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Meranti (*Shorea* sp.) Biochar Application Method on the Growth of Sengon (*Falcataria moluccana*) as a Solution of Phosphorus Crisis

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Abstract: Phosphorus (P) is a limiting nutrient mined from non-renewable sources. P is needed to stimulate trees growth in a forest plantation. P-fertilizer addition in the tropical forest field causes P-leaching flux to watershed and induces eutrophication. The high C contained in meranti (*Shorea* sp.) biochar can avoid the P-leaching process in the soil with a strategic application method. However, the biochar application method is poorly examined. This research aimed to develop a biochar application method to sequestrate P from the environment and examine its effect on the growth of sengon (*Falcataria moluccana*). *Shorea* sp. biochar pyrolyzed at 400 °C and 600 °C were added at a dosage of 0 t ha^{-1}, 25 t ha^{-1}, and 50 t ha^{-1} for six months in the field. The biochar was placed 20 cm under topsoil without soil mixing. This application method significantly increased total P in the soil without any P-fertilizer addition. The results showed that biochar pyrolyzed at 600 °C and a dosage of 25 t ha^{-1} increased the total P in the soil and CEC by 192.2 mg kg^{-1} and 25.98 me 100 g^{-1}, respectively. Biochar with a higher pyrolysis temperature increased higher soil pH. In contrast, the higher dosage increased organic-C higher than the lower dosage application. The most significant P-uptake, height, and diameter increments on *F. moluccana* were achieved using *Shorea* sp. biochar pyrolyzed at 600 °C with a dosage of 25 t ha^{-1} by 0.42 mg kg^{-1}, 222 cm, and 2.75 cm, respectively. The total P in the soil positively correlated with the P-uptake of *F. moluccana*. Furthermore, using the biochar application method P could be absorbed to the biochar layer and desorbed to the topsoil. Consequently, the biochar application method together with P-fertilizer addition could increase the availability of P in the soil and decrease P-leaching to the environment.

Keywords: biochar; *Falcataria moluccana*; phosphorus; *Shorea* sp.

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1. Introduction

Phosphorus (P) is a finite resource with no known alternative that becomes a significant growth-limiting factor in several sectors [1]. P fertilizer is produced through P-bedrock mining, which is non-renewable. It is predicted that P sources will be exhausted in the next 50–100 years [2]. In the forestry sector, P fertilizer is commonly used at an early stage of plantations. The forest plantation industry in Indonesia generally applies fertilizer to degraded lands and poor-nutrient soils [3]. Tropical soil is categorized as old soil [4]; hence, it has high Al and Fe contents [5,6]. On the other hand, P solubility is controlled by Fe- or Al-phosphates [7]. Thus, P-sequestration in low-solubility of Fe and Al-phosphate compounds and the effect of erosion and leaching mean that tropical soils lack soluble P [7]. P is a critical requirement for increasing root and shoot strength [8], cell elongation [9], and flower-seed formation [10]. P-deficient could inhibit plant growth [11] and increasing seedling mortality in a forest plantation. Conversely, P-addition to soil caused a problem called eutrophication [12] which is a water oxygen level degradation because of algae blooming caused by nutrient excess. Eutrophication is caused by the P-leaching process [13]. Forest P-leaching from topsoil with a 0–20 cm depth was 20 mg kg^{-1} [14]. P-leaching from forest yield unconsciously is more dangerous because forests control watershed flux into the ocean [1]. Hence, developing a method to conserve the nutrient cycle in forests is urgently needed.

Biochar is well known as an anti-leaching agent and one of the largest products resulting from the pyrolysis process [15]. Pyrolysis is the thermal modification of biomass whereby the combusting of the biomass is conducted in the absence of oxygen [16–19]. Biochar has been proven to conserve nutrients from leaching and evaporation [20,21]. Furthermore, biochar application is suitable for long-span forest cultivation due to its stable structure that can remain over a long span [8,22]. However, some factors that influence the ability of biochar to conserve P need to be examined.

Biochar contains high fixed carbon [17,23]. Biochar applied on soil sequestrates organic-C for the long term because of their predominantly aromatic nature [24]. The high C content of biochar increases soil organic matter (SOM) [25–27]. A previous study [28] revealed that the SOM from 10% biochar addition increased soil pH from 4.9 to 8.7 and dissolved organic matter (DOM)-water partitioning coefficients (K_d-values) from 0.2 to 590 L kg^{-1}. DOM is important to in the conservation of soil nutrients and microorganisms [29,30]. Biochar could increase the cation exchange capacity (CEC) by microbial association [31,32]. In addition, high SOM could decrease the leaching of nitrate, ammonium, and phosphate up to 34.0%, 34.7%, and 20.6%, respectively [20]. Biochar with high fixed carbon is suggested to conserve the soil nutrients [33]. Meranti (*Shorea* sp.) biochar contains fixed carbon, at a proportion of up to 84.9% [34], which is higher than teak wood (*Tectona grandis*) biochar, with a fixed carbon content of 75.51% [35], rubberwood (*Hevea brasiliensis*) biochar, of 77.2% [36], and sengon (*Falcataria moluccana*) biochar, of 72.4% [35]. In the last three years, *Shorea* sp. wood cultivation in Indonesia has increased by 1.5%, with a timber production of 2. 63 million m^3/year in 2020 [37]. However, the harvesting of *Shorea* sp. wood has not been optimal due to a lack of waste management [38]. The previous study revealed that 557.87 m^3 volume of *Shorea* sp. waste in the form of the rest of the bucking (5.69%), twigs (11.13%), stumps (13.63%), and branches (26.12%) occurred from 1042.11 m^3 *Shorea* sp. wood [39]. Pyrolysis could be a suitable process to increase the added value of the harvesting waste of *Shorea* sp. [40]. The biochar from the harvesting waste of *Shorea* sp. is potentially used to conserve P in the forest soil and support better waste management.

