Agro Bali : Agricultural Journal
Vol. 9 No. 1: 182-196, March 2026

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i1.2619

Rice Husk Biochar and Foliar Fertilizer Application in Improving Growth and Production of Patchouli Plants (*Pogostemon cablin* Benth)

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Article history: submitted: December 28, 2025; accepted: April 2, 2026; available online: April 10, 2026

Abstract. Patchouli (*Pogostemon cablin* Benth) is a major essential oil crop widely used in pharmaceutical, perfumery, and aromatherapy industries. Despite Indonesia supplying most of the global demand, productivity and oil quality remain inconsistent across production regions. Although rice husk biochar and foliar fertilizers are individually known to enhance plant growth, their synergistic interaction and optimal combined dosage for patchouli production have not been clearly established, representing an important research gap. This study represents the first experimental attempt to determine the optimal combined dosage of rice husk biochar and foliar fertilizer for improving patchouli growth and oil yield. A Randomized Complete Block Design with two factors (three biochar levels and three foliar fertilizer levels) and 3 replicates was implemented from June to December 2023 in West Sumatra, Indonesia. Significant interaction effects were observed across major growth and yield parameters. The combination of 200 g plant^{-1} biochar and 1 ml L^{-1} foliar fertilizer produced the highest biomass accumulation and oil yield compared with other treatments. These findings provide empirical evidence of a synergistic fertilization effect and offer a cost-efficient nutrient management strategy to enhance patchouli productivity under smallholder farming conditions.

Keywords: biochar; essential oil; foliar fertilizer; patchouli; sustainable fertilization

1. Introduction

Essential oils constitute an important global commodity in the pharmaceutical, cosmetic, perfumery, and aromatherapy industries, with increasing demand driven by natural product–based markets (Pandey et al., 2021). Among essential oil crops, patchouli (*Pogostemon cablin* Benth) is recognized as one of the most economically valuable due to its distinctive aroma and fixative properties (Fatima et al., 2023).

The patchouli plant (*Pogostemon cablin* Benth) is a fragrant shrub characterized by fibrous roots, woody stems of 10 to 20 mm diameter, and paired leaves on tiered branches, reaching approximately 1 meter in height within six months (Daniel, 2012). The patchouli plant is also one of the largest contributors to foreign exchange, among other essential oil plants. Indonesia supplies 90% of the world's patchouli oil needs. Initially, the centers of Indonesian patchouli oil production were in Java and Sumatra. In recent years, this role has been replaced by Sulawesi, which dominates up to 80% of national production. However, the minimum quality standard for Sulawesi patchouli oil is still below that of Sumatra patchouli oil, based on its patchouli alcohol content. Sumatra patchouli oil reaches between 30–34%, while production from Sulawesi is between 26–30%. In addition, at the same quality (30%), Sumatran patchouli oil is priced 6 USD kg^{-1} higher than that from Sulawesi (Sumatra 56 USD kg^{-1} and Sulawesi 50 USD kg^{-1}) (Caiger, 2016). These regional disparities indicate that, despite Indonesia's dominant global position, significant challenges remain in improving yield stability and oil quality at the national production level.

Improving oil productivity and quality can be achieved through three aspects: genetics, cultivation, and post-harvest (Hubert et al., 2023; Gao et al., 2025; Tong et al., 2025). Increasing productivity and quality through genetic improvement requires a high degree of diversity in the required traits (Swarup et al., 2021; Temesgen, 2021; Bint, 2024). Patchouli plants generally do not flower and are propagated vegetatively. Due to this characteristic, genetic diversity in patchouli can only result from natural mutations, which have a very low frequency (Shen et al., 2022). Therefore, the potential for increasing patchouli productivity through this aspect is difficult. Similarly, through the post-harvest aspect, sufficiently advanced technology and or large capital is required to obtain adequate oil quality (Beutel et al., 2020; Muhammad et al., 2022; Ribeiro et al., 2022). However, given the generally low economic conditions of oil producers in Indonesia (Putri et al., 2022), increasing oil productivity and quality through cultivation with simple, readily available materials or purchased on plantation sites is a suitable option. Examples include the use of biochar (rice husk charcoal) and foliar fertilizer.

