Menara Perkebunan 2025, 93(1), 57-67
p-ISSN: 0125-9318/ e-ISSN: 1858-3768
http://dx.doi.org/10.22302/iribb.jur.mp.v93i1.611
Accreditation Number: 177/E/KPT/2024.

The influence of pyrolysis temperature and dosage of shorea wood biochar produced on soil properties and sengon (*Falcataria moluccana*) seedling biomass

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Received 31 Jan 2025 / Revised 14 Feb 2025 / Accepted 30 Apr 2025

Abstract

This study explores the effects of pyrolysis temperature of shorea wood biochar and its doses on the soil properties and biomass of *Falcataria moluccana* seedlings. The focus is optimizing pyrolysis temperatures (400°C and 600°C) and biochar doses (0%, 25%, and 50%) to enhance soil fertility and seedling biomass. Both pyrolysis temperature and biochar dose are critical factors that influence the soil properties, directly affecting its effectiveness as a soil amendment. The research was conducted as a controlled greenhouse experiment over 120 days; each treatment was replicated 15 times. We observed several soil chemical properties, including pH, Cation Exchange Capacity (CEC), organic carbon (C-organic), total nitrogen (N-total), and total phosphorus (P-total). The growth parameters assessed included above ground biomass (AGB), below ground biomass (BGB), total biomass (TB), and root to shoot ratio (R:S). Data analysis involved one-way and two-way ANOVA. Results indicated that soil properties, particularly cation exchange capacity (CEC) and organic carbon content, were improved, thereby enhancing soil fertility. However, ANOVA indicated no statistically significant differences across treatments. Biochar significantly enhanced above-ground and below-ground biomass (AGB and BGB). Nevertheless, both pyrolysis temperature and biochar dose independently influenced biomass accumulation in *F. moluccana* seedlings. The highest increases were observed in the treatment with the highest pyrolysis temperature (600°C) and the highest dose (50%), which led to an 85% increase in AGB and a 60% increase in BGB compared to the control. Based on the study, Shorea wood biochar, particularly when used at 600°C and 50% dose, significantly improves soil fertility and seedling growth, providing a promising approach for developing *F. moluccana* plantations.

[Keywords: ameliorant, charcoal, meranti, sengon, waste]

Introduction

Falcataria moluccana, commonly known as sengon, plays a critical role in Indonesia's forestry sector, particularly in plantation forestry, land restoration, and agroforestry systems. This fast-growing species is highly valued for its wood, which is used in construction, furniture, and paper production (Karyati et al., 2019) and commercial timber production. In addition to its economic value, *F. moluccana* contributes to soil improvement, which enhances soil fertility (Sarminah et al., 2018). However, the successful growth of *F. moluccana* seedlings in degraded or nutrient-poor soils often requires the application of soil amendments that can boost soil fertility and improve plant growth. The use of biochar, a form of charcoal produced through pyrolysis of organic materials, has gained significant attention as a sustainable soil amendment that enhances soil properties and promotes plant growth (Rawat et al., 2019; Guo et al., 2020; Kamali et al., 2022).

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How to Cite: Riniarti, M., Hidayat, W., Prasetia, H., & Wijaya, B.A. (2025). The influence of pyrolysis temperature and dosage of shorea wood biochar produced on soil properties and sengon (*Falcataria moluccana*) seedling biomass. *Menara Perkebunan, 93*(1), 57-67 http://dx.doi.org/10.22302/iribb.jur.mp.v93i1.611

Recent studies have highlighted the positive impact of biochar on soil quality, particularly in improving nutrient availability, increasing cation exchange capacity (CEC), and enhancing organic carbon content. Research has consistently shown that biochar can improve soil structure, increase microbial activity, and promote plant growth by improving water retention and nutrient supply (Lehmann et al., 2015; Hossain et al., 2020). Biochar's potential as a soil amendment has been widely explored in various agricultural systems, with studies revealing its ability to mitigate soil acidity, enhance nutrient cycling, and reduce greenhouse gas emissions from soils (Agegnehu et al., 2017; Lehman et al., 2021). Specifically, the use of biochar in tropical soils has shown promise in enhancing the growth of tree species (Alling et al., 2014; Carneiro et al., 2021).