The biochar application method is another determining factor in the conservation of soil nutrients [41]. Biochar applied on the soil surface could increase water retention and decrease fertilizer evaporation [42]. Nonetheless, this application method is unsuitable for areas with high precipitation such as Indonesia because biochar will leach by surface runoff. The application of biochar to improve growth and nutrients is generally achieved by mixing with the soil. Biochar could optimally decrease the nitrate leaching by 8.3–17.0% and improve the soil's hydraulic conductivity (Ksat) by 20.9% by mixing with soil at a 10–20 cm depth [43]. Nevertheless, mixing biochar with soil is inefficient in large forest areas. On the other hand, research that evaluates the effect of biochar without blending with the soil under topsoil has never been conducted. Previous studies reported that biochar could sequestrate P from the environment due to its strong ionic bond [18,44]. Hence, biochar can desorb P to the topsoil to reach equilibrium [45].

Falcataria moluccana was planted to examine the biochar effect on plant growth by soil P increment. *F. moluccana* was chosen because legume plants can sensitively uptake P by producing organic acids, such as citrate and malate, to release inorganic-P from soil inorganic complexes by the ligand exchange mechanism [11]. Furthermore, *F. moluccana* is also an invasive tree that is not easily affected by climate, shade, or temperature [23,46]. Therefore, the increase in P can influence the growth effectively without bias effect. Moreover, *F. moluccana* is a mainstream commercial wood and easy to find in Indonesia because of its comprehensive cultivation, especially in the Sumatra and Java islands [47]. Therefore, the aim of this study was to investigate the biochar application method with a pyrolysis temperature of 400 °C and 600 °C to increase P in the soil that stimulates *F. moluccana* growth in the field for six months.

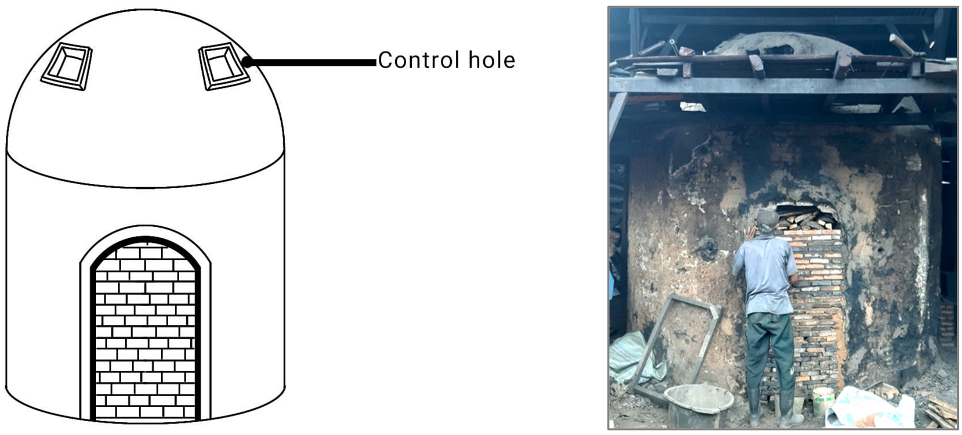
2. Materials and Methods

2.1. Site Study

This research was conducted at a field plot of 1 ha, near the Pesawaran Forest Management Unit Area, Lampung province, Indonesia (104° 59′ 22′′ E 5° 28′ 20.5′′ S). The field was covered by weed and grass without canopy trees or shade, and mimics the first stage of forest succession. This field plot has a warm-temperate monsoon humid climate with an average monthly precipitation of 161.8 mm month^{-1} [48]. The land slope was 5–15° and categorized as a gentle slope. The soil was classified as podsolic soil and formed due to high precipitation and low temperature [49]. The study site is an old mineral soil type with a reddish to yellowish color, indicating relatively low soil fertility.

2.2. Biochar Production

Biochar was produced using a dome kiln developed by Kendi Ltd., South Lampung Regency, Lampung Province, Indonesia. Bricks and clays were used to construct the dome kiln structure with a capacity of 12 m^3. The kiln was equipped with a door channel and holes to control the oxygen supply during the pyrolysis process (Figure 1).



(**a**) (**b**)

Figure 1. (**a**) The design of the dome kiln, and (**b**) the preparation activities before the pyrolysis process.

