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Full Length Research Article

Field Evaluation of Biochar Application on the Early Growth of *Falcataria moluccana*: Effects of Pyrolysis Temperatures and Biochar Application Rates

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ABSTRACT

Faltacaria moluccana at its early plantation, is devastated by heat and water stress due to current global climate change. Production forests in Indonesia suggested to use biochar to enhance the durability of early growth *F. moluccana* in the field. Empty fruit bunches (EFB), a gigantic abundant waste material in Indonesia, pose its potential as biochar feedstock. This study aims to evaluate the effects of EFB biochar on the growth of *F. moluccana* for one year in a field setting. The experiment used two biochar application rates (25 and 50 tons/ha) and biochar produced at two pyrolysis temperatures (400°C and 600°C). Climatic factors (rainfall and average temperature) were monitored to assess how biochar interacted with field conditions to influence the growth of *F. moluccana*. EFB biochar increased height and diameter increment by up to 25% and 42%, respectively, compared to control after one year. While pyrolysis temperatures show no impact on growth, biochar application rates of 25 and 50 tons/ha significantly boost diameter increments by 36% and 42%, respectively, compared to controls, without affecting height. Biochar also improves monthly growth increments under water and heat stress. EFB biochar optimizes growth under current climate conditions in Indonesia and mitigates the negative effects of extreme temperature fluctuations.

1. Introduction

Indonesia's wood industry is poised for growth in 2025, driven by domestic demand and international trade. According to the Indonesian Ministry of Environment and Forestry (KLHK), in 2023, Indonesia's forestry product exports totaled 17.19 million tons, marking a 9.03% increase from the previous year (KLHK 2023). The wood market's output is expected to reach approximately USD 8.3 billion, with a compound annual growth rate (CAGR) of 2.35% from 2025 to 2029 (Statista 2024). However, the export value declined by 10.20%, from USD 14.21 billion in 2022 to USD 12.76 billion in 2023 (KLHK 2023). Imbalance supply demand was blamed as troubleshooting has been done by several studies (Malau et al. 2022; Nasution et al. 2024; Natalia et al. 2024; Nijman 2024).

Meeting the demand, wood production should be sustained, yet the country's production forests face multiple challenges. Among those, climate change is a significant barrier to meeting the demand for forest products (Ayazi and Elsheikh 2019). Rising temperatures and prolonged droughts are expected to reduce suitable areas for several timber species by more than 50% by 2050 (Ramadhillah and Masjud 2024). From 2015 to 2019, unexpected droughts destroyed 9.61% of Indonesia's forest plantations, resulting in an annual loss of about 3.9 million tons of timber (Ayazi and Elsheikh 2019).

Falcataria moluccana is among the most impacted tree species in Indonesia's production forests, as it is extensively planted and forms the backbone of the country's forestry economy. As reported by Indonesia Statistical Bureau (BPS 2024), from 2010 to 2020, annual timber production of *F. moluccana* averaged approximately 100,000 m^3. However, within a single year (2020–2021), production plummeted by > 80%, posing a significant threat to the sustainability of Indonesia's production forests. Research shows that lower-elevation species like *F. moluccana*, which dominates Indonesian plantations, are highly susceptible to drought, with significantly higher mortality rates than higher-elevation species (Lalor et al. 2023). These vulnerabilities are most pronounced during the early stages of plantation growth, where droughts and heatwaves severely impact seedling survival (Carnegie et al. 2022; Jones et al. 2012). Enhancing resilience to heat and water stress at this critical stage is essential for ensuring the long-term sustainability of Indonesia's production forests.

Biochar, a carbon-rich material produced through biomass pyrolysis, has been widely studied for its ability to mitigate the negative effects of heat and water stress on juvenile plants/ seedlings (Ali et al. 2021; Guayasamín et al. 2024; Hong et al. 2020; Lehmann and Joseph 2015). One key benefit of biochar is its ability to stimulate early-stage root development in seedlings, which increases the durability of early plantation (Huang et al. 2021). By modulating soil pH and reducing aluminum toxicity (Jones et al. 2012), biochar helps seedlings become more resilient to drought and heat stress during their initial growth stages. Additionally, Wijaya et al. (2022) found that biochar derived from forest residues effectively retains water and nutrients due to its highly active surface and porous structure. This improves nutrient and water availability, thereby increasing the survival rate of plants under stress. Thus, biochar's benefits can be potentially tested on *F. moluccana* in Indonesia's climate to address heat and water stress for sustainable production forests.

Several studies have explored the use of biochar to mitigate heat and water stress during the early growth of plantations in field tests (Gale et al. 2016; Jones et al. 2012; Lalor et al. 2023; Uslu et al. 2020; Wijaya et al. 2022; Wu et al. 2023). However, these studies often utilize high-value feedstocks, making biochar production costly, with expenses ranging from USD 300 to 600 per ton (Campion et al. 2023). Such high costs render biochar application economically unfeasible for production forests. Additionally, biochar feedstocks from waste material commonly face supply chain and sustainability problems (Al-Rumaihi et al. 2022). Low-cost and sustainable biochar feedstocks need to be explored.

