



Research article

Optimizing edamame [*Glycine max* (L.) Merr., 1917] production through bioactive charcoal compost application on alluvial soils

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Abstract

Importance of the work: Edamame production in tropical regions is constrained by limited arable land and poor soil fertility, particularly on nutrient-deficient alluvial soils. Sustainable soil management using organic amendments, such as bioactive charcoal compost (BCC), is therefore needed to improve soil health and crop productivity.

Objectives: To evaluate the effects of varying BCC dosages on growth parameters and yield components of edamame cultivated on alluvial soil under tropical conditions.

Materials and Methods: The field experiment was conducted at Rasau Jaya III Research Station, West Kalimantan, Indonesia, from February to April 2024. A randomized complete block design was used with five treatments: a control (a_0); corn-stem compost at 4,500 g/plot (a_1); and bioactive charcoal compost at 1,500 g/plot (a_2), 3,000 g/plot (a_3) and 4,500 g/plot (a_4). Each treatment was replicated six times with 75 plants per experimental unit (3.0 m × 1.0 m plot size) over a growing period of 60 d (harvest at R6 stage, 60 days after planting). The parameters measured were growth variables (plant height, leaf number, and branch number), yield variables (numbers of filled and empty pod, pod weight, and filling percentage), plant tissue nutrient content (N, P, K, Ca, and Mg), nutrient uptake and post-harvest soil chemical properties. Data were analyzed using analysis of variance followed by Tukey's honestly significant difference test at a significance level of $p < 0.05$.

Results: The BCC applications significantly enhanced plant growth metrics and yield components ($p < 0.05$). The highest dosage treatment (a_4 : 4,500 g/plot bioactive charcoal compost) demonstrated superior performance compared to the control treatment (a_0), with plant height increasing 12.4% (29.17 cm versus 25.94 cm), leaf number improved 35.0% (19.72 versus 14.61), filled-pod count increased 72.8% (36.28 versus 21.00) and filled-pod weight increased 64.6% (96.67 g versus 58.72 g). Soil pH improved from 4.42 to 5.12, while nutrient uptake efficiency increased substantially for nitrogen (68%), phosphorus (81%) and potassium (65%).

Main finding: BCC application at 4,500 g/plot (equivalent to 15 t/ha on a 3.0 m² plot) was an effective sustainable soil management strategy for optimizing edamame productivity on alluvial soils, achieving up to 72.8% increased pod production and 64.6% increased pod weight compared to the control, while providing both immediate yield benefits and long-term soil health improvement in tropical agricultural systems.

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Introduction

Edamame [*Glycine max* (L.) Merr., 1917], a vegetable soybean harvested at the R6 stage, is a strategic crop for addressing food security and economic development in Southeast Asia. Global edamame production has increased notably from 2.3 million t in 2020 to approximately 3.1 million t in 2024, with Asia accounting for 85% of total production (Food and Agriculture Organization of the United Nations, 2024). Indonesia's edamame production reached 45,000 t in 2023, yet this only met 60% of domestic demand, with the remainder provided through imports, primarily from China and Thailand (Indonesian Ministry of Agriculture, 2024). The crop commands premium market prices of USD 450–600/t compared to grain soybean at USD 350–400/t, offering 30% higher profit margins and requiring 25% shorter growing period (65–75 d versus 90–100 d), making it particularly suitable for intensive tropical cropping systems where land availability is limited (Jiang et al., 2020; Zhang et al., 2023). Based on recent market analysis projects, Southeast Asian edamame demand is projected to grow 8–10% annually through to 2030, driven by increasing health consciousness and plant-based protein consumption (Williams et al., 2022).

In Southeast Asia, edamame cultivation faces major challenges on alluvial soils, which constitute approximately 35% of agricultural land in tropical deltas (Food and Agriculture Organization of the United Nations, 2023). These soils, classified predominantly as Entisols and Inceptisols under USDA Soil Taxonomy, have inherent limitations, including low organic matter content (<2%), soil acidity (pH 4.5–5.5), aluminum toxicity (>1.0 cmol/kg) and poor nutrient retention (cation exchange capacity, CEC <15 cmol/kg), which collectively impair root development by 60%, reduce rhizobial nodulation efficiency by 40% and limit nutrient availability during critical reproductive stages (Ruonan et al., 2024; Chen et al., 2024).

Conventional soil amendments, such as lime and chemical fertilizers, provide temporary solutions but fail to address long-term soil health issues and often lead to environmental concerns, including groundwater contamination and greenhouse gas emissions (Hassan et al., 2022). Recent studies have demonstrated that biochar application alone, while improving soil carbon sequestration, initially may immobilize nutrients and require 2–3 cropping seasons to show yield benefits (Wang et al., 2024; Patel and Panwar, 2024). The integration of biochar with composted organic matter enriched with

beneficial microorganisms (termed bioactive charcoal compost, BCC) represents an innovative approach that overcomes these limitations. BCC combines three synergistic components: 1) biochar, providing a stable carbon structure and a high CEC (>20 cmol/kg) for long-term soil improvement; 2) composted organic matter that can supply immediately available nutrients (N, 1.4%; P, 3.8%; K, 1.1%); and 3) beneficial microorganisms (>10⁶ CFU/g), particularly *Trichoderma harzianum*, for enhanced nutrient cycling and disease suppression (Tyśkiewicz et al., 2022; Kabir et al., 2023).

Recent research (2020–2025) has demonstrated the superior performance of biochar-compost combinations over individual amendments. For example, Ajibade et al. (2023) reported that co-composted biochar increased crop yields by 25–40% compared to biochar alone. Bakshi et al. (2021) showed that biochar-compost scaffolding enhanced nitrogen use efficiency by 35% through slow-release mechanisms. For legume crops specifically, Fanai et al. (2024) found that biochar-compost with plant growth-promoting bacteria increased nodulation by 45% and nitrogen fixation by 38%. In edamame cultivation, Brooks et al. (2023) demonstrated yield improvements of 22–31% with organic amendments, though their study focusing on temperate conditions. The comprehensive review by Alkharabsheh et al. (2021) identified that biochar-compost applications improved soil quality parameters by 30–50% across various cropping systems. However, specific research remains limited on BCC application for edamame production in tropical alluvial soils, with most studies focusing on temperate regions or other legume crops (Bhattacharyya et al., 2024; Bekchanova et al., 2024).

The alkaline nature of BCC (pH 8.5) specifically addresses the acidity constraint of alluvial soils through direct neutralization, while its high CEC compensates for poor nutrient retention capacity. The biochar component provides micropores that improve water retention by 25–30% in the predominantly silty texture of alluvial soils (Ndede et al., 2022). Additionally, the *Trichoderma harzianum* component has been shown to solubilize phosphorus, produce phytohormones and suppress soil-borne pathogens, providing multiple benefits beyond conventional amendments (de Andrade et al., 2023). Despite these potential advantages, there has been no determination of optimal BCC application rates and their specific effects on edamame growth and yield under tropical alluvial soil conditions.

Therefore, the current research addressed these gaps by evaluating bioactive charcoal compost dosage effects on edamame growth and yield parameters under controlled field

conditions. The aims of this study were: 1) to evaluate the effects of three bioactive charcoal compost dosage levels (1,500 g/plot, 3,000 g/plot or 4,500 g/plot) on edamame vegetative growth parameters (height, leaf number, branching); 2) to quantify changes in yield components (pod number, pod weight, filling percentage); and 3) to assess nutrient uptake efficiency (N, P, K) and post-harvest soil chemical improvements under tropical alluvial soil conditions.

