

Research Article

The Impact of Nickel Mining on Soil Properties and Growth of Two Fast-Growing Tropical Trees Species

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Opencast nickel mining is common in natural forests of Indonesia. However, rehabilitation of postmining degraded land is difficult. We investigated the effect of opencast nickel mining on soil chemical properties and the growth of two fast-growing tropical tree species, *Falcataria moluccana* and *Albizia saman*. Soil was collected from post-nickel mining land and a nearby natural forest. Soil pH, available phosphorus (P) concentration, total carbon (TC) and total nitrogen (TN) concentration, C/N ratio, cation exchange capacity (CEC), and exchangeable K, Na, Mg, Ca, Fe, and Ni concentrations were determined. *Falcataria moluccana* and *A. saman* were then grown in the collected soils for 15 weeks in a greenhouse. Shoot height and shoot and root dry weights of the seedlings were measured. The post--nickel mining soils TN, TC, available P, CEC, and exchangeable Ca and Na concentrations decreased by 98%, 93%, 11%, 62%, 85%, and 74%, respectively, in comparison with the natural forest soils. The pH of postmining soil was higher than natural forest soil. Shoot dry weight of *F. moluccana* seedlings grown in postmining soil was significantly ($P < 0.05$) lower than that of seedlings grown in natural forest soil. However, there was no difference in shoot dry weight between *A. saman* seedlings grown in natural forest soil and postmining soil, as well as root dry weights of both species. The results indicate that opencast nickel mining decreased soil fertility, which subsequently inhibited the growth of *F. moluccana* and *A. saman* seedlings.

1. Introduction

Nickel is one of the most important mining products in the world. In Indonesia, nickel is produced from opencast mines. Opencast nickel mining is an intensive process that has a significant impact on tropical rainforests, affecting both indigenous vegetation and soil fertility. Mining activity belongs to the land exploitation with consequent loss of ecological function and services [1]. It results in wide environmental degradation of the mined area and tends to destroy terrestrial ecosystems. Furthermore, it results in the loss of structure and function of soil due to the removal of the top layer of soil, with subsequent reductions in biodiversity and socioeconomic impacts [2].

To reduce damage caused by nickel mining, land rehabilitation activities are required. Rehabilitation land after mining activity to a previous forested land condition can guarantee the services of these areas for economic and ecosystem purposes [3]. Land should become a productive forested area for the sustainability of social authorization [4]; however, this is not easy. Revegetation of forests needs time and takes decades [5]. Forests are the ecosystems that consist of community, interacting as a system between living organisms and the nonliving components of the environment. They have undergone successional changes, in many ways, which take years or decades [6]. Returning disturbed land to become a forested area is required to guarantee the continuation of economic and ecosystem services to the environment.

Nickel mining mostly belongs to the geological of serpentinite regions. These are found contaminated with a tremendous amount of trace metals which include Cr, Ni, and associated metals (Mg, Pb, Co, Zn, etc.) with other elements [7]. Nickel mining also causes drastic changes to the physical and chemical characteristics of the land [8]. Mining activities can cause the release of toxic metals to the environment; damage to heritage; pollution; and acid mine drainage. In serpentinite soils regions, this condition results unfavorable for most plants and habitat development that house certain plant biodiversity and communities with many endemic species [9].

