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Synergistic Effects of Plant Growth-Promoting Rhizobacteria and Corn Cob Biochar on Growth and Yield of Chili Pepper (*Capsicum frutescens* L.)

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ABSTRACT

Chili pepper (Capsicum frutescens L.) is an economically important horticultural crop, but its productivity in Indonesia has declined due to soil fertility degradation, excessive use of inorganic fertilizers, and unfavorable climatic conditions. This study evaluated the individual and combined effects of plant growth-promoting rhizobacteria (PGPR) and corn cob biochar on the growth and yield of chili pepper. A field experiment was conducted from December 2022 to May 2023 at It was conducted at the experimental farm of Hasanuddin University, Makassar, Indonesia, using a split-plot design with three levels of biochar (0, 7.5, and 15 t ha $^{-1}$*) and three concentrations of PGPR (0, 10, and 20 g L* $^{-1}$*). Data were analyzed using ANOVA followed by LSD at a = 0.05. Results indicated that neither PGPR nor biochar alone had significant effects on most growth parameters. However, their interaction significantly enhanced yield-related traits. The combination of 15 t ha* $^{-1}$ *biochar with 20 g L* $^{-1}$ *PGPR (*M_2P_2*) produced the highest fruit number (69.17 fruits plant* $^{-1}$*), fresh fruit weight (72.30 g plant* $^{-1}$*), and yield (3.62 t ha* $^{-1}$*). These findings demonstrate the synergistic role of biochar and PGPR in improving chili productivity and highlight their potential as eco-friendly inputs for sustainable chili cultivation.*

Keywords:
Biochar; Capsicum frutescens; PGPR; sustainable agriculture; yield.

1. Introduction

The ornamental hot pepper *Capsicum frutescens* L. stands out as one of the most commercially cultivated horticultural crops owing to its rich nutritional profile—high in vitamins, carotenoids, and capsaicinoids—and its substantial economic value in household consumption and food-processing industries. For example, a value-chain study in Indonesia found that farmers captured over 60% of the value added in this commodity, underscoring its high potential for rural income (Pardian et al., 2023; Putri et al., 2025). In South Sulawesi, the production of bird's eye chili has shown a declining trend from 2020 to 2023. Production reached 24,051 tons in 2020, increased slightly to 26,423 tons in 2021, but declined again to 23,761 tons in 2022 (BPS, 2023). This downward trend is inconsistent with the rising market demand, resulting in unmet consumer needs.

The reduced productivity of chili is attributed to several factors, including low soil fertility, inappropriate cultivation practices, a high incidence of pests and diseases, and unfavorable weather conditions, such as excessive rainfall, which can lead to crop failure. Improper fertilizer application—whether in type, timing, dosage, or method—further affects soil physical, chemical, and biological properties. Continuous overuse of inorganic fertilizers not only degrades soil fertility but also poses environmental risks, ultimately leading to yield stagnation (Baharuddin, 2016). To overcome these challenges, the application of biofertilizers, particularly rhizobacteria, has been explored as an eco-friendly alternative nutrient source.

Rhizobacteria play a crucial role in nutrient availability and solubility in the rhizosphere, thereby influencing plant growth and productivity (Rante et al., 2015). Among these, plant growth-promoting rhizobacteria (PGPR) have been widely recognized for their ability to enhance plant growth and provide protection against certain pathogens (Ollo et al., 2019). PGPR can produce phytohormones such as auxins, gibberellins, and cytokinins, while also functioning in phosphate solubilization and nitrogen fixation. These mechanisms collectively improve nutrient uptake and facilitate plant development (Cahyani et al., 2018). Lisa et al. (2018) further reported that PGPR application at a dose of 9 mL L^{-1} significantly increased phosphorus uptake in chili plants.

Organic matter serves as a vital nutrient source for soil microorganisms. Its addition stimulates microbial population growth and activity, particularly in decomposition and mineralization processes, while also supplying carbon as an energy source (Lisa et al., 2018). Corn cob biochar, rich in nitrogen and potassium, represents a promising organic amendment to support microbial activity and plant growth (Ni'mah & Yuliani, 2022). Hanpattanakit et al. (2021) demonstrated that corn cob biochar application improved soil chemical properties, including organic matter content, C-organic levels, and pH, while also enhancing the growth and productivity of chili plants. Similarly, corn cob biochar at 6.25–12.5 t ha^{-1} increased root elongation and yield of red chili.

The integration of biochar with PGPR has been shown to enhance soil fertility and crop productivity more effectively than either input alone. Biochar is particularly beneficial when combined with organic amendments such as compost, manure, and biofertilizers (Ikraman et al., 2022). Previous studies reported that biochar–biofertilizer interactions improved plant growth and yield (Nafi'ah et al., 2021). For instance, Alianti et al. (2016) found that the combination of 6 t ha^{-1} biochar with 2 t ha^{-1} PGPR-based biofertilizer resulted in the highest tomato yield.