Air-dried *Shorea* sp. woods with an average moisture content of 11.6% and 40 cm length were used as raw materials for biochar production. The raw material was positioned horizontally until the kiln's maximum capacity to minimize oxygen entering the kiln was reached (Figure 1b). The kiln door was then covered with bricks and clays. The *Shorea* sp. biochars were produced using the slow pyrolysis method [45,50,51], consisting of the following three stages: heating, maintaining peak temperature, and cooling. During the heating stage, materials were burned at the upper part of the stack for ±3 days to reach the targeted peak temperature. The targeted peak temperatures of 400 °C and 600 °C were maintained for ±4 days. The kiln temperature was measured hourly to maintain the targeted peak temperature by opening the control holes when the peak temperature decreased and by closing the control holes when the peak temperature increased. The cooling stage was carried out by closing all control holes for ±7 days. One production batch was conducted for each of the experimental temperatures. The biochar properties can be seen in Table 1.

Table 1. *Shorea* sp. biochar properties according to previous research [52].

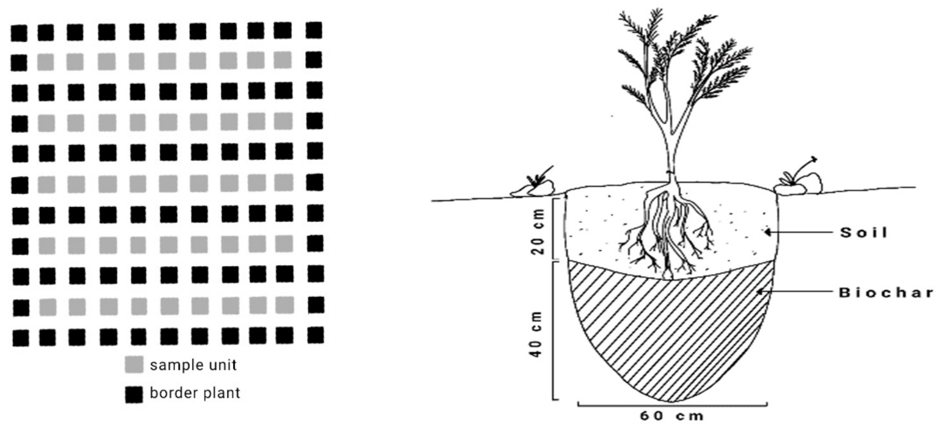
Properties	Pyrolysis Temperature	
	400 °C	600 °C
Ash content	0.76	02.52
Volatile matter	42.62	31.11
Fixed carbon	56.62	66.35
pH	8.5	8.7

2.3. Experiment Design

This study used a randomized experimental design factorial with two factors, namely pyrolysis temperature and dosage. The treatments were as follows: dosage 0 t ha^{-1} (control), dosage 25 t ha^{-1} at 400 °C (D25T400), dosage 25 t ha^{-1} at 600 °C (D25T600), a dosage of 50 t ha^{-1} at a temperature of 400 °C (D50T400), and a dosage of 50 t ha^{-1} at a temperature of 600 °C (D50T600). Each treatment was replicated ten times in the field plots. The total sample unit was fifty *F. moluccana* seedlings. The growth of *Shorea* sp. seedlings was monitored once a month. The growth measurement was height and diameter increment, soil chemical properties after six months, P on the leaf, and dry weight leaf.

2.4. Biochar Application

The biochars produced were pulverized by crushing them into smaller particles and then separated using a 2 mm fine-size sieve before being applied to the plantation site. Eighty-four planting holes were prepared for the plantation. The holes had a 60 cm depth with a diameter of 20 cm. The distance between the holes was 5 m x 5 m. Border plants, *F. moluccana*, were planted between treatment plots to minimalize the bias effect of biochar treatments (Figure 2a). The planting hole was filled with biochar to a depth of 40 cm and then covered with a topsoil layer of 20 cm depth (Figure 2b). The sixth-month *F.* moluccana seedlings with an identical stem height were selected as experimental samples. *F. moluccana* seedlings from polybags were transferred to the planting holes and planted in the topsoil to avoid direct contact with the biochar (Figure 2b).



(**a**) (**b**)

Figure 2. (**a**) The plantation site design, and (**b**) application of biochar and soil in planting holes.

2.5. P-Uptake on Leaves

F. moluccana leaves samples for measuring P-uptake were picked from the bottom, middle, and upper parts collected from six plants to avoid the edge effect. The leaf samples were kept at 23–25 °C for 24 h. Prior to P analysis, leaves were dried in the oven until reaching a constant weight. The leaves were weighed with a precision scale of 0.0001 g. The samples were ground into a powder and then sieved using a 0.5 mm mesh screen and combusted at 500 °C. A 5 mg sample was placed in a 50 mL Erlenmeyer with 25 mL of deionized water, and 1 mL of HCl was added. The solution was heated to evaporate the water. Then, a cooling bulb was placed on top of the flasks. After the color turned yellow and transparent, the sample was rotated to remove ash particles from the wall and adjusted the volume to 100 mL with deionized water. The sample was filtered through a GF/C filter connected to a 20 mL syringe. A 10 mL sample was placed in a glass tube. The P-uptake concentration was analyzed by atomic absorption spectrophotometry (AAS) [53].