Empty fruit bunches (EFBs), a by-product of palm oil production, offer a promising biochar feedstock. As the world's largest palm oil producer, Indonesia generates approximately 45 million tons of EFB annually (Nabila et al. 2023). EFBs are readily available at palm oil mills (POM), ensuring convenient access. Priced at USD 50–70 per ton, EFB is 5 to 6 times cheaper than other agricultural waste (Erivianto et al. 2022). In some regions of Indonesia, EFB is even free, as it is often regarded as a low-value waste material. Additionally, EFB contributes to significant environmental issues, including emissions of up to 30 million tons of CO_2e per year during decomposition (Subramaniam et al. 2021). With open burning banned due to environmental concerns, EFB has become a significant waste management challenge for Indonesia's palm oil industry. Therefore, utilizing EFB as a biochar feedstock for soil application is not only economically feasible but also provides a sustainable solution for waste management in Indonesia.

While biochar has been extensively studied for enhancing plant resilience to drought, few studies have evaluated its long-term impact on tropical timber species like *Falcataria moluccana* under field conditions in Indonesia. This study evaluates the effects of EFB biochar on the growth of *F. moluccana* over one year in a field setting. The experiment uses two biochar application rates (25 and 50 tons/ha) and biochar produced at two pyrolysis temperatures (400°C and 600°C). Climatic factors, including rainfall and average temperature, are also monitored to assess how biochar interacts with field conditions to influence the growth of *F. moluccana*. This research will provide a potential biochar feedstock option to overcome Indonesia's sustainable production forest problem due to global climate change.

2. Materials and Methods

2.1. Biochar Preparation

Biochar produced in this research was done at the South Lampung Regency biochar production workshop under the supervision of University Lampung. EFB was collected from the nearby oil palm plantation. The EFB did not need any pre-treatment because the biochar production used a conventional dome kiln made of brick (**Fig. 1**). Thus, the big chunk of EFB with moderate moisture content could be processed directly.

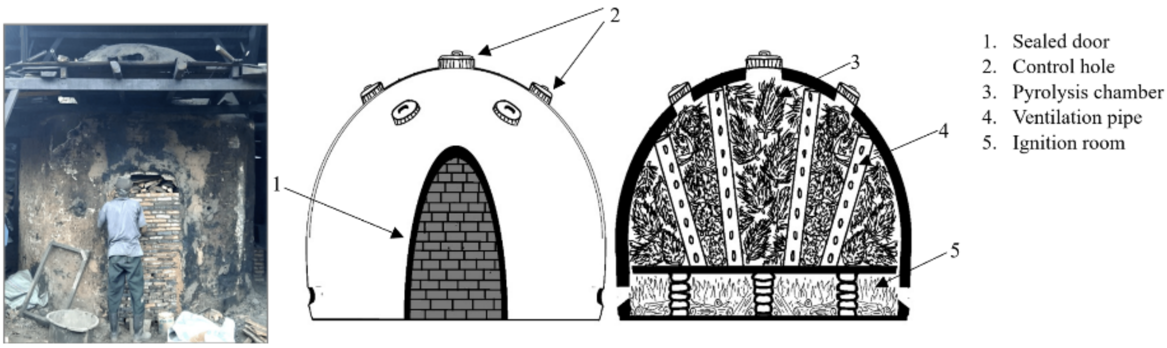

Fig. 1. Conventional brick dome kiln design for EFB biochar.

The dome kiln consists of (1) a sealed door, (2) control holes, (3) a pyrolysis chamber, (4) ventilation pipes, and (5) ignition room. The control holes regulate the temperature of the pyrolysis process. The holes will be opened when the targeted temperature drops, and vice versa. The ventilation pipes channel oxygen to go down far from the control holes. The production was started by fully charging the pyrolysis chamber with raw EFB (1–2 tons). The door was sealed with brick and clay to ensure no oxygen entered the pyrolysis chamber. After that, the fire feedstock (forest waste material) was loaded into the ignition room, and the fire was started with petroleum. The targeted temperature (400 and 600°C) was monitored with temperature with a residence time of up to 6 days. The door was opened, and the biochar was air dried (**Fig. 1**). After the biochar was cold, it was pulverized into powder-like material and ready to be applied to the soil.

Fig. 2. EFB biochar produce from conventional brick dome kiln.

The characteristics of EFB biochar at two pyrolysis temperature ranges, 400°C and 600°C, are compared in **Table 1**. The pH remains constant at 10, indicating strong alkalinity, while the CEC slightly decreases from 35 to 33 meq/100 g, and the BET surface area shows a minimal increase from 4.1 to 4.2 m²/g. Higher temperatures enhance carbonization, as shown by an increase in carbon content (61.96% to 64.53%) and a decrease in nitrogen (1.08% to 0.72%), while sulfur remains unchanged at 0.02%. The concentrations of ash alkali elements, such as potassium, calcium, and magnesium, increase significantly at higher temperatures, with potassium rising from 4.18% to 6.55%. Other elements, like aluminum, silicon, sodium, phosphorus, and iron, show minor increases or stability. These changes indicate that higher pyrolysis temperatures improve carbon content and nutrient availability, making the biochar more suitable for applications like soil amendment. However, the slight reduction in CEC may affect its nutrient retention capacity.

Table 1. Characteristics of EFB biochar at two pyrolysis temperature ranges (400°C and 600°C)

Characteristics	Pyrolysis temperature	
	400°C	**600°C**
Ash [a]	33.74	38.98
Fixed carbon [a]	31.43	37.55
pH [a]	10	10
CEC (mq/100g) [b]	35	33
BET surface area (m^2/g) [b]	60	60
Elemental analysis (wt%) [c]		
C	61.96	64.53
N	1.08	0.72
S	0.02	0.02
Ash alkali matter (wt%) [c]		
Al	0.05	0.06
Ca	0.38	0.56
Fe	0.10	0.15
Mg	0.26	0.42
Si	0.03	0.02
Na	0.05	0.06
P	0.10	0.19
K	4.18	6.55

Notes: [a] this study; [b](binti Ab Aziz et al. 2015); [c] (Abdul and Abdul 2017).