Despite the growing body of research highlighting the benefits of biochar and PGPR, studies specifically investigating their interactive effects on chili pepper (*Capsicum frutescens* L.) under tropical field conditions remain limited. Most existing reports focus on single applications of biochar or PGPR, whereas their combined influence on soil nutrient dynamics, plant physiological responses, and yield components of chili has not been fully clarified. Furthermore, the optimal rate of corn cob biochar and concentration of PGPR for maximizing growth and fruit production in C. frutescens have yet to be determined. Therefore, this study was designed to fill this gap by evaluating the synergistic effects of biochar and PGPR on the growth and yield of bird's eye chili. It was hypothesized that the combined application of corn cob biochar and PGPR would enhance nutrient availability and uptake, leading to improved plant growth and higher fruit yield compared to their single applications. Based on this background, the present study was conducted to examine the effects of different PGPR concentrations and corn cob biochar rates on the growth and yield of bird's eye chili (*Capsicum frutescens* L.).

2. Materials and Methods

2.1 Study site and duration

The field experiment was conducted from December 2022 to May 2023 at the Experimental Farm, Faculty of Agriculture, Hasanuddin University, Makassar, South Sulawesi, Indonesia.

2.2 Experimental design

The experiment was laid out in a split-plot design with three replications. The main plots consisted of biochar derived from corn cobs at three rates:

- M_0 = 0 t ha^{-1} (control)
- M_1 = 7.5 t ha^{-1}
- M_2 = 15 t ha^{-1}

The subplots were PGPR concentrations:

- P_0 = 0 g L^{-1} (control)
- P_1 = 10 g L^{-1}
- P_2 = 20 g L^{-1}

A total of 9 treatment combinations were established with 3 replications, and six plants per plot, resulting in 162 plants.

2.3 Plant materials and treatments

Seeds of chili pepper cultivar Dewata 76 were used. PGPR inoculum contained *Bacillus subtilis*, *Pseudomonas fluorescens*, *Trichoderma harzianum*, *T. viride*, and *Trichoderma sp.* Biochar was produced by slow pyrolysis of dried corn cobs.

2.4 Crop management

Seeds were pre-soaked in warm water and germinated in seed trays containing a soil–manure–rice husk medium (1:1:1). After four weeks, seedlings were transplanted at 50 × 40 cm spacing into raised beds covered with silver-black plastic mulch. Basal fertilization consisted of NPK 16-16-16 (10 g plant^{-1}). PGPR was applied twice: (i) seed soaking (50% of the treatment dose) and (ii) soil drenching one week after transplanting. Standard agronomic practices, including staking, weeding, irrigation, and pest control, were applied uniformly.

2.5 Data collection

Measured parameters included:

1. Soil analysis: conducted before planting to determine soil chemical properties (e.g., pH, organic C, N, P, K) at the experimental site.

2. Plant height (cm): measured from the soil surface to the shoot apex of the main stem. Measurements were taken every two weeks at 2, 4, 6, 8, and 10 weeks after transplanting (WAT).
3. Stem diameter (mm): measured after the second harvest using a digital caliper at 5 cm above the soil surface on the main stem.
4. Days to flowering (days): recorded from transplanting until 50% of the plants within each plot had fully opened flowers.
5. Days to harvest (days): calculated from transplanting to the first harvest.
6. Fruit length (cm): measured on five randomly selected fruits at each harvest using a ruler, from the apex to the pedicel attachment.
7. Fruit diameter (mm): measured on five randomly selected fruits at each harvest using a digital caliper at the mid-point of the fruit.
8. Fresh weight per fruit (g): determined by weighing five randomly selected fruits from each harvest.
9. Fruit drop percentage (%): calculated using the formula:

$$Fruit\ Drop\ (\%) = \frac{Number\ of\ Fruits\ Dropped}{Total\ number\ of\ Fruit\ Formed} X100\%$$

10. Number of fruits per plant (fruits): calculated by counting all physiologically mature fruits harvested from each plant and summing across harvests.
11. Fresh weight of fruits per plant (g): determined by weighing the total fresh fruit yield from each plant at every harvest and summing across harvests.
12. Yield per hectare (t ha^{-1}): estimated by converting the total fresh weight yield per plant to a per-hectare basis using the formula:

$$\text{Yield (t } ha^{-1}) = \text{FreshWeight per Plant (g)} X\ Number\ of\ Plants\ per\ Hectare$$

13. Fruit pungency: assessed through an organoleptic taste test, where 15 panelists evaluated the pungency level of chili fruits using a three-point scoring scale: very hot (3), moderately hot (2), and not hot (1).

2.6 Statistical analysis.

Data were analyzed using ANOVA, which is appropriate for a split-plot design. Treatment means were compared with the LSD test at the 5% significance level.

3. Results and Discussion

3.1. Result

3.1.1 Plant height (cm)

Plant height increased progressively from 2 to 10 weeks after planting across all treatments (Fig. 1). At 2 WAP, plant height ranged from 23.8 cm (M_1P_2) to 26.5 cm (M_0P_2), with no significant differences among treatments. By 6 WAP, the tallest plants were observed in treatments M_1P_1 and M_2P_1 (≈32–33 cm), while the lowest was recorded in M_1P_2 (28.8 cm). At 8 WAP, the highest plant height was found in M_1P_1 (36.1 cm), closely followed by M_1P_0 (36.1 cm) and M_2P_0 (34.9 cm), whereas M_0P_1 and M_0P_2 remained shorter (≈31–32 cm). At the final observation (10 WAP), the tallest plants were produced by the application of 7.5 t ha^{-1} biochar without PGPR (M_1P_0, 37.9 cm), followed by M_2P_2 (36.9 cm) and M_2P_0 (37.4 cm). In contrast, the shortest plants were