2.6. Total-P, Organic-C, pH, and CEC Analysis

After six months, soil samples were collected by mixing three spots around the sample unit. Two spots were collected 30 cm from the sample unit, and one spot was directly below the sample unit. The soil was collected at a depth of 10–20 cm. The soil sample was stored at 23–25 °C for seven days. Total P was analyzed with AAS [54]. The calibration graph of absorbance was correlated to standard concentration in ppm to determine P concentration on the soil sample. Organic-C was analyzed using the Walkley–Black method [55]. A blank titration was compared to the $FeSO_4$ added. Organic-C was determined by this equation:

$$WBC = M + \frac{(v_1 - v_2)}{W} \times 0.30 \times CF$$

where *WBC* is Walkley–Black organic carbon (%), *M* is the molarity of the $FeSO_4$ solution from blank titration (mol/L), V_1 is the volume (L) of $FeSO_4$ required in blank titration, V_2 is the volume (L) of $FeSO_4$ required in actual titration, *W* is the weight (g) of the oven-dried soil sample, and *CF* is the correction factor. CEC was analyzed with the atomic absorption spectrophotometry method developed by [56]. The pH was analyzed with Potentiometric [57].

2.7. Statical Analysis

Two-way ANOVAs were used to test for the statistical significance of the treatments with a confidence level of 95%. The Least Significant Difference (LSD) was used for multiple comparisons at a probability level of 0.05. Correlations were analyzed using Pearson tests (two-tailed, $p < 0.05$). All statistical analyses were performed using SPSS 20.0 software (SPSS Inc., Chicago, IL, USA).

3. Results

3.1. Biochar Effect on Total P, Organic-C, CEC, and pH

The interaction treatment of total P, organic-C, CEC, and pH were significant by *p*-value < 0.001. Treatment with T600D45 provides the most effective total P in the soil and CEC by 192.2 mg kg^{-1} and 25.98 me 100 g^{-1}, sequentially (Figure 3a–d). Meanwhile, the treatment with the most significant effect on the organic-C content is T400D50 by 2.83%. Nonetheless, T600D50 was in the same class as T400D50, which means that the treatment affected the organic-C matter in the soil. It showed that treatment with a higher dosage resulted in higher organic-C to the soil. Furthermore, all *Shorea* sp. biochar treatments significantly affected soil pH compared to control, showing the highest value in T600D25 (Figure 3d). It could be concluded that a higher pyrolysis temperature might lead to a high soil pH increase.

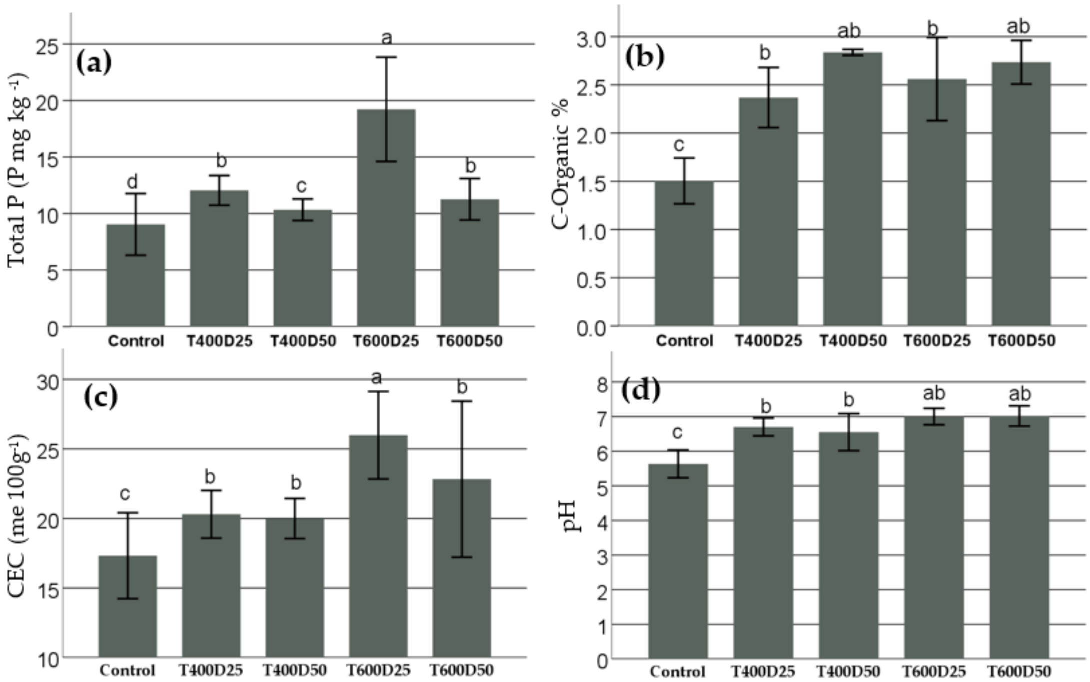


Figure 3. (**a**) P-total P, (**b**) organic-C, (**c**) CEC, and (**d**) pH in the five experimental treatments: dosage 0 t ha^{-1} (control), dosage 25 t ha^{-1} at 400 °C (D25T400), a dosage of 50 t ha^{-1} at a temperature of 400 °C (D50T400), dosage 25 t ha^{-1} at 600 °C (D25T600), and a dosage of 50 t ha^{-1} at a temperature of 600 °C (D50T600) after six months planted in the field. Different letters above the bars indicate statistically significant differences between the sampling times within the same treatment ($p \leq 0.05$). Vertical bars represent the standard error of the mean.