In the agricultural industry, the use of biochar and foliar fertilizers has had a significant impact on improving soil quality and fertility, as well as plant growth (Khomphet et al., 2023; Nepal et al., 2023; Gu et al., 2025). Biochar, derived from rice husks, can improve soil structure and increase nutrient retention (Ding et al., 2022; Omokaro et al., 2025). Adding biochar to growing media offers several benefits, including increasing the effectiveness of fertilization (Zhang et al., 2024). Besides improving soil properties (porosity and aeration), biochar also acts as a nutrient binder, allowing plants to utilize it when needed. In other words, biochar helps release nutrients slowly according to plant needs (Elkhlifi et al., 2023; Kabir et al., 2023).

In parallel, foliar fertilizers have been recognized as a source of nutrients readily available to plants, supporting photosynthesis, vegetative development and yield (Wang et al., 2021; Rodrigues et al., 2021). Foliar fertilizers are organic or chemical fertilizers applied to plants through the leaf openings or stomata, by spraying them to provide additional nutrients to plants beyond those absorbed by the roots (Shahverdi et al., 2020; Viçosi et al., 2020; Singh et al., 2025). The concentration of foliar fertilizer used is crucial. It has been reported that the minimum concentration for foliar fertilizer spraying is 1%, while the maximum concentration is 2% to reduce leaf burn or other adverse effects (Januszkiewicz et al., 2023).

The dosage levels selected in this study (100, 200, and 300 g plant^{-1} biochar; 1, 1.5, and 2 ml L^{-1} foliar fertilizer) were determined based on previously reported agronomic ranges and practical field recommendations for biochar soil amendment and foliar nutrient application. These dosage ranges were chosen to represent low, moderate, and relatively high application levels to enable optimization analysis while avoiding phytotoxic effects or excessive nutrient accumulation.

Although both biochar and foliar fertilizers are known to individually benefit plant growth, existing research has predominantly examined the effects of biochar and foliar fertilizers separately, focusing on their individual roles in soil and plant improvement. However, the synergistic effects of combining rice husk biochar with foliar fertilization in patchouli cultivation remain largely unexplored, particularly regarding how their interaction influences growth and essential oil yield. Moreover, there is a lack of studies optimizing the combined application dosages to maximize patchouli productivity and quality. This represents a significant research gap, as synergistic nutrient management strategies may substantially enhance productivity in low-input farming systems.

This study investigates how combined rice husk biochar and foliar fertilizer applications influence patchouli productivity, specifically addressing their combined impact on growth, oil yield, and optimal application rates to enhance patchouli quality. This study is novel as it represents the first dosage optimization study for patchouli using the combined application of rice husk biochar and foliar fertilization. By exploring this synergistic relationship, it is hoped that the results will provide new insights into soil nutrient management and fertilization strategies to achieve optimal patchouli plant production.

2. Materials and Methods

The research was conducted in polybags in the Garden at IPPTP Balittro Laing Solok, West Sumatra, Indonesia, from June to December 2023. The materials used were Sidikkalang variety patchouli cuttings, ultisol soil, cow manure, rice husk biochar, foliar fertilizer, polybags, label paper, and plastic. The tools used in this research consisted of hoes, shovels, buckets, staplers, pruning shears, hand sprayers, analytical scales, measuring cups, digital cameras, sigmats, rulers, and stationery.

Topsoil was gathered from five separate locations at a depth of 20 cm. After being sieved, the soil was left to air dry for a week. For future usage, each polybag containing 7 kg of soil was allowed to incubate for 7 days. Biochar was mixed directly into the growing medium, and no further additions were made during the planting period. The control growing medium composition ratio was 2:1 between soil and manure. Foliar fertilizer was Bayfolan inorganic fertilizer containing 11% macronutrients N, 10% P, and 6% K, as well as micronutrients Fe, Mn, Cu, Zn, Co, and Mo. It was applied three times or once a month.

The dosage levels of rice husk biochar (100, 200, and 300 g polybag^{-1}) were selected based on previously reported agronomic application ranges for biochar in pot experiments and preliminary field recommendations to represent low, moderate, and relatively high amendment rates without causing excessive nutrient accumulation. Similarly, the foliar fertilizer concentrations (1, 1.5, and 2 ml L^{-1}) were chosen according to manufacturer recommendations and published agronomic guidelines to remain within the safe application threshold (1–2%) while enabling response optimization analysis.

This study used a Randomized Complete Block Design (RCBD) with two factors. The first factor is the dose of rice husk biochar with 3 levels of treatment: 1) 100 g polybag^{-1}; 2) 200 g polybag^{-1}; 3) 300 g polybag^{-1}. The second factor is the dose of foliar fertilizer with 3 levels of treatment: 1) 1 ml L^{-1}; 2) 1.5 ml L^{-1}; 3) 2 ml L^{-1}. Thus, 9 treatments were obtained with the codes: A1D1, A1D2, A1D3, A2D1, A2D2, A2D3, A3D1, A3D2, A3D3. Each treatment consists of 3 replications, and each experimental unit consists of 5 plants, so that there are 150 experimental units.

