



Research article

Cocoa pod biochar improves yield performance of brinjal (*Solanum melongena* L.) in a controlled pot experiment

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Abstract

Importance of the work: Assessment of the impact of underutilized cocoa pod biochar on brinjal (*Solanum melongena* L.) yield in soil addresses both waste valorization and productivity gaps.

Objectives: To evaluate the effects of cocoa pod biochar on the morphological traits and yield performance of brinjal cultivated in soil.

Materials and Methods: Brinjal plants were grown in polybags filled with soil amended with cocoa pod biochar at different rates in six treatments: 0 g (T0, the control); 20 g (T1); 40 g (T2); 60 g (T3); 80 g (T4); and 100 g (T5) per polybag. A randomized complete block design was used with five replications. The measured parameters were: plant height, leaf number, SPAD value, root and shoot biomass, fruit count, fruit weight and total yield. Results were reported as mean $\pm$ SD values.

Results: Only leaf number showed a significant ($p < 0.01$) morphological response to biochar, with the highest value (46.4 ± 5.13 leaves) in T3 (60 g). Yield attributes were highly significantly ($p < 0.001$) affected. Treatment T2 (40 g) recorded the highest yield (3576.2 ± 640.09 g per plant) and the highest fruit count (19.4 ± 3.85). The control produced the lowest yield and fruit number (633.1 ± 540.93 g and 6.0 ± 4.70 , respectively). These findings highlighted the positive impact of moderate biochar application on brinjal yield performance.

Main finding: Cocoa pod biochar at 40 g per plant or 60 g per plant improved brinjal yield and growth in soil, demonstrating its effectiveness as a sustainable amendment. This finding supports waste valorization and advances soil cultivation practices for enhanced brinjal productivity.

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Introduction

Increasingly, sustainable agriculture relies on waste valorization, converting agricultural byproducts into value-added resources. For example, often, cocoa pods, a major residue from cocoa production, are discarded, posing environmental concerns yet offering potential as biochar feedstock (Gopal et al., 2025). Through pyrolysis, cocoa pod husks can be transformed into a carbon-rich amendment with high surface area, porosity, alkaline pH and elevated nutrient content, particularly potassium, calcium and phosphorus, making it suitable for acidic tropical soils (Leng et al., 2021; Kabir et al., 2023). Such properties enhance nutrient retention, improve soil structure and promote beneficial microbial activity (Poveda et al., 2021; Iacomino et al., 2022).

While biochar from common feedstocks has been well-studied, cocoa pod biochar remains underexplored, especially for horticultural crops, such as brinjal (*Solanum melongena* L.) a nutrient-demanding crop that responds positively to organic amendments; however, data on the effects of cocoa pod biochar are scarce. This knowledge gap is crucial for integrated soil fertility management, which aims to reduce reliance on synthetic fertilizers.

In Malaysia and Southeast Asia, brinjal is cultivated widely for both domestic consumption and export, yet yields are often constrained by suboptimal soil fertility and high input costs (Sahu et al., 2020). Biochar has emerged as a promising amendment to improve soil quality and crop productivity, with studies on Solanaceae crops showing positive effects when derived from feedstocks such as rice husk, bamboo, and wood (Wani and Rao, 2012; Hayet et al., 2021). However, the reported outcomes vary depending on crop species, soil type, and biochar source (Cedeño et al., 2024), indicating the importance of identifying optimal application rates. While moderate doses have been associated with improved growth and yield traits, excessive applications may lead to imbalances in biomass allocation or reduced efficiency (Guo et al., 2020; Sheffield et al., 2024).

Despite these insights, few studies have investigated the optimal application rate of cocoa pod-derived biochar for brinjal, particularly under the low-fertility soils commonly used in polybag cultivation in Sarawak, Malaysia (Bahrun et al., 2018). Furthermore, little is known about the economic feasibility of such applications in smallholder systems. Therefore, the current study evaluated the agronomic response of *Solanum melongena* L. to cocoa pod-derived biochar applied

at varying rates, with a focus on yield performance and selected morphological traits under controlled conditions. In addition, a cost-benefit evaluation was included to assess the financial feasibility of cocoa pod biochar application at different rates, since economic sustainability remains a crucial consideration when adopting such amendments in resource-limited farming systems. The findings should highlight the potential of cocoa pod biochar as both a sustainable soil amendment derived from agricultural waste and a cost-effective solution to enhance productivity in brinjal cultivation.