The effectiveness of biochar as a soil amendment is influenced by several factors, including its source material, application rate, and most importantly, the pyrolysis temperature at which it is produced. Pyrolysis temperature affects biochar's physical and chemical properties, such as its surface area, pore structure, and nutrient content, which in turn influence its ability to improve soil fertility. Lower pyrolysis temperatures (e.g., 400°C) typically produce biochar with higher surface area and greater nutrient retention capacity, while higher pyrolysis temperatures (e.g., 600°C) result in biochar with a more stable carbon structure, which can persist longer in soils and contribute to long-term soil improvement (Yuan et al., 2015; Tomczyk et al., 2020; Wang et al., 2020). However, the relationship between pyrolysis temperature and biochar quality is complex, and understanding how different temperatures influence biochar's effectiveness in improving soil and plant growth is essential for optimizing its use in forestry and agriculture. The higher the fixed carbon content in biochar, the better it conserves soil nutrients (Xie et al., 2016; Domingues et al., 2017). According to Mazlan et al. (2015), biochar derived from Shorea wood pyrolyzed at 600°C contains 84.9% fixed carbon, which is higher than that of rubberwood at 77.2% which pyrolyzed at 550°C, *Tectona grandis* at 75.51% fixed carbon and F. *moluccana* at 72.4% (both pyrolyzed at 600°C (Gupta et al., 2019). This makes Shorea wood biochar particularly attractive for agricultural and forestry applications. Currently, Shorea wood waste (including the log part of the commercial stem, short pieces, stumps, branches, and twigs) amounts to 557.87 m³ (Sari, 2018), and converting this waste into biochar represents a promising waste management strategy; it effectively returns carbon to the soil, enhances soil fertility and promotes sustainable land management practices.

Given the increasing interest in biochar's role in sustainable land management, this study aims to explore how different biochar doses and pyrolysis temperatures influence the growth and biomass production of *F. moluccana* seedlings, with a focus on optimizing biochar application for enhanced soil fertility and seedling quality. By examining the effects of Shorea wood biochar produced at 400°C and 600°C on *F. moluccana* seedlings, this research contributes to a deeper understanding of biochar's potential to enhance the growth of key tree species in forest plantation. Moreover, this study aims to determine the optimal biochar treatment conditions for improving both plant performance and soil quality, providing valuable insights for the future use of biochar in sustainable forestry across Indonesia.

Material and Methods

The biochar production process followed the procedure described by Hidayat et al. (2021), conducted at the research and development facility of PT. Kendi Arindo Lampung, Indonesia, uses traditional batch-type kilns with a capacity of 12 m³. The kilns were equipped with five control holes to regulate the oxygen supply. Shorea wood was horizontally stacked to full capacity and ignited from the top layer. Once the upper layer began to burn, the control holes were gradually closed to limit oxygen, creating a low-oxygen pyrolysis environment. The process targeted peak temperatures of 400°C and 600°C, which were monitored hourly. Kiln temperature was regulated by partially opening or closing the control holes, depending on temperature fluctuations. Each pyrolysis batch lasted approximately 14 days, including initial burning, peak temperature maintenance, and natural cooling. The pyrolysis process was conducted separately for each treatment temperature (400°C and 600°C), but only one batch was produced per temperature. Following the pyrolysis, the biochar was exposed to ambient conditions for 24 hours and then sieved to separate ash and combustion residues. To ensure uniform application, the biochar was crushed and passed through a 2 mm sieve, which aligns with standard biochar soil amendment practices. The biochar was then applied to the planting medium for *Falcataria moluccana* seedlings.

F. molucanna seeds were germinated over two weeks in a controlled nursery environment. Sand served as the primary growth medium throughout the initial stages of seedling development. Before sowing, the seeds underwent scarification via hot water immersion at 80°C followed by a soaking duration of 24 hours (Rupinta et al., 2014). Once germination occurred, the seedlings were transplanted into pots measuring 180 mL in volume.

As soon as they developed their first set of leaves and woody structures, the seedlings were moved to larger containers holding 320 mL each. At this point, they were planted in a custom-prepared growing medium composed of air-dried, sieved topsoil blended with biochar according to specific treatment dosages. Throughout their cultivation cycle, regular maintenance included maintaining optimal watering levels, implementing pest management measures, controlling disease outbreaks, and conducting periodic weeding activities.