Blocking in the RCBD was implemented to control potential environmental heterogeneity within the experimental area. The blocks were arranged based on spatial variation in light exposure, soil moisture distribution, and microclimatic conditions within the garden area. This approach was applied to reduce experimental error and increase the precision of treatment comparisons.

To avoid pseudoreplication, the polybag (containing five plants) was considered the experimental unit for statistical analysis. Therefore, data from the five plants within each polybag were averaged before analysis, and the mean value per polybag was used as one independent replicate. In total, 27 experimental units (9 treatments × 3 blocks) were analyzed.

After 3 months, all populations were test samples with observed variables in the form of plant height (cm), stem diameter (mm), number of leaves (blades), leaf length (cm), leaf width (cm), number of branches (stems), fresh weight (g), dry weight (g), and yield (g). Data were subjected to analysis of variance (ANOVA) at the 5% significance level. Before ANOVA, assumptions of normality and homogeneity of variance were tested using the Shapiro–Wilk test and Levene’s test, respectively. When necessary, data were transformed to meet ANOVA assumptions. If the F-test indicated significant differences, treatment means were separated using the Least Significant Difference (LSD) test at p <

0.05. Pearson correlation analysis was performed to evaluate relationships among growth and yield parameters. All statistical analyses were conducted using appropriate statistical software.

3. Results and Discussion

Response of Rice Husk Biochar and Foliar Fertilizer on The Growth of Patchouli Plant

The results of statistical analysis showed that there was an interaction between the dose of rice husk biochar and foliar fertilizer on the height, stem diameter, number of branches, leaf length, and leaf width of patchouli plants (Table 1). The best combination was a dose of biochar 200 g plant^{-1} + foliar fertilizer 1 ml plant^{-1}. The application of this combination showed the best growth in plant height (58.02 cm), diameter (1.56 cm), and number of branches (54.23). The application of this combination also showed the best growth in leaf length (12.46 cm) and leaf width (7.38 cm), significantly different from the application of rice husk biochar dose of 300 g plant^{-1} and foliar fertilizer dose of 1 ml l^{-1} plant^{-1} (8.08 cm). Although not significantly different from other treatments, it showed consistent results for the five parameters measured.

The enhanced growth observed in this study suggests that plant growth media significantly influence the plant's root system (Ötvös et al., 2021; Van Gerrewey et al., 2024). Organic growth media, such as biochar, have a structure that is better able to maintain an aeration balance than inorganic media (Banitalebi et al., 2024).

Rice husk biochar, when applied alongside other fertilizers, improves the physical structure of the media, making it more crumbly than soil alone. This structural improvement allows roots to move in all directions, facilitating optimal growth, enhancing nutrient uptake, and promoting higher nitrogen use efficiencies and biomass accumulation (Khan et al., 2021; Li et al., 2023).

Biochar contains a high silica (Si) content of 16.98%, and this Si is known to improve the physical properties of soil or growing media (Hossain et al., 2020; Yuan et al., 2025), thereby affecting P solubility in the soil (Alkharabsheh et al 2023). Moreover the application of rice husk biochar influences the activity of microorganisms in the soil, which play a role in N mineralization (Selvarajh et al., 2021; El-Naggar et al., 2022), and absorb $NH4^+$ and $NO3^-$, thereby reducing N loss from the soil and maintaining availability of N for plan uptake (Selvarajh et al., 2021; Ding et al., 2022).

Physicochemically, biochar contains high levels of organic carbon capable of reducing bulk density and altering electrical conductivity (EC), while increasing soil cation exchange capacity (CEC) and pH (Laird et al., 2010; Dume et al., 2016; Sun et al., 2022; Zanutel et al., 2024). Increasing soil organic carbon and CEC will reduce the risk of nutrient loss, especially N, P, and K, maintain nutrient availability, and enhance plant growth (Mattila & Rajala, 2022; Amorim et al., 2022; Dhamu et al., 2024;Goda et al., 2025).