Materials and Methods

Experimental design and treatments

The planting medium comprised commercially available topsoil commonly used in polybag cultivation in Sarawak. This soil was used as the base medium in all treatments. A randomized complete block design was used, with five blocks arranged to account for variation in sunlight exposure. Within each block, all six treatments were randomly assigned to polybags, with five plants (one plant per 40.6 cm × 40.6 cm polybag) per treatment. Sunlight exposure was used as the blocking factor, with blocks arranged across rows to minimize the influence of light variation within the experimental area. The treatments were: T0 (control; 100% soil), T1 (20 g cocoa pod biochar + soil), T2 (40 g cocoa pod biochar + soil), T3 (60 g cocoa pod biochar + soil), T4 (80 g cocoa pod biochar + soil) and T5 (100 g cocoa pod biochar + soil), following the approach by Bahrun et al., (2018). Each treatment was replicated five times and the plants were grown in 40.6 cm × 40.6 cm polybags. Each polybag was filled with 10.0 kg of topsoil; for T1–T5, the stated biochar dose (20–100 g) was mixed thoroughly into the same amount of soil per polybag.

Preparation of cocoa pod biochar

Cocoa pod biochar was produced using a drum kiln. Carbonization was conducted for at a peak temperature of 700°C for 2 hr, monitored using a kiln-mounted thermometer. Immediately after pyrolysis, the hot biochar was quenched with distilled water to halt combustion, air-dried to ambient moisture content and subsequently ground, before being passed through a 2 mm sieve.

Nitrogen (N) was determined using the Kjeldahl method through three main steps: digestion, distillation and titration

(Bremmer, 1965). Approximately 0.50 g of dry sample was digested with 5 mL concentrated sulfuric acid (H_2SO_4) and a K_2SO_4 - CuSO_4 catalyst at 420°C for about 60 min until the solution became clear, having converted organic nitrogen into ammonium sulfate. After cooling, the digest was diluted with water and neutralized with 40% NaOH, releasing ammonia (NH_3) which was steam-distilled into 25 mL of 4% boric acid containing Tashiro's indicator. Then, the trapped ammonia was titrated with 0.1 N HCl and the nitrogen content was calculated from the volume of acid used and expressed as a percentage of the dry weight. The phosphorus (P) and potassium (K) concentrations were determined using inductively coupled plasma optical emission spectrometry in accordance with the Association of Analytical Chemists Official Methods of Analysis (Eiterman, 2014) and the results were expressed in milligrams per kilogram. Each sample was analyzed in triplicate and the results were presented in boxplot format. Only the yield-critical macronutrients (N, P and K) were quantified. Calcium (Ca) and other physicochemical attributes—pH, electrical conductivity (EC) and cation exchange capacity (CEC)—were not assayed, which were recognized limitations imposed due to the cost constraints within the project scope. Future work should pair agronomic endpoints with full biochar and soil chemistry to resolve mechanisms.

Planting material

Brinjal was used as the test crop. Seeds were sourced from a commercially available variety (EP517). Germination was carried out in seedling trays filled with peat moss. After approximately 3 wk, when the seedlings had developed

their third true leaf, they were transplanted into the polybags containing the respective treatment media (Quamruzzaman et al., 2025).

Irrigation regime

Throughout the experiment, all plants received standardized management practices. Each polybag was irrigated daily to maintain field capacity, with the water volume adjusted according to plant growth stage (200–400 mL per day per polybag). The effect of biochar amendment was isolated by not applying fertilizer. Pest monitoring and manual removal of weeds were performed on a weekly basis; pest management chemicals were excluded to avoid confounding effects.