The treatments applied in this study were three doses of Shorea wood biochar to the planting medium. The treatments consisted of a control (0% biochar or 100% soil), D25 (25% Shorea wood biochar and 75% soil), and D50 (50% Shorea wood biochar and 50% soil). Seedling growth was observed for 120 days. The observed parameters included several soil chemistry properties: pH, Cation Exchange Capacity (CEC), C-organic, N-total, and P-Total. Soil pH was measured using a 1:2.5 soil-to-water suspension method with a pH meter. The cation exchange capacity (CEC) was determined through the ammonium acetate method at pH 7. C-organic content was analyzed using the Walkley-Black method. N-total was assessed using the Kjeldahl digestion method. For P-total, the extraction was performed using the Bray I method, and the phosphorus concentration was quantified using Atomic Absorption Spectrophotometry (AAS). The growth parameters were above ground biomass (AGB), below ground biomass (BGB), total biomass (TB), height, diameter, and root to shoot (R:S) ratio. Biomass values were obtained by measuring the biomass after oven-drying at 80°C until a constant weight was achieved.

The study analyzed the effect of biochar on the biomass growth of *F. moluccana* seedlings, focusing on pyrolysis temperature and the dose. To address the imbalance in sample size when comparing treatments to the control, we used one-way ANOVA for the control (Control), 25% dose (D25), and 50% dose (D50). We then applied two-way ANOVA to explore the combined effects of pyrolysis temperature (400°C - T400, 600°C - T600) and dose (D25, D50) across treatments (T400D25, T600D25, T400D50, T600D50). Each treatment included 15 replicates. We analyzed variables that met ANOVA assumptions quantitatively, while we described those that did not qualitatively.

One-way and two-way ANOVA analyses were conducted in OriginLab to evaluate the effects of pyrolysis temperature and biochar dose and their interaction on the response variable. For one-way ANOVA, the dose (Control, 25%, 50%) was analyzed using 15 observations per group. Assumptions of normality and homogeneity of variance were tested using built-in tools in OriginLab, and post hoc comparisons were performed using Tukey's HSD test. The results were visualized with boxplots to illustrate group differences. Two-way ANOVA was used to examine the main effects of Temperature (400°C, 600°C), dose (25%, 50%), and as well as their interaction, with 15 observations per combination ($n = 60$). Interaction effects were analyzed and visualized using interaction plots and grouped boxplots to assess how temperature modified the effect of dose.

The correlation between soil analysis and biomass growth was determined using the Pearson correlation in OrginLab. The result is then displayed in the heat map to show the strength and type of relation between soil and biomass growth.

Results and Discussion

Soil characteristics/properties

The results of soil chemical analysis are presented in Table 1, including pH, cation exchange capacity (CEC), organic carbon (C-organic), total nitrogen (N-total), and total phosphorus (P-total) after 120 days of treatment. Although ANOVA indicated no statistically significant differences across treatments ($p > 0.05$), some observable trends emerged.

Soil pH tended to increase slightly with the application of biochar produced at 600°C, while a modest reduction was observed with 400°C biochar. This pattern is consistent with previous findings indicating that high-temperature biochar contains higher concentrations of basic cations such as Ca^{2+}, Mg^{2+}, and K^{+}, which contribute to pH elevation (Chandra & Bhattacharya, 2019). In contrast, according to Ding et al. (2014), lower-temperature biochar tends to retain a higher proportion of volatile organic compounds and acidic functional groups, leading to a slight reduction in soil pH when incorporated into the growing medium.

The addition of biochar enhances the soil's CEC, with biochar produced at 400°C, resulting in the highest CEC values, ranging from 71-9.6 me/100g, particularly at higher application doses. This aligns with studies suggesting that lower-temperature biochar preserves a greater abundance of oxygen-containing functional groups (e.g., –COOH and –OH), which enhance CEC and nutrient retention (Chen et al., 2016; Fan et al., 2018). As pyrolysis temperature increases, the aromaticity of biochar also increases, reducing the density of surface functional groups and thereby lowering CEC (Bolan et al., 2022).

C-organic content generally increases with biochar application, though the T600D25 treatment shows a C-organic level comparable to the control (1.2%). However, N-total decreases in all biochar treatments compared to the control, indicating a potential adverse effect of biochar on soil nitrogen levels. Haider et al. (2022) explain this may be due to nitrogen immobilization resulting from the high C:N ratio of biochar, reducing immediate nitrogen availability. Moreover, increased microbial activity stimulated by biochar may influence nitrogen dynamics through competition or enhanced volatilization under higher aeration (Lehmann et al., 2015).

No clear treatment effect was observed for total phosphorus (P-total), suggesting that short-term biochar application may have limited impact on P availability under the experimental conditions. However, long-term field studies are required to validate this pattern in different soil types.