One rehabilitation strategy for degraded tropical lands is to plant fast-growing tropical trees. Such plantations may help to reduce the negative impacts of degraded lands and may contribute to the long-term livelihood of forest communities following mining. It is important to select fast-growing tropical trees species for increasing the success rate of rehabilitation. *Falcataria moluccana*, also known as batay, is one of the most important fast-growing multipurpose tree species in Indonesia. It is intended for industrial forest plantations because *F. moluccana* plants are included in fast-growing species and have high ability to grow on a different type of soil condition, favorable silvicultural characteristics, and marketable quality of wood for forestry industries [10]. This species can be used for pulp and paper, fuelwood, shade trees, and as a nitrogen supplier to soil [11]. Moreover, *Falcataria moluccana* plays an important role in both commercial and traditional farming systems that are commonly called as huma in Indonesia. The plant has been adopted and cultivated by the village people, such as integration into the development of traditional agroforestry in huma [12]. *Albizia saman* (Fabaceae), with the preferred common name as rain tree, is originally from Northern South America and has become naturalized in the tropics, grows in a wide range of climatic conditions, best in the lowlands from sea level to 300 m with rainfall 600–3000 mm, and is mainly used on agroforestry system for silvopasture and crop shade [13]. *Albizia saman* is an important species, a multipurpose tree with potentialities as an alternative feed for animals [14]. It also produces variation in breast diameter, attractive wood color, and physical properties of wood, such as green density and volume shrinkage [15]. *Albizia saman* has a massive root system with an equally large canopy. Most roots of *A. saman* expand horizontally, but many fibrous roots expand vertically [16]. Both species belong to the nitrogen-fixing trees commonly used for the revegetation of postmining land and for national programs of revegetation in Indonesia. The species of nitrogen-fixing trees are able to form symbioses with nodulating nitrogen-fixing bacteria. Rehabilitation of postmining land takes place across a wide variety of climatic and edaphic conditions [17]. For example, soil chemical properties of post-nickel mining sites can be strongly influenced by the presence of vegetation or tree species. Before implementing rehabilitation in degraded mining lands, it is necessary to select tropical tree seedlings that are adapted to postmining soil.

The objective of this study was to determine the impact of opencast nickel mining on soil chemical properties and,

subsequently, its effect on the growth of two fast-growing tropical tree species, *F. moluccana* and *A. saman*, under greenhouse conditions.

2. Materials and Methods

2.1. Soil Sampling. Soil samples were collected from the top layer at PT Vale Indonesia, a nickel mining site in Sorowako, East Luwu, South Sulawesi, Indonesia (Figure 1). PT Vale Indonesia, previously named PT International Nickel Indonesia (INCO), was founded in 1968. The company, currently, has mining concessions belonging to Wallace's line of almost 120.00 hectares, most of which are still in the form of natural forests. The samples were collected from 3 natural forest sites ($2^{\circ}34'06''S$, $121^{\circ}20'52''E$; $2^{\circ}34'20''S$, $121^{\circ}25'03''E$; and $2^{\circ}34'20''S$, $121^{\circ}25'03''E$) and 3 post-nickel mining sites ($2^{\circ}34'26''S$, $121^{\circ}21'37''E$; $2^{\circ}35'19''S$, $121^{\circ}22'30''E$; and $2^{\circ}31'36''S$, $121^{\circ}29'47''E$) to characterize soil properties. Litter, roots, and stones were scraped away from the surface before soil samples were taken. The samples were collected using a hand scope and mixed thoroughly before being placed in a clean and seal plastic bag. Five soil samples were collected from each site at a depth of 0–25 cm. A small subsample was taken and ground for chemical analysis. The remaining soil was kept for the plant growth experiment.

2.2. Analysis of Soil Properties. The soil was air-dried and passed through a <2 mm sieve. Soil pH was analyzed through two ways: using H₂O and using KCl. Available phosphorus (P) [18] was extracted with 0.001 M sulfuric acid and analyzed using the ammonium molybdate method. Total carbon (TC) and total nitrogen (TN) were analyzed using a C:N analyzer (Sumigraph NC-220F, Tokyo) [19]. Exchangeable potassium (K), sodium (Na), magnesium (Mg), and calcium (Ca) were extracted with 1 M (pH 7) ammonium acetate analyzed using an atomic absorption spectrophotometer (Hitachi model Z-5000 series Polarized Zeeman, Tokyo) [19]. To determine cation exchange capacity (CEC), excess NH₄⁺ was removed, and an extraction was performed with 100 g L⁻¹ KCl. The supernatant was analyzed using the semi-micro Schöllenger method [19].

