)	0.4–0.5 (moderate)	0.6–1.0 (high)	>1.0 (very high)	Dierolf et al. (2001)
Score	0	1	2	2	2	
Al-saturation (%)	<35 low	35–50 moderate	50–70 high	>70 very high		Dierolf et al. (2001)
Score	2	1	1	0		
Base Saturation (%)	<20 (very low)	20–40 (low)	41–60 (moderate)	61–80 (high)	>80 (very high)	ICSR (1983)
Score	0	1	2	2	2	
Texture class	fine (f)	slightly fine (sf)	medium (m)	slightly coarse (sc)	coarse (c)	Ritung et al. (2011) Arsyad (2010)
Score	1	2	2	1	0	
Bulk Density (g cm^{-1})	<1.1 (normal)	1.1–1.6 (high)	>1.6 (very high)			Daniels and Zipper (1997) Arshad et al. (1996)
Score	2	1	0			

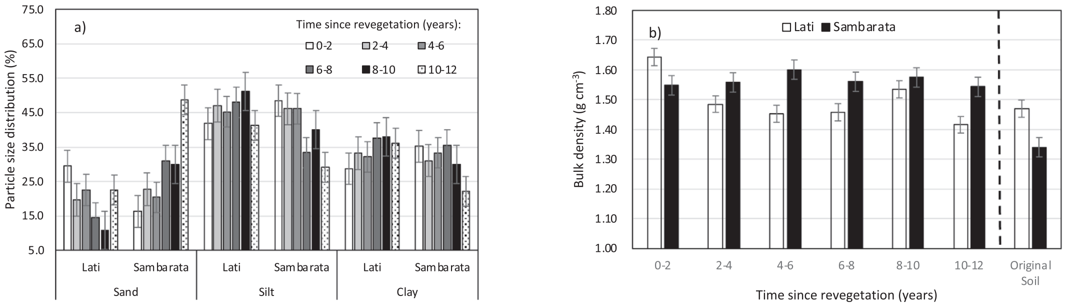

Fig. 2. Particle size distribution (a) and bulk density (b) of the mine soils in the six age groups since revegetation at the Lati and Sambarata sites.

those at the Sambarata site, ranging from 12.8 to 19.3 and 12.3–17.2 cmol$_c$ kg^{-1}, respectively (Fig. 6a), but the difference between the two locations was significant in the degree of BS and composition of the cations at exchange sites (Fig. 6c and d). The mine soils at the Sambarata site attained a higher percentage of the BS than those at the Lati site, at 44.2–77.6% versus 19.4–48.4% (Fig. 6b). The high percentage of the BS at the Sambarata site was caused by the large amounts of exchangeable Ca^{2+} and Mg^{2+}, i.e., 1.69–8.56 and 3.39–5.47 cmol$_c$ kg^{-1}, respectively (Fig. 6c), while at the Lati site, these levels ranged from 1.04 to 3.36 and 1.38–3.50 cmol$_c$ kg^{-1}, respectively (Fig. 6d). Fig. 6d and 6e also shows that the adsorption complexes in the Lati mine soil are dominated by exchangeable Al^{3+}, which is attributed to the strongly acidic pH of the

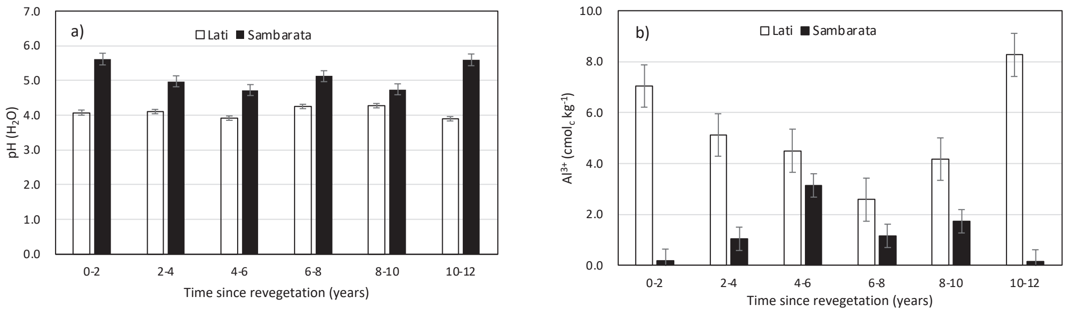

Fig. 3. Values of the pH (a) and exchangeable Al^{3+} (b) in the mine soils in the six age groups since revegetation at the Lati and Sambarata sites.