In summary, although statistical significance was not achieved, the directional trends observed in this study align with existing literature and provide useful insight into the interactive effects of pyrolysis temperature and biochar dose on tropical soil chemical properties.

Growth of Falcataria moluccana *seedling*

The summary of ANOVA for all experimental designs is presented in Table 2. The ANOVA results in the table provide insights into the effects of pyrolysis temperature and biochar dose on different biomass measurements (AGB, BGB, and TB). The one-way ANOVA shows that the biochar dose (control, 25%, and 50%) significantly affects AGB, BGB, and TB, with F-values of 14.17, 6.96, and 15.21, respectively, and all p-values are below 0.01, indicating strong significance.

In the two-way ANOVA, the pyrolysis temperature (400°C and 500°C) significantly affects all biomass measurements: AGB (F-value: 45.05, $p < 0.01$), BGB (F-value: 5.18, $p < 0.05$), and TB (F-value: 35.71, $p < 0.01$). while comparing only the 25% and 50% doses, the dose significantly affects AGB (F-value: 12.55, $p < 0.01$) and TB (F-value: 10.24, $p < 0.01$), but there is no significant effect on BGB (F-value: 1.15, $p > 0.05$). However, the interaction between pyrolysis temperature and dose does not show a significant effect on any of the measurements, with all p-values being non-significant.

Table 1. Soil characteristics of planting medium after 120 days of treatment

Treatment	pH	CEC (me/100g)	C-Organic (%)	N-total (%)	P-total (%)
Control	5.0	6.0	1.2	1.7	0.1
T400D25	4.8	7.1	1.3	1.2	0.1
T600D25	5.2	6.2	1.2	1.4	0.1
T400D50	4.6	9.6	1.3	1.5	0.1
T600D50	5.4	7.0	1.3	1.5	0.1

Notes: control= 0% biochar; T400=400°C pyrolysis temperature; T600= 600°C pyrolysis temperature; D25= 25% biochar dose; D50= 50% biochar dose.

Table 2. Summary of ANOVA

ANOVA	Factor	Measurement	p-value
One-way	Dose (Control, 25%, and 50%)	AGB	**
		BGB	**
		TB	**
Two-way	Pyrolisis temperature (400 and 600°C)	AGB	**
		BGB	*
		TB	**
	Dose (25% and 50%)	AGB	**
		BGB	ns
		TB	**
	Interaction	AGB	ns
		BGB	ns
		TB	ns

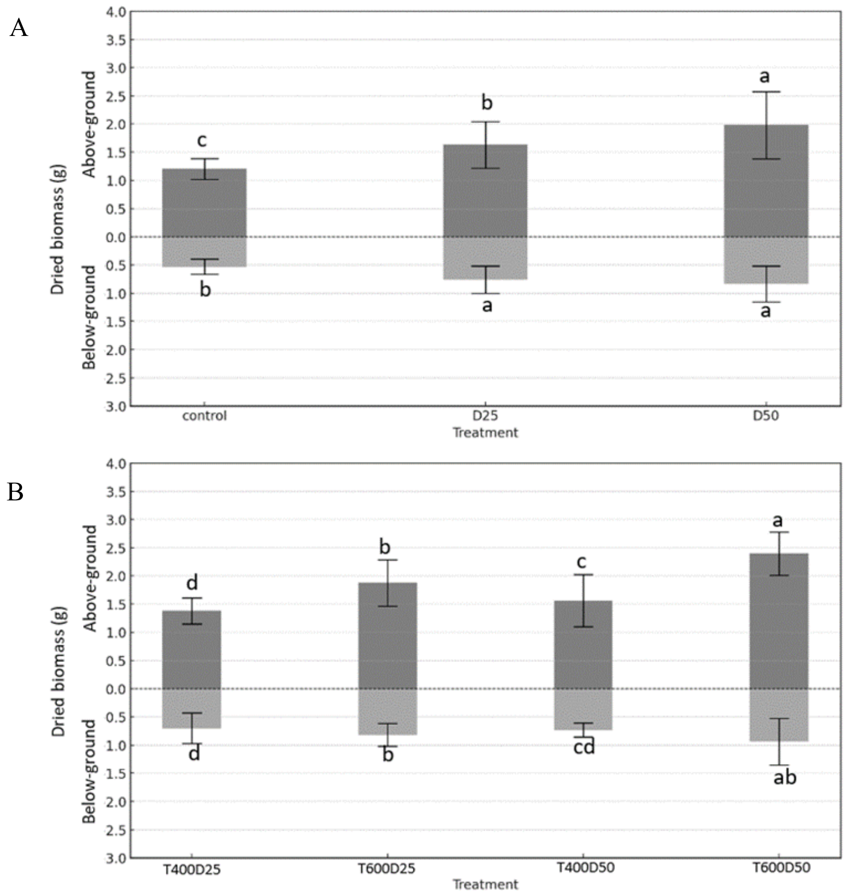
Notes: *significant at 95%;**significant at 99%;ns not significant. (AGB = above ground biomass; BGB= below ground biomass; TB= total biomass).