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recorded in M_0P_1 (33.3 cm) and M_0P_2 (33.2 cm). Although numerical differences were observed, statistical analysis revealed that the effects of biochar, PGPR, and their interaction on plant height were not significant ($p > 0.05$). Although treatment means diverged numerically, the lack of statistical separation likely reflects (i) moderate baseline soil fertility and uniform basal NPK that reduced treatment contrasts, and (ii) very high rainfall during early growth, which can suppress rhizosphere oxygen, slow biochar oxidation, and limit PGPR colonization. In nutrient-adequate and waterlogged conditions, short-term differences in vegetative growth are often muted even when longer-term soil benefits accrue.

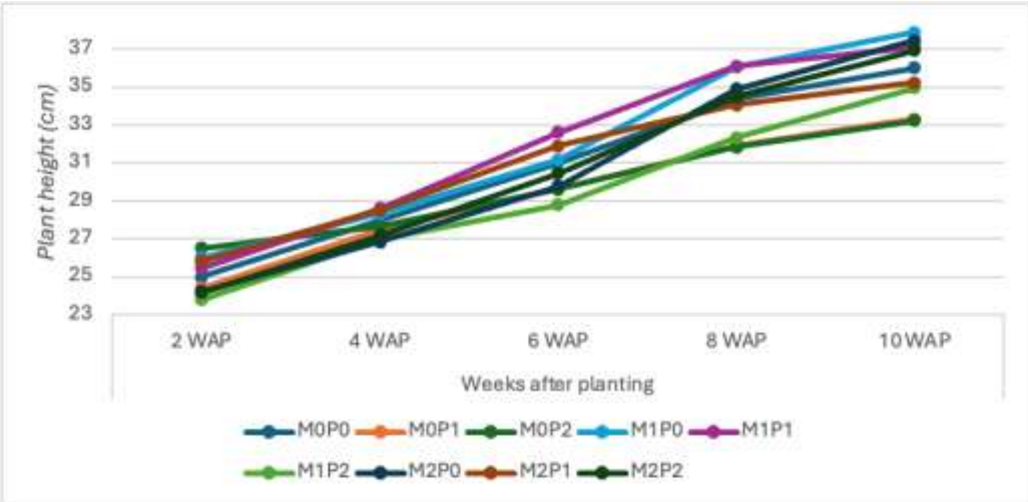

Figure 1. Plant height (cm) of chili (*Capsicum frutescens* L.) as affected by corn cob biochar and PGPR application from 2 to 10 weeks after planting (WAP).

3.1.2. Stem Diameter (mm)

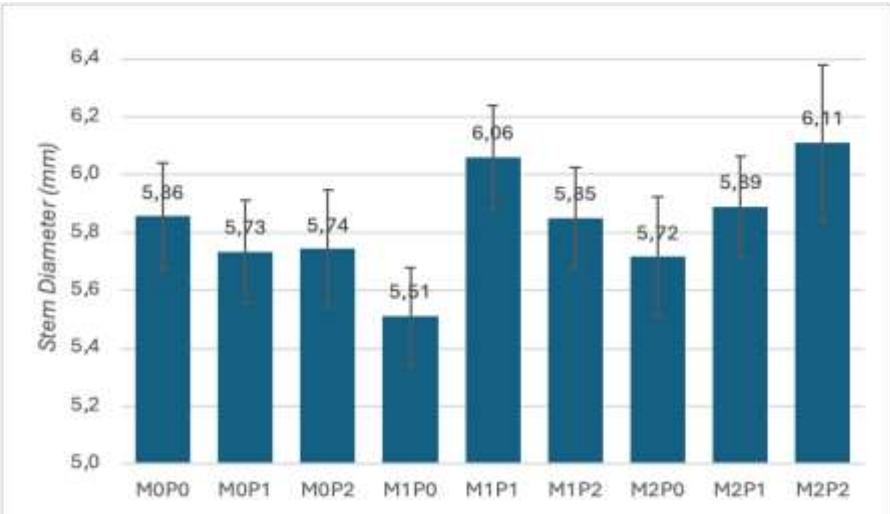

Figure 2. Effect of corn cob biochar and PGPR on stem diameter (mm) of chili (*Capsicum frutescens* L.). Bars represent means ± standard error (SE).

Stem diameter of chili plants ranged from 5.51 to 6.11 mm across treatments (Fig. 2). The narrowest stems were observed in treatment M_1P_0 (biochar 7.5 t ha^{-1} without PGPR, 5.51 mm), whereas the thickest stems were found in treatment M_2P_2 (biochar 15 t ha^{-1} with PGPR 20 g L^{-1}, 6.11 mm). Treatments M_1P_1 (6.06 mm) and M_2P_1 (5.89 mm) also tended to produce larger stem diameters compared with the control (M_0P_0, 5.86 mm). However, analysis of variance indicated that the effects of biochar, PGPR, and their interaction were not statistically significant ($p > 0.05$). Non-significance for stem diameter suggests that structural growth was not nutrient-limited under our conditions. PGPR effects on stem thickening typically appear when root growth and water status are stressed; neither constraint was present in this trial, further explaining the small effect sizes.