Biochar has a positive impact on the growth of various plant species. At doses of 0.4 to 12 tons/ha, biochar can significantly increase productivity by 20-220%, with yields reaching 120-320% compared to controls or without biochar (Sandiwantoro et al., 2017; Lehmann and Joseph, 2024). Bayfolan foliar fertilizer alone may not significantly impact the processes mentioned above. Previous research on Gmelina seedlings showed that the fertilizer did not provide significant results on any measured growth parameters (Umalekhoa et al., 2017). However, when combined with rice husk biochar in this study, the two synergized well to support patchouli plant growth, at optimum doses of 1 ml plant^{-1} and 200 g plant^{-1}, respectively.

Despite these promising results, several constraints must be acknowledged to guide future investigations. This study was primarily limited to pot-scale experiments and focused on vegetative growth without an in-depth analysis of the essential oil's chemical profile, such as its patchouli alcohol content. Furthermore, the short duration of the experiment and the lack of longitudinal soil chemistry data prevent a full assessment of the long-term impact of biochar on soil microbial dynamics.

Table 1. The effect of the interaction of rice husk biochar and leaf fertilizer on plant height, stem diameter, number of branches, leaf length, and leaf width of patchouli plants.

Foliar fertilizer (D) (ml l^{-1} plant^{-1})	Rice husk biochar (A) (g plant^{-1})		
	100	200	300
	Plant height (cm)		
1	53.28±0.06 bB	58.02±0.69 aA	48.60±0.50 aC
1.5	55.89±0.33 aA	53.95±2.56 abA	44.20±3.00 aB
2	47.46±1.00 cB	51.43±0.09 bA	48.40±0.52 aB
Significance A		**	
D		**	
A X D		**	
	Stem diameter (cm)		
1	1.10±0.02 aB	1.56±0.02 aA	1.03±0.01 aC
1.5	1.03±0.01 aA	1.05±0.02 bA	0.98±0.05 aA
2	1.06±0.03 aA	1.02±0.01 bAB	0.95±0.01 aB
Significance A		**	
D		**	
A X D		**	
	Number of branches		
1	46.38±1.03 aB	54.23±0.57 aA	36.46±1.46 aC
1.5	43.40±1.10 aA	38.26±2.14 bAB	34.46±3.29 aB
2	41.46±3.48 aA	37.06±2.40 bA	35.33±3.53 aA
Significance A		**	
D		**	
A X D		*	
	Leaf length (cm)		
1	0.62±0.34 aAB	12.46±1.02 aA	8.08±0.65 aB
1.5	9.62±0.27 abA	8.58±0.28 bAB	8.13±0.40 aB
2	8.44±0.34 bA	8.31±0.23 bA	8.54±0.22 aA
Significance A		**	
D		**	
A X D		**	
	Leaf width (cm)		
1	6.28±0.18 aAB	7.38±0.12 aA	5.73±0.41 aB
1.5	6.82±0.07 aA	5.99±0.24 bB	5.90±0.24 aB
2	7.05±0.44 aA	5.94±0.31 bB	5.58±0.29 aB
Significance A		**	
D		ns	
A X D		**	

Note: A. rice husk biochar; D. foliar fertilizer; numbers followed by the same lowercase letter in one column and the same uppercase letter in one row are not significantly different in the BNT test ($p < 0.05$); ns, not significant; * $p < 0.05$; ** $p < 0.01$. Data are presented as means ± standard error.

Statistical analysis revealed that unlike the other five growth parameters, there was no interaction between rice husk biochar and foliar fertilizer on the number of patchouli leaves (Table 2). The combination of 200 g biochar plant^{-1} consistently produced the highest yield, at 380.96 leaves. However, this result was not significantly different from other treatments. Similarly, the 1 ml foliar fertilizer treatment (383.09 leaves) the 1 ml l^{-1} foliar fertilizer treatment produced 383.09 leaves, which also showed no statistical difference compared to other dosage levels. Notably, the lowest dosage combination (100 g plant^{-1} biochar and 1 ml l^{-1} foliar fertilizer) produced a relatively similar number of leaves as the higher dosage treatments, indicating that leaf initiation was not sensitive to the increased nutrient levels provided in this study.

The number of leaves on a plant is influenced by nutrient availability (Jin et al., 2021; MacTavish & Anderson, 2022). In fact, adequate nutrient supply during the plant's growth period encourages faster and more complete photosynthesis (Rogers et al., 2024; Ferreira et al., 2025). This enables the proper formation of carbohydrates, fats, and proteins in all plant parts, including leaves. However, in this study, the nutrient dosage level did not affect the number of leaves formed. The lowest dosage (100 g of biochar plant^{-1} and 1 ml of foliar fertilizer plant^{-1}) produced a relatively similar number of leaves as the higher dosage treatment.