The ANOVA results demonstrate that both pyrolysis temperature and biochar dose independently influenced biomass accumulation in *F. moluccana* seedlings. Pyrolysis temperature showed an even stronger effect on all biomass parameters, particularly on AGB ($F = 45.05$, $p < 0.01$). This could be explained by the chemical characteristics of biochar produced at higher temperatures, which tend to have higher pH, greater ash content, and more stable carbon structures, as well as enhanced porosity and surface area (Jindo et al., 2014; Tomczyk et al., 2020). These properties improve nutrient adsorption (Agegnehu et al., 2017; Liu et al., 2021), reduce aluminum toxicity in acidic soils, and promote root expansion and microbial activity (Tomczyk et al., 2020).

The significant effects of biochar dose on AGB and TB are likely attributed to soil's enhanced physical and chemical properties resulting from biochar addition, such as improved moisture retention, nutrient availability, and root aeration. Higher doses (50%) likely substantially improved the soil environment, facilitating better plant growth.

Despite the strong independent effects of temperature and dose, their interaction did not significantly influence biomass production. This suggests that each factor contributes through separate mechanisms that do not amplify or suppress one another when combined. In other words, increasing the dose does not necessarily enhance or reduce the effect of pyrolysis temperature, and vice versa. Such additive but non-synergistic responses are not uncommon in soil amendment studies, particularly when both factors are operating near their functional thresholds.

The effects of shorea wood biochar on *F. moluccana* biomass are highlighted in Figure 1. In the one-way ANOVA, D50 increased AGB by 75% over the control and 40% over D25, while BGB increased by about 50% for both D25 and D50 compared to the control, with no significant difference between the two rates (Figure 1A).



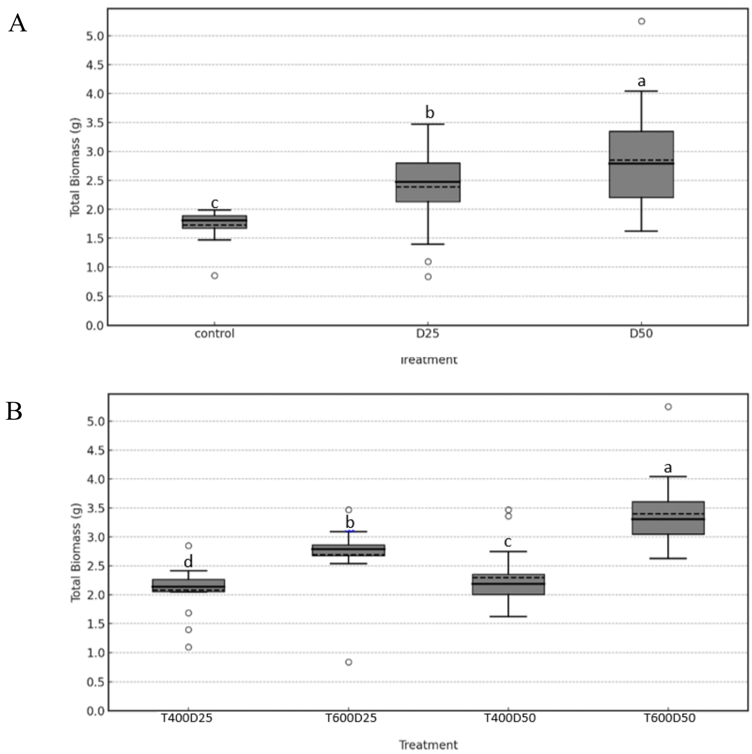
Notes: Different alphabets represent different groups based on posthoc analysis per each measurement