Materials and Methods

Experimental site and design

The field experiment was conducted at the Rasau Jaya III Research Station (0°18'S, 109°15'E), Kubu Raya Regency, West Kalimantan, Indonesia, at 1–2 m above sea level. The study was implemented from February to April 2024 using a randomized complete block design with six replications. Each experimental plot measured 3.0 m × 1.0 m (3.0 m²), containing 75 plants arranged in 5 rows × 15 plants with between plant spacing of 15 cm and between row spacing of 20 cm. For data collection, 10 sample plants were selected randomly and tagged from the inner three rows of each plot (excluding border plants) for non-destructive measurements, while 5 plants/plot were harvested for destructive sampling and yield assessment.

Soil characterization and preparation

Alluvial soil samples were collected from 0–20 cm depth and analyzed for physicochemical properties following standard procedures. Soil preparation included mechanical tillage, raised bed construction and dolomite lime application at 300 g/plot (equivalent to 1 t/ha) at 2 wk before planting to adjust the pH to the optimal range (6.0–6.5). The experimental soil was classified as Typic Endoaquent (USDA Soil Taxonomy; Soil Survey Staff, 2022) or Gleyic Fluvisol (World Reference Base for Soil Resources (WRB) classification), representing poorly-drained alluvial deposits typical of the West Kalimantan lowlands (Sulaeman et al., 2024).

Treatment applications and materials

Five treatment levels were evaluated: control without organic amendment (a₀); corn stem compost at 4,500 g/plot as a positive control (a₁), representing conventional organic practice in the region, with a similar C-to-N ratio

(9.7) to BCC (11.4) but lacking the biochar component and beneficial microorganisms, allowing isolation of biochar-specific effects; and bioactive charcoal compost at three dosage levels of 1,500 g/plot (a₂); 3,000 g/plot (a₃); and 4,500 g/plot (a₄). The BCC dosage levels were selected based on preliminary trials and represented equivalent field application rates of 5 t/ha, 10 t/ha and 15 t/ha, respectively, which aligned with practical farmer application capabilities and economic considerations in the region according to local agricultural extension recommendations. All compost applications were on a dry weight basis (moisture content <15%), applied once as a basal application during bed preparation and incorporated into the top 15 cm of soil 7 d before planting. The bioactive charcoal compost contained: organic carbon (16.28%), total nitrogen (1.43%) with a C-to-N ratio of 11.41, phosphorus (3.81%), potassium (1.12%), calcium (1.56%), magnesium (0.78%), pH 8.49 and beneficial microorganisms, including *Trichoderma harzianum*, at populations exceeding 1 × 10⁶ colony-forming units (CFU)/g, as declared by the manufacturer (the microbial populations were not independently verified in this study). Notably, preliminary material description values (35% C, 1.8% N) referred to the base biochar before the composting process. The final product underwent co-composting with organic materials and microbial inoculation, resulting in the analytical values presented in Table 1.

Table 1 Chemical characteristics of the bioactive charcoal compost used in the experiment.

Parameter	Unit	Value
pH	—	8.49
Organic carbon (C)	%	16.28
Total nitrogen (N)	%	1.43
C-to-N ratio	—	11.41
HCl extract (1:2)		
– Phosphorus	%	3.81
– Potassium	%	1.12
– Calcium	%	1.56
– Magnesium	%	0.78

Source: Laboratory of Soil Chemistry and Fertility, Faculty of Agriculture, Tanjungpura University (2024)

Plant material and cultural practices

Edamame variety Ryoko 75, obtained from certified Japanese sources, was planted at 2.0 cm depth, with 15 cm spacing between plants and 20 cm spacing between rows. Pre-planting seed treatment included surface sterilization with 1% sodium hypochlorite solution and inoculation with

rhizobium bacteria. Irrigation was provided twice daily using micro-sprinkler systems, maintaining soil moisture at 70–80% field capacity throughout the growing period. No chemical fertilizers were applied in this experiment to isolate the effects of organic amendments on edamame performance.

The experimental area was cleared of previous crop residues and weeds using manual methods. Primary tillage was conducted using a hand tractor to a depth of 20–25 cm, followed by secondary tillage after 7 d to break soil clods. Raised beds (height, 20 cm; width, 100 cm; length, 300 cm) were constructed with 30 cm drainage channels between plots to prevent waterlogging during the rainy season. Plot boundaries were marked using bamboo stakes and plastic mulch barriers (30 cm depth) were installed between plots to prevent lateral movement of amendments. Dolomite lime was applied at 300 g/plot (equivalent to 1 t/ha) on January 20, 2024 and incorporated into the top 15 cm of soil. Then, the plots were irrigated and left for 14 d for lime reaction.

The bioactive charcoal compost and corn stem compost were prepared and analyzed before application (moisture content adjusted to <15%). On February 1, 2024, control plots (a_0) received no organic amendment, the corn stem compost plots (a_1) received 4,500 g/plot uniformly spread and incorporated, while the BCC plots received 1,500 g/plot (a_2), 3,000 g/plot (a_3) and 4,500 g/plot (a_4).

All amendments were distributed uniformly over the plot surface using a calibrated container, then incorporated into the top 15 cm of soil using a hand hoe. Plots were irrigated immediately after application to initiate microbial activity and left for 7 d before planting.

Certified Ryoko 75 edamame seeds were obtained from PT. Mitratani Dua Tujuh, East Java (95% germination rate). Seeds were surface-sterilized with 1% sodium hypochlorite for 5 min and then rinsed three times with sterile water. Planting was conducted in the morning (0600–0900 hours) to avoid heat stress. Two seeds were planted per hole at 2.0 cm depth using a dibble stick. Planting spacing was maintained at 15 cm between plants and 20 cm between rows, resulting in 75 plants per plot (250,000 plants/ha equivalent).

Crop maintenance included thinning at 10 d after planting (DAP) when the plants had reached 5–7 cm height, retaining one healthy seedling per planting point; weaker seedlings were removed by cutting at soil level to avoid root disturbance.

Micro-sprinkler irrigation was applied twice daily (0600 hours and 1700 hours) for 30 min each, delivering approximately 5 mm/d. The soil moisture was maintained at 70–80% field capacity, with the irrigation frequency adjusted

during the flowering and pod-filling stages (35–55 DAP) based on weather and evapotranspiration.

Manual weeding was performed at 14 DAP, 28 DAP and 42 DAP by hand-pulling within rows and hoeing between rows. Pest monitoring used yellow sticky traps (2/plot) from 15 DAP, twice-weekly scouting for pod borer (*Etiella zinckenella* (Treitschke, 1832)) and leaf folder (*Lamprosema indicata* (Fabricius, 1775)) and preventive *Bacillus thuringiensis* Berliner, 1915 applications (2 g/L) at 25 DAP and 40 DAP. No major pest or disease incidence was recorded. No additional chemical fertilizers were applied to isolate the effects of organic amendments.

Harvesting was conducted at the R6 stage (60 DAP) in the early morning (0600–0800 hours) when the pods were fully filled but still green (seeds filling 80–90% of pod cavity). Five sample plants from the inner rows were uprooted for growth parameter measurements and the remaining sample plants in each plot were harvested by hand-picking. Fresh pod weight was recorded within 2 hr using an analytical balance (± 0.01 g), pods were sorted into filled and empty categories and plant height, leaf number and branch number were measured on harvested sample plants. Root systems were washed and assessed for nodulation and plant tissues were prepared for nutrient analysis.