Table 2. The effect of rice husk biochar fertilizer and foliar fertilizer on the number of patchouli plant leaves.

Treatment	Number of leaves (blades)
Rice husk biochar (A) (g plant^{-1})	
100	356.40±8.72 a
200	380.96±34.65 a
300	344.92±10.44 a
Foliar fertilizer (D) (ml l^{-1}plant^{-1})	
1	383.09±36.34 a
1.5	347.97±15.21 a
2	351.21±5.48 a
Significance	
A	ns
D	ns
A X D	ns

Note: Numbers followed by the same lowercase letter in one column are not significantly different in the LSD test ($p < 0.05$); ns, not significant; * $p < 0.05$; ** $p < 0.01$. Data are presented as means ± standard error.

The Fresh Weight, Dry Weight, and Oil Yield of Patchouli Plant as Affected by The Rice Husk of Biochar and Foliar Fertilizer

The number of plant leaves correlates with the increase in plant fresh weight, because leaves are the organs where photosynthesis occurs (Momayyezi et al., 2022; Ye et al., 2022). However, in this study, the number of leaves was relatively the same and was not directly proportional to the fresh weight. The results of statistical analysis of the fresh weight of patchouli plants showed that there was an interaction between the doses of rice husk biochar and foliar fertilizer (Table 3). The application of rice husk biochar at a dose of 200 g plant^{-1} and the application of foliar fertilizer at a dose of 1 ml l^{-1} showed the best growth in patchouli fresh weight (74.09 g), which was significantly different from the combination of rice husk biochar and foliar fertilizer at a higher dose (60.68 g).

The observation that maximum fresh and dry weights were achieved without a corresponding increase in leaf number suggests that the combination of 200 g plant^{-1} biochar and 1 ml l^{-1} foliar fertilizer optimizes photosynthetic efficiency. Under these conditions, the products of photosynthesis (assimilates) are likely not concentrated solely in the leaves but are effectively translocated to all parts of the plant. This phenomenon is often attributed to the availability of sufficient and balanced nutrients, which facilitates the movement of assimilates to various plant tissues (Yan et al., 2023), thereby increasing the overall dry weight.

Table 3. Effect of interaction between rice husk biochar and foliar fertilizer on the fresh weight of patchouli plants.

Foliar fertilizer (D (ml l^{-1}plant^{1})	Rice husk biochar (A) (g plant^{-1-1})		
	100	200	300
	Fresh weight (g)		
1	71.91±1.34 aA	74.09±0.14 aA	60.68±0.52 bB
1.5	69.86±0.42 abA	67.31±1.92 aA	59.00±1.00 bB
2	68.30±0.76 bA	67.17±3.21 aA	65.34±1.92 aA
Significance A		**	
D		*	
A X D		**	

Note: A, rice husk biochar; D, foliar fertilizer; numbers followed by the same lowercase letter in one column and the same uppercase letter in one row are not significantly different in the LSD test ($p < 0.05$); ns, not significant; * $p < 0.05$; ** $p < 0.01$. Data are presented as means ± standard error.

Statistical analysis indicated that there was no interaction between rice husk biochar and foliar fertilizer on the dry weight of patchouli plants (Table 4). However, biochar application at a dose of 200 g plant^{-1} resulted in the highest dry weight (319.17 g). This was significantly different from higher biochar doses. Similarly, foliar fertilizer application at a dose of 1 ml plant^{-1} resulted in the highest dry weight (313.74 g).

The result indicates that photoassimilates are effectively translocated to various plant tissues rather than accumulating solely in the leaves, a process facilitated by balanced nutrient availability (Yan et al., 2023). Conversely, the biomass decline at higher dosages implies a physiological threshold, potentially due to altered soil osmotic potential or nutrient imbalances. While the observed synergy promotes optimal biomass partitioning, this study is constrained by its pot-scale design and short duration, which may limit root expansion and a comprehensive understanding of long-term carbon sequestration. Future research utilizing field trials and nutrient tracing is essential to further elucidate these assimilated translocation pathways.

Table 5 shows the amount of patchouli oil yield after distillation. The application of 100 g of rice husk biochar per plant and 1 ml l^{-1} of foliar fertilizer per plant showed the highest yield (25.56 g). The lowest yield was found with the application of 300 g of rice husk biochar per plant and 1.5 ml l^{-1} of foliar fertilizer per plant (14.52 g). Since the main product of the patchouli plant is its oil content, the best treatment to increase its productivity is the treatment that optimizes the distillation yield, namely the treatment of 200 g of rice husk biochar + 1 ml l^{-1} of foliar fertilizer. However, regarding its effect on oil quality, further research is needed.