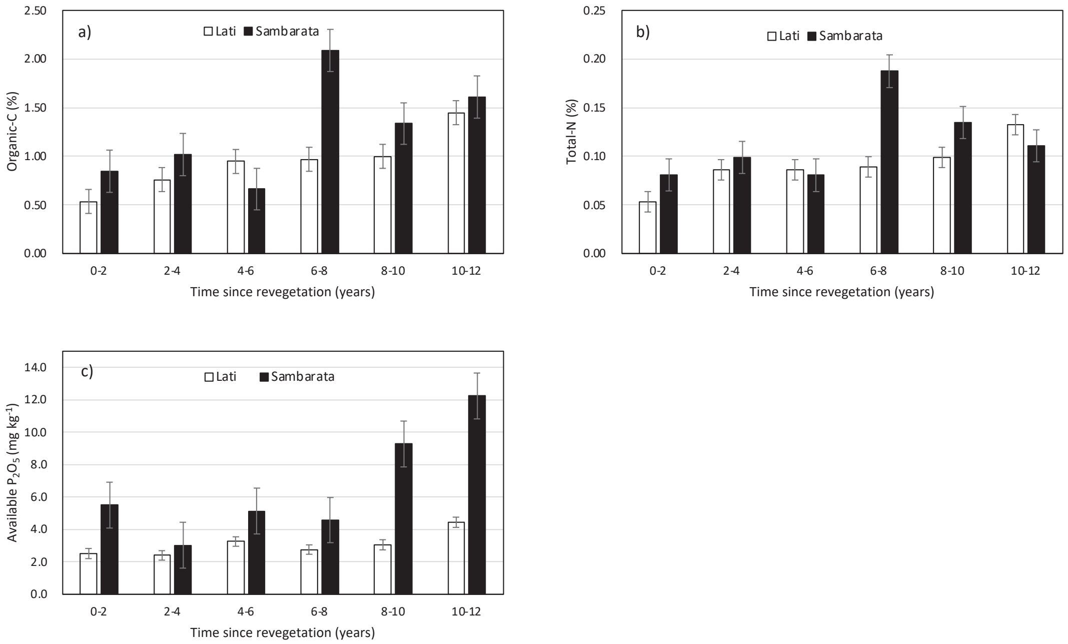

Fig. 4. Levels of organic C (a), total N (b), and available P_2O_5 (c) in the mine soils in the six age groups since revegetation at the Lati and Sambarata sites.

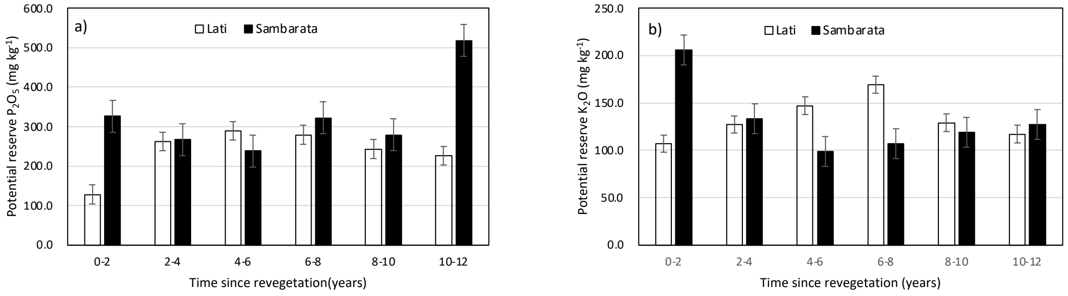

Fig. 5. Levels of the potential P_2O_5 (a) and K_2O (b) reserves of mine soils in the six age groups since revegetation at the Lati and Sambarata sites.

Lati mine soils (Fig. 3a). The composition of the adsorbed cations of these two different types of mine soils is in accordance with the properties of the natural soils from which they originate: Typic Dystrudepts at the Lati site and Typic Eutrudepst and Typic Hapludalfs at the Sambarata site (IAARD, 2016).

Based on the soil chemical properties determined, pH, organic C, total N, available P_2O_5, exchangeable Ca^{2+} and Mg^{2+}, and BS, it was evident that the soil chemistry of the mine soils at the Sambarata site was more favourable for plant growth than that of the mine soils at the Lati site.

3.2. *Soil quality index*

The SQI also reveals differences in soil properties from the two sites investigated. Table 4 shows that the mine soil of the Sambarata site has a higher SQI (varied from 50 to 73) than the mine soil of the Lati site (varied from 32 to 50).