Composite soil samples were collected at two stages: pre-planting for initial characterization and post-harvest for final soil assessment. Five sub-samples per plot were collected using a soil auger (0–20 cm depth), mixed thoroughly and a 500 g composite sample prepared for analysis. Growth parameters were measured on 10 tagged plants/plot, while yield components were assessed on five inner-row plants and tissue analysis was conducted on the third trifoliate leaves composited from 10 plants/plot at the R5 stage.

Data collection and measurements

Growth parameters were measured at harvest (60 DAP). Plant height was measured from the soil surface to the apical meristem using a precision ruler (± 0.1 cm). The total leaf number/plant and primary branch count per plant were recorded. Yield components consisted of total pod number (filled and empty pods), fresh pod weight/plant using an analytical balance (± 0.01 g) and the pod-fill percentage.

Soil analysis methods consisted of: 1) pH, using the glass electrode method (1:1 soil-to-water ratio and 1:1 soil-to-1N KCl ratio), according to Thomas (1996); 2) organic carbon, using the Walkley-Black wet oxidation method (Nelson and

Sommers, 1996); 3) total nitrogen, using the Kjeldahl digestion method (Bremner, 1996); 4) available phosphorus, using Bray I extraction for acid soils (Kuo, 1996); 5) exchangeable cations, based on 1N NH₄OAc extraction at pH 7.0 (Sumner and Miller, 1996); 6) CEC, using the summation method (Ross, 1995); and 7) particle size, using the pipette method (Gee and Bauder, 1986).

Post-harvest soil sampling was based on composite soil samples (0–20 cm depth) collected from each plot immediately after harvest. Five sub-samples/plot were mixed, air-dried and passed through a 2 mm sieve for chemical analyses, following the same methods as for the initial soil characterization.

Plant tissue analysis methods

Leaf samples were collected from the third fully expanded trifoliate leaf from the top at the R5 stage (beginning seed fill). Samples were washed with deionized water, oven-dried at 65°C for 72 hr and ground to pass through a 0.5 mm sieve. Total N was determined using the Kjeldahl method (Bremner, 1996), P using the vanadomolybdate colorimetric method after wet digestion (Murphy and Riley, 1962) and K, Ca, Mg using atomic absorption spectrophotometry after wet digestion with HNO₃-HClO₄ (Jones, 2001). Nutrient uptake measured in grams per plant was determined based on Equation 1:

$$\text{Nutrient uptake} = \frac{\text{Nutrient concentration} \times \text{Total dry biomass}}{100} \quad (1)$$

where the nutrient concentration was measured as a percentage and the dry biomass was measured in grams per plant.

Statistical analysis

Prior to analysis of variance, data normality was assessed using the Shapiro-Wilk test and homogeneity of variance was verified using Levene's test, with all data meeting the assumptions required for parametric analysis. Next, the data were subjected to analysis of variance appropriate for a randomized complete block design using R, a language and environment for statistical computing and graphics (version 4.3.0; R Core Team, 2023). Treatment means were compared using Tukey's honestly significant difference test at the 5% probability level. Coefficient of variation was calculated to assess experimental precision.

Ethics statements

This study was conducted using standard agricultural practices and did not involve human subjects, animals, or genetically modified organisms. All experimental procedures followed ethical guidelines for environmental research.

Results and Discussion

Soil health and environmental interactions

The experimental soil analysis revealed multiple constraints for edamame cultivation in tropical alluvial conditions (Table 2). The soil pH levels of 4.35 (H₂O) and 3.89 (KCl) were strongly acidic, according to soil classification criteria for tropical agriculture (Havlin et al., 2023). This pH level is substantially below the optimal range of 6.0–6.8 required for effective nitrogen fixation in *Glycine max*, according to Ruonan et al. (2024), who reported 40% reduction in rhizobial activity at pH levels below 5.5. The delta pH (pHKCl - pHH₂O = -0.46) indicated a net negative charge, characteristic of weathered tropical soils with variable charge minerals (Chen et al., 2024).

The exchangeable aluminum at 1.05 cmol(+)/kg exceeded

Table 2 Initial chemical characteristics and nutrient status of the alluvial soil used in the experiment.

Analysis parameter	Value
pH H ₂ O	4.35
pH KCl	3.89
Organic carbon (%)	1.41
Total nitrogen (%)	0.17
Bray I extraction	
- P ₂ O ₅ (parts per million)	42.30
NH ₄ OAc 1N pH: 7 extraction	
- Calcium (cmol(+)/kg)	6.10
- Magnesium (cmol(+)/kg)	3.52
- Potassium (cmol(+)/kg)	0.14
- Sodium (cmol(+)/kg)	0.13
- Cation exchange capacity (cmol(+)/kg)	13.83
- Base saturation (%)	71.51
KCl 1N extraction	
- Aluminum (cmol(+)/kg)	1.05
- Hydrogen (cmol(+)/kg)	1.15
Texture	
- Sand (%)	2.31
- Silt (%)	75.64
- Clay (%)	22.05

the critical toxicity threshold of 0.5–1.0 cmol(+)/kg for soybean cultivation. At this concentration, aluminum saturation reached approximately 10% of effective CEC, sufficient to cause substantial root growth inhibition and reduced nodulation in legumes (Kochian et al., 2004). In the current study, this aluminum toxicity effect was evident in the control treatment, where the plants had restricted growth (25.94 cm height) and limited pod production (21.00 pods/plant), consistent with the well-documented growth suppression effects of acidic soil conditions on leguminous crops (Bekchanova et al., 2024; Ruonan et al., 2024).

The organic carbon content of 1.41% classified this soil as having low organic matter status (<2.0% threshold for tropical soils), while total nitrogen at 0.17% fell below the 0.20% critical level for sustaining biological nitrogen fixation (Bhattacharyya et al., 2024). The C-to-N ratio of 8.3 indicated an advanced decomposition stage with insufficient organic matter reserves. These deficiencies manifested in the experimental results through poor nutrient retention and limited vegetative growth in the unamended plots, aligning with Bekchanova et al. (2024), who reported 35% yield reduction in nutrient-poor sandy soils.

Despite the phosphorus availability of 42.3 ppm exceeding the critical level of 10–15 ppm for legumes, the strongly acidic conditions likely reduced its bioavailability through aluminum-phosphate precipitation (Zhang et al., 2024). Exchangeable potassium at 0.14 cmol(+)/kg was critically deficient, falling below the 0.20 cmol(+)/kg threshold for soybean production (Kochian et al., 2004). This deficiency contributed to the poor pod-fill percentage (69.5%) observed in the control treatments, supporting the findings by Brooks et al. (2023) on potassium's role in pod development.

The soil texture analysis revealed silty clay characteristics (75.6% silt, 22.1% clay), which under tropical conditions creates drainage limitations and restricted aeration (Ndede et al., 2022). The CEC of 13.83 cmol(+)/kg indicated moderate nutrient retention capacity, though base saturation at 71.5% suggested incomplete neutralization of exchange sites (Pandian et al., 2024). Collectively, these physical and chemical constraints limited edamame productivity in the unamended conditions, necessitating soil amendment strategies, as recommended by Kabir et al. (2023).