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i1.2619

Table 4. Effect of rice husk biochar fertilizer and foliar fertilizer on the dry weight of patchouli plants.

Treatment	Dry weight (g)
Rice husk Biochar (A) ((g plant^{-1})	
100	294.91±17.13 a
200	319.17±31.52 a
300	250.95±13.95 b
Foliar fertilizer (D) (ml l^{-1}plant^{-1})	
1	313.74±33.34 a
1.5	252.55±13.33 b
2	298.74±19.27 a
Significance	
A	**
D	**
A X D	NS

Note: Numbers followed by the same lowercase letter in one column are not significantly different in the BNT test ($p < 0.05$); NS, not significant; * $p < 0.05$; ** $p < 0.01$. Data are presented as means ± standard error.

The optimization of oil yield at 200 g plant^{-1} biochar and 1 ml l^{-1} foliar fertilizer indicates a critical equilibrium between nutrient availability and the plant's metabolic capacity for essential oil synthesis. This synergy likely emerges from biochar’s role in stabilizing the rhizosphere, complemented by immediate nutrient assimilation from foliar application to support secondary metabolic pathways. Conversely, the significant yield decline at higher dosages (300 g plant^{-1} biochar and 1.5 ml l^{-1} foliar fertilizer) suggests an inhibitory effect triggered by physiological stress, which diverts energy allocation away from oil biosynthesis toward basic maintenance. While quantitatively significant, this study is constrained by its pot-scale design and the absence of qualitative profiling, such as patchouli alcohol determination via GC-MS.

Table 5. Amount of patchouli oil yield after distillation.

Treatment	Yield		
	Volume (ml)	Weight (g)	%
Biochar 100 g + foliar fertilizer 1 ml l^{-1}	25	20.55	2.06
Biochar 100 g + foliar fertilizer 1,5 ml l^{-1}	26	21.16	2.65
Biochar 100 g + foliar fertilizer 2 ml l^{-1}	28	22.99	2.58
Biochar 200 g + foliar fertilizer 1 ml l^{-1}	29	25.56	2.92
Biochar 200 g + foliar fertilizer 1,5 ml l^{-1}	27	23,28	3.10
Biochar 200 g + foliar fertilizer 2 ml l^{-1}	24	20.00	2,53
Biochar 300 g + foliar fertilizer 1 ml l^{-1}	26	19.21	2.59
Biochar 300 g + foliar fertilizer 1,5 ml^{-1}l	19	14.52	2.23
Biochar 300 g + foliar fertilizer 2 ml l^{-1}	26	21.48	2.75

Pearson Correlation Between Parameters Observed and Its Correlation With Yield Weight of Patchouli Plant

Table 6 shows the correlation between the observed parameters. There were several positive and significant correlations between the parameters in this study. The results of the pearson correlation analysis show a positive correlation between (1) yield weight with yield volume (r = 0.950), (2) yield weight with yield percentage (r = 0.681) and (3) yield weight with fresh weight, while (4) fresh weight is correlated with plant height, number of leaves, leaf length, and number of branches. It indicates that the yield is influenced by the plant's fresh weight. It increases with the increase of plant height, number of leaves, leaf length, and number of branches. This conclusion is in line with the research conducted by Qi et al. (2022), Sree & Rao (2023), and Li et al. (2025), which stated that there was a positive correlation between plant height, number of leaves and leaf length, number of branches, fresh weight, and dry weight with yield. Increases in plant height due to certain treatments have also been linked to increases in the number of branches, fresh weight, and yield. The greater the proportion of stalks, the higher the oil content and oil yield. In addition, some studies indicate that oil yield is significantly influenced by some factors, including characteristics and raw materials (Ashaq et al., 2024), conditions and methods of extraction (Gaikwad et al., 2025), genetic factor (Zhang et al., 2023), and raw materials of post-harvest handling (Lubis et al., 2022).