The sequence of parameters contributing to the observed difference in SQI (Table 2) between the two mine soils is in the following order: pH value > exchangeable–Ca > base saturation > Al–saturation. These parameters are interrelated and derived from the properties of the parent material. The mine soil of the Sambarata site was derived from

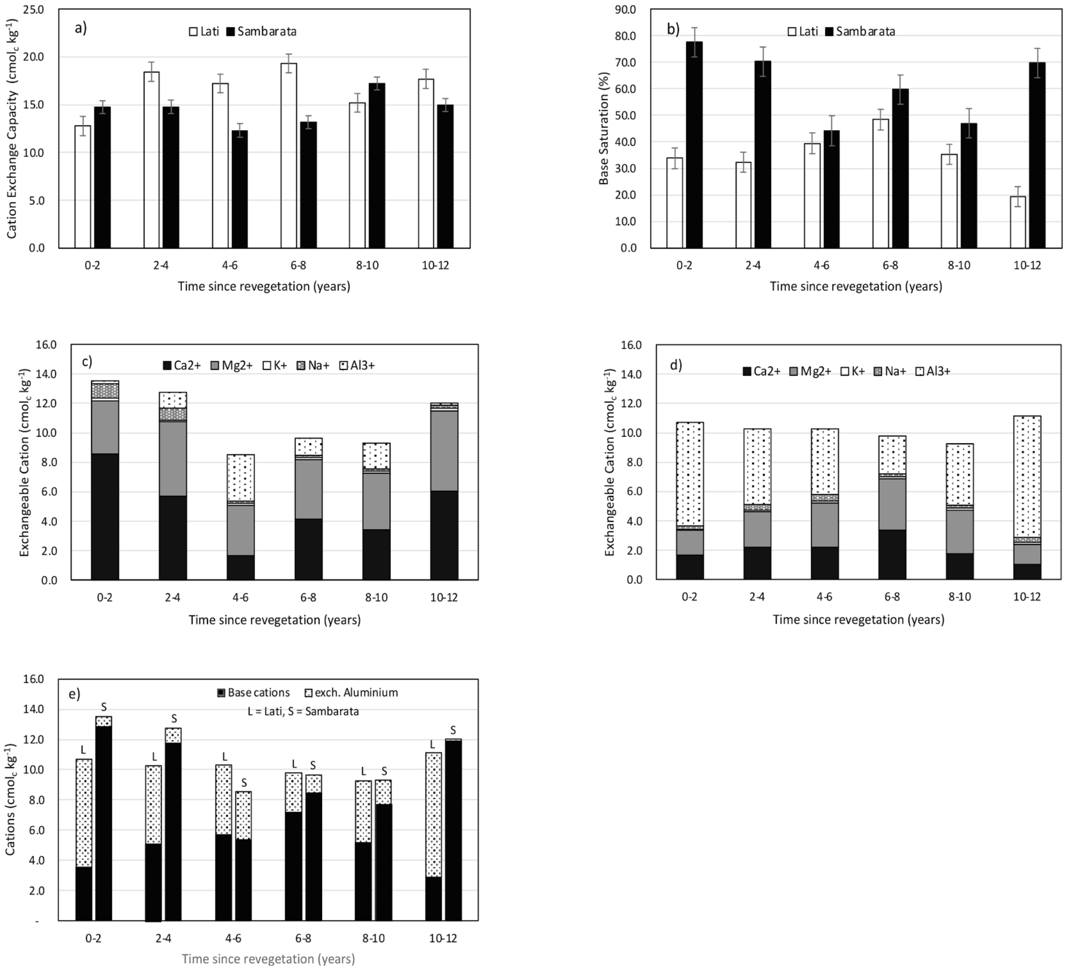

Fig. 6. Cation exchange capacity (a), base saturation percentage (b), kind of exchangeable cations in the Sambarata (c) and Lati (d), and cations domination in the adsorption complexes (e) of mine soils in the six age groups since revegetation.

the original soil Typic Hapludalfs and Typic Eutrudepts which developed from the calcareous sandstone, while the mine soil of the Lati site was derived from the original soil Typic Dystrudepts which developed from the sandstone (IAARD, 2016). The difference in SQI is also caused by the differences in the score values for parameters organic C and total N. These parameters related to the growth rate of revegetation plants (Iskandar et al., 2022).

3.3. Growth parameters of plants

Because in the observation plots various plant species were found with varying numbers and growth rates, for comparison of the growth rates of plants in revegetation areas of the same age, only the same plant species were selected at the two observation sites. The growth rates of plants compared were the number of plants in the structure of seedlings, saplings, poles, and trees. The results for 2017 indicated that the structure of the plant stands in the group of 0–2 year since revegetation, at both the Lati and Sambarata sites, still occurred at the seedling and sapling levels (Table 5). However, at an age from 2 to 4 years, the revegetation plant stand structure began to change. At the Lati site, apart from the seedling and sapling levels, the pole level was found, while at the Sambarata site, revegetation plants were found at the growth rate of saplings, poles, and even trees, with seedlings not observed. This suggests that the speed of plant growth at the Sambarata site is higher than that at the Lati site and that the mine soil quality at the Sambarata site provides better plant growth opportunities than that at the Lati site. Starting from the age group of 4–6 years and above, the stand structure was generally uniform, namely, saplings, poles, and trees were found at both locations. Despite this fact, the number of species reaching the tree level at the Sambarata site was higher than that at the Lati site (Table 5).