2.3. Growth of Two Fast-Growing Tropical Tree Species. Two fast-growing tropical tree species, *F. moluccana* and *A. saman*, were selected for this study. Seeds of both tree species were purchased from a local company, Central Java, Indonesia. The seeds were soaked in water at 80°C for 2 min. They were then pregerminated in plastic containers using zeolite as a germination medium. After radicle growth, individual plants were selected for sowing based on uniformity. Trees were grown in polyethylene pots (height: 7.5 cm, diameter: 5 cm) containing 200 g of soil. Each pot contained soil from a different soil sample, resulting in 30 pots, 15 with natural forest soil, and 15 with postmining soil. Two tree seedlings were transplanted for each soil sample, resulting in a total of 60 pots. Pots were positioned in a greenhouse in a randomized block design. The greenhouse was located in the Forest Microbiology Laboratory, Research



FIGURE 1: The location of soil sample collection at PT Vale Indonesia, Sorowako, East Luwu, South Sulawesi, Indonesia.

and Development Agency (FORDA), the Ministry of Environment and Forestry, Bogor, West Java, Indonesia ($6^{\circ}36''S$, $106^{\circ}45''E$). The temperature varied between 25 and $37^{\circ}C$, relative humidity was 80%–90%, and the photoperiod was approximately 12 h. The plants were grown for 15 weeks, and watering by deionized water was applied to maintain a moisture content similar to field capacity.

2.4. Harvest. Shoot height, measured 1 cm from the soil surface in the pot, was determined every 2–3 weeks. After 15 weeks, the shoots were harvested and oven-dried at $70^{\circ}C$ for 72 h before dry weight was recorded.

2.5. Statistical Analysis. Data on laboratory tests of soil chemical properties and plant growth were analyzed using a statistical test, Student's *t*-test at 95% confidence interval ($P < 0.05$) in Minitab (Minitab Inc., USA). When the *F* value was significant, the least significant difference (LSD) was calculated to compare treatment means.

3. Results and Discussion

3.1. Impact of Nickel Mining on Soil Chemical Properties. We found that the chemical properties of post-nickel mine soil differed significantly from nearby natural forest soil (Table 1). Total N, TC, available P, CEC, exchangeable Ca, and Na were lower in post-nickel mine soil than natural forest soil. Conversely, soil pH and C/N ratio were higher

in post-nickel mine soil than natural forest soil. There were no differences in Mg, K, Fe, and Ni between natural forest soil and post-nickel mine soil.

Opencast nickel mining activities have an impact on soil fertility. In opencast mining, rock or minerals are extracted from an open pit or burrow. Topsoil and vegetation are seriously damaged during opencast nickel mining, thus decreasing soil fertility. Nickel ultramafic soils are commonly known as serpentines in the botanical and ecological literature [9]. The serpentinized and ultramafic soil/rock are distinguished by high levels concentration of heavy metals and unbalanced Ca/Mg ratio [7] and poor plant nutrient content such as N, P, and K [9]. Nitrogen and phosphorous are the most important nutrients for soil productivity and plant development. It significantly enhances plant growth and productivity, chlorophyll and carotene contents, and promotes root morphology [20]. Most studies have demonstrated the influence of nitrogen enrichment on plant communities. Soils are known to have heterogeneous physical, chemical, and biological properties. Soil heterogeneity is closely related to nitrogen enrichment to determine plant growth and nutrient status [21]. The availability of N in the soil directly influences a wide range of ecological processes, both above and below ground, at the physiological, community, environment, ecosystem services, and global levels [22]. In our study, we found that post-nickel mine soil had 98% less TN than a nearby natural forest soil. This indicates a greater decline in TN compared with gold mine tailings in Indonesia (91.3%) [23], an opencast bauxite mine in Bintan Island, Indonesia (75% reduction) [24], and

TABLE 1: Chemical properties of soils from natural forest and post-nickel mining land. Different letters within row indicate significant difference ($P < 0.05$) by t -test. Mean \pm standard error are shown ($n = 15$).