Data collection and analysis

At final harvest (90 d after transplanting), morphological traits were measured, consisting of plant height and stem diameter (measured in centimeters), shoot dry weight and root dry weight (measured in grams), number of leaves and SPAD reading. When the fruits had reached market maturity, yield-related parameters were measured, consisting of fruit number per plant, average fruit weight and total yield per plant, where the fruit number was recorded as the total count of marketable fruits per plant, the average fruit weight (measured in grams) was calculated as the total fruit weight divided by the number of fruits for each plant and the total yield per plant (measured in grams) was determined as the sum of all marketable fruits harvested from each plant. The parameters measured are summarized in Table 1.

Table 1 Morphological and yield attributes collected for brinjal

Parameter	(Unit)	Description
Morphological parameter		
Plant height	(cm)	The height of each plant from the soil level to the tip was measured with a tape measure.
Number of leaves	(No.)	The total count of leaves present on the plant.
SPAD Chlorophyll	SPAD unit	Total chlorophyll concentration in leaves.
Stem girth	(mm)	Use the Stem girth method, measuring 5cm from the base of the plant stalk with an absolute digital caliper.
Number of fruits	(Count)	The number of fruits produced by the plant is calculated based on each treatment.
Root dry weight	(g)	Total oven weighed roots per plant.
Shoot dry weight	(g)	Total oven-weighted shoots per plant.
Root to shoot ratio		Calculated as the ratio of root dry biomass (g) to shoot dry biomass (g), representing the relative allocation of biomass between belowground and aboveground plant parts.
Yield attributes		
Yield per plant	(g)	Total weight of fruits from the first harvest to the last harvest.
Number of fruits per plant	(Count)	Total number of fruits harvested from each individual plant
Weight per fruit	(g)	Average fruit weight calculated by dividing the total fruit weight per plant by the number of fruits produced.

Data were analyzed using R Studio (version 4.3.2; Posit Software, PBC; Boston, MA, USA). Treatment effects were evaluated using analysis of variance based on a randomized complete block design, with treatment as the main factor and sunlight exposure included as a blocking factor. Normality and homogeneity of variance were assessed using the Shapiro-Wilk and Bartlett's tests, respectively. *Post-hoc* comparisons were performed using Tukey's honestly significant difference test at $p < 0.05$. Additionally, Pearson's correlation analysis (r) was performed to assess the relationships between yield and morphological traits. Graphical summaries were generated using the 'ggplot2' package (Wickham, 2016) in R, a language and environment for statistical computing and graphics (R Core Team, 2025).

Cost-benefit data were used to evaluate the economic performance of each treatment. Production cost per plant included expenses for polybag, topsoil, labor and cocoa pod biochar. The gross return was calculated as the market selling price of brinjal (converted from the original Malaysian currency into USD per kilogram), multiplied by the total yield per plant, following standard gross income calculations in crop economic analysis, where the yield is multiplied by the farm-gate or field price (Sharma and Suryavanshi, 2021). The cost-benefit ratio (CBR) was calculated as the ratio of total gross return to total production cost, consistent with the commonly used benefit-cost ratio formula, shown in Equation 1:

$$\text{CBR} = \text{Gross return} / \text{Total production cost} \quad (1)$$

where all values are measured in US dollars per plant.

Results were presented as mean $\pm$ SD values, unless stated otherwise.

Results and Discussion

Nutrient profile of cocoa pod biochar

The cocoa pod biochar was rich in K, with concentrations in the range 59,372–59,376 mg/kg and a median of 59,374

mg/kg (Fig. 1). The P and N levels were comparatively lower, averaging 419 mg/kg and 1.02%, respectively. This high K content is advantageous for reproductive growth and fruit development in brinjal, as K supports flowering, fruit set and translocation of assimilates (Ahmad et al., 2023). The presence of moderate P and N levels may also contribute to early vegetative growth and root establishment. These findings aligned with reports that K-rich biochar from plant-based residues can enhance soil fertility and improve productivity in solanaceous crops (Kabir et al., 2023).

Morphological attributes

The analysis of variance (Table 2) revealed that only leaf number differed significantly among treatments ($p < 0.01$), while the other traits (plant height, stem girth, SPAD value, shoot biomass, root biomass, root-to-shoot ratio) were not significantly different. The data presented in Tables 2 and 3 were collected at 90 d after transplanting, representing the plants' morphological attributes at this specific growth stage. Although data from multiple plant ages may provide insights into growth rates over time, the current study focused on this defined developmental stage to provide a comprehensive assessment of the treatment effects on plant morphology.