In general, the plants growing at the Sambarata site exhibit a larger diameter and are taller than the plants growing at the Lati site. This also suggests that the mine soil quality at the Sambarata site is better than that at the Lati site. Plant growth expressed in the form of the annual increase in plant height and diameter of the trunk is shown in Fig. 7. Because a sufficient number of plant species was not obtained for all plants screened in each age group, only selected species could be compared. The increase in diameter and height of *Cassia siamea*, *Melaleucca leucadendron*, and *Falcataria moluccana* plants in the 0–2 year age group and *Cassia siamea* and *Falcataria moluccana* plants in the 2–4 year age group at Sambarata was much larger than that at the Lati site (Fig. 7a and b, respectively). A comparison of the shape of *Falcataria moluccana* plants in the 0–2 year age group at the Lati and Sambarata sites is shown in Fig. 8. In addition to the difference in growth of *Falcataria moluccana* plants, Fig. 8 shows that the land cover crop (legumes and grasses) growing at the Sambarata site is better, more evenly distributed, and greener than that growing at the Lati site.

A larger increase in the trunk diameter and plant height for the Sambarata mine soils than that for the Lati mine soils also occurred in the 4–6 year age group for *Anthocephalus cadamba, Cassia siamea, Melaleucca leucadendron, Falcataria moluccana* plants and in the 6–8 year age group for *Cassia siamea, Melaleucca leucadendron, Entorolobium cyclocarpum, Falcataria moluccana* plants (Fig. 7c and 7d, respectively).

Data on plant growth in the 8–10 and 10–12 year age groups (Fig. 7e

Table 4
Score values for each parameter and soil quality index for each observation plot at the Lati and Sambarata sites.

Parameters	0-2 y*)		2-4 y		4-6 y		6-8 y		8-10 y		10-12 y	
	value	Score	value	Score	value	Score	value	Score	value	Score	value	Score
pH in H_2O	4.1	0	4.1	0	3.9	0	4.2	0	4.3	0	3.9	0
Organic C (%)	0.53	0	0.76	0	0.95	0	0.97	0	1	1	1.44	1
Total N (%)	0.05	0	0.09	0	0.09	0	0.09	0	0.1	1	0.13	1
Pot. reserve K_2O (mg/100g)	10.7	1	12.7	1	14.7	1	16.9	1	12.9	1	11.7	1
Exch. Ca (cmol$_c$ kg^{-1})	1.68	0	2.2	1	2.19	1	3.36	1	1.76	0	1.04	0
Exch. K (cmol$_c$ kg^{-1})	0.08	0	0.1	1	0.14	1	0.14	1	0.16	1	0.15	1
Exch. Na (cmol$_c$ kg^{-1})	0.22	1	0.39	2	0.33	1	0.19	1	0.17	1	0.31	1
Base Saturation (%)	33.9	1	32.3	1	39.4	1	48.4	2	35.3	1	19.4	0
Al-saturation (%)	55.2	1	27.7	2	26.1	2	13.4	2	27.4	2	46.7	1
Texture class **)	sf	2	sf	2	sf	2	sf	2	sf	2	sf	2
Bulk Density (g cm^{-1})	1.6	1	1.5	1	1.5	1	1.5	1	1.5	1	1.4	1
Total Score		7		11		10		11		11		9
SQI		**32**		**50**		**45**		**50**		**50**		**41**
SAMBARATA SITE												
pH in H_2O	5.6	2	5	1	4.7	1	5.1	1	4.7	1	5.6	2
Organic C (%)	0.84	0	1.02	1	0.66	0	2.09	1	1.34	1	1.61	1
Total N (%)	0.08	0	0.1	1	0.08	0	0.19	1	0.13	1	0.11	1
Pot. reserve K_2O (mg/100g)	20.6	1	13.3	1	10	1	10.7	1	11.9	1	12.7	1
Exch. Ca (cmol$_c$ kg^{-1})	8.56	2	5.7	2	1.69	0	4.16	1	3.41	1	6.04	2
Exch. K (cmol$_c$ kg^{-1})	0.17	1	0.11	1	0.13	1	0.14	1	0.12	1	0.16	1
Exch. Na (cmol$_c$ kg^{-1})	0.99	2	0.85	2	0.18	1	0.16	1	0.17	1	0.21	1
Base Saturation (%)	77.6	2	70.2	2	44.2	2	59.8	2	46.9	2	69.7	2
Al-saturation (%)	1.2	2	7.1	2	25.5	2	8.9	2	10.1	2	1.1	2
Texture class**)	sf	2	sf	2	sf	2	sf	2	sf	2	m	2
Bulk Density (g cm^{-1})	1.5	1	1.6	1	1.6	1	1.6	1	1.6	1	1.5	1
Total Score		15		16		11		14		14		16
SQI		**68**		**73**		**50**		**64**		**64**		**73**

Table 5
Composition of the stand structure of the revegetation plants in each of the six age groups at the Lati and Sambarata sites observed in 2017.