Chemical properties	Natural forest		Postmining land		Change (%)
pH (H ₂ O)	5.02 \pm 0.10	b	6.31 \pm 0.05	a	+1.29 (26)
pH (KCl)	4.66 \pm 0.10	b	6.31 \pm 0.07	a	+1.65 (35)
Total carbon (g/kg)	40.20 \pm 0.25	a	2.90 \pm 0.05	b	-37.30 (93)
Total nitrogen (g/kg)	2.60 \pm 0.02	a	0.057 \pm 0.01	b	-2.54 (98)
C/N (ratio)	15.84 \pm 0.29	b	65.12 \pm 8.72	a	+49.28 (311)
Available P (mg P ₂ O ₅ /kg)	12.30 \pm 0.02	a	11.00 \pm 0.02	b	-1.30 (11)
CEC (cmol kg ⁻¹)	8.23 \pm 0.67	a	3.15 \pm 0.71	b	-5.08 (62)
Ca (mg/kg)	5.85 \pm 0.93	a	0.86 \pm 0.29	b	-4.99 (85)
Mg (mg/kg)	7.32 \pm 0.81	a	6.27 \pm 1.18	a	-1.05 (14)
K (mg/kg)	10.84 \pm 6.23	a	5.25 \pm 5.25	a	-5.59 (52)
Na (mg/kg)	0.81 \pm 0.19	a	0.21 \pm 0.08	b	-0.6 (74)
Fe (mg/kg)	2.12 \pm 0.09	a	38.30 \pm 18.73	a	+36.18 (1707)
Ni (mg/kg)	3.30 \pm 0.33	a	3.17 \pm 0.45	a	-0.13 (4)

an opencast coal mine in India (53% reduction in TN) [25] and USA (53%–80% reduction) [26].

Phosphorus is another essential plant macronutrient. In the present study, the available P of post-nickel mine soil was 11.00 ± 0.02 mg P₂O₅/kg, which was lower than that in natural forest soil (12.30 ± 0.02 mg P₂O₅/kg). Soil phosphorus is the element considered important in determining the biodiversity and biomass of natural ecosystems [27]. Production of many ecosystems especially in subtropical and tropical regions is strongly considered to be P rather than N limited [28]. Recent literature indicates that in tropical forests, a large fraction of P is found as organic and microbial P in the soil; plant adaptations to absorb organic P, including the phosphatase enzymes. Plants also cope with low P availability in the soil through enhancements in P use-efficiency resulting from increased retention time of P in biomass and decreased tissue P concentration [29].

The impact of surface mine activity involves drastic disturbances to the ecosystem and soil properties including the reduction of soil organic material (SOM) and organic carbon [30]. Soil organic matter is lost as a result of the initial stripping of the soil from the site. Further losses occur while the soil is stored in stockpiles during replacement to the reclaimed site. This has serious implications because SOM plays an important role such as in soil fertility and water holding capacity. Soil is the primary store of terrestrial carbon [31]. Topsoil management plays an important role that rehabilitation of postmining land leads to prevention of carbon losses. Soils' surfaces after reclamation of post-coal mines in Wyoming are sequestering C at a rapid rate. For example, soil organic C content at one reclaimed mine site near Hanna, WY, USA, increased from 10.9 g C kg^{-1} in 1983 to 20.5 g C kg^{-1} in 2002 [32]. Carbon is an important soil parameter; it improves soil physical and chemical properties and overall soil quality. Soil carbon exists in various forms that are functionally different and have contrasting residence times. Removal of topsoil from mining sites and subsequent replacement and mixing with underlying soil considerably reduces the concentration of soil organic C. In the current study, we found that TC was 93% lower in post-nickel mine soil compared to natural forest soil, with concentrations of

2.90 ± 0.05 g/kg and 40.20 ± 0.25 g/kg, respectively. This decline in TC is greater than that of oil palm plantations, in which TC can decline by 42% [33].