2.2. Plantation Preparation and Biochar Application

The research was conducted on a 1-ha field plot near the Pesawaran Forest Management Unit in Lampung Province, Indonesia (104° 59′ 22″ E and 5° 28′ 20.5″ S). The plot has a gentle slope (5–15°C) and features podsolic soil formed due to high precipitation and low temperatures. The reddish-to-yellowish mineral soil indicates low fertility. Covered with weeds and grass without canopy trees or shade, the site mimics the initial stage of forest succession. The area experiences a warm-temperate monsoon humid climate with an average monthly precipitation of 161.8 mm.

Planting holes were dug 60 cm deep and 20 cm wide, corresponding to the number of *F. moluccana* seedlings required for the experimental design. The spacing was 50 cm between replicates and 200 cm between treatment groups. Biochar was applied at the bottom of each hole, and six-month-old *F. moluccana* seedlings with uniform characteristics (height: 55–60 cm, diameter: 0.4–0.5 cm), prepared in a nursery, were planted above the biochar layer and covered with topsoil. Weeding was performed four times during the observation period, and the site was watered in the afternoons during dry months. No fertilizer was added to the plantation.

2.3. Growth Measurements

The initial growth of *F. moluccana* seedlings was observed over 12 months, from May 2020 to April 2021. The height was measured from the soil to the top of the main branch using a roll meter. The diameter was measured 30 cm above the soil in the same spot for 12-month observation. The growth increment rate of height and diameter is also measured by Equation 1:

$$\Delta IG_i = G_i - G_{i-1} \qquad (1)$$

where ΔIGi is the increment growth rate at i month, IG_i is the increment growth at i month, and G_{i-1} is the growth at $_{i-1}$ month.

The rainfall and average temperature were recorded to analyze their interference with the sample in the field experiment. The data was collected from the meteorological station with a radius of 25 km from the plot.

2.4. Design Experiments and Statistical Analysis

Due to the challenges of applying a completely randomized design in a field setting, a split-plot design was used to evaluate the early-stage growth of *F. moluccana*. The dose of EFB biochar (25 and 50 tons/ha or D25 and D50, respectively) served as the plot factor. In contrast, the biochar pyrolysis temperature (400°C and 600°C or T400 and T600, respectively) was the subplot factor, with seven replicates per treatment, resulting in 28 samples. A two-way ANOVA was conducted to assess the variance between and within treatment groups. Since including a control group (0 ton/ha biochar) resulted in an imbalanced sample size, a one-way ANOVA was separately performed to compare the effects of biochar doses of 25 ton/ha (D25), 50 ton/ha (D50), and the control on seedling growth. The post-hoc (Tukey) analysis was performed on different factor groups. Furthermore, repeated measures ANOVA was used to analyze monthly growth increment rates, treating time as a within-subject factor.

Last, all factors identified as significantly different in the ANOVA test were further examined to analyze the relationship between plant growth and climatic factors (rainfall and average temperature). First, we visualized scatter plots of *F. moluccana*'s physiological growth (height and diameter increment) against each climatic factor (rainfall and average temperature) and computed correlation coefficients to assess initial trends. Linear regression models were fit using $y = a_0 + a_1x$, and residuals were analyzed for random scatter, indicating linearity or patterns suggesting non-linearity. Additional tests, including the Ramsey RESET Test and Lack-of-Fit Test, were used to verify linearity. Polynomial models were applied for non-linear trends, starting with quadratic and cubic fits, generating higher-order terms as necessary. Models were evaluated using adjusted R^2. The best model was selected based on a combination of metrics, residual analysis, and simplicity, ensuring the least squared error of the fit. In this research, the fitting line is used to analyze the change of intersect and slope of different factors to identify the climatic factor to the growth of *F. moluccana*. Analysis was done by OriginLab.

3. Results and Discussion

3.1. Results

3.1.1. Statistic analysis

The summary of one-way ANOVA, two-way ANOVA, and repeated measurement ANOVA are presented in **Table 2**. In the one-way ANOVA, comparisons of control, D25, and D50 for height and diameter increments showed significant differences, indicating that biochar application has a distinct effect compared to the control. For the two-way ANOVA, only the biochar dose and the interaction between factors were significantly different for diameter increment. This suggests that the pyrolysis temperatures (400°C or 600°C) does not affect the diameter increment of *F. moluccana*. Neither the biochar dose nor pyrolysis temperature significantly affected height increment, implying that these factors do not influence height growth. The repeated measures ANOVA for monthly measurements showed significant differences in height and diameter growth increments, indicating that monthly variations in growth measurements significantly affect the overall growth of *F. moluccana.*

Table 2. Summary of ANOVA

ANOVA	Factor	Measurement	*F*-value	*p*-value
One-Way	Dose (Control, 25, and 50 tons/ha)	Height increment	7.1	**<0.05***
		Diameter increment	32.1	**<0.001****
Two-way	Dose (25 and 50 tons/ha)	Height increment	1.8	1.9.E-01 ^{ns}
		Diameter increment	5.3	**<0.05***
	Py. Temp. (400 and 600°C)	Height increment	1.5	0.23 ^{ns}
		Diameter increment	3.2	0.86 ^{ns}
	Interaction	Height increment	0.4	0.55^{ns}
		Diameter increment	2.8	**<0.05***
Repeated measurement	Monthly measurement	Height growth increment	25.6	**<0.001****
		Diameter growth increment	26.9	**<0.001****

Note(s): *significant at 95%;**significant at 99%;^{ns} not significant.