Figure 1. Shorea wood biochar effect on above and below-ground biomass of *F. moluccana* seedling; (A) one-way ANOVA design experiment; (B) two-way ANOVA design experiment. (control= 0% biochar; T400=400^{o}C pyrolysis temperature; T600= 600^{o}C pyrolysis temperature; D25= 25% biochar dose; D50= 50% biochar dose)

This shows that higher doses are more effective for AGB but not for BGB. In the two-way ANOVA, T600D50 achieved the highest biomass, with an 85% increase in AGB and a 60% increase in BGB compared to T400D25. T600D25 also outperformed T400D25, highlighting the critical role of pyrolysis temperature (Figure 1B). However, an anomaly was observed in T400D50, where biomass gains were closer to T400D25 than T600D50, suggesting pyrolysis temperature outweighs dose at lower temperatures.These results indicate that combining 600°C pyrolysis with 50% biochar maximizes biomass, with a high probability (>90%) of significant improvement. Optimization of pyrolysis conditions and dose is essential in achieving consistent results.

The box plots further demonstrate the effects of shorea wood biochar on total dried biomass. In the one-way ANOVA (Figure 2A), the D50 treatment results in the highest total biomass, significantly exceeding both D25 and the control. Specifically, the biomass in the D50 group is approximately 72% higher than the control and 28% higher than D25. Similarly, D25 produces about 35% higher biomass than the control. These results emphasize the substantial positive effect of increasing biochar rates on total biomass.

In the two-way ANOVA (Figure 2B), the combination of 600°C temperature and 50% dose (T600D50) achieves the highest biomass, significantly outperforming all other treatments. The total biomass in T600D50 is approximately 85% higher than T400D50 and 98% higher than T400D25, which has the lowest biomass among all treatments. At 600°C and 25% dose (T600D25), it also produces 49% higher biomass than T400D25, showing the beneficial impact of higher pyrolysis temperatures. The T400D50 treatment results in intermediate biomass levels, 47% lower than T600D50 but 38% higher than T400D25.These findings highlight the synergistic effect of elevated pyrolysis temperatures and higher biochar application rates. The T600D50 combination is the most effective treatment, maximizing biomass production with substantial gains over other treatments.



Notes: Different alphabets represent different groups based on post hoc analysis

Figure 2. Box plot comparison of forest residue biochar effect to total dried biomass of *F. moluccana* seedling; (A) one-way ANOVA design experiment; (B) two-way ANOVA design experiment. (control= 0% biochar; T400=400°C pyrolysis temperature; T600= 600°C pyrolysis temperature; D25= 25% biochar dose; D50= 50% biochar dose)

The results of this study demonstrate the significant potential of Shorea wood biochar to enhance the growth and biomass production of *F. moluccana* seedlings. Our findings align with a growing body of literature highlighting biochar's role in soil improvement and plant development (Lehmann et al., 2015; Jeffery et al., 2017). Specifically, applying biochar produced at higher pyrolysis temperatures, such as 600°C, exhibited pronounced benefits in seedling quality, root-to-shoot biomass ratio, and total biomass. These effects were particularly evident when higher biochar doses (50%) were applied, supporting earlier studies showing pyrolysis temperature and biochar dose as key determinants in optimizing plant responses (Gao et al., 2021).

Our data indicate that both pyrolysis temperature and biochar dose significantly influence the growth of *F. moluccana* seedlings, each having independent effects on biomass production. The highest biomass increases were observed in the T600D50 treatment, where both elevated pyrolysis temperature and higher dose synergistically enhanced biomass production. This agrees with other studies that show higher pyrolysis temperatures and larger biochar doses often lead to increased plant growth due to improved soil fertility and enhanced microbial activity (Murtaza et al., 2021). The substantial increases in observed in this treatment suggest that biochar not only improves nutrient availability but also helps in the stabilization of plant growth by influencing root development (Naeem et al., 2016).

The root-to-shoot biomass ratio (R:S) was figured out in Figure 3 for the control and biochar treatment groups. The control group shows a relatively balanced and consistent R:S ratio, with a median of approximately 0.5 and minimal variability. Among the biochar treatments, notable differences emerge based on the dose and pyrolysis temperature.

For T400D25, the R:S ratio exhibits high variability, with a wider interquartile range compared to the control, indicating inconsistent biomass allocation between roots and shoots. T600D25 reduces this variability and maintains a slightly lower median R:S ratio, suggesting improved stability in biomass distribution. At the higher dose (D50), T400D50 demonstrates a consistent median ratio similar to the control but with outliers that indicate occasional shifts in allocation. Conversely, T600D50 shows the lowest median R:S ratio (~0.4) and reduced variability, signifying a stronger shift toward shoot biomass under these conditions.