Soil pH was higher in post-mine soil compared with natural forest soil, by 26% for the H₂O method and by 35% for the KCl method. This happens because of the loss of vegetation cover on the top layer of soil on postmining land. Most postmining land is categorized as dry land which contains metals such as Mg, Na, K, and Ca which are very high in soil pH of 9.0 [34]. In their natural forest environment, however, soil chemicals such as Mg, Na, Ca, K, and other chemical characteristics produced from the decomposition process of organic soil material will be absorbed by the plants. It results in the conservation and efficiency of the nutrient with a closed ecological nutrient cycle [35, 36]. The higher pH of postmining soil could support mining rehabilitation activities. Soil pH is influenced by various soil biological, chemical, and physical properties that affect the growth of plants and biomass yield [37]. For example, many N and C mineralization processes occur at a pH between 6.5 and 8. The application of dolomite may be considered to increase soil pH even further. It can also increase many other soil nutrients, including Mg [38].

Soil cation exchange capacity (CEC) is a major soil chemical property. It reflects the surface properties of soil colloids, and the retention and supply proportions of soil fertilizer. Cation exchange capacity is a key indicator for evaluating soil fertility, plant growth, and pollutants partition and transport in soils. It is also an important parameter that influences the adsorption of heavy metals and organic pollutants in soils [39]. We found that CEC in the present study was 62% lower in post-nickel mining, in comparison with natural forest soil. The decrease in CEC is greater compared to post-bauxite mining [24] and is lower compared to gold tailings [23], in which CEC can decrease by 30% and 76%, respectively. Some of the important micronutrients that are essential for plant growth are Ni and Fe. The micronutrient is available in the soil due to the continuous weathering of minerals mixed with primary minerals. Nickel contributes to the nitrogen fixation in legume plants and is the component of the urease enzyme which

brings about hydrolysis of urea [40], while Fe is a major micronutrient for almost all living organisms which plays important role in metabolic processes such as photosynthesis, DNA synthesis, and respiration. Furthermore, many metabolic pathways are stimulated by Fe, and it is a prosthetic group constituent of many enzymes [41]. In high-level concentration, however, Fe is toxic. It can act catalytically through the Fenton reaction to generate hydroxyl radicals, which can destroy proteins, lipids, and DNA. Consequently, plants must respond to Fe stress because of both Fe deficiency and Fe overload [41]. In the current study, we found that Fe was 1707% tending to higher in post-nickel mine soil compared to natural forest soil, with concentrations of 38.30 ± 18.73 mg/kg and 2.12 ± 0.09 mg/kg, respectively.

3.2. Growth of Fast-Growing Tropical Tree Species. The shoot height of *F. moluccana* seedlings grown in both the natural forest soil and post-nickel mine soil increased from 2 to 15 weeks after planting (Figure 2). In comparison with natural forest soil, shoot height at 10, 13, and 15 weeks after planting was significantly lower in post-nickel mine soil. No significant difference in shoot height was shown between natural forest and post-nickel mine soil at 2, 4, 6, and 8 weeks after planting. The shoot dry weight of *F. moluccana* grown in post-nickel mine soil was significantly ($P < 0.05$) lower than that of natural forest soil (Figure 3). Root dry weight of *F. moluccana* grown in natural forest soil was generally higher in comparison with post-nickel mine soil without statistical significance. The shoot height of *A. saman* seedlings of natural forest and post-nickel mine soil increased from 2 to 15 weeks after planting (Figure 4). Shoot height 15 weeks after planting was significantly lower in the post-nickel mine soil than that in the natural forest soil. Shoot dry weight in natural forest soil was generally higher than that in post-nickel mine soil (Figure 5), while root dry weight in post-nickel mine soil was generally higher than that in natural forest soil without statistically significance.