The BCC had chemical properties suitable for addressing the identified soil constraints (Table 1). The alkaline pH of 8.49 provided a 4.14 pH units differential from the acidic soil, indicating strong amelioration potential (Patel and Panwar, 2024). With 16.28% organic carbon, BCC application

at 4,500 g/plot contributed approximately 733 g organic carbon/plot, sufficient to elevate the soil organic matter above critical thresholds, consistent with Wang et al. (2024), who demonstrated similar carbon enrichment in paddy soils.

The C-to-N ratio of 11.41 in the BCC indicated stabilized organic matter with balanced mineralization potential (Ajibade et al., 2023). This ratio, lower than the 25:1 threshold for net nitrogen mineralization, ensured immediate nitrogen availability upon application. In the current study, this characteristic manifested through increased leaf nitrogen content from 3.24% (control) to 3.89% (a₄ treatment), demonstrating effective nitrogen supply, as reported by Bakshi et al. (2021) for biochar-compost scaffolds.

The phosphorus content of the BCC (3.81%) substantially exceeded typical compost standards (0.5–2.0%), according to Alkharabsheh et al. (2021). At the highest application rate, this contributed 171 g P₂O₅ per plot, explaining the 32% increase in available soil phosphorus post-harvest, despite high crop removal. The elevated potassium (1.12%) addressed the critical soil deficiency, with application providing 50.4 g K per plot at the highest rate.

The maize-stem compost had comparable alkalinity (pH 8.02) but higher contents of organic carbon (24.72%) and nitrogen (2.55%) than the BCC (Table 3). However, its lower calcium (1.02% versus 1.56%) and magnesium (0.51% versus 0.78%) contents provided less base cation supplementation (Singh et al., 2022). The intermediate performance of the maize-stem compost treatment (31.06 filled pods versus 36.28 filled pods in BCC a₄) reflected these compositional differences, aligning with the observations by Fanai et al. (2024) on calcium's role in legume productivity.

The superior performance of the BCC over the maize-stem compost, despite their similar C-to-N ratios, resulted

Table 3 Chemical characteristics of the maize-stem compost used in the experiment.

Parameter	Unit	Value
pH	—	8.02
Organic carbon (C)	%	24.72
Total nitrogen (N)	%	2.55
C -to-N ratio	—	9.69
HCl extract (1:2)		
– Phosphorus	%	3.87
– Potassium	%	1.22
– Calcium	%	1.02
– Magnesium	%	0.51

Source: Laboratory of Soil Chemistry and Fertility, Faculty of Agriculture, Tanjungpura University (2024)

from the biochar component's unique properties. The biochar fraction provided a stable carbon structure with a high surface area ($>200 \text{ m}^2/\text{g}$ typical for rice husk biochar), creating microsites for nutrient retention and microbial colonization (Tyśkiewicz et al., 2022). This structural advantage, combined with *Trichoderma harzianum* inoculation ($>1 \times 10^6 \text{ CFU/g}$), enhanced nutrient cycling efficiency, as evidenced by the 81% increase in phosphorus uptake at the highest BCC rate (de Andrade et al., 2023).

The complementary effects of pH amelioration, organic matter addition and nutrient supplementation from the BCC application addressed multiple soil constraints simultaneously (Pandian et al., 2024). This integrated improvement strategy proved more effective than addressing individual limitations, as demonstrated by the synergistic enhancement of growth parameters (35% increase in leaf number) and yield components (72.8% increase in filled pods) at the optimal BCC dosage, supporting the findings by Sinclair et al. (2023) on integrated nutrient management in legumes.

Growth response to bioactive charcoal compost application

The application of BCC produced dose-dependent growth responses in the edamame plants measured at 60 DAP (Table 4). Plant height showed significant treatment effects ($p = 0.001$), though meaningful increases only occurred at doses $\geq 3,000 \text{ g/plot}$. The threshold response between 1,500 g/plot (25.72 cm, no significant difference from control) and 3,000 g/plot (27.67 cm, $p = 0.018$) indicated minimum BCC requirement for effective soil amelioration. At 4,500 g/plot, the 12.4% height increase corresponded with the soil pH improvement from 4.42 to 5.12 (Table 5). As discussed further in the Post-harvest Soil section, this pH improvement reflected that the combined effect of uniformly applied dolomite lime and BCC and should not be attributed solely to BCC.

The limited response at 1,500 g/plot BCC suggested insufficient amendment to overcome aluminum toxicity (0.78 cmol/kg, remaining above the threshold) and pH constraints (4.75 remaining strongly acidic). This finding aligned with Wang et al. (2024), who reported similar threshold effects in biochar-amended paddy soils, where benefits manifested only above 10 t/ha application rates. The corn stem compost treatment (26.94 cm height) showed intermediate performance, despite comparable nutrient contents, indicating the importance of biochar's structural properties beyond simple nutrient addition.

Leaf number had the strongest response to BCC application ($p < 0.001$), with progressive increases across all amendment rates. The 35% increase at 4,500 g/plot (19.72 versus 14.61 leaves in the control) correlated directly with the enhanced nitrogen uptake efficiency observed in tissue analysis (3.89% N in a_4 versus 3.24% in the control, Table 6). This relationship between leaf production and nitrogen status supported the finding by Sinclair et al. (2023) that leaf number in soybean served as a sensitive indicator of nitrogen availability.

The dose-response pattern for leaf number (14.61 $\rightarrow$ 15.44 $\rightarrow$ 17.78 $\rightarrow$ 19.72) for the treatments a_0 , a_2 , a_3 and a_4 , respectively, matched the pattern of soil organic carbon increase (1.45% $\rightarrow$ 1.68% $\rightarrow$ 1.85% $\rightarrow$ 2.03%, Table 5), demonstrating the critical role of organic matter in supporting vegetative growth. Each 0.2% increase in soil organic carbon corresponded to approximately 2.5 additional leaves per plant, indicating the quantitative relationship between soil improvement and plant response. Bhattacharyya et al. (2024) reported similar correlations in their multi-location trials with biochar amendments.

The presence of *Trichoderma harzianum* ($>1 \times 10^6 \text{ CFU/g}$) in the BCC likely contributed to enhanced nutrient acquisition efficiency. The 68% increase in nitrogen uptake at the highest BCC dose (a_4 , Table 7) exceeded what would be expected from

Table 4 Effect of bioactive charcoal compost (BCC) dosage on edamame growth parameters measured at harvest (60 d after planting).

Treatment	Plant height (cm)	Leaf number	Branch number
Control (a_0)	25.94 $\pm$ 1.20 ^a	14.61 $\pm$ 1.80 ^a	2.78 $\pm$ 0.40
Corn stem compost (a_1)	26.94 $\pm$ 1.10 ^{ab}	16.06 $\pm$ 2.10 ^{ab}	2.56 $\pm$ 0.50
1,500 g/plot BCC (a_2)	25.72 $\pm$ 1.30 ^a	15.44 $\pm$ 2.00 ^{ab}	2.56 $\pm$ 0.40
3,000 g/plot BCC (a_3)	27.67 $\pm$ 1.40 ^{bc}	17.78 $\pm$ 2.20 ^{bc}	2.72 $\pm$ 0.60
4,500 g/plot BCC (a_4)	29.17 $\pm$ 1.00 ^c	19.72 $\pm$ 1.90 ^c	3.06 $\pm$ 0.40
<i>p</i> value	0.001	<0.001	0.84
CV (%)	4.52	11.23	15.67

Mean $\pm$ SD values within each column followed by different lowercase superscript letters are significantly different ($p < 0.05$). CV = Coefficient of variation.

Table 5 Effect of bioactive charcoal compost (BCC) on post-harvest soil chemical properties (60 d after planting).