Species		n	Lati site*)				n	Sambarata site*)			
			Seedling	Sapling	Pole	Tree		Seedling	Sapling	Pole	Tree
Group of Plant Age 0–2 year											
1	*Cassia siamea*	20	18 (90)	2 (10)	-	-	87	54 (62)	33 (38)	-	-
2	*Falcataria moluccana*	159	77 (48)	82 (52)	–	–	84	–	84 (100)	–	–
3	*Melaleucca leucadendron*	13	13 (100)	–	–	–	4	–	4 (100)	–	–
Group of Plant Age 2–4 year											
1	*Cassia siamea*	41	27 (66)	14 (34)	–	–	1	–	1 (100)	–	–
2	*Falcataria moluccana*	106	–	106 (100)	–	–	16	–	8 (50)	5 (31)	3 (19)
Group of Plant Age 4–6 year											
1	*Cassia siamea*	7	–	4 (57)	3 (43)	–	57	–	13 (23)	43 (75)	1 (2)
2	*Falcataria moluccana*	28	–	7 (25)	19 (68)	2 (7)	250	–	19 (8)	175 (70)	56 (22)
3	*Melaleucca leucadendron*	35	–	22 (63)	13 (37)	–	50	–	36 (72)	14 (28)	–
4	*Anthocephalus cadamba*	1	–	1 (100)	–	–	41	–	11 (23)	26 (63)	4 (10)
Group of Plant Age 6–8 year											
1	*Cassia siamea*	39	–	29 (74)	10 (26)	–	14	–	5 (36)	9 (64)	–
2	*Falcataria moluccana*	324	–	87 (27)	176 (54)	61 (19)	39	–	3 (8)	24 (62)	12 (30)
3	*Melaleucca leucadendron*	60	–	42 (70)	18 (30)	–	10	–	2 (20)	7 (70)	1 (10)
4	*Entorolobium cyclocarpum*	103	–	72 (70)	29 (28)	2 (2)	25	–	15 (60)	9 (36)	1 (4)
Group of Plant Age 8–10 year											
1	*Falcataria moluccana*	75	–	12 (16)	23 (31)	40 (53)	23	–	–	5 (22)	18 (78)
2	*Acacia mangium*	8	–	5 (62)	–	3 (38)	20	–	1 (5)	7 (35)	12 (60)
Group of Plant Age 10–12 year											
1	*Falcataria moluccana*	32	–	2 (6)	6 (19)	24 (75)	15	–	–	1 (7)	14 (97)
2	*Entorolobium cyclocarpum*	147	–	10 (7)	54 (37)	83 (56)	2	–	–	–	2 (100)

*) Note: the number in brackets is the percentage of the sum of all trees.

and f) also showed that the increase in diameter and plant height at the Sambarata site was generally greater than that at the Lati site indicating that in the presence of very similar soil physical properties between both sites, soil chemical properties such as a favourable pH, absence of Al^{3+} and marked nutrient availability play a regulatory role in plant growth. These issues already generated marked effects on the growth of small plants in the 0–2 year age group, which exhibit lower demands for nutrients than those of the large plants in the 10–12 year age group.

4. Discussion

4.1. Plant growth and physical properties of mine soil

In the mine soils under investigation, revegetation plants of the same species in each age group since revegetation indicated that the composition of the stand structure (Table 5) and plant growth, traced by increasing the trunk diameter and plant height (Fig. 7a to f), were better and larger at the Sambarata site than those at the Lati site. In the