Anomalies are evident in outliers, particularly in T400D25 and T400D50, where R:S ratios occasionally deviate significantly from the main data distribution. This could indicate sporadic responses to lower pyrolysis temperatures or environmental factors. The trends suggest that higher pyrolysis temperatures and higher doses (e.g., T600D50) optimize shoot allocation while reducing variability, likely contributing to improved overall biomass productivity.

These results emphasize the importance of treatment optimization, as higher pyrolysis temperatures and biochar doses promote consistent and favorable biomass allocation, with a high probability of reduced root dominance and enhanced shoot growth. The observed anomalies highlight the need for further investigation into treatment-specific responses.

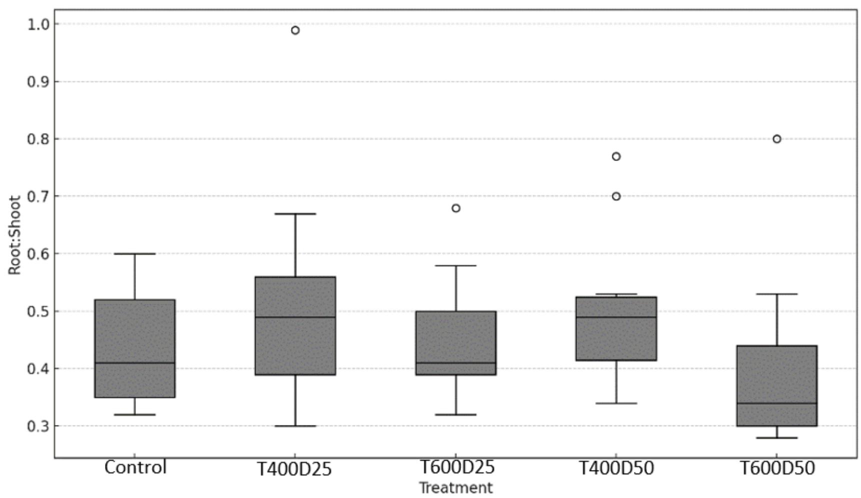


Figure 3. Box plot comparison of root-to-shoot biomass ratio value for control and biochar treatment group. (control= 0% biochar; T400=400°C pyrolysis temperature; T600= 600°C pyrolysis temperature; D25= 25% biochar dose; D50= 50% biochar dose)

The Root-to-Shoot (R:S) ratio analysis further reinforced the benefits of biochar, particularly in optimizing shoot growth. Biochar treatments, especially at 600°C, were associated with a significant reduction in the R:S ratio variability, suggesting more consistent and efficient biomass allocation towards shoot development. This result aligns with findings by Manzoor et al. (2022), who reported that biochar can promote a better root-to-shoot ratio by improving plant water and nutrient uptake. The mechanism behind this improvement lies in biochar's ability to enhance soil structure, increase water-holding capacity, and improve nutrient retention, all of which contribute to a more favorable growing environment for plant roots. Biochar's highly porous structure allows it to retain moisture for extended periods, reducing drought stress and ensuring water availability to plants (Guo et al., 2021).

The Pearson correlation matrix (Figure 4) provides valuable insights into the interrelationships among soil properties and biomass production parameters. A moderately strong positive correlation was found between soil organic carbon (C-organic) and cation exchange capacity (CEC) (r = 0.55), suggesting that increasing organic matter enhances the soil's ability to retain essential nutrients. This is consistent with previous studies that have demonstrated that higher levels of C-organics, particularly from biochar and compost sources, contribute significantly to the accumulation of negatively charged functional groups that increase CEC (Haider et al., 2020).

Total phosphorus (P-total) also showed a positive correlation with above-ground biomass (AGB) (r = 0.42) and total biomass (TB) (r = 0.44), highlighting the importance of phosphorus availability in supporting plant growth. Phosphorus plays a vital role in photosynthesis, root development, cell division, and energy transfer through ATP formation, making it a key driver of biomass accumulation, specially in nutrient-poor tropical soils (Veiga et al., 2021).

A noteworthy negative correlation was observed between CEC and pH (r = -0.52), implying that cation retention may increase in acidic soils due to the higher availability of exchangeable H^+ and Al^{3+} ions. Additionally, a mild negative correlation between C-organic and pH (r = -0.25) may result from the gradual release of organic acids during the decomposition of carbon-rich amendments such as biochar and compost (Khan et al., 2023). These correlation patterns suggest complex, interdependent mechanisms governing soil fertility and plant productivity and reinforce the value of integrating biochar as an organic amendment in soil management strategies.