The relationship between climatic factors (rainfall and average temperature) and the physiological growth of *F. moluccana* (height and diameter) under different treatments is presented in **Table 3**. The table presents the results of model selection for fitting the relationships between environmental factors (rainfall and average temperature) and the physiological growth of *F. moluccana* (height and diameter) under different treatments (control, biochar, D25, and D50). For rainfall, height increment under both the control and biochar treatments shows a significant positive linear relationship, with biochar treatment yielding a slightly higher adjusted R^2 (0.56) compared to the control (0.50). Diameter growth also exhibits significant linear relationships with rainfall across all treatments, with higher adjusted R^2 values for biochar applications (D25: 0.77, D50: 0.72) compared to the control (0.63).

Table 3. Result of model selection for fitting line compression of *F. moluccana* physiological growth and climatic factor

Independent variable	Dependent variable	Factor	Form	Intersect	*b*	*c*	Adj. R^2	*p*-value
Rainfall	Height	Control	Linear	11.33	0.15	na	0.50	**<0.01****
		Biochar	Linear	13.72	0.17	na	0.56	**<0.01****
	Diameter	Control	Linear	0.09	0.011	na	0.63	**<0.01****
		D25	Linear	0.17	0.016	na	0.77	**<0.01****
		D50	Linear	0.23	0.015	na	0.72	**<0.01****
Average temperature	Height	Control	Quadratic	-9711.12	687.06	-12.08	0.44	**<0.05***
		Biochar	Quadratic	-7187.39	500.56	-8.63	0.64	0.12^{ns}
	Diameter	Control	Quadratic	-121.24	8.69	-0.16	0.24	**<0.05***
		D25	Quadratic	-109.83	7.75	-0.14	0.69	**<0.01****
		D50	Quadratic	-83.44	5.91	-0.10	0.21	**<0.01****

Notes: *significant at 95%; **significant at 99%; ns not significant.

For average temperature, height and diameter growth follow significant quadratic relationships under most treatments. Height growth under biochar application shows a relatively high adjusted R^2 (0.64) but is not statistically significant ($p = 0.12$). Conversely, height growth in the control is significant ($p < 0.05$) but with a lower adjusted R^2 (0.46). Diameter growth, however, shows significant quadratic relationships across all treatments, with biochar treatments (D25: 0.69, D50: 0.21) outperforming the control (0.12) in terms of adjusted R^2 values. These results highlight the potential of biochar to optimize growth in *F. moluccana*, especially under specific climatic scenarios.

3.1.2. The effect of EFB biochar on the physiology growth of F. moluccana

The effect of EFB biochar on the height and diameter increment of *F. moluccana* is shown in **Fig. 3**. Neither biochar dose nor pyrolysis temperature significantly influenced height increment. However, EFB biochar effectively increased height growth increment compared to the control. After 12 months, the control group showed a height increment of 379 cm, while the biochar-treated groups ranged from 446 to 489 cm, reflecting up to a 25% increase in height increment with biochar application.

Dose significantly affected diameter increment, while pyrolysis temperature did not. Compared to the control, biochar application also significantly increased diameter growth. After 12 months, the diameter increments for the control, D25, and D50 treatments were 3.3 cm, 5.2 cm, and 5.7 cm, respectively, representing 36% and 42% increases for D25 and D50. These results suggest that biochar dose has a greater influence on the initial physiological growth of *F. moluccana* than pyrolysis temperature.

3.1.3. Climatic factor to growth of *F. moluccana in field observation*

To understand the effect of EFB biochar on the initial growth of *Falcataria moluccana* under field conditions, it is essential to account for climatic factors during the observation period. The height increment of the control and biochar-treatment group followed the patterns of monthly rainfall and average temperature during 12-month observation (**Fig. 4**).