3.2. Correlation of Total P with Organic-C, pH, and CEC

All treatments show a positive correlation between soil total P with organic-C and pH. Meanwhile, the correlation between soil total P to CEC, T400D25, negatively correlates by −0.088 (Table 2). Organic-C correlation to soil total P, T400D50, T600D25, and T600D50 had the highest number of Pearson coefficients, categorized as a very strong correlation [58]. It indicates that higher temperatures will improve organic-C matter in the ground. Still, a lower dosage with a lower pyrolysis temperature makes a minor increment in the organic-C value in the soil (Figure 4a–e). On CEC correlation with total P, T400D25 and T600D25 provide the most robust relation of 0.969 and 0.948, respectively. Based on [47], this was classified as a strong correlation. It is suspected that the smaller dosage has a more substantial correlation between P total and CEC (Figure 4f–j). On pH correlation, all treatments have a strong correlation. It shows that total P is strongly influenced by the increase in pH (Figure 4k–o).

Table 2. Pearson correlation analysis of total P with organic-C, pH, and CEC.

Parameter	Total P				
	Control	**T400D25**	**T400D50**	**T600D25**	**T600D50**
Organic-C	0.540	0.292	0.832	0.937	0.885
pH	0.777	0.896	0.775	0.954	0.894
CEC	0.589	0.969	−0.088	0.948	0.412

Notes: dosage 0 t ha^{-1} (control), dosage 25 t ha^{-1} at 400 °C (D25T400), a dosage of 50 t ha^{-1} at a temperature of 400 °C (D50T400), dosage 25 t ha^{-1} at 600 °C (D25T600), and an amount of 50 t ha^{-1} at a temperature of 600 °C (D50T600).

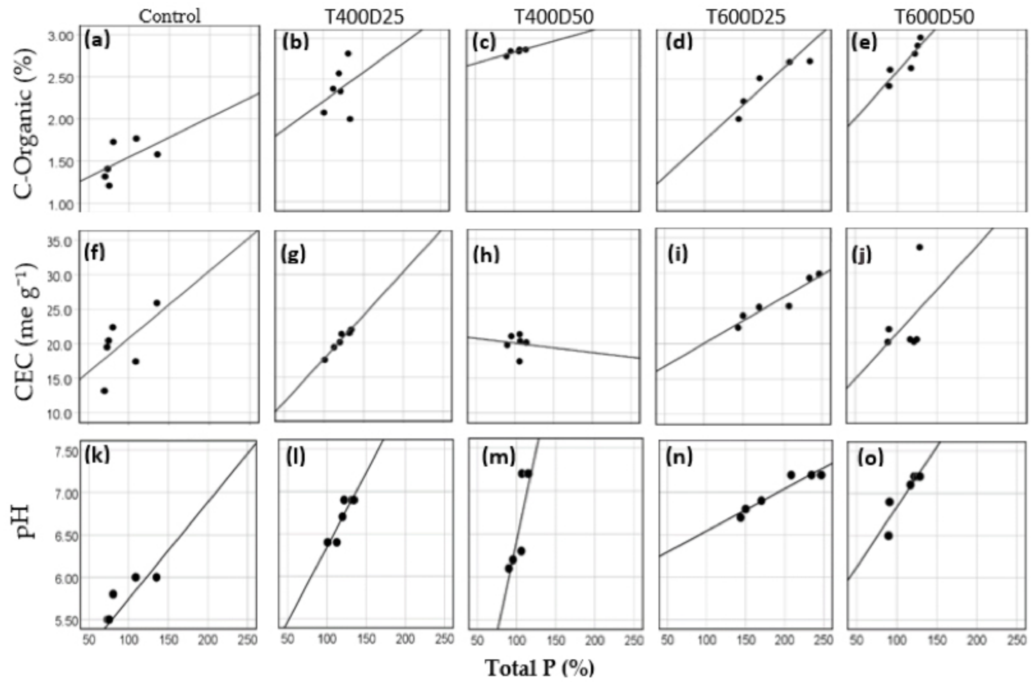


Figure 4. (**a**–**e**) correlation between Total P to organic-C, (**f**–**j**) CEC, and (**k**–**o**) pH in the five experimental treatments: dosage 0 t ha^{-1} (control), dosage 25 t ha^{-1} at 400 °C (D25T400), a dosage of 50 t ha^{-1} at a temperature of 400 °C (D50T400), dosage 25 t ha^{-1} at 600 °C (D25T600), and an amount of 50 t ha^{-1} at a temperature of 600 °C (D50T600) after six months planted in the field. The line indicated the slope and form of correlation between the two parameters.

3.3. P-Uptake on Leaf

The interaction treatment at P-uptake on the leaf analysis was significant with a *p*-value < 0.001. Similar to the height and diameter increment, biochar with a pyrolysis temperature of 600 °C and a dosage of 25 t h^{-1} provided the most sign P absorption by 0.42 mg kg^{-1} (Figure 5). Sequentially, the correlation between the height and diameter increment to P absorption on leaf had coefficients 0.92 and 0.91 (Figure 6). It indicated that the form of its correlation is a positive correlation. The height and diameter increment will increase by enhancing P on the leaf and vice versa (Figure 6a,b). Based on Pearson strength correlation classification, the Pearson correlation coefficients of height and diameter increment indicates a strong relation. A slight change in one of the variables will change others sensitively.