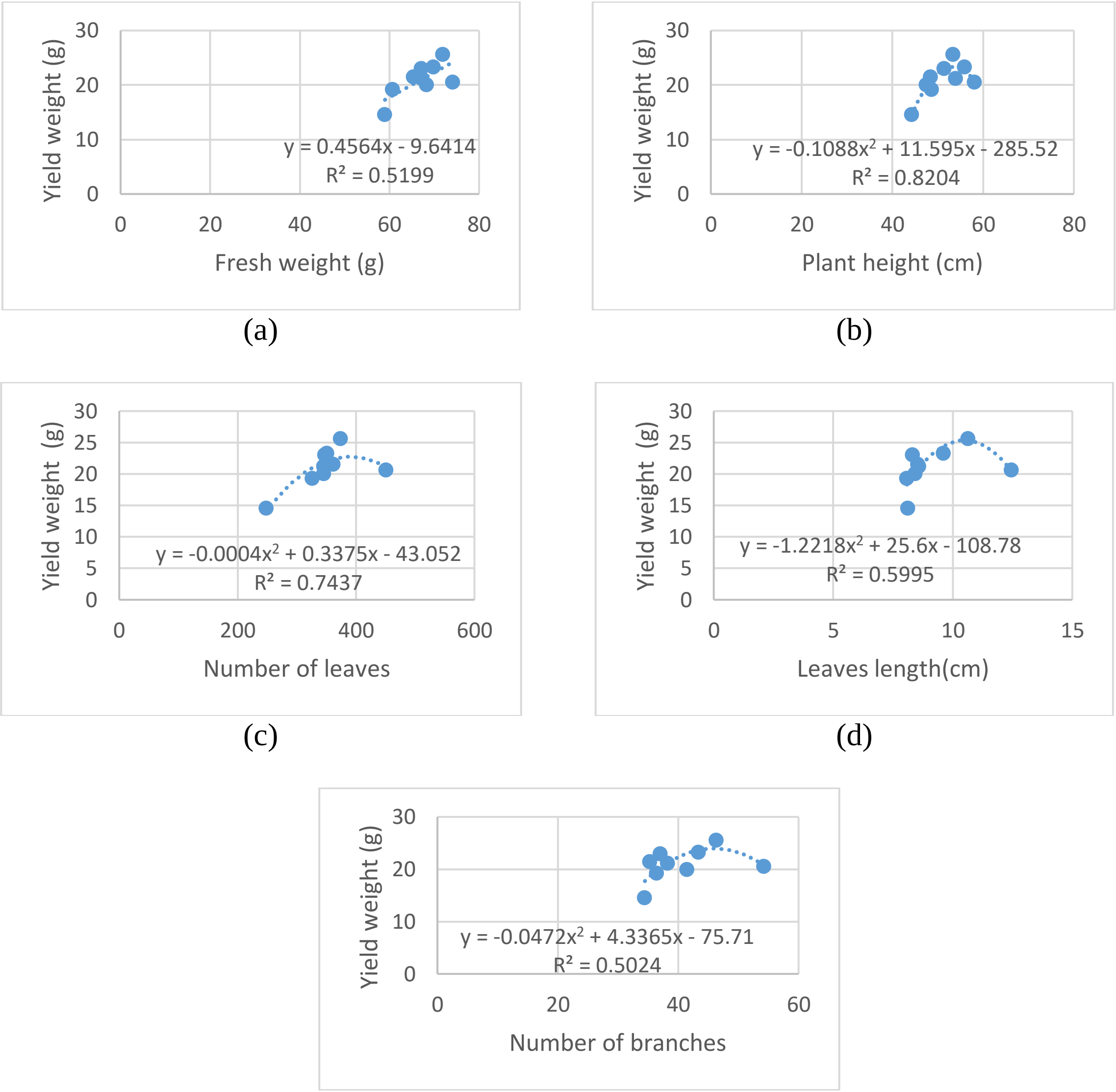
Table 6. Pearson correlation between observed parameters.

	PH	SD	NL	LL	LW	NB	FW	DW	V Yield	W Yield	% Yield
PH	1										
SD	0.648	1									
NL	0.802**	0.764*	1								
LL	0.770*	0.888**	0.810**	1							
LW	0.226	0.602	0.188	0.539	1						
NB	0.773*	0.885**	0.818**	0.959**	0.633	1					
FW	0.835**	0.645	0.868**	0.810**	0.383	0.865**	1				
DW	0.643	0.685*	0.825**	0.736*	0.229	0.739*	0.813*	1			
V Yield	0.598	0.033	0.573	0.256	-0.451	0.281	0.574	0.548	1		
W Yield	0.640	0.068	0.598	0.371	-0.262	0.397	0.721*	0.603	0.950**	1	
% Yield	0.169	-0.560	-0.048	-0.198	-0.439	-0.166	0.150	-0.142	0.640	0.681*	1

Note: PH = plant height; SD = stem diameter; NL = number of leaves; LL = leaf length; LW = leaf width; NB = number of branches; FW = fresh weight; DW = dry weight; V Yield = yield volume; W Yield = yield weight; % Yield = yield percentage; * = significantly correlated at $p < 0.05$; ** = significantly correlated at $p < 0.01$.