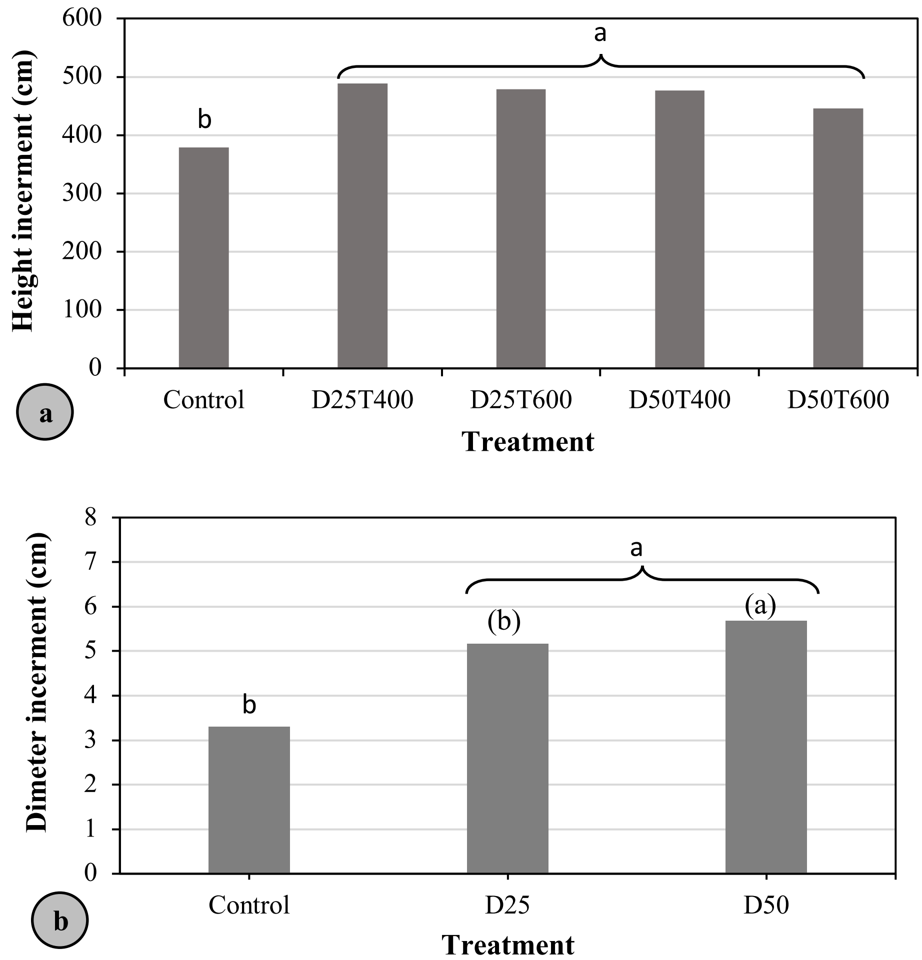

Fig. 3. Height (a) and diameter (b) increment of EFB biochar on *Falcataria moluccana* after 12 months (Different alphabets represent different groups based on post-hoc analysis; the alphabet in bracket is from a two-way analysis; the alphabet without bracket is from a one-way analysis).

From April to August, the monthly height increments of the control and biochar-treated groups were similar, with minimal differences. As rainfall dropped to 15.5 mm in August, height increments for both groups decreased to approximately 20 cm. However, after August, the biochar-treated group showed consistently higher height increments compared to the control. Notably, during November, the peak of rainfall, the control group surpassed the biochar-treated group's height increment by 19%. In contrast, starting in late February, height increments declined for both groups, but the reduction was more pronounced in the control group. The biochar treatment group showed a 65% higher height increment than the control group.

A similar pattern was observed with average temperature. When temperatures ranged between 26–28°C, the height increment of *F. moluccana* showed a positive correlation in both the control and biochar-treated groups. However, as temperatures rose above 28°C, height increments began to decline starting in March. This period also coincided with reduced rainfall, further hindering the physiological growth of *F. moluccana* in the field. The lowest height increment occurred in May when the temperature peaked at 29.5°C. In that month, the height increments were 58.2 cm for the biochar-treated group and 37.9 cm for the control group, indicating that the biochar-treated group demonstrated better resilience to high temperatures than the control. Due to the significantly different dose factors (D25 and D50, control), **Fig. 5** displays rainfall and average temperature with diameter increments of significantly different samples.

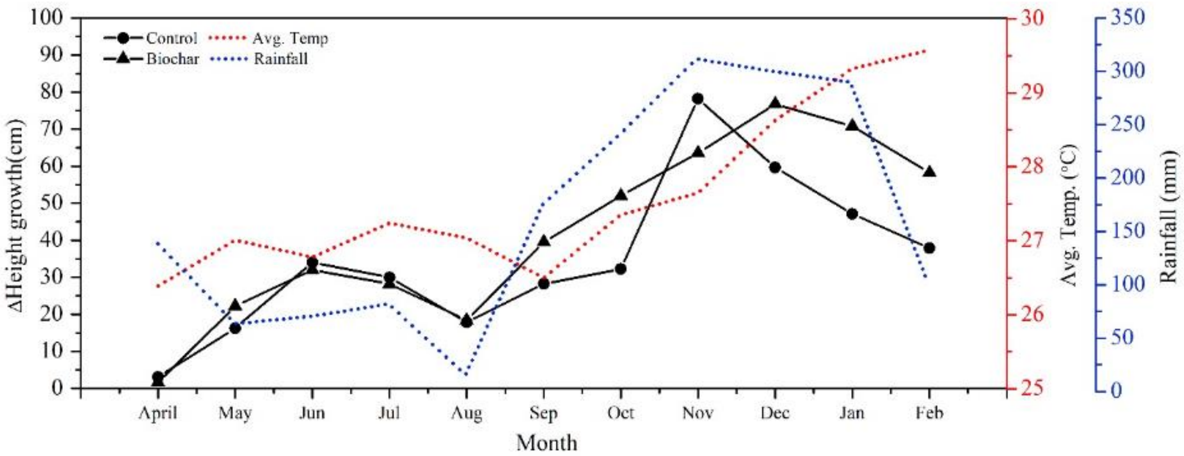

Fig. 4. Monthly Height diameter growth of *F. moluccana* affected by EFB biochar addition and climatic factor.