3.1.3. Days to Flowering (days)

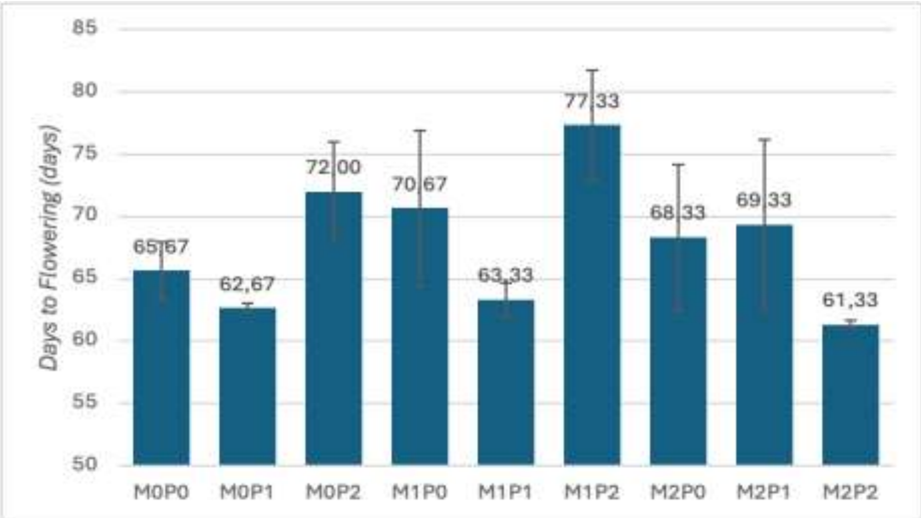

Figure 3. Effect of corn cob biochar and PGPR on days to flowering (days after planting) of chili (*Capsicum frutescens* L.). Bars represent means ± standard error (SE).

Days to flowering of chili plants ranged from 61.3 to 77.3 days after planting across treatments (Fig. 3). The earliest flowering was recorded in treatment M_2P_2 (61.3 days), followed by M_0P_1 (62.7 days) and M_1P_1 (63.3 days). In contrast, the latest flowering was observed in treatment M_1P_2 (77.3 days), followed by M_0P_2 (72.0 days) and M_1P_0 (70.7 days). Although numerical variation was present, statistical analysis indicated that the effects of biochar, PGPR, and their interaction were not significant ($p > 0.05$). Phenology responded weakly to treatments, indicating that flower initiation was driven more by genotype and temperature/photoperiod than by marginal improvements in nutrient supply. PGPR and biochar may influence phenology indirectly via stress alleviation; however, the relatively favorable temperature regime likely minimized this pathway.

3.1.4. Days to first harvest (days after planting)

Days to first harvest of chili plants were uniform across most treatments, averaging 110 days after planting (Table 1). Only treatment M_0P_2 (without biochar + PGPR 20 g L^{-1}) showed a slight delay, with an average of 111.3 ± 1.3 days**.** Statistical analysis indicated that biochar, PGPR, and their interaction had no significant effect on days to first harvest ($p > 0.05$). The uniformly ~110-day harvest time indicates limited phenological plasticity in 'Dewata 76' under the study climate. Where biochar/PGPR advances harvest elsewhere, the mechanism is usually drought mitigation or micronutrient correction; neither factor was limiting here.

Table 1. Effect of corn cob biochar and PGPR on days to first harvest (days after planting) of chili plants

Treatment	Mean ± SE (days)
M_0P_0	110.0 ± 0.0 a
M_0P_1	110.0 ± 0.0 a
M_0P_2	111.3 ± 1.3 a
M_1P_0	110.0 ± 0.0 a
M_1P_1	110.0 ± 0.0 a
M_1P_2	110.0 ± 0.0 a
M_2P_0	110.0 ± 0.0 a
M_2P_1	110.0 ± 0.0 a
M_2P_2	110.0 ± 0.0 a

Note: Values are means ± standard error (SE). Means followed by the same letter are not significantly different at $p > 0.05$ according to Tukey's HSD test.

3.1.5. Fruit length (cm)

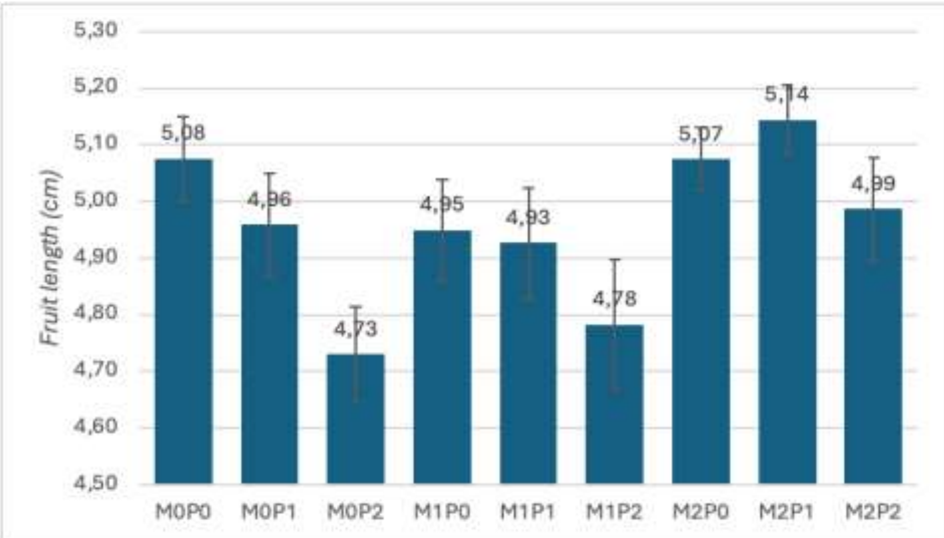

Figure 4. Effect of corn cob biochar and PGPR on fruit length (cm) of chili (*Capsicum frutescens* L.). Bars represent means ± standard error (SE).