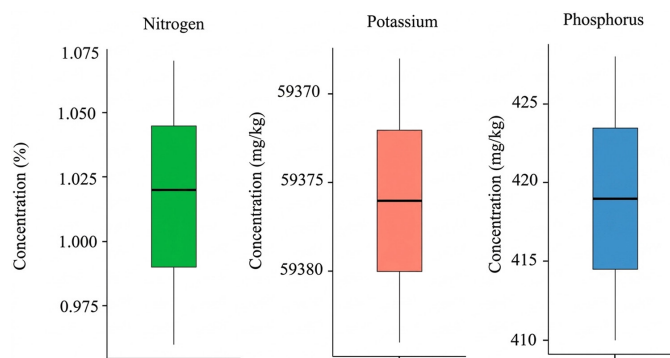


Fig. 1 Boxplot representation of total nitrogen, potassium and phosphorus concentrations in cocoa pod biochar, where vertical lines represent the minimum and maximum values and the bold horizontal line represents the median.

Table 2 Analysis of variance for morphological traits of brinjal under different rates of cocoa pod biochar as amended planting medium

SOV	DF	Height (cm)	Number of leaves	Chlorophyll (SPAD)	Girth (mm)	Root biomass (g)	Shoot biomass (g)	Root-to-shoot ratio
Treatment	5	64.38	107.39	441.3	1.513	42,928	79.87	16.16
Block	4	293.03	41.25	432.6	9.678	17,866	296.63	7.332
Residuals	20	285.71	24.81	271.2	2.802	22,231	114.07	10.557

SOV = source of variation; DF = degrees of freedom

Table 3 Mean comparison of morphological traits of brinjal under different rates of cocoa pod biochar as amended planting medium

Treatment (cocoa pod biochar)	Height (cm)	Number of leaves	Chlorophyll (SPAD)	Girth (mm)	Root Biomass (g)	Shoot Biomass (g)	Root shoot ratio
T0- Soil only	94.8 ± 11.32 ^a	35.6 ± 7.96 ^b	40.8 ± 5.74 ^a	12.5 ± 1.48 ^a	142.8 ± 75.23 ^a	49.0 ± 9.03 ^a	3.2 ± 2.42 ^a
T1 (20 g)	96.6 ± 11.93 ^a	35.8 ± 3.19 ^b	46.5 ± 18.74 ^a	13.6 ± 1.60 ^a	153.8 ± 54.03 ^a	52.6 ± 8.82 ^a	3.0 ± 1.16 ^a
T2 (40 g)	105.2 ± 26.40 ^a	44 ± 5.43 ^{ab}	48.7 ± 18.05 ^a	13.2 ± 2.78 ^a	189.0 ± 151.14 ^a	55.8 ± 21.66 ^a	3.4 ± 1.94 ^a
T3 (60 g)	97.4 ± 13.67 ^a	46.4 ± 5.13 ^a	52.6 ± 11.42 ^a	14.1 ± 1.44 ^a	328.2 ± 111.35 ^a	59.4 ± 7.83 ^a	5.5 ± 1.77 ^a
T4 (80 g)	99.6 ± 15.42 ^a	36.4 ± 4.67 ^{ab}	67.8 ± 25.98 ^a	13.3 ± 2.52 ^a	204.2 ± 96.83 ^a	58.8 ± 11.01 ^a	3.7 ± 2.13 ^a
T5 (100 g)	98.6 ± 18.16 ^a	40.8 ± 3.77 ^{ab}	57.0 ± 16.53 ^a	13.0 ± 1.69 ^a	362.4 ± 275.36 ^a	53.0 ± 7.48 ^a	7.6 ± 6.44 ^a
Mean	98.7	39.8	52.22	13.28	230.071	54.8	4.4

Values presented as mean ± SD followed by same lowercase superscript within each column are not significantly different at $p \leq 0.05$, based on Tukey's honestly significant difference multiple mean comparisons.