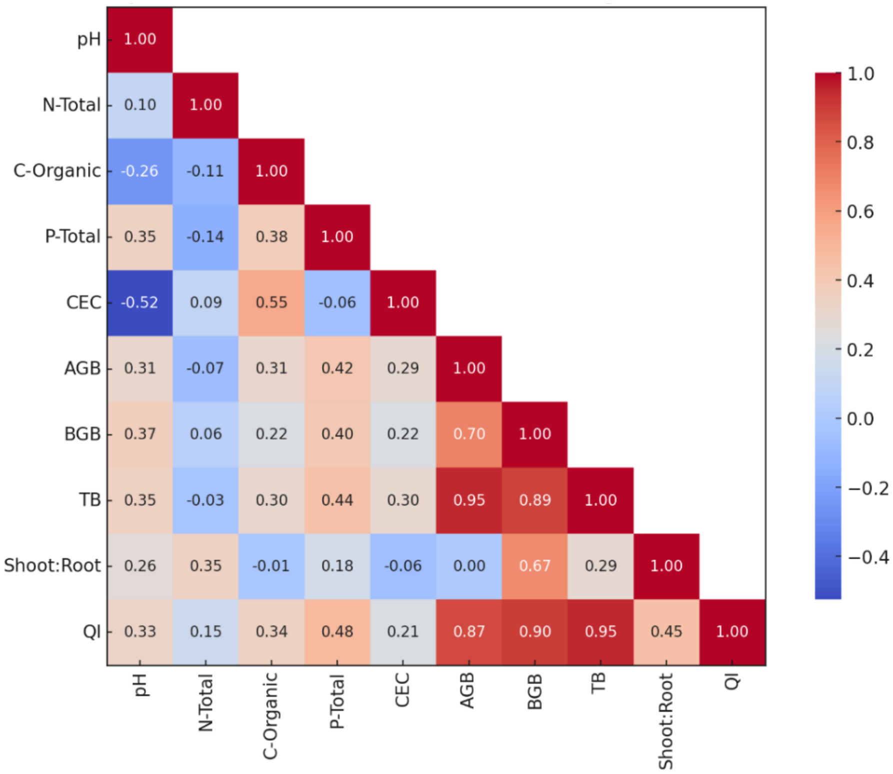


Figure 4. Pearson correlation matrix heatmap of biomass and soil analysis variables

Biochar has long been recognized as an effective soil ameliorant. However, most existing studies have predominantly focused on biochars derived from agricultural residues such as rice husks, corn cobs, and straw (Agegnehu et al., 2017). In contrast, the potential of biochar produced from tropical hardwood waste, particularly Shorea spp., remains largely underexplored. Notably, Shorea-derived biochar is characterized by a remarkably high fixed carbon content (up to 84.9%), suggesting its superior capacity to retain soil nutrients and enhance soil quality when compared to biochars derived from agricultural residues or fast-growing softwoods such as *F. moluccana* and even teak (*Tectona grandis*) (Khosravi et al., 2022). Moreover, studies investigating the efficacy of biochar under factorial combinations of pyrolysis temperature and application dosage remain limited. Although previous research has highlighted the benefits of biochar in improving water retention, microbial activity, and nutrient availability (Rawat et al., 2019; Hossain et al., 2020; Pathy et al., 2020), the complex interactions between pyrolysis temperature, application dose, and species-specific plant responses to biochar derived from tropical hardwoods remain poorly documented, particularly in the context of tropical sylviculture.

Conclusion

This study examined the effects of biochar pyrolysis temperatures and application dose on soil chemical properties and the early growth of *F. moluccana* seedlings under tropical conditions. While differences in soil pH, CEC, and organic carbon were not statistically significant, a general trend of improvement was observed, particularly in treatments involving higher application rates and lower pyrolysis temperatures. Biomass production responded significantly to both pyrolysis temperature and biochar dose, with the highest yield observed under the pyrolysis temperature of 600°C and 50% dose. However, no significant interaction effect was detected between the two factors, suggesting their influence operates independently. These findings highlight the potential of biochar as a soil amendment to enhance plant performance and underscore the importance of optimizing both pyrolysis conditions and dosage to maximize biochar efficacy in tropical reforestation systems.

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