Fruit length of chili ranged from 4.73 to 5.14 cm across treatments (Fig. 4). The shortest fruits were observed in treatment M_0P_2 (without biochar + PGPR 20 g L^{-1}, 4.73 cm), followed by M_1P_2 (7.5 t ha^{-1} biochar + PGPR 20 g L^{-1}, 4.78 cm). In contrast, the longest fruits were obtained from treatment M_2P_1 (15 t ha^{-1} biochar + PGPR 10 g L^{-1}, 5.14 cm), followed closely by M_2P_0 (5.07 cm) and M_0P_0 (5.08 cm). Although numerical differences were evident, statistical analysis showed that the effects of biochar, PGPR, and their interaction on fruit length were not significant ($p > 0.05$).

3.1.6. Fruit diameter (mm)

smallest fruits were recorded in treatment M_1P_2 (biochar 7.5 t ha^{-1} with PGPR 20 g L^{-1}, 7.13 mm), followed by M_0P_2 (7.30 mm) and M_0P_0 (7.34 mm). In contrast, the largest fruits were observed in treatment M_2P_2 (biochar 15 t ha^{-1} with PGPR 20 g L^{-1}, 7.74 mm), followed by M_2P_1 (7.67 mm) and M_2P_0 (7.67 mm). Although some treatments produced numerically larger fruit diameters, statistical analysis showed that the effects of biochar, PGPR, and their interaction on fruit diameter were not significant ($p > 0.05$). Fruit size traits showed small, non-significant differences. Because these traits have high genetic control and low responsiveness to moderate changes in soil fertility, meaningful shifts generally require either strong source–sink changes or stress reduction; our single-season trial under adequate fertilization produced neither.

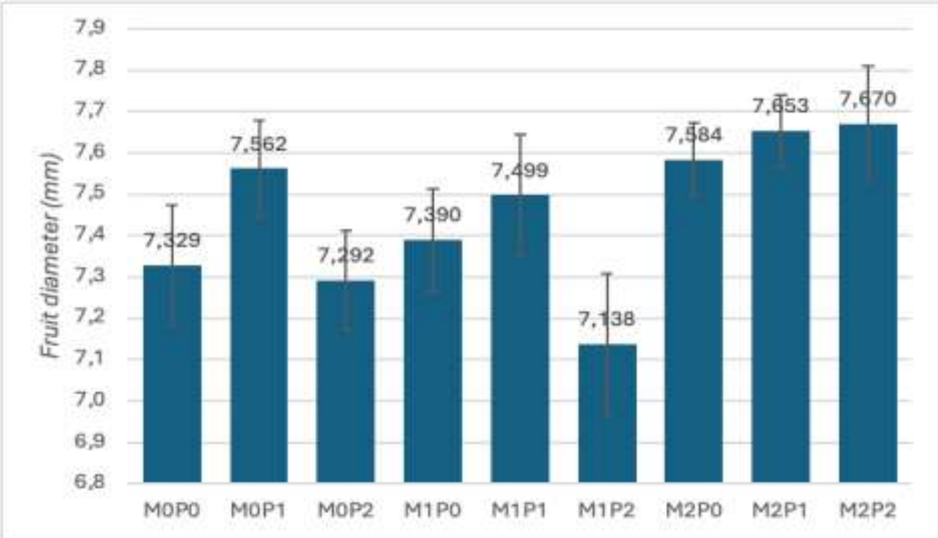

Figure 5. Effect of corn cob biochar and PGPR on fruit diameter (mm) of chili (*Capsicum frutescens* L.). Bars represent means ± standard error (SE).