Treatment	pH (H ₂ O)	Organic Carbon (%)	Total N (%)	Avail. P (ppm)	Exch. K (cmol/kg)	Exch. Ca (cmol/kg)	Exch. Mg (cmol/kg)	CEC (cmol/kg)	Base Sat. (%)	Exch. AL (cmol/kg)
Control (a ₀)	4.42±0.08 ^a	1.45±0.12 ^a	0.18±0.02 ^a	44.2±3.5 ^a	0.15±0.02 ^a	6.22±0.45 ^a	3.58±0.28 ^a	14.05±0.92 ^a	72.3±4.2 ^a	0.98±0.12 ^a
Corn stem compost (a ₁)	4.68±0.10 ^b	1.72±0.14 ^b	0.21±0.02 ^b	48.6±4.1 ^{ab}	0.17±0.02 ^{ab}	6.58±0.48 ^{ab}	3.72±0.30 ^{ab}	14.42±0.95 ^{ab}	74.8±4.5 ^{ab}	0.82±0.10 ^b
1,500 g/plot BCC (a ₂)	4.75±0.11 ^b	1.68±0.13 ^b	0.20±0.02 ^{ab}	50.3±4.5 ^b	0.16±0.03 ^a	6.65±0.50 ^{ab}	3.68±0.29 ^{ab}	14.38±0.94 ^{ab}	75.2±4.6 ^{ab}	0.78±0.09 ^b
3,000 g/plot BCC (a ₃)	4.96±0.12 ^c	1.85±0.15 ^{bc}	0.22±0.03 ^{bc}	54.8±4.8 ^{bc}	0.19±0.03 ^{bc}	6.92±0.52 ^{bc}	3.85±0.31 ^{bc}	14.78±0.98 ^{bc}	77.5±4.8 ^{bc}	0.65±0.08 ^c
4,500 g/plot BCC (a ₄)	5.12±0.13 ^d	2.03±0.16 ^c	0.24±0.03 ^c	58.4±5.2 ^c	0.21±0.03 ^c	7.18±0.55 ^c	3.98±0.33 ^c	15.12±1.07 ^c	79.8±5.1 ^c	0.52±0.07 ^d
p value	<0.001	<0.001	0.002	<0.001	0.003	0.004	0.008	0.012	0.006	<0.001
CV (%)	2.45	8.67	10.23	9.12	11.34	7.89	8.45	6.78	6.45	12.56

Mean ± SD values within each column followed by different lowercase superscript letters are significantly different ($p < 0.05$). ppm = parts per million; CV = Coefficient of variation.

nutrient addition alone, suggesting biological mechanisms enhanced nutrient availability. De Andrade et al. (2023) demonstrated that *Trichoderma* inoculation increased the root surface area by 40–50% through production of auxin-like compounds, explaining the improved nutrient acquisition observed in the current study.

Branch number remained unaffected by treatments ($p = 0.84$), ranging narrowly from 2.56 to 3.06 branches across all treatments. This genetic constraint of the determinate Ryoko 75 variety was expected, as Liang et al. (2022) established that the *Dt2* gene controls 80–85% of branching variation in determinate soybeans. The slight numerical increase at 4,500 g/plot (3.06 branches) likely represented random variation rather than a treatment effect, given the high coefficient of variation (15.67%) for this parameter.

The integrated analysis of growth parameters revealed that BCC effectiveness depends on achieving threshold application rates sufficient to ameliorate multiple soil constraints simultaneously. The parallel improvements in soil pH (15.8% increase), organic carbon (40% increase) and aluminum reduction (47% decrease) at 4,500 g/plot created synergistic conditions for optimal plant growth. This finding supported the concept of "critical amendment mass" proposed by Pandian et al. (2024) , where biochar benefits manifested only after surpassing minimum thresholds for soil modification.

The superior performance of the BCC over the corn stem compost, despite similar macronutrient content, demonstrated the importance of amendment physical properties. The high surface area (>200 m²/g) and microporosity of the BCC provided sustained nutrient release, as evidenced by the maintained high tissue nutrient concentrations at R5 stage (Table 6). Patel and Panwar (2024) reported that the persistence of the structure of the BCC benefited across growing seasons, unlike conventional organic amendments that decompose rapidly in tropical conditions.

The growth enhancement observed at the optimal BCC dosage (4,500 g/plot) resulted from resolution of multiple growth-limiting factors: aluminum toxicity neutralization (0.52 cmol/kg below the threshold), pH optimization (5.12 approaching the ideal range), organic matter enrichment (2.03% above the critical level) and enhanced nutrient availability (58.4 ppm P, 0.21 cmol/kg K). This comprehensive soil improvement translated to measurable plant responses, validating BCC as an effective amendment strategy for tropical alluvial soils.

Yield component response and quality parameters

The yield component analysis at 60 DAP revealed pronounced dose-dependent responses to BCC application (Table 8). Filled pod number increased significantly from 21.00 pods/plant in the control to 36.28 pods/plant at 4,500 g/plot BCC ($p < 0.001$), representing a 72.8% enhancement. This notable improvement corresponded directly with the documented soil chemical improvements: pH increase from 4.42 to 5.12, aluminum reduction from 0.98 to 0.52 cmol/kg and phosphorus increase from 44.2 to 58.4 ppm (Table 5).

The threshold response pattern for filled pods

(21.00→26.61→31.11→36.28) for the treatments a_0 , a_2 , a_3 and a_4 , respectively, matched the pattern of phosphorus uptake efficiency (0.21→0.24→0.32→0.38 g/plant, Table 7), demonstrating the critical role of phosphorus in pod formation. The 81% increase in phosphorus uptake at the highest BCC dose exceeded the proportional increase in soil available phosphorus (32%), indicating enhanced root acquisition efficiency beyond simple nutrient availability. Brooks et al. (2023) reported similar phosphorus-dependent pod formation in edamame, with optimal pod set occurring at tissue P concentrations above 0.35%, as achieved by the a_4 treatment in the current study (0.38%, Table 6).

Table 6 Effect of bioactive charcoal compost (BCC) on nutrient content in edamame leaf tissue assessed at harvest (60 d after planting).

Treatment	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Control (a_0)	3.24±0.15 ^a	0.28±0.03 ^a	1.85±0.12 ^a	1.02±0.08 ^a	0.35±0.04 ^a
Corn stem compost (a_1)	3.56±0.18 ^b	0.31±0.04 ^{ab}	2.03±0.14 ^{ab}	1.15±0.09 ^{ab}	0.38±0.05 ^{ab}
1,500 g/plot BCC (a_2)	3.48±0.16 ^{ab}	0.30±0.04 ^a	1.98±0.13 ^{ab}	1.12±0.09 ^{ab}	0.37±0.04 ^{ab}
3,000 g/plot BCC (a_3)	3.72±0.19 ^{bc}	0.35±0.05 ^{bc}	2.18±0.15 ^{bc}	1.22±0.10 ^{bc}	0.41±0.05 ^{bc}
4,500 g/plot BCC (a_4)	3.89±0.20 ^c	0.38±0.05 ^c	2.35±0.17 ^c	1.28±0.11 ^c	0.44±0.05 ^c
<i>p</i> value	<0.001	0.003	<0.001	0.002	0.004
CV (%)	5.23	8.76	7.12	8.45	9.03

Mean ± SD values within each column followed by different lowercase superscript letters are significantly different ($p < 0.05$). CV = Coefficient of variation.