The rehabilitation of land after nickel mining is a mandatory activity for all mining companies in Indonesia. One rehabilitation approach is to plant fast-growing tropical leguminous trees that have a high level of adaptation and survival on post-nickel mining land and improve the fertility of the soil. Our results, as show in Figure 5, suggest that *A. saman* is more tolerant to growth on post-nickel mining land than *F. moluccana*. *Albizia saman* is a fast-growing tropical leguminous tree that is highly adapted to various types of soil with a wide pH range and poor drainage [16]. Planting leguminous trees that can grow on post-nickel mining land can improve the ability of the soil to retain water. Large pores in the surface layer of natural forest soils (due to the activity of microbes and roots) allow infiltration of rainwater into the soil. In post-nickel mining land with low nitrogen concentration, the leguminous trees as nitrogen-fixing species could be used for revegetation. Several studies on revegetation of postmining land in Africa have shown that leguminous tree species have a high survival rate [42]. The successful use of leguminous trees for postmining land reclamation has also been demonstrated in Brazil.

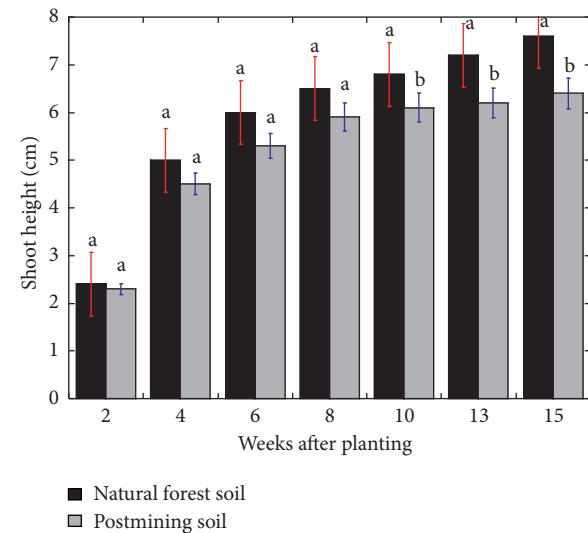


FIGURE 2: Mean shoot height of *Falcataria moluccana* grown in soil from post-nickel mining land and natural forest for 15 weeks under greenhouse condition. Different letters indicate significant differences ($P = 0.05$). Error bars indicate standard error ($n = 15$).

Leguminous trees form a symbiosis with nodulating N-fixing bacteria [43]. Several leguminous trees, including *Caesalpinia sappan* L., *Enterolobium cyclocarpum* (Jacq.) Griseb., *Gliricidia sepium* (Jacq.) Walp., *Delonix regia* (Hook.) Raf., and *Cassia siamea* Lamk., have been used in the rehabilitation of a former tin mining area in Bangka Island, Indonesia [44].

The use of organic amendments and microbial inoculants could increase soil fertility and help plant growth in post-nickel mine soil. For example, chicken manure, cow manure, mulch, municipal green waste, and litter compost might increase the success of rehabilitation. The application of chicken manure to post-coal mining land in Indonesia, which had very low soil nutrient concentrations, increased the growth of *Samanea saman* [45]. The treatment of municipal green waste had growth rates comparable to untreated plants for mine site rehabilitation. The use of municipal green waste on degraded opencast coal land in South East Wales, the United Kingdom, had significantly greater survival rates, compared with trees planted without green waste [46]. Other studies have shown that the addition of compost not only increases soil fertility and plant biomass but also reduces the concentration of trace elements in plant species grown in metal-contaminated mine soils [47]. Oyebamiji et al. [48] reported the distribution of heavy metal such as, Pb, Zn, Cu, Ni, Cr, and Fe in active mining soils in southwestern Nigeria. Incorporation of compost provides benefits for remediating trace elements (Cu, Pb, Zn, and As) in polluted soil [49]. The dissolution of organic matter can increase the solubility of Al, Fe, and Pb within the reclaimed soils [50]. The application of microbial inoculants, such as arbuscular mycorrhizal fungi (AMF), could improve the growth and survival of trees on post-nickel mining land. Plants are part of the ecosystem with many and diverse microorganisms in the soil. It has been established that some