3.1.7. Fresh fruit weight (g)

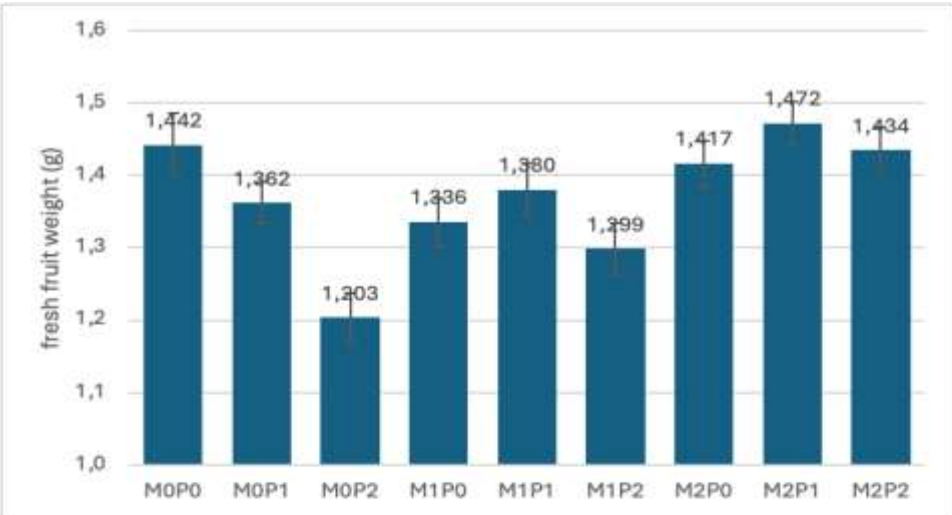

Figure 6. Effect of corn cob biochar and PGPR on fresh fruit weight (g) of chili (*Capsicum frutescens* L.). Bars represent means ± standard error (SE).

Fresh fruit weight of chili ranged from 1.20 to 1.47 g across treatments (Fig. 6). The lowest fruit weight was recorded in M_0P_2 (without biochar + PGPR 20 g L^{-1}, 1.20 g), followed by M_1P_2 (7.5 t ha^{-1} biochar + PGPR 20 g L^{-1}, 1.30 g). In contrast, the heaviest fruits were obtained from M_2P_1 (15 t ha^{-1} biochar + PGPR 10 g L^{-1}, 1.47 g), closely followed by M_0P_0 (1.74 g) and M_2P_2 (1.43 g). Although numerical differences were observed, statistical analysis indicated that the effects of biochar, PGPR, and their interaction on fresh fruit weight were not significant ($p > 0.05$). Per-fruit mass did not differ statistically, consistent with the fruit-size results. The yield gains observed later arose from more fruits per plant rather than larger fruits, suggesting that biochar–PGPR primarily affected sink number (flower set/retention) rather than sink size.

3.1.8. Fruit drop percentage (%)

Table 2. Effect of corn cob biochar and PGPR on fruit drop percentage of chili plants

Treatment	Mean ± SE (%)	Rank
M_0P_0	2.18 ± 0.01	7
M_0P_1	3.18 ± 0.00	3
M_0P_2	4.01 ± 0.00	2
M_1P_0	2.87 ± 0.01	5
M_1P_1	1.75 ± 0.01	8
M_1P_2	3.10 ± 0.01	4
M_2P_0	2.51 ± 0.00	6
M_2P_1	4.19 ± 0.01	1
M_2P_2	1.60 ± 0.00	9

Note: Values are means ± SE. Means with the same letter are not significantly different at $p > 0.05$ (Tukey's HSD).

Fruit drop percentage of chili plants ranged from 1.60% to 4.19% across treatments (Table 2). The lowest fruit drop was recorded in treatment M_2P_2 (biochar 15 t ha^{-1} with PGPR 20 g L^{-1}, 1.60%), followed by M_1P_1 (1.75%). In contrast, the highest fruit drop was observed in treatment M_2P_1 (4.19%), followed by M_0P_2 (4.01%). The control treatment (M_0P_0) showed a moderate fruit drop percentage of 2.18%. Despite these numerical variations, statistical analysis indicated that the effects of biochar, PGPR, and their interaction on fruit drop were not significant ($p > 0.05$). Plant height increased progressively from 2 to 10 weeks after planting across all treatments. Although most comparisons were non-significant, the lower means in M2P2 and M1P1 point to a plausible role of PGPR in reducing early fruit abscission via improved nutrient status and hormonal balance. Given the relatively high between-plant variability (see SE bars), a larger sample or multi-season testing may be required to detect this effect reliably.

3.1.9. Number of Fruits per Plant (fruit)

Table 3. Number of Fruits per Plant (fruit)

Biochar Dosage (ton ha^{-1})	PGPR Dosage (g L^{-1})			CV LSD 0.05
	0 (P_0)	10 (P_1)	20 (P_2)	
0 (M_0)	42.44^{a}_{p}	48.89^{a}_{p}	39.44^{b}_{p}	21.81
7.5 (M_1)	34.17^{a}_{q}	64.56^{a}_{p}	40.06^{b}_{q}	
15 (M_2)	48.11^{a}_{pq}	45.17^{a}_{q}	$\mathbf{69.17^{a}_{p}}$	
CV LSD 0.05		21.86		

Remarks: Numbers followed by the same letter in columns (a, b) or rows (p, q) mean that there is no significant difference in the LSD test, α=0.05.

The results of the LSD test at α = 0.05 (Table 3) indicated that the application of 15 t ha^{-1} corn cob biochar combined with PGPR at 20 g L^{-1} (M_2P_2) produced the highest average number of fruits per plant (69.17 fruits). This treatment was significantly higher compared with M_1P_2 (40.06 fruits) and M_0P_2 (39.44 fruits).

Furthermore, M_2P_2 was statistically similar to M_2P_0 (48.11 fruits), but significantly different from M_2P_1 (45.17 fruits), suggesting that the interaction of higher biochar dosage with PGPR at 20 g L^{-1} was most effective in increasing fruit number.

On the other hand, the lowest fruit number (34.17 fruits per plant) was recorded in the treatment with 7.5 t ha^{-1} biochar without PGPR (M_1P_0). This indicates that insufficient biochar combined with the absence of PGPR limited nutrient availability, thereby reducing fruit formation.