Table 7 Effect of bioactive charcoal compost (BCC) on nutrient uptake in edamame at harvest (60 d after planting).

Treatment	N uptake (g/plant)	P uptake (g/plant)	K uptake (g/plant)
Control (a_0)	0.82±0.08 ^a	0.21±0.03 ^a	0.54±0.06 ^a
Corn stem compost (a_1)	1.06±0.10 ^b	0.27±0.04 ^b	0.68±0.08 ^b
1,500 g/plot BCC (a_2)	0.97±0.09 ^{ab}	0.24±0.03 ^{ab}	0.62±0.07 ^{ab}
3,000 g/plot BCC (a_3)	1.18±0.11 ^{bc}	0.32±0.04 ^{bc}	0.75±0.09 ^{bc}
4,500 g/plot BCC (a_4)	1.38±0.13 ^c	0.38±0.05 ^c	0.89±0.10 ^c
<i>p</i> value	<0.001	<0.001	<0.001
CV (%)	9.87	11.23	10.45

Mean ± SD values within each column followed by different lowercase superscript letters are significantly different ($p < 0.05$). CV = Coefficient of variation.

Table 8 Effect of bioactive charcoal compost (BCC) on edamame yield components assessed at harvest (60 d after planting).

Treatment	Filled pods/plant	Empty pods/plant	Filled pod weight (g)	Pod filling (%)
Control (a_0)	21.00±3.10 ^a	9.22±2.80 ^{ab}	58.72±8.40 ^a	69.5
Corn stem compost (a_1)	31.06±4.20 ^{bc}	9.78±3.10 ^{ab}	86.28±9.70 ^{bc}	76.1
1,500 g/plot BCC (a_2)	26.61±3.80 ^b	8.17±2.50 ^a	77.11±8.90 ^b	76.5
3,000 g/plot BCC (a_3)	31.11±4.00 ^{bc}	9.83±3.00 ^{ab}	90.28±10.20 ^{bc}	76.0
4,500 g/plot BCC (a_4)	36.28±3.50 ^c	12.94±3.40 ^b	96.67±9.10 ^c	73.7
<i>p</i> value	<0.001	<0.001	<0.001	-
CV (%)	11.87	32.45	10.93	-

Mean ± SD values within each column followed by different lowercase superscript letters are significantly different ($p < 0.05$). CV = Coefficient of variation.

Table 9 Summary of percentage improvements at optimal bioactive charcoal compost (BCC) dose (4,500 g/plot) compared to control at harvest (60 d after planting).

Parameter	Control	BCC 4,500 g/plot	% Improvement
Plant height (cm)	25.94	29.17	+12.4%
Leaf number	14.61	19.72	+35.0%
Filled pods	21.00	36.28	+72.8%
Pod weight (g)	58.72	96.67	+64.6%
Soil pH	4.42	5.12	+15.8%
N uptake (g/plant)	0.82	1.38	+68.3%

Filled pod weight showed parallel improvements, increasing 64.6% from 58.72 g (control) to 96.67 g (4,500 g/plot BCC). This enhancement resulted from both increased pod number and improved individual seed filling, as evidenced by the maintained high pod filling percentage (73.7%) despite the increased pod load. The relationship between pod weight and soil organic carbon content (coefficient of determination = 0.89) indicated that organic matter played a crucial role in supporting reproductive sink strength. Research on soil organic carbon and legume productivity has shown that organic carbon levels above 2.0% are critical for maintaining assimilate supply during pod filling (Kabir et al., 2023; Bhattacharyya et al., 2024). In the current study, the highest BCC treatment achieved this level (2.03%, Table 5).

Empty pod production showed an unexpected pattern, with the highest BCC dose producing 12.94 empty pods compared to 9.22 in the control ($p = 0.008$). This 40% increase in empty pods at the high BCC dose, concurrent with increased filled pods, indicated enhanced flower initiation exceeding the plant's carbon assimilation capacity. The total pod production (filled + empty) increased from 30.22 (control) to 49.22 (a_4), suggesting that nutrient availability stimulated reproductive development beyond the plant's filling capacity. Sinclair et al. (2023) reported similar source-sink imbalances in high-fertility environments, where flower production exceeded photosynthetic capacity.

The pod-fill percentage revealed an optimum at an intermediate BCC dose (76.5% at 1,500 g/plot) compared to 73.7% at the highest dose. This inverse relationship between total pod production and filling efficiency reflected the physiological trade-off between pod number and individual seed size. The improved filling percentage at all BCC doses compared to the control (69.5%) indicated better resource allocation efficiency, likely due to improved water and nutrient status during critical reproductive stages.

The corn stem compost treatment achieved intermediate performance (31.06 filled pods, 86.28 g pod weight) despite

similar macronutrient content to the BCC. This 48% yield increase over the control, compared to 72.8% with the BCC at an equivalent dose, demonstrating the added value of the structural properties of the BCC. The difference could be attributed to the BCC's superior pH buffering capacity (8.49 versus 8.02) and higher calcium content (1.56% versus 1.02%), which better addressed the soil acidity constraint.

Regarding the microbial component, while the current study specified *Trichoderma harzianum* in BCC at $>1 \times 10^6$ CFU/g based on the manufacturer's specifications, microbial populations in the current experiment were not verified. The observed growth and yield improvements could be attributed primarily to the documented soil chemical improvements (pH, aluminum reduction, nutrient availability) rather than assumed microbial effects. De Andrade et al. (2023) and Tyśkiewicz et al. (2022) demonstrated *Trichoderma* benefits in controlled studies; however, the current results should be interpreted based on measured parameters rather than presumed microbial activity.

The yield improvements achieved with BCC application resulted from addressing multiple limiting factors simultaneously. The reduction in aluminum toxicity (47% decrease) removed the primary constraint on root development, while pH amelioration (15.8% increase) improved nutrient availability. The enhanced availability of phosphorus (32% increase) and potassium (40% increase) supported increased pod formation and filling. Bhattacharyya et al. (2024) reported similar synergistic effects when multiple soil constraints had been addressed through biochar-compost amendments.

The practical relevance of these yield improvements extends beyond simple productivity gains. The 64.6% increase in pod weight at the optimal BCC dose translates to potential yield increases from approximately 1.5 t/ha (control equivalent) to 2.5 t/ha (a_4 equivalent), approaching the regional yield potential for edamame. Zhang et al. (2023) reported that achieving yields above 2.0 t/ha is viable economically for smallholder farmers in Southeast Asia, suggesting that BCC application could transform marginal alluvial soils into productive edamame systems.

Plant tissue nutrient analysis and its implications

The effect of BCC on leaf nitrogen concentration was highly significant ($p < 0.001$), with progressive increases across doses. Nitrogen levels rose from 3.24% in the control to 3.89% at 4,500 g/plot BCC, though significant differences from the control only occurred at 3,000 g/plot BCC (3.72%,

$p = 0.009$) and 4,500 g/plot BCC ($p < 0.001$). The corn stem compost (3.56%, $p = 0.024$) and 1,500 g/plot BCC (3.48%, $p = 0.067$) showed intermediate responses. The highest BCC dose achieved nitrogen levels within the optimal range (3.5–4.0%) for soybean productivity (Table 6). This improvement aligned with the critical nitrogen threshold of 3.5–4.0% required for optimal soybean productivity during reproductive stages, as established by Sinclair et al. (2023) in their comprehensive meta-analysis of legume nutrition. The enhanced nitrogen status correlated directly with the observed increases in leaf number and photosynthetic capacity, supporting the yield improvements documented in the current study.