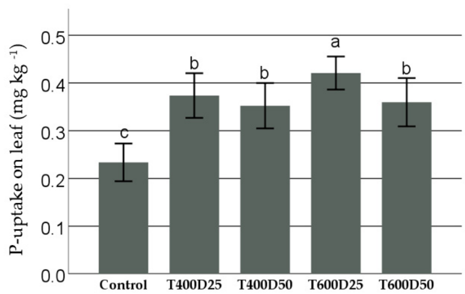


Figure 5. P absorption on the leaf in the five experimental treatments: dosage 0 t ha^{-1} (control), dosage 25 t ha^{-1} at 600 °C (D25T400), a dosage of 50 t ha^{-1} at a temperature of 400 °C (D50T400), dosage 25 t ha^{-1} at 600 °C (D25T600), and a dosage of 50 t ha^{-1} at a temperature of 600 °C (D50T600) after six months planted in the field. Different letters above the bars indicate statistically significant differences between the sampling times within the same treatment ($p \leq 0.05$). Vertical bars represent the standard error of the mean.

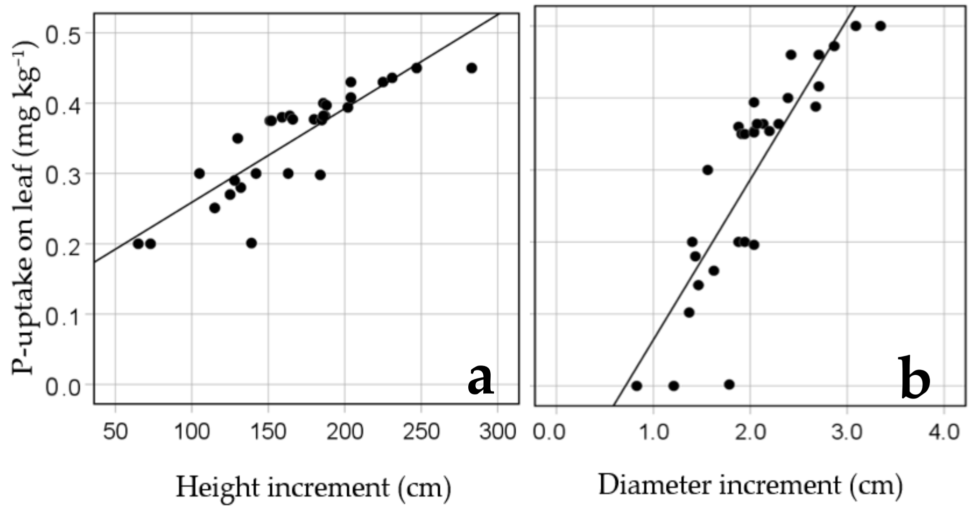


Figure 6. (**a**) correlation between P absorption on the leaf to height, and (**b**) diameter increment after six months planted in the field. The line indicated the slope and form of correlation between the two parameters.

3.4. Plant Growth

All *Shorea* sp. biochar application interaction treatments significantly affected the growth of the *F. moluccana* seedling in terms of height and diameter increment after six months, with a *p*-value for height and diameter increment <0.001. *Shorea* sp. biochar with a pyrolysis temperature of 600 °C and a dosage of 25 t h^{-1} (T600D25) provided the greatest height and diameter increment by 222 cm and 2.75 cm, respectively (Figure 7a,b). Furthermore, T600D25 was 42.26% and 42.22% higher than the control, respectively. Based on the increment in the height and diameter, a similar effect pattern was observed. However, all biochar treatments to the height increment are in the same class, which means that these four treatments have the same effect on the height increment except the control.