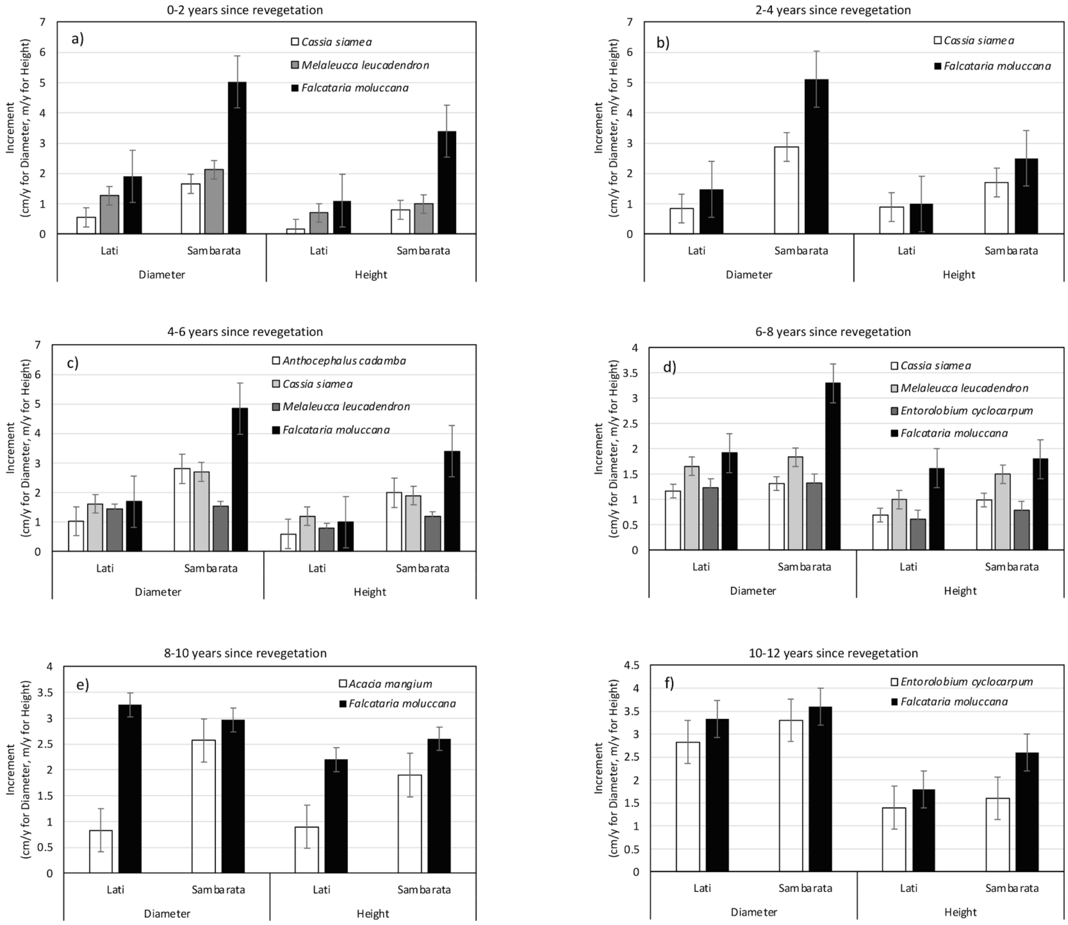

Fig. 7. Increase in the trunk diameter and plant height in the 0–2 (a), 2–4 (b), 4–6 (c), 6–8 (d), 8–10 (e), and 10–12 (f) years since revegetation for the mine soils at the Lati and Sambarata sites.

Fig. 8. Shape of the *Falcataria moluccana* revegetation plants (arrows) at the Lati (a) and Sambarata (b) post-mine landscape sites in the 0–2 year age group.

presence of similar soil physical properties (texture and bulk density) between both sites, this fact seems to be related to the more favourable chemical properties of the mine soils for plant growth at the Sambarata site than those of the mine soils at the Lati site. This finding does not agree with Sobek et al. (2000), who pointed out that the soil productivity is more determined by physical properties. Here, the presence of the soil skeleton (strongly depending on the rock type), coarse texture of fine soil, and low water holding capacity could limit plant growth more severely than could a low or high soil pH, poor nutrient availability, and low organic matter content because the latter properties can be easily overcome via amelioration. Cavalcante et al. (2019) also emphasize the importance of soil physical properties in the sustainability of mine soil. In this case, the rehabilitation strategy needs to pay attention to the carbon management index (CMI) by choosing the application method and type of vegetation, including ground cover plants, which can increase soil organic matter and aggregate stability of the soil.

The bulk density is a soil physical property strongly related to the water holding capacity and the penetrability of plant roots. Although the value ranges of the bulk density are larger at the Sambarata site than those at the Lati site (Fig. 2b), the bulk density, especially that of the surface layer, is classified as that of productive natural soils (Haigh, 1995; Daniels and Zipper, 1997). Therefore, in this case, the physical properties of the two mine soils are still favourable for the growth of revegetation plants.

5. Plant growth and chemical properties of mine soil

Marked differences between the two sites lie in the soil chemical properties, whereby the pH values of the mine soil are the most striking. The pH range at the Lati mine soil site is 3.91–4.27 and much lower than that at the Sambarata mine soil site with a pH ranging from 4.72 to 5.62 (Fig. 3a). This marked difference is also observable for the exchangeable Al^{3+}, a property strongly related to the pH. Here, the exchangeable Al^{3+} content in the Lati mine soil is much higher than that in the Sambarata mine soil, namely, 2.6–8.3 and 0.2–3.1 $cmol_c\ kg^{-1}$, respectively (Fig. 3b).