The equation that can be produced by the correlation between yield weight and fresh weight, plant height, number of leaves, leaf length, and number of branches, can be seen in Figure 1. Yield weight can be predicted by the equation: (a) $y = 0.4564\ x - 9.6414$, $R^2 = 0.5199$, if x is fresh weight; (b) $y = -0.1088\ x^2 + 11.595\ x - 285.52$, $R^2 = 0.8204$, if x is plant height; (c) $y = -0.0004\ x^2 + 0.3375\ x - 43.502$, $R^2 = 0.7437$, if x is the number of leaves; (d) $y = -1.2218\ x^2 + 25.6x - 108.78$, $R^2 = 0.5995$, if x is leaf length, and; $y = -0.0472\ x^2 + 4.3365x - 75.71$, $R^2 = 0.5024$, if x is the number of branches.

e-ISSN 2655-853X
https://doi.org/10.37637/ab.v9i1.2619



(a) (b) (c) (d) (e)

Figure 1. Graph of the correlation equation between yield weight and (a) fresh weight, (b) plant height, (c) number of leaves, (d) leaf length, and (e) number of branches.

4. Limitations and Future Directions

The research provided empirical evidence regarding the synergistic effects of rice husk biochar and foliar fertilizer on patchouli growth; several limitations must be acknowledged. First, the research was conducted under controlled pot-scale conditions, which may not fully capture the complexities of open-field environments, such as fluctuating soil types, microclimates, and natural pest dynamics. Second, this study focused primarily on growth and biomass yield without assessing the chemical composition of the essential oil. Given that patchouli alcohol content is a critical determinant of market value and quality, its response to these specific treatments remains undetermined.

Future research should prioritize field-scale trials across diverse agroecological zones to validate the scalability and consistency of these findings. Investigations into the long-term effects of repeated biochar application on soil biochemical properties and sustained patchouli productivity are also warranted. Furthermore, subsequent studies should incorporate Gas Chromatography-Mass Spectrometry (GC-MS) analysis to evaluate the impact of synergistic fertilization on the volatile profile and patchouli alcohol concentration of the oil. Exploring alternative foliar formulations or integrated nutrient management strategies could further optimize the sustainable production of high-quality patchouli oil.

5. Conclusion

This study shows that the combined application of rice husk biochar and foliar fertilizer effectively improves the growth and productivity of patchouli plants. Significant interactions were observed in major growth and yield parameters, with the application of 200 g $plant^{-1}$ rice husk biochar combined with 1 ml l^{-1} foliar fertilizer producing the best overall performance and highest oil yield. These findings provide the current state of knowledge by identifying a cost-effective and sustainable nutrient management strategy that addresses the inconsistency in patchouli productivity among smallholder farmers. Beyond mere yield increases, this research provides a scientific justification for integrating organic soil amendments with liquid fertilization to optimize nutrient uptake efficiency. This approach offers practical applications for intensifying patchouli cultivation in degraded soils, providing a scalable model for improving essential oil production and supporting the economic stability of the fragrance and pharmaceutical industries.

This study was primarily limited to pot-scale experiments and focused on vegetative growth without an in-depth analysis of the essential oil's chemical profile, such as its patchouli alcohol content. Consequently, future research should transition to field-scale trials across diverse agroecological zones to validate the consistency and scalability of this synergistic effect. Subsequent studies, some of which are currently underway, will incorporate Gas Chromatography-Mass Spectrometry (GC-MS) analysis to evaluate the impact of these treatments on oil quality. Furthermore, adopting more rigorous methodologies to investigate the long-term impact of biochar on soil microbial dynamics and exploring alternative theoretical frameworks for integrated nutrient management will be essential to further deepen

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work, the author(s) did not used ChatGPT to proofread and take(s) full responsibility for the content of the publication.

Authorship Contribution Statement

Eliza Mayura: conceptualization, methodology, software, validation, formal analysis, investigation, data curation, writing original draft, visualization; Bambang Hariyanto: conceptualization, methodology, writing - review & editing; Neneng Ratna Purnamasari: validation, writing - review & editing; Herwita Idris: validation, formal analysis. Rasiska Tarigan: investigation, writing - review & editing; Rina C. Hutabarat: writing - review & editing.

Declaration of Competing Interest

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

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