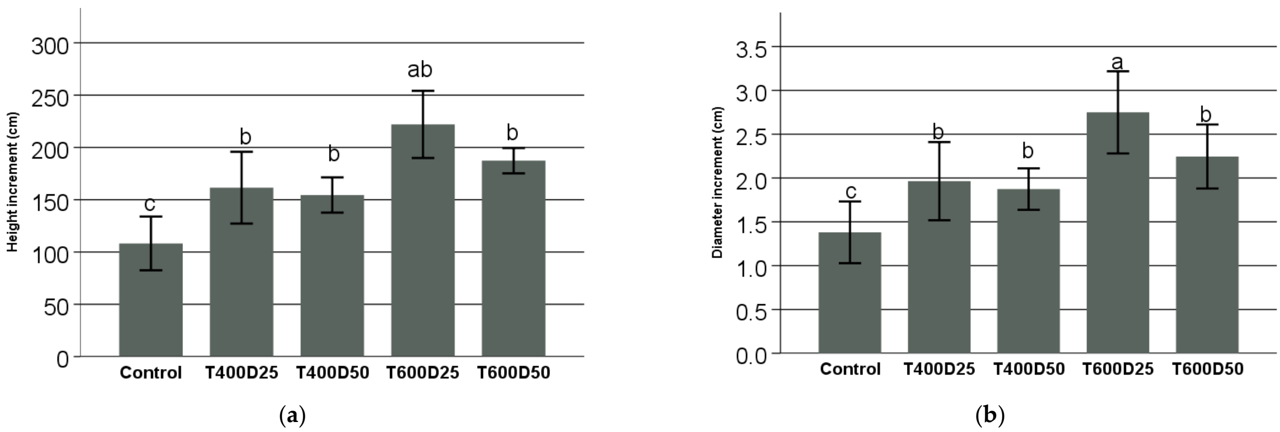


Figure 7. (**a**) Height increment, and (**b**) Diameter increment in the five experimental treatments: dosage 0 t ha^{-1} (control), dosage 25 t ha^{-1} at 400 °C (D25T400), a dosage of 50 t ha^{-1} at a temperature of 400 °C (D50T400), dosage 25 t ha^{-1} at 600 °C (D25T600), and a dosage of 50 t ha^{-1} at a temperature of 600 °C (D50T600) after six months planted in the field. Different letters above the bars indicate statistically significant differences between the sampling times within the same treatment ($p \leq 0.05$). Vertical bars represent the standard error of the mean.

4. Discussion

In this application method, P fertilizer was not added. However, it increased the total P higher than control. This might be because biochar absorbs P from mineral leaching during the P cycle [59]. In the terrestrial area, the common pool resource of P is from bedrock and organisms [60]. P is weathered from bedrock and leached by runoff to the soil, mainly in the form of apatite ($Ca_{10}(PO_4)6(OH, F, Cl)_2$) [61]. The study in [1] demonstrated that the solubility of P in the soil changes during soil development. At the early stage, it is dominated by insoluble apatite. At mid-stage, organic-P increases as a less-soluble mineral. At the late stage, P is partitioned between organic-P and refractory minerals. Decomposed leaf litter also uplifts the P from the earth and assimilates P reservoirs on the topsoil [62].

The biochar application method also might increase P in soil. Biochar was positioned before the topsoil without mixing with the soil. Biochar plays a role in P storage, as it absorbs P from the environment and releases it to the soil above. This is supported by [63], stating that biochar could increase P on the soil by P-sorption and -desorption mechanisms. Biochar P-sorption mechanism sequestrates P via its strength ionic exchange. Biochar acquisition supplies some metal ions such as Al^{3+} and Fe^{2+} to the soil [64], and these ions form a solid ionic bond with P in the soil. The ionic bond then sequestrates P inside the biochar solution. The P-desorption mechanism releases P to the soil solution. When soil depletes P, biochar desorbs to equilibrium and makes P soluble [45]. Thus, the total P increases in the soil. In addition, Biochar undergoes intra-biochar diffusion before releasing P to the soil solution [65]. The intra-biochar diffusion is relatively slow [45]. Therefore, it is possible to slow-release P-desorption from biochar to a soil solution. This biochar application design could maximize P retention in the soil for a long time span and can help to avoid leaching because the P is saved inside the biochar layer. Furthermore, this application method can preserve several fertilizers added into the site and promotes slow-release from the addition of the fertilizer.

Additionally, T600D25 increased total-P in the soil and P-uptake to *F. moluccana,* was found to produce a higher increase than T600D50. The high dosage might be the reason. As explained previously, the nutrient undergoes an intra-biochar diffusion to release soluble P to the soil. The biochar-application design of a dosage of 50 t ha^{-1} has a longer dimension than the smaller dosages. In [45], it was estimated that the rate of intra-biochar diffusion is 1.5×10^{-12} cm^2 s^{-1}. To reach the topsoil, the intra-biochar diffusion of P requires more time to release P into the soil due to this longer dimension. It might cause P-uptake in the topsoil by *F. moluccana*'s root to become inefficient. However, this assumption needs to be proven by calculating the exact time of intra-biochar diffusion in further research.

Biochar pyrolyzed at 600 °C has a higher increase in total-P than the treatment at 400 °C because biochar pyrolyzed at 600 °C has a better thermal decomposition of its structure than 400 °C. A previous study [34] evaluated the thermal decomposition of *Shorea* sp. wood during pyrolysis and reported that hemicellulose, cellulose, and lignin were decomposed at 210–310 °C, 300–400 °C, and 150–900 °C, respectively. The *Shorea* sp. biochar used in this study pyrolyzed at 600 °C and almost optimally decomposed, resulting in a broader surface area than the biochar pyrolyzed at 400 °C. In [45], it was revealed that biochar at a pyrolysis temperature of 600 °C has a surface area 28.3 times wider than biochar with a pyrolysis temperature of 350 °C. Furthermore, the author elucidated that a higher pyrolysis temperature could absorb the ionic P by a rate of 58% higher than a lower pyrolysis temperature. The wider surface also increases ionic exchange [66]. Thus, it increases the P-sorption in biochar.

A wider surface area also increased CEC. Several studies have proven that biochar with a wide surface area will increase CEC [25,27,67–70]. Biochar has a high surface area charge density and a large surface area per unit mass [25]. It increases the soil colloid and maximizes nutrient absorption in the soil [27]. Moreover, biochar production with a high pyrolysis temperature produces a higher ash content. Biochar with an ash-rich content will enhance CEC in the soil [71,72]. *Shorea* sp. biochar with a pyrolysis temperature of 600 °C has an ash content 3.34 times higher than the lower temperature pyrolysis [52]. Therefore, T600D25 has the highest CEC increment when compared with the other treatments.