The phosphorus concentration in the leaf tissue showed significant treatment effects ($p = 0.003$), though responses were less pronounced than for nitrogen. The control plants contained 0.28% phosphorous, while significant increases occurred only at 3,000 g/plot BCC (0.35%, $p = 0.018$) and 4,500 g/plot BCC (0.38%, $p = 0.002$). The corn stem compost (0.31%, $p = 0.082$) and 1,500 g/plot BCC (0.30%, $p = 0.124$) did not differ significantly from the control. The highest BCC dose exceeded the critical threshold of 0.35% phosphorous required for optimal pod formation. Recent research by Zhang et al. (2024) demonstrated that biochar-compost combinations increased phosphorus bioavailability through multiple mechanisms: pH-induced reduction of aluminum activity, organic acid-mediated phosphate solubilization and microbial phosphatase enzyme production. The phosphorus levels achieved in the 4,500 g/plot treatment exceeded the critical threshold of 0.35% for maximum pod formation in tropical soybean systems (Brooks et al., 2023; Kochian et al., 2004).

Potassium accumulation showed highly significant responses ($p < 0.001$), with dose-dependent increases from 1.85% in the control to 2.35% at 4,500 g/plot BCC. Significant improvements occurred at 3,000 g/plot BCC (2.18%, $p = 0.007$) and 4,500 g/plot BCC ($p < 0.001$), while there were marginal increases in the corn stem compost (2.03%, $p = 0.051$) and 1,500 g/plot BCC (1.98%, $p = 0.089$). The highest dose achieved potassium levels within the sufficiency range (2.0–2.5%) for vegetable soybean. Wang et al. (2018) reported similar potassium enhancement in biochar-amended systems, attributing the response to increased CEC and reduced leaching losses. The potassium levels achieved in the current study exceeded the sufficiency range of 2.0–2.5% recommended by Jones (2001) for vegetable soybean production.

The calcium and magnesium concentrations followed similar patterns ($p = 0.002$ and $p = 0.004$, respectively). Calcium increased from 1.02% in the control to 1.28% at 4,500

g/plot BCC, with significant differences at 3,000 g/plot (1.22%, $p = 0.014$) and 4,500 g/plot BCC ($p = 0.001$). Magnesium rose from 0.35% to 0.44%, with significant increases at the two highest BCC doses ($p < 0.05$).

Post-harvest soil chemical dynamics

The soil pH showed highly significant treatment effects ($p < 0.001$), with progressive amelioration of acidity across the BCC doses. The pH increased from 4.42 in the control to 5.12 at 4,500 g/plot BCC, representing a 0.70 unit increase. Significant differences from the control occurred with the corn stem compost (4.68, $p = 0.008$) and all the BCC treatments, though 1,500 g/plot BCC (4.75) did not differ significantly from the corn stem compost ($p = 0.214$). The 3,000 g/plot BCC achieved pH 4.96 ($p < 0.001$), while maximum amelioration occurred at 4,500 g/plot BCC (5.12, $p < 0.001$). Research on soil pH and nitrogen fixation has demonstrated that pH increases within the 4.5–6.0 range meaningfully enhance rhizobial survival and nodule formation in leguminous crops (Kochian et al., 2004; Ruonan et al., 2024). However notably, dolomite lime was applied uniformly to all plots at 2 wk before treatment application. Although the dose was standardized across all treatments, the post-harvest soil pH data could not separate fully the contribution of the BCC from the residual effect of liming, as the soil pH after liming but before treatment application was not measured. Therefore, the observed pH differences among the BCC treatments and the control should be interpreted as the combined effect of liming and BCC and the Discussion section has been worded accordingly to avoid over-attributing pH amelioration solely to the BCC.

The organic carbon content demonstrated significant enrichment ($p < 0.001$), increasing from 1.45% in the control to 2.03% at the highest BCC dose. The corn stem compost (1.72%, $p = 0.012$) and 1,500 g/plot BCC (1.68%, $p = 0.024$) showed similar improvements, while 3,000 g/plot BCC (1.85%, $p = 0.003$) showed greater enhancement. The 4,500 g/plot BCC treatment exceeded the 2.0% threshold considered critical for soil biological activity ($p < 0.001$). The enhanced organic carbon levels approached the critical threshold of 2.0% considered necessary for maintaining soil biological activity in tropical agricultural systems (Kabir et al., 2023; Pandian et al., 2024). The persistence of elevated organic carbon levels post-harvest indicated the recalcitrant nature of biochar carbon, supporting long-term soil quality improvement.

The available phosphorus increased significantly ($p < 0.001$) from 44.2 ppm in the control to 58.4 ppm at 4,500 g/plot BCC. The effect became significant at 1,500 g/plot BCC

(50.3 ppm, $p = 0.038$), with progressive increases at 3,000 g/plot BCC (54.8 ppm, $p = 0.004$) and a maximum at 4,500 g/plot BCC ($p < 0.001$). This 32% enhancement occurred despite high phosphorus removal during pod filling, suggesting that BCC application maintained adequate phosphorus supply throughout the growing season. The mechanisms underlying this phosphorus enhancement likely involved both direct phosphorus addition from the compost component and indirect effects through pH modification and organic acid production. Chen et al. (2019) demonstrated that biochar-compost combinations sustained phosphorus availability through slow-release mechanisms and protection against re-fixation in acidic soils.

The exchangeable aluminum showed considerable reduction ($p < 0.001$), decreasing from 0.98 cmol/kg in the control to 0.52 cmol/kg at 4,500 g/plot BCC. Significant aluminum reduction occurred with the corn stem compost (0.82 cmol/kg, $p = 0.021$) and all BCC treatments. The 3,000 g/plot BCC reduced aluminum to 0.65 cmol/kg ($p = 0.002$), while 4,500 g/plot BCC achieved maximum reduction ($p < 0.001$), bringing levels below the toxicity threshold of 0.5–1.0 cmol/kg. (Table 7). This reduction is critical for root development and function in acidic soils, where aluminum toxicity represents the primary constraint to crop productivity. Generally, the threshold for aluminum toxicity in soybean is 0.5–1.0 cmol/kg, depending on cultivar sensitivity. In the current study, the reduction achieved through BCC application moved the soil below this critical threshold, explaining the enhanced root development and nutrient uptake observed in treated plants.

Base saturation increased significantly ($p = 0.006$) from 72.3% in the control to 79.8% at 4,500 g/plot BCC. Progressive improvements occurred across all treatments, with significant differences at 3,000 g/plot BCC (77.5%, $p = 0.018$) and 4,500 g/plot BCC ($p = 0.002$). The enhanced base saturation exceeded the 75% threshold associated with optimal legume productivity. This improvement resulted from combined increases in exchangeable calcium (15% increase), magnesium (11% increase) and potassium (40% increase). The enhanced base cation status provided multiple benefits: improved soil structure through calcium-mediated aggregation, enhanced enzyme function through magnesium availability and improved water relations through potassium sufficiency. Research on base cation dynamics in tropical soils has indicated that base saturation above 75% is associated with optimal legume productivity (Singh et al., 2022; Pandian et al., 2024).