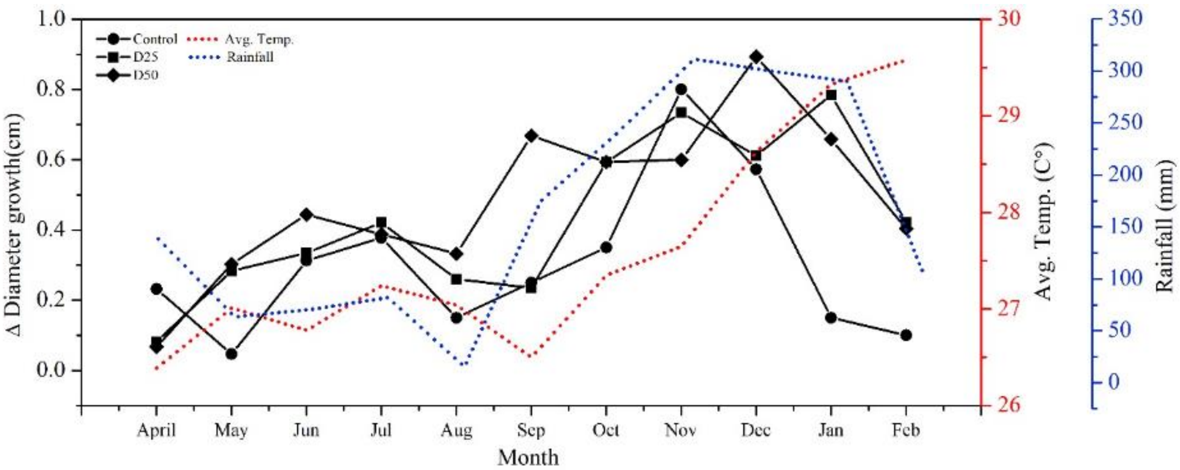

Fig. 5. Monthly diameter increment growth of *F. moluccana* affected by EFB biochar addition and climatic factor.

The diameter increment of *F. moluccana* closely followed the rainfall pattern over 12 months. During months of low rainfall—May (63.5 mm), August (15.5 mm), and February (104 mm)—the diameter increments of all groups were lower than in the previous month. However, the decreases in D25 and D50 were smaller compared to the control group. During the dry season (May to August), D25 and D50 maintained better diameter increments than the control. When rainfall was relatively high (November to January), D50 consistently showed greater diameter increments than D25. An anomaly occurred in November (the peak of rainfall) when the diameter increment of D50 dropped below that of D25 and the control. The control group also suppressed D25 this month. This suggests that excessive rainfall may negatively affect the diameter growth of biochar-treated groups.

Similar to height increment, diameter increment positively correlated with average temperature. A negative correlation was observed in February when the average temperature reached 27.7°C for the control and D25, while D50 began to decline in the following month as the temperature rose to 28.63°C. At the highest recorded temperature in May (29.5°C), the biochar-treated groups achieved a diameter increment of up to 0.4 cm, 30% higher than the control. This indicates that biochar application helps *F. moluccana* maintain diameter growth under temperature stress. **Fig. 6** displays the result of line fitting from the dependent variable (*F. moluccana* physiological growth) and independent variable (climatic factor) at different treatments.