CEC determines the amount of total P in the soil [73]. However, the availability of P is determined by pH [60]. Both T600D25 and T600D50 have a higher soil pH than T400D25 and T400D50. The *Shorea* sp. biochar pH increases during production with increasing temperatures [52]. Biochar application on soil depends on the biochar pH [74]. Furthermore, pH is essential in supplying soluble P because it causes the release of ionic nutrients that bond with the soil colloid. P is soluble at a pH of 6.5–7 [75]. P reacts with Al^{+3}, $Mg^{+2,}$ and Fe^{+2} at a lower pH; at higher pH, P reacts with Ca^{+2} [1]. It can be assumed that *Shorea* sp. biochar produced with a lower pyrolysis temperature in 6 months application was not capable of increasing soil pH to the extent that *Shorea* sp. biochar produced with a high pyrolysis temperature was able to. Further research needs to be conducted to examine the change of *Shorea* sp. biochar pH for longer time spans in the soil.

Organic-C matter in the soil affects the increment in CEC and pH [76]. All *Shorea* sp. biochar treatments led to an increase in the organic-C content. The *Shorea* sp. biochar feedstock already contains a high C content compared to other wood species [40]. C content on raw *Shorea* sp. feedstock is 41.7 wt.%; after pyrolysis, the C content increases two-fold [34]. This abundance in C content in the biochar will increase the organic-C matter in the soil. The dosage is in line with the increase in organic-C. Nonetheless, the overapplication of biochar presents some problems, such as filling soil pore spaces [77] and the excessive accumulatio of heavy metal elements in the soil [78].

The soil's increment in organic-C affects the microorganism colonization [30]. Microorganism colonization is essential for P for plant growth. Nonetheless, soluble P is not always available for plants [1]. P-uptake to the plant by its root is in the form of HPO_4 and H_2PO_4 [79]. In general, there are three mechanisms by which soil microorganism transforms and enhance the capacity of P as an essential nutrient for plant growth. First, by stimulating root–phosphorous mycorrhiza association to increase soluble P [80] or producing stimulation-like hormones to enhance the development of root, branch or reproductive organs [81], for example producing GAs, indole-3-acetic acid, or alternative plant ethylene precursors enzyme, such as carboxylate deaminase, or 1-aminocyclopropane-1 [82]. Second, by customizing the P equilibrium in the soil. This either increases the net transfer of orthophosphate ions to the soil solution or promotes organic P directly or indirectly via microbial turnover [83]. The third mechanism is by directly solubilizing P from available soil and inducing metabolic processes that are effective in mineralizing inorganic and organic P [84,85].

There is a positive relationship between the increase in the CEC, pH, and organic-C to total P in the soil from the explanation above. The increment in CEC leads to organic-C retention. Thus the abundance of organic-C increases soil microorganisms. Expanded soil-microorganism colonization transforms and mobilizes P to the soil and increases its concentration. This mechanism will increase P-uptake to *F. moluccana*. The highest P-uptake into *F. moluccana* is achieved with T600D25. That is because T600D25 has the highest P assimilation in the soil. The availability of P in soil solution determines the P-uptake to the plant. It causes the concentration difference between root and soil. High P concentration differences boost the P transporter present in the root plasma membrane against the concentration gradient [86]. The P transporter is an integral membrane protein consisting of 12 membrane members of the Major Facilitator Super family (MFS) [87]. It uses an H^+ gradient to drive the transport process [11].

Additionally, T600D25 resulted in the highest height and diameter increment. This is a result of the highest P-uptake for T600D25. In the plant, phosphorus constructs the component of high energy bonds, including phosphoanhydride, enol phosphate, and acyl phosphate. It plays a role in controlling cellular metabolism by transferring energy required by the acceptor molecules [88]. P is also well recognized as the main component in ATP. ATP supports some cellular processes, including membrane phospholipids [89], synthesis of macromolecules [90], and nutrient transport due to its high concentration gradient [91]. The relative P growth decreases during P deficiency because ATP is reduced in several vital organs such as roots and leaves [11,88]. Hence, the height and diameter increment in *F. moluccana* is determined by P concentration in the plant.

5. Conclusions

The *Shorea* sp. Biochar-application method in this study could increase the soil total-P and the growth of *F. moluccana*. Additionally, T600D25 increased the height and diameter of *F moluccana* seedlings by 51.04% and 49.82% higher than control, respectively. The biochar layer can sequestrate P from the environment and release it to the topsoil. Biochar treatments with high dosages, T400D50 and T600D50, increased higher organic-C in the soil than lower dosage treatments and control. Biochar pyrolyzed at a higher temperature (600 °C) increased CEC and pH higher than biochar pyrolyzed at a lower temperature (400 °C), even with the high dosage. The increment in the CEC and soil pH induced soluble P on topsoil. Furthermore, T600D25 led to the highest P in topsoil among other treatments, of 192.2 mg kg^{-1}. Soluble P on the topsoil was absorbed by *F. moluccana* seedlings. The P-uptake increment on *F. moluccana* seedlings improved its height and diameter. This biochar application method can maximize fertilizer addition in the future. It can store nutrients from the fertilizer in the biochar layer and slow-release it to the topsoil.

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