Differences in the pH and exchangeable Al^{3+} are of course related to the original parent material for soil formation and the soil age. Of the two investigated sites, the parent material is sandstone at the Lati site and calcareous sandstone at the Sambarata site (IAARD, 2016). This difference in the soil pH affects not only the exchangeable Al^{3+} but also the availability of plant nutrients and microbial activity (Brady, 1984). At a low pH, Al^{3+}, Fe^{2+}, and Mn^{2+} ions become more soluble and can yield unfavourable effects on plants.

McGrath et al. (2014) argued that weathered soils in areas with humid climates function as weak acid systems. In these soils, the total acidity value is much higher than the active acidity value, so the potential acidity is high. The soil system becomes more acidic because H^{+} ions can be released into the soil solution through acid dissociation or ionisation. This risk is reflected in the relatively low BS ranging from 19.4 to 48.4% for the Lati mine soil (Fig. 6b). Here, the exchange sites are generally dominated by exchangeable Al^{3+}, ranging from 2.6 to 8.3 $cmol_c\ kg^{-1}$ (Fig. 6d, 6e). This result is in contrast to the BS of the Sambarata mine soil (44.2–77.6%), where the adsorption complex is generally dominated by the exchangeable Ca^{2+} (1.7–8.6 $cmol_c\ kg^{-1}$) and exchangeable Mg^{2+} (3.4–5.5 $cmol_c\ kg^{-1}$) (Fig. 6b, c). High concentrations of Al^{3+} and Mn^{2+} combined with a low availability of K, P, Mg, Ca, and micronutrient Mo could limit crop production in acidic soils (Schjoerring et al., 2019).

The bioavailability and toxicity of Al^{3+} occur mainly in acidic soils at $pH < 5.5$ and consequently reduce crop production (Silva, 2012; Alori and Fawole, 2012). Al^{3+} ions trigger plant cell death due to an Fe-mediated increase in lipid peroxidation (Yamamoto, 2019). This causes the growth of revegetation plants at the Sambarata site to be better than that of the revegetation plants at the Lati site. The findings here are in line with the results of Budi et al. (2020), who found that *Falcataria moluccana* plants grown in post-mining soils with a $pH > 5$ grew better than those grown in soils with a $pH < 5$.

It is a common property among initial mine soils with a generally very low pedogenic organic matter content that they require fertilisers to fulfil the demand of plants for N and P (Bendfeldt et al., 1999; Zipper et al., 2013; Mushia et al., 2016). In mine soils, low levels of soil organic matter are caused by the mechanical mixing of soil materials derived from horizons A, B, and C at the time of salvage, upon temporary stockpiling of the topsoil material, and during distribution across the final surface of reclaimed land. A relatively fast gradual increase in the organic C and total N contents in mine soils is triggered by vegetation growth, whereby both trees and herbaceous cover crops contribute (Iskandar et al., 2022). Here, it was shown that the better the vegetation growth, the faster the increase in the organic C and total N contents in the mine soil will be. Our study revealed that the organic C and total N contents in the mine soils at the Sambarata site were higher than those in the mine soils at the Lati site, indicating that the vegetation growth at the Sambarata site was better than that at the Lati site (Fig. 4).

Data on the growth rate of plant species clearly support the above finding (Fig. 7a to f). The increase in trunk diameter and plant height of the same plant species in the same age group for the mine soils at the Sambarata site was generally larger than that at Lati site, so that this affected the stand structure of the revegetation plants at the Sambarata site, which was better than that at the Lati site. The important role of soil organic matter in increasing plant growth in acidic soils is well known (Escobar and Hue, 2008; Bougnom et al., 2010). Soil organic matter exerts a direct effect on decreasing Al toxicity, increasing the soil pH, and supporting soil biota, aggregate stability, soil enzymatic activity, and dissolved organic matter (DOM) (Medina and Azcon, 2010). Increased levels of organic matter in mine soils impose a positive effect on the amount of available P_2O_5, most likely through anion competition (Negassa et al., 2008). In our study, the level of available P_2O_5 in the top 30 cm of the soil at the Sambarata site ranged from 3.0 to 12.2 $mg\ kg^{-1}$ and was markedly higher than that in the top 30 cm of the soil at the Lati site, which ranged from 2.4 to 4.4 $mg\ kg^{-1}$ (Fig. 4c). As a consequence of the higher availability of P_2O_5, plant roots can take up more of the essential mineral nutrient P for growth, which accounts for up to 0.2% of the dry weight of plant cells and is essential for plant development (Stark et al., 2010). High shares of exchangeable Al^{3+} at the external and internal exchange sites of soil compounds, as observed in the mine soils at the Lati site, decrease the P availability. Desorption of P could be induced by increasing the pH towards a slightly acidic pH, neutralising the positive surface charge of Al and the presence of DOM, in which P anions can be released via ion competition (Negassa et al., 2008). Here, Ch'ng et al. (2014) reported that Al^{3+} and Fe^{3+} ions in acidic soils can be effectively bound by organic matter, thereby releasing P from Al-P and Fe-P bonds. According to Yang et al. (2019), organic matter can also increase the P availability by reducing the strength of P adsorption and the maximum buffering capacity of phosphates. Here, the increase in soil organic matter content, also driven by the growth rate of the revegetation plants, is an important measure to ensure the P availability for crops during the development of mine soils.