The highest mean leaf number was in T3 (46.4 ± 5.13 leaves), followed by T2 (44.0 ± 5.43 leaves). The control (T0) had the lowest count (35.6 ± 7.96 leaves). Moderate biochar rates (40–60 g) appeared to improve vegetative vigor, likely due to enhanced rhizosphere conditions and nutrient availability (Neenu et al., 2023).

The SPAD readings, used as an indirect measure of the chlorophyll content, did not differ significantly between treatments. This suggested that biochar did not consistently influence leaf chlorophyll concentration; therefore, chlorophyll was not a primary driver of yield in the study. This observation was consistent with other reports, where biochar may have enhanced nutrient availability without necessarily increasing foliar chlorophyll (Prendergast-Miller et al., 2014). In contrast, leaf number had a moderate, positive correlation with fruit number and total yield, suggesting a role for canopy development (Penzel and Tsoulas, 2022), although future studies are needed incorporating leaf area measurements to confirm this relationship.

Yield attributes

The analysis of variance revealed that the biochar application had a significant impact on all yield traits (Table 4). Mean comparison revealed that the T2 treatment produced the highest total yield per plant (3576.2 ± 640.09 g), fruit number (19.4 ± 3.85) and fruit weight (185.7 ± 17.08 g per fruit), outperforming both the control and other biochar rates. In addition, T3 improved the total yield per plant and the number of fruits per plant ($1752.3 \pm$

505.81 g and 15.8 ± 5.50 , respectively), but was lower than T2, suggesting diminishing returns beyond the optimal rate (Table 5). This reflected a dose-dependent response, where moderate biochar application favored higher fruit numbers and total yield, while higher rates promoted fewer but larger fruits (Premalatha et al., 2023). Similar patterns have been reported in tomato and maize under biochar amendments (Shumaila et al., 2023). These outcomes may be linked to the nutrient composition of cocoa pod biochar, which is particularly rich in K and contains moderate levels of P and N. K is well known for supporting flowering, fruit set and assimilate translocation, which may partly explain the higher fruit numbers observed at moderate application rates (Villette et al., 2020; Wu et al., 2024), although soil nutrient availability and plant tissue nutrient uptake were not measured. Conversely, excessive biochar may disrupt nutrient balance, favoring fruit enlargement rather than fruit number. At very high rates, biochar has been reported to alter soil chemical or physical properties, such as pH or pore space, which may reduce nutrient uptake efficiency (Rodríguez-Vila et al., 2022).

Table 4 Analysis of variance for yield and yield attributes of brinjal under different rates of cocoa pod biochar as an amended planting medium

SOV	DF	Yield per plant (g)	Number of fruits per plant	Weight per fruit (g)
Treatment	5	4760541	133.2	8637
Block	4	660279	36.13	1478
Residual	20	184320	10.05	495

SOV = source of variation; DF = degrees of freedom.

Table 5 Mean comparison for yield and yield attributes of brinjal under different rates of cocoa pod biochar as amended planting medium

Treatment (cocoa pod biochar)	Yield (g)	Number of fruits	Weight per fruit (g)
T0- Soil only	633.1 ± 540.93 ^c	6.0 ± 4.70 ^d	106.4 ± 19.83 ^b
T1 (20 g)	1,427.2 ± 484.90 ^{bc}	7.4 ± 1.95 ^{cd}	190.6 ± 34.58 ^a
T2 (40 g)	3,576.2 ± 640.09 ^a	19.4 ± 3.85 ^a	185.7 ± 17.08 ^a
T3 (60 g)	1,752.3 ± 505.81 ^b	15.8 ± 5.50 ^{ab}	114.3 ± 21.70 ^b
T4 (80 g)	1,473.3 ± 366.36 ^{bc}	12.6 ± 3.13 ^{bc}	119.2 ± 25.92 ^b
T5 (100 g)	1,776.6 ± 504.36 ^b	9.4 ± 2.41 ^{cd}	190.0 ± 30.45 ^a
Mean	1773.12	11.77	151.03

Values presented as mean ± SD followed by same lowercase superscript within each column are not significantly different at $p \leq 0.05$, based on Tukey's honestly significant difference multiple mean comparisons.