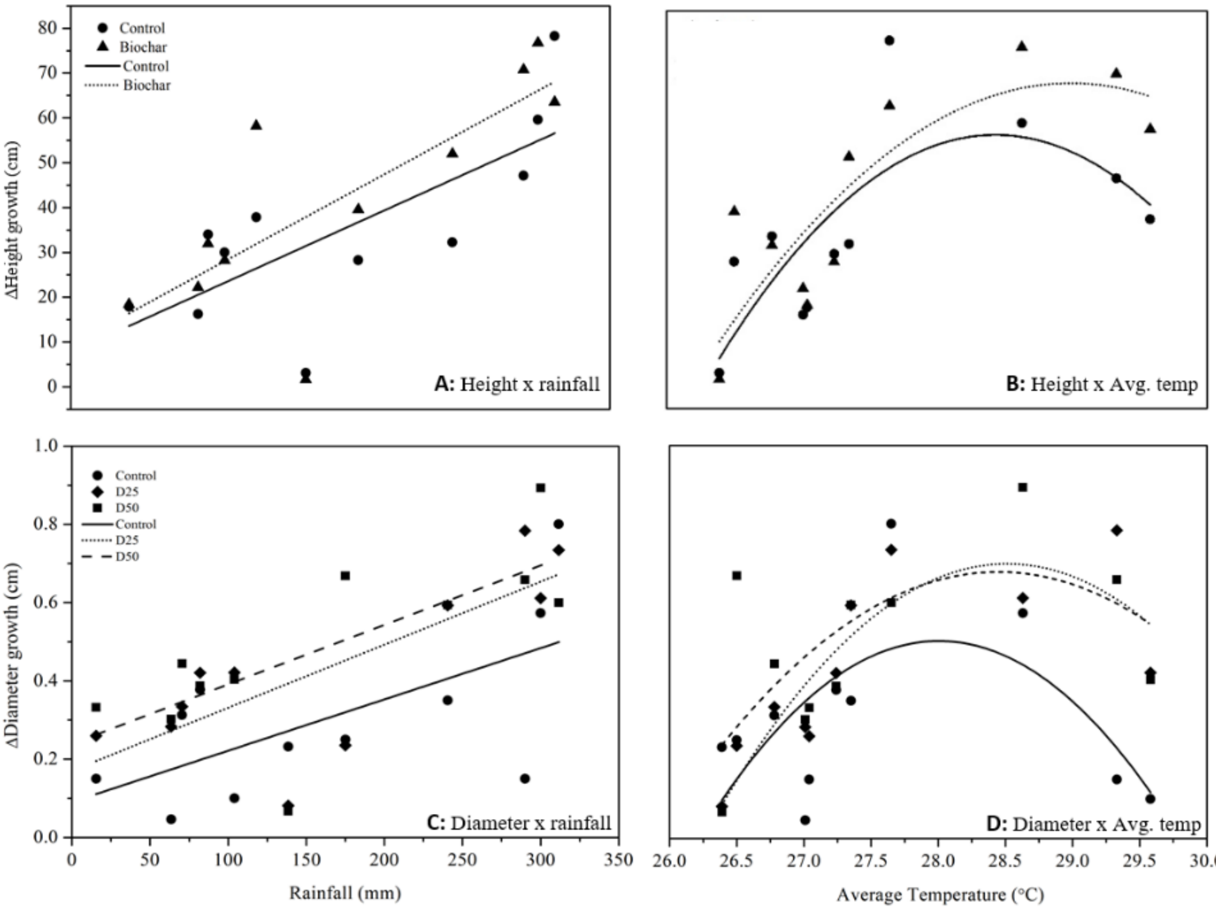

Fig. 6. Scatter plot of *F. moluccana* physiological growth and climatic factor under different treatments with its fitting line superimposed on the data set; (A) Correlation of height increment to rainfall; (B) Correlation of height increment to average temperature; (C) Correlation of diameter increment to rainfall; (D) Correlation of diameter increment to average temperature.

The fitting lines in **Table 3** reveal that biochar treatments significantly increase growth increments in *F. moluccana* compared to the control, as evidenced by higher intercepts. Correlating with rainfall (**Fig. 6 A** and **C**), biochar applications boost height and diameter increments by approximately 33% and 75%, respectively, under a linear model. At higher rainfall (300 mm), the height increment for biochar-treated groups is 66% greater than at low rainfall (15.5 mm), with a similar trend observed in diameter growth. This indicates that biochar mitigates water stress and optimizes monthly growth. Furthermore, the diameter increment of D50 is 1 cm higher than D25, suggesting doses effectively maximize diameter increments.

Unlike rainfall, the relationship between average temperature and *F. moluccana* growth follows a quadratic pattern (**Fig. 6 B** and **D**). Growth decreases when temperatures exceed optimal levels. The ideal average temperature range is 28–28.5°C. Within this range, biochar-treated groups achieve height and diameter increments of up to 60 cm and 0.65 cm, respectively—

approximately 1.6 times higher than the control under the same conditions. This finding showcases that EFB biochar addition maximizes the growth of *F. moluccana* at a tropical average temperature profile. For height increment, growth begins to decline above 28.5°C, while for diameter increment, the threshold is 28°C. At a low threshold (25.5°C), the difference between biochar-treated and control groups is minimal, with only D50 showing a higher intercept. However, at higher thresholds (25.5°C), biochar-treated groups outperform the control in height and diameter increments, with differences of up to 43% and 85%, respectively. At the high threshold, the control group's diameter increment is comparable to its growth at the low threshold. However, with EFB biochar application, the reduction in diameter increment at the high threshold is less pronounced, indicating that EFB biochar mitigates high-temperature stress.

3.2. Discussion

Biochar amendments have significantly benefited forest soil quality and tree growth in various contexts. In nutrient-poor Scots pine stands in Finland, biochar application increased diameter growth by 25% over three years (Palviainen et al. 2020). Combining biochar with biosolids in urban settings significantly improved soil quality and tree sapling growth compared to conventional amendments (Scharenbroch et al. 2013). A systematic review of studies in China highlighted biochar's potential to enhance degraded forest soils and support tree growth by improving soil properties and nutrient uptake (Zhang et al. 2022). Similarly, in Amazonian Ecuador, biochar additions enhanced soil organic matter, electrical conductivity, and nutrient availability, leading to a 23–29% increase in the aboveground biomass of secondary forest trees (Guayasamín et al. 2024). Biochar significantly improves the characteristics of Indonesian forest soil in vitro experimental design. This research suggests that adding 40 tons/ha biochar to the soil will increase pH, CEC, organic-C, p-available, and total-N (Herviyanti et al. 2023).

This study validates the hypothesis that EFB biochar effectively enhances the early plantation growth of *F. moluccana* in a field setting. Biochar application has been widely reported to positively impact early plant growth across various species, including increased biomass production in maize (Ali et al. 2021), vegetables (Hong et al. 2020), fodder crops (Uslu et al. 2020), and forest trees (Robertson et al. 2012). Prolonged observations in sub-boreal forest soils showed that lodgepole pine biochar increased aboveground biomass of alder and pine by up to fivefold compared to controls after four months in the field (Robertson et al. 2012). Furthermore, Jones et al. (2012), conducting 3 years of observation of biochar in the field setting, found that biochar maximized the growth of pine and alder at the early plantation stage. Gene expression studies further reveal that biochar enhances early plant development by upregulating growth-promoting hormones and cell wall-loosening genes while suppressing defense-related gene development (Viger et al. 2015). However, the effects of biochar are dose-dependent and species-specific (Gale and Thomas 2019).