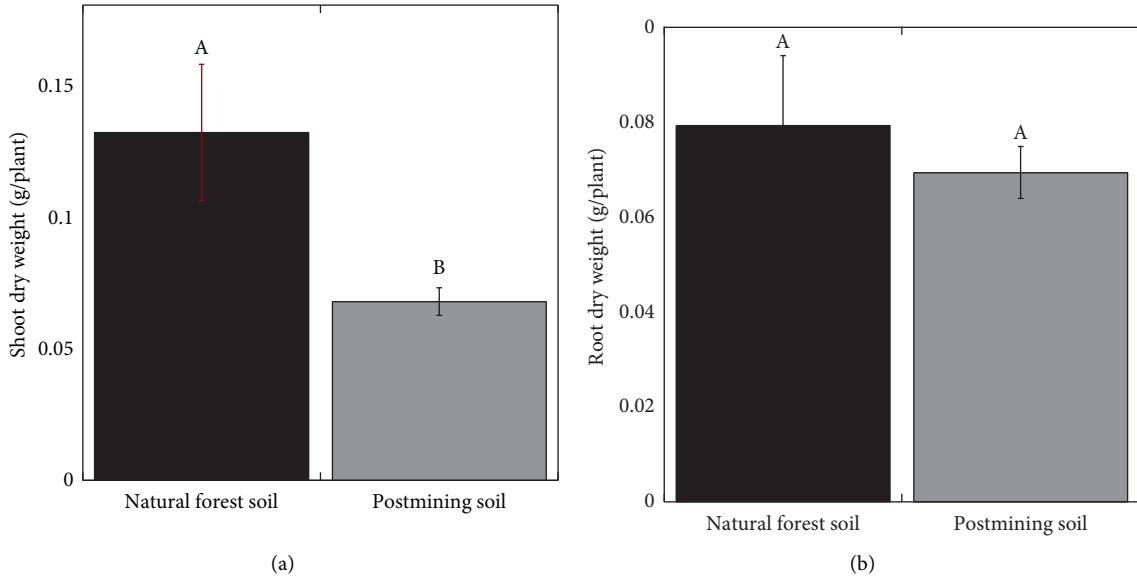


FIGURE 3: Mean shoot (a) and root (b) dry weight of *Falcataria moluccana* 15 weeks after planting in soil from post-nickel mining land and natural forest. Different letters indicate significant differences ($P = 0.05$). Error bars indicate standard error ($n=15$).

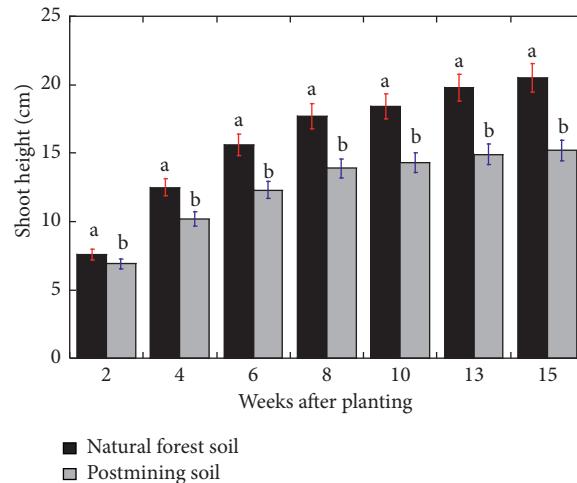


FIGURE 4: Mean shoot height of *Albizia saman* grown in soil from post-nickel mining land and natural forest for 15 weeks under greenhouse condition. Different letters indicate significant differences ($P = 0.05$). Error bars indicate standard error ($n=15$).

of these microbes, such as mycorrhizal fungi or nitrogen-fixing bacteria, play important roles in plant development by improving mineral nutrition [51]. Several investigations have shown good results; the application of AMF increased the growth and survival of *P. falcataria* and *A. saman* in post-coal mining land in Indonesia [52]. Additionally, the use of coconut powder inoculated with AMF increased the survival of *Anadenanthera colubrina* seedlings in post-mining soil in Brazil [53]. The application of AMF and leguminous trees might be used to increase the success of revegetation programs in post-nickel mining land. In our study, Fe content in postmining soil was seventeen times higher than that in natural forest soil. Agus et al. [54] reported that revegetation with fast-growing legume species of *Pongamia pinnata* and AMF application can not only

increase nutrient contents of post-coal mining soil but also increases Fe absorption, which is mostly accumulated in the root system.