3.1.10. Fresh Weight of Fruit per Plant (g)

Table 4. Fresh Weight of Fruit per Plant (g)

Biochar Dosage (ton ha^{-1})	PGPR Dosage (g L^{-1})			CV LSD 0.05
	0 (P_0)	10 (P_1)	20 (P_2)	
0 (M_0)	42.50^{a}_{p}	50.03^{a}_{p}	39.55^{b}_{p}	18.99
7.5 (M_1)	36.03^{a}_{q}	63.77^{a}_{p}	43.89^{b}_{q}	
15 (M_2)	50.19^{a}_{q}	49.02^{a}_{q}	**72.30^{a}_{p}**	
CV LSD 0.05		19.45		

Notes: Numbers followed by the same letter in columns (a, b) or rows (p, q) mean that there is no significant difference in the LSD test α 0.05.

The results of the LSD test at α = 0.05 (Table 4) showed that the application of 15 t ha^{-1} corn cob biochar combined with PGPR at 20 g L^{-1} (M_2P_2) produced the highest average fresh fruit weight per plant (72.30 g). This treatment was significantly different from M_1P_2 (43.89 g) and M_0P_2 (39.55 g), both of which received PGPR at the same dosage but with lower or no biochar application.

Furthermore, M_2P_2 was also significantly higher compared with M_2P_1 (49.02 g) and M_2P_0 (50.19 g), indicating that the combination of higher biochar and the maximum PGPR dosage was more effective than biochar alone or with a lower PGPR concentration.

The lowest fresh fruit weight (36.03 g per plant) was recorded in the treatment with 7.5 t ha^{-1} biochar without PGPR (M_1P_0), suggesting that insufficient biochar application combined with the absence of PGPR limited nutrient availability, thereby reducing fruit biomass.

3.1.11. Production per Hectare (ton)

The results of the LSD test at α = 0.05 (Table 5) showed that the treatment of 15 t ha^{-1} corn cob biochar combined with PGPR at 20 g L^{-1} (M_2P_2) produced the highest yield per hectare (3.62 t ha^{-1}). This value was significantly higher compared with M_1P_2 (2.19 t ha^{-1}) and M_0P_2 (1.98 t ha^{-1}), both of which received PGPR at the same dosage but with lower or no biochar application.

M_2P_2 was also significantly different from M_2P_1 (2.45 t ha^{-1}) and M_2P_0 (2.51 t ha^{-1}), indicating that the synergistic combination of high biochar and PGPR dosages was more effective than biochar alone or in combination with a lower PGPR dose.

The lowest yield (1.80 t ha⁻¹) was observed in the treatment with 7.5 t ha⁻¹ biochar without PGPR (M_1P_0), highlighting that suboptimal biochar levels combined with the absence of PGPR reduced nutrient availability and limited yield performance.

Table 5. Number of Fruits per Plant (fruit)

Biochar Dosage (ton ha^{-1})	PGPR Dosage (g L^{-1})			CV LSD 0.05
	0 (P_0)	10 (P_1)	20 (P_2)	
0 (M_0)	2.13$^{a}_{p}$	2.50$^{a}_{p}$	1.98$^{b}_{p}$	0.95
7.5 (M_1)	1.80$^{a}_{q}$	3.19$^{a}_{p}$	2.19$^{b}_{q}$	
15 (M_2)	2.51$^{a}_{q}$	2.45$^{a}_{q}$	**3.62$^{a}_{p}$**	
CV LSD 0.05		0.97		

Remarks: Numbers followed by the same letter in columns (a, b) or rows (p, q) mean that there is no significant difference in the LSD test α 0.05.

3.2. Discussion

The present study demonstrated that the interaction between corn cob biochar and PGPR significantly affected three yield-related parameters: the number of fruits per plant, fresh fruit weight per plant, and yield per hectare. This interaction is attributable to the complementary roles of biochar and PGPR in nutrient management. PGPR enhances nutrient availability and uptake, whereas biochar mainly functions as a soil conditioner rather than a direct nutrient source. Nafi'ah et al. (2021) emphasized that biochar alone cannot supply nutrients and should be complemented by organic or biological fertilizers. Similarly, Ikraman et al. (2022) reported that biochar is more effective when combined with compost, manure, inorganic fertilizers, or biofertilizers. Biochar can also act as a source of organic matter for rhizobacteria, providing a favorable microhabitat for soil microbial activity (Mautuka et al., 2022).

However, several vegetative parameters—such as plant height, stem diameter, and flowering time—did not differ significantly among treatments. This lack of significance does not necessarily imply that biochar and PGPR were ineffective, but rather that their influence may have been moderated by environmental and management conditions during the experiment. High baseline soil fertility and uniform NPK fertilization likely minimized nutrient limitations, thereby reducing treatment contrasts. Furthermore, excessive rainfall recorded from January to May 2023 (>150 mm day⁻¹; BMKG, 2023) may have restricted oxygen availability in the root zone and hindered microbial colonization and activity, masking the potential benefits of PGPR and biochar under more optimal conditions.