The higher dose of EFB biochar addition significantly gives a higher *F. moluccana* diameter increment as it aligns with our second hypothesis. Research done by Gale et al. (2019) found that biochar at 30 tons/ha improved the aboveground increment fivefold compared to the control. That study also revealed that low biochar addition (2 ton/ha) had a similar effect to the control group. The dose of 10–30 tons/ha is considered the best for the growth of plants. In our study, the difference between D25 and D50 in the mean diameter increment is not high (<1 cm). Furthermore, The dose of biochar did not influence the height increment. Due to the experiment setting in the field, leaching of low molecular weight (LMW) compound might be a reason why the factor of different doses is not pronounced and even disappears between dose groups (Gale et al. 2016). Biochar nutrient-rich composition and susceptibility to leaching may have led to micronutrient provisioning across the plot, reducing the apparent differences between dose groups (Kloss et al. 2014). Additionally, the liming effect of biochar also allegedly caused an inefficient dose factor (Gale and Thomas 2019). As indicated in **Table 1**, EFB biochar exhibits an alkaline pH, which improves soil health and nutrient accessibility. However, explaining the lack of dose influence on height increment and the subtle impact on the control group remains challenging. While biochar might have indirectly affected the control group, its influence was likely minimal, as reflected in the statistically significant differences observed in the post-hoc analysis.

Different pyrolysis temperatures of 400 and 600°C of EFB biochar did not influence the growth of *F. moluccana* in this study. However, different pyrolysis temperatures significantly increase the aboveground biomass in several studies (Hagner et al. 2016; Lu et al. 2019; Rahman et al. 2024; Setyawati et al. 2023; Wijaya et al. 2022). Biochar characteristics are significantly influenced by pyrolysis temperature and feedstock type, affecting its suitability for soil applications (Lehmann and Joseph 2015). Higher pyrolysis temperatures generally increase carbon content, pH, surface area, and pore volume while decreasing the H/C ratio and nitrogen content (Baker 2010; Hagner et al. 2016). This study's insignificant finding of the temperature factor is blamed on our experimental design in this field study. The distance of each sample should be further. Different plot locations are also suggested to hinder the effect of LMW, which gives obscure results of the study in a field setting.

During the 12-month observation, the height and diameter increments were higher every month than in the control group. It suggests that EFB biochar optimizes the growth of *F. moluccana* in the field. Research on biochar research drove chipped trunks and large branches of *Fraxinus excelsior*, *Fagus sylvatica*, and *Quercus robur* to enhance plant growth in 3 years field trial (Jones et al. 2012). Biochar application was shown to enhance nutrient availability in the long span (Wijaya et al. 2021). Baker et al. (2010) found that an increase in carbon availability in the soil will drastically enhance the growth rate of tropical trees. **Table 1** shows that EFB biochar poses high carbon content. The application of EFB biochar will directly increase the arability of carbon for plant growth.

Dose treatment shows that dose is significant on diameter growth but not height. Diameter growth is a secondary growth induced by resource surplus nutrient allocations in the soil-plant system (Henry et al. 1999). Meanwhile, the height growth in primary-growth plants tends to prioritize almost every condition, including stress and non-stress (Sumida et al. 2013). It is suspected that during the optimal condition, adequate water and heat, samples with higher doses of biochar treatment have more surplus nutrients, affecting a higher diameter increment. This does not affect the height increment due to its nature of primary growth or the surplus not being adequate for the plant to show a significant difference. Further analysis of physiological growth and biochar effect nexus is needed.

The addition of EFB biochar mitigated water stress, enabling *F. moluccana* to maintain better growth under stress conditions compared to the control group. With its high porosity and a BET surface area of 60 m^2/g, EFB biochar possesses a water-holding capacity 2–5 times greater than other agricultural waste biochar (Batista et al. 2018). Wijaya et al. (2021) applied biochar to the soil using a layering technique over one year and found that biochar effectively retains water during the dry season. Their research also suggests that biochar stores nutrients and gradually releases them to the topsoil through an intra-diffusion mechanism during dry months.

EFB biochar effectively mitigates the negative effects of heat stress in plants. Biochar helps maintain ionic homeostasis, reduces the production of reactive oxygen species, and enhances antioxidant activity under heat-stress conditions (Wu et al. 2023). Additionally, biochar has been shown to alleviate heat stress by improving root morphology and architecture and modulating the expression of heat-shock proteins (Huang et al. 2021). During high heat stress with low rainfall volume, the root development of early-growth seedlings can be inferior. However, root development is better during biochar application, making it more resistant to stress in the field. Under high heat stress and low rainfall, root development in early-growth seedlings is often inhibited. Applying biochar enhances root development, improving the seedlings' resilience to stress in field conditions (Jones et al. 2012).

4. Conclusions

EFB biochar significantly enhances the diameter and height of *F. moluccana* up to 25% and 45%, respectively, in the field test by the end of the observation period. The factor of pyrolysis temperature (400 and 600°C) did not significantly affect the diameter and height increment of *F. moluccana*. However, 25 and 50 tons/ha biochar doses significantly affected diameter increment by 36% and 42%, respectively, compared to control groups, but they did not affect the height increment. During water and heat stress, adding biochar tackles the decrease of diameter and height increment. While the rainfall level is high, adding biochar will maximize the plant growth compared to the control. From this study, we recommend to apply a biochar dose of up to 50 tons/ha with produce at 400°C for maximum plant growth and efficient biochar preparation. Higher biochar dose combined with other soil enhancers and fertilizers needs to be examined further.

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