Notably, the heaviest average fruits were produced at the lowest and highest biochar rates of T1 (190.6 ± 34.58 g per fruit) and T5 (190.0 ± 30.45 g per fruit), indicating that fruit size and fruit number may respond differently to biochar application (Simiele et al., 2022). The control (T0) had the lowest yield (633.1 ± 540.93 g per plant) and fruit number (6.0 ± 4.70 number of fruits per plant), consistent with nutrient-poor soil limiting productivity. This outcome aligned with reports on other crops, where biochar increased individual fruit mass but did not consistently enhance fruit number. For example, tomato and bean plants showed significant increases in average fruit biomass but not in fruit number under biochar amendment (Sheffield et al., 2024). Similarly, Adekiya et al. (2025) reported that biochar increased tomato fruit weight per plant more than fruit count, while Micheal et al., (2017) observed improvements in cucumber vine length, number of fruits, fruit length and yield of cucumber.

Pearson's correlation

Based on the correlation results (Fig. 2), there was a very strong positive relationship between the root biomass and the root-to-shoot ratio ($r = 0.94$), indicating that the larger root systems were associated with increased belowground biomass allocation. Root biomass was correlated positively with biochar application, indicating a potential relationship with enhanced nutrient uptake and plant stability (Ren et al., 2021).

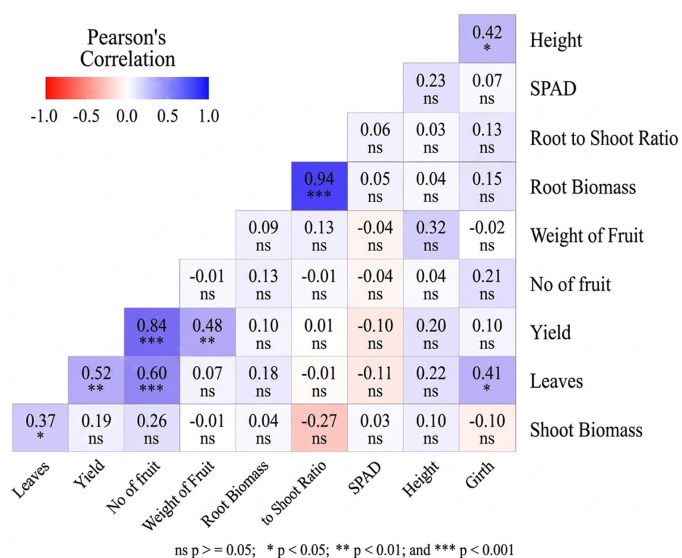


Fig. 2 Correlation between measured parameters based on Pearson's correlation analysis. ns indicates not significant; * p < 0.05; ** p < 0.01; and *** p < 0.001.

There was a very strong positive correlation between the root biomass and the root-to-shoot ratio ($r = 0.94$), suggesting an association between the higher root biomass and greater belowground biomass allocation. This pattern was consistent with other findings on the role of root development for resource acquisition and plant support (Ren et al., 2021), although the current correlation did not establish a causal effect of biochar on root growth. The weak negative correlation between the shoot biomass and the root-to-shoot ratio ($r = -0.27$) may indicate variation in biomass partitioning; however, this should be interpreted cautiously because the correlation was weak and not statistically significant.

The total yield was strongly correlated with fruit number ($r = 0.84$) and moderately with fruit weight ($r = 0.48$), indicating that fruit number was the main driver of yield under the current biochar-amended conditions. In addition, yield showed a moderate positive correlation with leaf number ($r = 0.52$), suggesting that cocoa pod biochar enhanced vegetative growth that indirectly supported reproductive development (Smith et al., 2018). In general, photosynthetic capacity depends on both leaf area and chlorophyll content (Patil et al., 2018). In the current study, the cocoa pod biochar in T3 increased the number of leaves, which may have expanded the light interception area and enhanced photosynthetic potential, thereby contributing to improved fruit set and total yield. These relationships imply that yield improvement under biochar amendment was driven primarily by increased assimilate production through better canopy development rather than by changes in the chlorophyll concentration or plant height (Klára et al., 2020). Future studies incorporating leaf area measurements would allow a clearer understanding of how canopy traits influence yield formation under biochar-enriched conditions.