Fast-growing tropical leguminous trees that belong to the N-fixing species may contribute to improving soil quality on degraded soil of post-nickel mining land. Some results indicate that legumes plant may increase the resistances of soil physicochemical and biological properties to the ecosystem disturbance [55]. Legumes fix the atmospheric nitrogen, release in the soil high-quality organic matter, and facilitate soil nutrients' circulation and water retention [56]. It could be investigated in future studies, in which fast-growing tropical leguminous trees of *F. moluccana* or *Albizia saman* have a better impact to increase soil quality on post-nickel mining land.

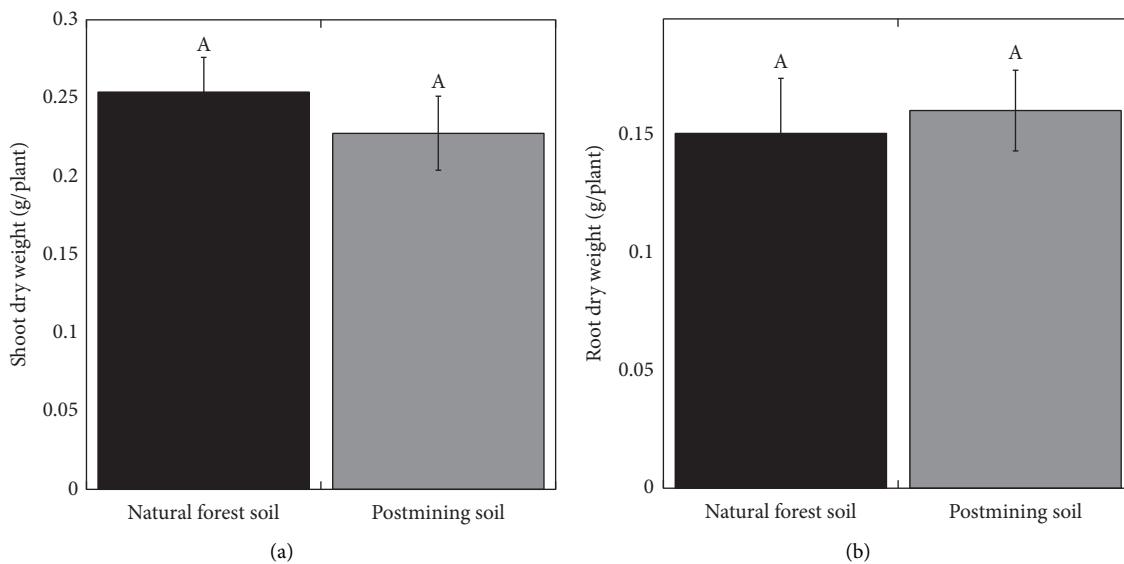


FIGURE 5: Mean shoot (a) and root (b) dry weight of *Albizia saman* 15 weeks after planting in soil from post-nickel mining land and natural forest. Different letters indicate significant differences ($P = 0.05$). Error bars indicate standard error ($n = 15$).

4. Conclusions

Opencast nickel mining impacted soil fertility. Total N, TC, available P, and exchangeable Ca and Na concentrations of post-nickel mine soil were 98%, 93%, 11%, 85%, and 74% lower than natural forest soil, respectively. The reduced fertility of postmining soil resulted in lower growth of the fast-growing tropical tree species *F. moluccana* and *A. saman*. However, our results suggest that *A. saman* was better adapted to growth on post-nickel mining land. There was no significant difference in biomass between *A. saman* on post-nickel mining soil and natural forest soil. In future studies, the comparison between *F. moluccana* and *A. saman* could be investigated to have a better impact on soil improvement on post-nickel mining land.

Data Availability

The data used for this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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