The interaction of biochar and PGPR improved fruit number and fresh fruit weight. The combined application of 15 t ha⁻¹ biochar with 20 g L⁻¹ PGPR resulted in the highest number of fruits (69.17 fruits plant⁻¹) and the highest fresh fruit weight (72.30 g plant⁻¹). This improvement may be associated with the increased supply of essential nutrients, particularly nitrogen, phosphorus, and potassium, compared with control treatments. In contrast, plants grown without biochar and without PGPR received no additional nutrient inputs, which limited fruit formation and growth. Potassium plays a pivotal role in fruit formation, as highlighted by Ermawati et al. (2021), who stated that potassium is irreplaceable in fruit development. Nitrogen also contributes to fruit growth and quality, as noted by Lingga and Marsono (2010).

It is worth noting that while fruit size traits (length, diameter, and single-fruit weight) were statistically similar across treatments, their small numerical increases under combined treatments suggest that biochar–PGPR effects were more pronounced on reproductive sink number than on sink size. This aligns with the idea that improved nutrient cycling primarily enhances flower retention and fruit set rather than individual fruit enlargement, particularly under humid tropical conditions where source capacity (photosynthesis) is not limiting.

At the yield level, the interaction of biochar and PGPR also resulted in the highest production per hectare. The combined treatment of 15 t ha^{-1} biochar and 20 g L^{-1} PGPR produced 3.62 t ha^{-1}, confirming that biochar–biofertilizer interactions enhance crop productivity (Nafi'ah et al., 2021). Biochar provides a habitat and carrier medium for microbial inoculants, improving nutrient cycling and plant growth (Bolan et al., 2023). Supporting this, Alianti et al. (2016) reported that biochar–PGPR combinations produced the highest harvest weights in tomato.

The lack of significant differences in some yield components could also stem from the short experimental duration and the fact that biochar's full agronomic benefits often appear after multiple cropping cycles once its surface chemistry stabilizes and it integrates with soil organic matter. This suggests that the neutral or modest responses observed in early growth stages may transition to stronger effects over time.

Conversely, the treatment without biochar combined with PGPR 10 g L^{-1} resulted in the lowest yield components, with only 34.17 fruits $plant^{-1}$, 36.03 g fresh fruit weight $plant^{-1}$, and 1.80 t ha^{-1} yield, similar to the control (no biochar, no PGPR). This poor performance can be attributed to limited macronutrient (NPK) availability. Zalfadyla et al. (2022) stated that nitrogen and phosphorus are essential for cell division, while potassium increases fruit number and weight by enhancing pericarp thickness and seed weight.

In contrast to the production traits, biochar and PGPR did not significantly affect vegetative growth parameters. This is likely due to adverse weather conditions and extreme rainfall during the vegetative phase, which constrained plant development. According to BMKG (2023), South Sulawesi experienced extreme rainfall (>150 mm day^{-1}) from January to May 2023. Such excess water disrupts plant physiology and nutrient uptake, reducing growth and potential yields. Irsyad et al. (2019) also highlighted that climatic factors strongly influence plant growth, as adequate climatic conditions are necessary for proper physiological processes.

The absence of significant vegetative responses in this study should not be interpreted as a lack of treatment efficacy, but rather as an indication that biochar and PGPR are more effective under nutrient-deficient or drought-prone conditions than in high-rainfall, fertile-field environments. This is supported by Zhang et al. (2021) and Ahluwalia et al. (2021), who observed amplified effects of biochar and PGPR under stress due to improved nutrient-use efficiency and stress tolerance.

Practically, the combined application of corn cob biochar at 15 t ha^{-1} and PGPR at 20 g L^{-1} is recommended as a synergistic strategy to enhance chili yield in low-fertility or degraded soils, although short-term vegetative benefits may be limited in well-fertilized, high-rainfall settings. Notably, parameters such as flowering time, harvest time, fruit length, and diameter were not significantly affected, suggesting these traits are less responsive to soil amendments and more influenced by genetic or external environmental factors. Consistent with Gupta et al. (2023), this implies that PGPR and biochar primarily improve physiological efficiency and nutrient uptake rather than directly modifying morphological characteristics. Future research should focus on multi-season and multi-location trials, partial fertilizer substitution, and soil–microbe interactions under varying climatic conditions to optimize PGPR–biochar integration.

Overall, the results indicate that while single applications of biochar or PGPR did not significantly affect growth or yield traits, their combined application enhanced fruit production and yield, supporting the concept that biochar and PGPR act synergistically to improve chili productivity.

4. Conclusion

The combined application of PGPR (20 g L^{-1}) and corn cob biochar (15 t ha^{-1}) significantly enhanced cayenne pepper performance, yielding the highest fruit count (69.17 fruits per plant), fresh weight (72.30 g per plant), total yield (3.62 t ha^{-1}), and pungency level, while single applications of either PGPR or biochar showed no notable effects. These results highlight a synergistic interaction between biochar and PGPR, suggesting their integration as a promising strategy for sustainable soil improvement, particularly in nutrient-deficient or degraded areas. Although vegetative growth benefits were limited under high rainfall, biochar's long-term impact on soil fertility may become more pronounced over time. Future studies should investigate multi-season outcomes, potential reductions in chemical fertilizer use, and microbial dynamics across diverse soil and climate conditions to optimize this approach for sustainable chili cultivation.

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