Regarding the research questions raised, it could be shown that for almost the same physical soil properties of the mine soils at both sites under investigation, the pH of the substrate appears to be the overall parameter triggering the growth of revegetation plants. The initial difference in pH between the mine soils at the Sambarata and Lati sites in the group of 0–2 year since revegetation was 4.1 for Lati versus 5.6 for Sambarata, which was related to other soil chemical properties, such as the exchangeable Al^{3+} and BS. Secondary effects on plant growth enhancement included a faster increase in the soil organic matter content and a higher availability of P, increasing the soil fertility.

6. Sustainability of Ex-coal mining land management

Dozens of revegetation plant species were planted at the study site, but only 6 of them were comparable in their growth rate because they were found in both Sambarata and Lati sites. Observations on changes in plant stand structure showed that *F. moluccana* grew the fastest followed by *C. siamea*, *A. cadamba*, *M. leucadendron*, and *E. cyclocarpum* (Table 5). The development of the stand structure of *A. mangium* could not be compared because it was only found once, i.e., in the group of 8–10 years since revegetation. The difference in chemical properties between mine soil at the Sambarata site and mine soil at the Lati site indicates that amelioration of mine soils with an acidic pH by using lime or dolomite is an important management option to produce more favourable conditions for the growth of revegetation plants. Here, it must be considered that this measure alone cannot fully replace the provision of various elements needed for plant growth stemming from mineral weathering of the carbonate- and silicate-rich parent material, as observed at the Sambarata site. At the beginning of revegetation, the two mine soils at the Lati and Sambarata sites contained very low to low levels of C, N and available P (Fig. 4). To improve the soil chemical and physical properties and to stimulate plant growth when seedlings are small, the application of compost and P fertiliser in planting holes should be considered.

7. Conclusions

The chemical and physical properties of mine soil are very important in supporting the development of revegetation plants. This study shows that the mine soil at Lati and Sambarata sites has almost the same physical properties, i.e., the texture is dominated by silt, followed by clay and sand, and BD ranges from 1.54 to 1.60 g cm^{-3} at the Sambarata site and 1.42–1.64 g cm^{-3} at the Lati site. Difference between the two sites lies in their chemical properties as shown in their soil quality index. The mine soil at the Sambarata site has a pH of 4.7–5.6 and a high BS with the adsorption complex dominated by exchangeable Ca^{2+} and Mg^{2+}, while the mine soil at the Lati site has a pH of 3.9–4.3 and a low BS whose exchange complex is dominated by exchangeable Al^{3+}. The levels of C, N and available P at both sites were low and increased with increasing revegetation age. The difference in pH and the type of dominant cations in the adsorption complex is closely related to the nature of the original soil. The Sambarata mine soil was originated from Typic Eutrudepst and Typic Hapludalfs which develops from calcareous sandstone, while the Lati mine was originated from Typic Dystrudepts which develops from sandstone. With the quality of the mine soil, revegetation plants at the Sambarata site grew better than that at the Lati site, as indicated by stems diameter, plants height, and stand structures. Among the plants studied, the fastest-growing revegetation plant was *F. moluccana* followed by *C. siamea*, *A. cadamba*, *M. leucadendron*, and *E. cyclocarpum*. Taking the soil quality of the Sambarata site as an example, the strategy for reclamation of acid mine soil is through an amendment by providing ameliorant materials that can increase soil pH as well as macronutrients, such as dolomite or lime, rock phosphate, and compost.

CRediT authorship contribution statement

Iskandar Iskandar: Conceptualization, Investigation, Methodology, Validation, Writing – original draft, Supervision. **Dyah Tjahyandari Suryaningtyas:** Methodology, Formal analysis. **Dwi Putro Tejo Baskoro:** Investigation. **Sri Wilarso Budi:** Methodology, Investigation, Validation. **Imam Gozali:** Investigation, Project administration. **Saridi Saridi:** Investigation, Project administration. **Muhammad Masyhuri:** Investigation, Project administration. **Stefan Dultz:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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