The SPAD values were weakly correlated with yield, reinforcing that chlorophyll content alone does not determine productivity when biochar affects root nutrient uptake more than foliar characteristics (Prendergast-Miller et al., 2014). In contrast, leaf number differed significantly across treatments and had a moderate correlation with fruit number and total yield. More leaves likely provide greater photosynthetic surface, supporting assimilate production and reproductive growth (Penzel and Tsoulis, 2022). This relationship underscores the significance of canopy development as a crucial determinant of yield response to biochar, indicating that future investigations should quantify canopy parameters to establish stronger physiological connections between biochar application and crop productivity.

Cost-benefit analysis

The gross margin increased with the biochar rate up to 40 g per plant (T2), where profit peaked at USD 4.48 per plant (Fig. 3). The high return in T2 reflected both maximum yield and low input cost (USD 0.053 per plant at 40 g rate).

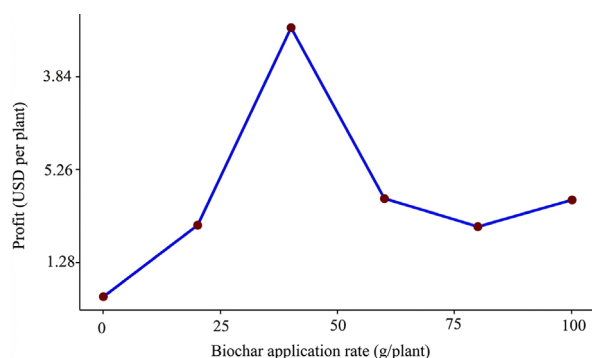


Fig. 3 Profit per plant of brinjal as influenced by cocoa pod biochar rates

At higher rates, the yield gains were insufficient to offset the additional cost of biochar. For example, T5 yielded more than the control, but profit dropped to USD 2.19 per plant, demonstrating the economic principle of diminishing returns, where excessive input raises costs without proportionate yield benefits (Zulfiqar et al., 2022).

These findings confirmed that moderate biochar rates delivered the best balance between agronomic gains and profitability, making them ideal for adoption in both smallholder and commercial brinjal systems.

Beyond nutrient availability, other mechanisms may explain the positive effects of biochar on crop yield. Often, in acidic soils, biochar moderates pH and increases cation exchange capacity, thereby enhancing nutrient retention and availability to plants (Nega et al., 2025; Šimanský and Juriga, 2025). In addition, biochar enhances soil physical properties, such as porosity and water-holding capacity, which can mitigate drought stress and promote more stable plant growth (Joseph et al., 2021). Furthermore, biochar provides a favorable habitat for soil microbial communities, which contribute to nutrient cycling and plant health (Yan et al., 2022; Huang et al., 2023). The current study did not include baseline soil chemical characterization (pH, EC, CEC, nutrient availability) and therefore any mechanistic attribution of yield responses is based on net agronomic performance rather than changes in soil properties. Future work should incorporate soil chemical and physical analyses to identify any more direct links between biochar-induced changes in soil conditions and crop responses.

Conclusion

Cocoa pod biochar showed potential as a soil amendment for brinjal cultivation under the conditions of this controlled pot experiment, with the application rate affecting yield performance more clearly than most measured vegetative traits. A moderate rate of 40 g per plant produced the highest yield (3,576.2 g per plant) and profit margin (USD 4.48 = per plant), mainly associated with a higher number of fruits per plant. At lower and higher rates, some treatments produced differences in average fruit weight or root biomass; however, these responses did not translate consistently into proportional yield gains. These findings highlight the importance of optimizing the biochar rate to improve agronomic and economic outcomes. Beyond enhancing productivity, cocoa pod biochar may provide a sustainable pathway for valorizing agricultural waste in tropical farming systems. Future studies should evaluate its long-term effects on soil chemical and physical properties, nutrient availability, plant nutrient uptake, performance across different environments and integration with other soil improvement strategies.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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