Nutrient uptake efficiency and plant-soil interactions

Nitrogen uptake showed highly significant treatment effects ($p < 0.001$), increasing from 0.82 g/plant in the control to 1.38 g/plant at 4,500 g/plot BCC. Significant improvements occurred with the corn stem compost (1.06 g/plant, $p = 0.012$), while 1,500 g/plot BCC showed a marginal increase (0.97 g/plant, $p = 0.054$). The 3,000 g/plot BCC achieved 1.18 g/plant ($p = 0.003$), with the maximum uptake at 4,500 g/plot BCC ($p < 0.001$), representing 68% enhancement over the control. This improved efficiency likely resulted from multiple factors: enhanced root development in the ameliorated soil environment, increased mineralization of organic nitrogen from the compost component and potentially improved biological nitrogen fixation due to favorable pH conditions.

Phosphorus uptake demonstrated the greatest relative improvement ($p < 0.001$), increasing 81% from 0.21 g/plant in the control to 0.38 g/plant at 4,500 g/plot BCC. Significant effects occurred with the corn stem compost (0.27 g/plant, $p = 0.019$), 3,000 g/plot BCC (0.32 g/plant, $p = 0.002$) and were maximized at 4,500 g/plot BCC ($p < 0.001$). The 1,500 g/plot BCC showed an intermediate response (0.24 g/plant, $p = 0.087$). This notable enhancement reflected both increased phosphorus availability in the soil and improved root acquisition capacity. The phosphorus uptake efficiency (uptake per unit of available P) actually increased with BCC application, suggesting that the treatment enhanced root physiological capacity for phosphorus acquisition beyond simple availability effects. This finding was consistent with reports that biochar amendments improved the root phosphorus acquisition capacity through multiple mechanisms (Alkharabsheh et al., 2021; Kabir et al., 2023). Potassium uptake followed similar patterns ($p < 0.001$), with a 65% increase from the control (0.54 g/plant) to 4,500 g/plot BCC (0.89 g/plant). Significant improvements occurred with the corn stem compost (0.68 g/plant, $p = 0.024$), 3,000 g/plot BCC (0.75 g/plant, $p = 0.006$) and were maximized at 4,500 g/plot BCC ($p < 0.001$).

The comprehensive improvements in soil chemistry and plant nutrition documented in the current study have important implications for sustainable edamame production in tropical alluvial soils. The simultaneous amelioration of multiple soil constraints through a single amendment application represents an efficient management strategy for resource-limited farming systems. The persistence of soil improvements post-harvest suggests potential cumulative benefits over multiple cropping cycles, improving the economic viability of BCC application.

The nutrient uptake efficiency improvements observed with BCC application indicated the potential for reduced fertilizer requirements in subsequent crops. Based on the nutrient composition of the BCC and the observed improvements in plant nutrient uptake, BCC may contribute to reduced fertilizer requirements in future cropping systems. However, this possibility requires further validation through dedicated fertilizer substitution trials and any specific replacement values should be interpreted with caution given the single-season nature of the current study.

Economic and sustainability implications

The dose-response analysis of BCC application suggests economic optimization potential for edamame production on alluvial soils. The 64.6% yield increase at 4,500 g/plot (equivalent to 15 t/ha) translates to additional production of approximately 1.0 t/ha. A preliminary cost-benefit estimate, based on current Southeast Asian edamame price data and estimated BCC production costs (Zhang et al., 2023; Patel and Panwar, 2024), suggested that BCC application may be economically promising; however, this estimate should be interpreted cautiously as the current study did not include any direct evaluation of production costs, market price fluctuations and residual multi-season effects.

The persistent increase in post-harvest soil organic carbon (from 1.45% to 2.03%) and the reduction in exchangeable aluminum suggested that BCC application may provide soil health benefits beyond the current cropping season. However, since the current study covered only a single growing season, the duration and magnitude of any multi-year benefits remain to be confirmed through long-term field evaluation (Wang et al., 2024; Pandian et al., 2024).

Based on the nutrient composition of BCC and the observed improvements in plant nutrient uptake, BCC may contribute to reduced fertilizer costs in future cropping seasons; however, a direct fertilizer substitution rate cannot be established from this single-season study and requires validation through dedicated substitution trials. A preliminary estimate suggested BCC application may offer favorable economic returns (Salo et al., 2024); however, this should be interpreted cautiously as production costs, market prices and residual effects were not directly measured.

The sustainability implications are equally important. The 40% increase in soil organic matter enhanced water retention capacity by an estimated 25–30%, reducing irrigation requirements and improving drought resilience (Ndede et al., 2022). The enhanced base saturation (from 72.3% to 79.8%)

and CEC improvement create more stable soil conditions, reducing nutrient leaching losses by approximately 35–40%, based on similar studies in tropical soils (Bekchanova et al., 2024).

From a carbon footprint perspective, the observed increase in post-harvest soil organic carbon (from 1.45% to 2.03%) suggested that BCC may have potential to improve soil carbon status. The biochar component has been reported to resist rapid decomposition (Weng and Cowie, 2025; Gui et al., 2025), potentially contributing to longer-term carbon storage; however, net carbon balance and greenhouse gas implications were not measured in the current study and so should be assessed in future multi-year research.

The current study demonstrates that under the conditions of this single-season field trial, BCC at 4,500 g/plot (15 t/ha) was the most effective treatment tested for edamame production in tropical alluvial soils. Multi-site and multi-season validations are required before broader recommendations can be made. The dosage of BCC at 4,500 g/plot (15 t/ha) achieved maximum performance across all measured parameters: 12.4% increase in plant height (29.17 cm), 35.0% increase in leaf number (19.72 leaves/plant), 72.8% increase in filled pods (36.28 pods/plant) and 64.6% increase in pod weight (96.67 g/plant) compared to the control.

The superiority of the 4,500 g/plot BCC treatment resulted from achieving critical thresholds for multiple soil improvements: soil pH reached 5.12 (approaching the optimal range), exchangeable aluminum decreased to 0.52 cmol/kg (below the toxicity threshold), organic carbon increased to 2.03% (above the critical level) and available phosphorus rose to 58.4 ppm (optimal for pod formation). While the 3,000 g/plot dose showed significant improvements, it failed to achieve these critical thresholds, producing only 31.11 filled pods compared to 36.28 at the highest dose.

In addition, the BCC treatment at 4,500 g/plot outperformed corn stem compost at equivalent dosage (4,500 g/plot), producing 16.8% more filled pods and 12.0% higher pod weight, demonstrating the added value of biochar's structural properties beyond simple nutrient addition. A preliminary cost-benefit analysis indicated that BCC application at this rate may be economically viable under current price conditions; however, this projection requires cautious interpretation as production costs, market price fluctuations and residual multi-season effects were not evaluated directly.

Based on the current results, for practical implementation in tropical alluvial soil regions, the recommended BCC application is 15 t/ha (equivalent to 4,500 g per 3 m² plot) as

a basal amendment before planting. This single application showed promise in addressing multiple soil constraints simultaneously—acidity, aluminum toxicity, low organic matter and nutrient deficiencies—while the observed post-harvest soil improvements suggested potential for sustained soil health benefits. Notably, long-term carbon sequestration and multi-season cumulative effects require confirmation through extended multi-year studies.

The current study was limited to a single growing season under specific climatic conditions. Multi-year evaluation is required to determine any long-term effects of BCC application on soil health, microbial community dynamics and cumulative crop productivity. Furthermore, the economic analysis was based on current market prices and did not account for potential fluctuations or regional variations in BCC production costs. Future research should investigate optimal reapplication intervals, residual effects on subsequent crops and the development of locally-sourced biochar production systems to enhance economic viability for smallholder farmers.

Conflict of Interest

The authors declare no conflict of interest related to this research.

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