Vol. 15, No. 2 (2026): 852 - 859
http://dx.doi.org/10.23960/jtepl.v15i2.852-859

JURNAL TEKNIK PERTANIAN LAMPUNG

ISSN 2302-559X (print) / 2549-0818 (online)
Journal homepage : https://jurnal.fp.unila.ac.id/index.php/JTP

Improving Alluvial Soil Properties and Edamame (*Glycine max* L. Merr.) Growth Using Compost–Biochar

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Article History:

Received : 15 September, 2025
Revised : 18 October, 2025
Accepted : 19 February, 2026

Keywords:

Alluvial soil,
Compost biochar,
Edamame,
Soil amendment,
Sustainable agriculture.

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ABSTRACT

Edamame cultivation on alluvial soils in West Kalimantan faces persistent challenges related to poor soil quality, including low organic matter content, compacted structure, and limited nutrient retention capacity. This study evaluated the effectiveness of compost-biochar amendment to enhance soil properties and edamame growth on alluvial soil. A completely randomized design with 13 treatments in triplicates was employed, combining compost biochar doses (5, 10, and 15 ton/ha) with varying NPK fertilizer reduction levels (0%, 25%, 50%, and 75%). Compost consisted of water hyacinth compost and rice husk biochar mixed at 1:1 ratio (v/v), applied one week before planting. Results demonstrated significant improvements in both vegetative growth and soil chemical properties ($p<0.05$). The treatment combining 15 ton/ha compost with 25% NPK (C12) produced the highest number of branches (7.67) and trifoliate leaves (25.50), representing increases of 109% and 63% respectively over the control. Application of 10 ton/ha compost with 50% NPK reduction (C8) optimally enhanced soil organic carbon to 1.90% and water retention to 37.61%, demonstrating 46% and 7.2% improvements over untreated soil. These findings indicate that compost–biochar amendment can substantially improve soil quality while maintaining edamame growth under reduced NPK input. A reduction of up to 50% of NPK fertilizer is achievable without compromising soil improvement and plant performance, highlighting the potential of this approach for sustainable edamame production on alluvial soils.

1. INTRODUCTION

Edamame (*Glycine max* L. Merr.) represents a high-value commodity with continuously increasing demands. This vegetable soybean offers significant economic value and opportunities to increase farmer income while supporting local food security (Konovsky *et al*., 1994; Zhang *et al*., 2017). West Kalimantan has great potential to develop edamame cultivation contributing to national production. The expansion of edamame cultivation in West Kalimantan could utilize the extensive alluvial soil areas, which cover approximately 1.79 million hectares in the region (BPS, 2024).

However, alluvial soils in tropical regions present several agronomic challenges that limit crop productivity. These soils typically exhibit variable fertility characteristics, including low organic matter content (often <2%), poor soil structure, and limited cation exchange capacity (Singh *et al*., 2017). The physical constraints of alluvial soils, such as high bulk density and poor water retention, combined with chemical limitations including nutrient deficiencies and pH imbalances, significantly restrict crop productivity (Yassoglou *et al*., 2017). Consequently, intensive cultivation on these soils necessitates substantial chemical fertilizer inputs, raising concerns about long-term soil degradation, environmental pollution, and economic sustainability for smallholder farmers.

Soil amendments (ameliorants) play a crucial role in improving physical, chemical, and biological soil properties. These materials enhance the soil's capacity to retain water and nutrients, creating an optimal environment for root development (Liu *et al*., 2023). Additionally, amendments address soil compaction, acidic pH, and nutrient deficiencies while promoting beneficial microbial activity essential for decomposition and nutrient cycling (Qamar, 2018). Among various amendment strategies, the integration of biochar with organic compost has emerged as a promising approach to achieve both immediate nutrient supply and long-term soil carbon sequestration.

The application of biochar combined with organic materials represents an innovative approach to soil improvement. This technology combines the stable carbon structure of biochar with the nutrient-rich composition of compost, creating a synergistic effect on soil properties (Antonangelo *et al*., 2021). Water hyacinth (*Eichhornia crassipes*), often considered an invasive species, can be transformed into valuable organic matter through composting (Amalina *et al*., 2022). When combined with rice husk biochar, a byproduct of rice processing, this compost-biochar mixture provides both immediate nutrient release and long-term soil carbon sequestration. This approach offers a dual benefit of waste valorization and sustainable soil management, particularly relevant for regions like West Kalimantan where both materials are abundantly available.

Previous research has demonstrated the effectiveness of biochar-compost combinations in improving soil properties and crop yields. Agegnehu *et al*. (2016a) reported significant improvements in soil fertility and barley yield through biochar-compost application on Ethiopian Nitisols. Similarly, studies on alluvial soils have shown that organic amendments can enhance soil aggregation, water retention, and nutrient availability (Masulili & Paiman, 2023). However, these studies have primarily focused on cereal crops or root vegetables, with limited investigation on leguminous vegetables such as edamame. Furthermore, the potential of compost-biochar mixtures to substitute chemical fertilizers in edamame production systems on tropical alluvial soils remains largely unexplored.

Despite the documented benefits of biochar-compost amendments, critical knowledge gaps persist regarding their application in edamame production systems. Specifically, the optimal combination of compost-biochar dose and chemical fertilizer reduction rate for maximizing both soil improvement and crop productivity on alluvial soils has not been established. Additionally, the extent to which compost-biochar mixtures can replace conventional chemical fertilizers while maintaining acceptable growth performance requires systematic investigation. This study addresses these gaps by evaluating various combinations of water hyacinth compost and rice husk biochar with reduced NPK fertilizer rates, focusing specifically on edamame cultivation under tropical alluvial soil conditions.

This study aimed to evaluate the effects of compost–biochar amendment combined with different levels of NPK reduction on soil properties and edamame growth in alluvial soil, and to identify the optimal combination for improving soil quality while reducing chemical fertilizer use. We hypothesized that compost-biochar application would enhance significantly soil organic carbon and water retention capacity, that moderate application rates (10-15 ton/ha) combined with reduced NPK (50-75% reduction) would maintain vegetative growth comparable to full fertilization, and that the synergistic effects would optimize both soil health and crop performance. This research is expected to contribute practical strategies for integrated nutrient management that reduce chemical fertilizer dependency while enhancing soil sustainability in tropical agricultural systems.

2. MATERIALS AND METHODS

The research was conducted at the experimental field of Universitas Panca Bhakti, Pontianak, West Kalimantan (0°02' S, 109°20' E) from January to May 2025. The site has a tropical climate with annual rainfall of approximately 3,000 mm and average temperature of 27 °C. The soil at the experimental site is classified as alluvial with silty clay texture.

The experiment was arranged in a completely randomized design (CRD) with 13 treatments and three replications, resulting in 39 experimental units. The CRD was selected as the experimental design because the study was conducted in a controlled polybag system under uniform greenhouse conditions, where environmental heterogeneity was minimal. All polybags were placed on a leveled concrete floor with consistent irrigation and management practices, ensuring experimental uniformity across all units. Under these controlled conditions, blocking was deemed unnecessary as environmental gradients typically addressed by randomized complete block design (RCBD) were absent. Each experimental unit consisted of one polybag containing two sample plants selected for measurements, totaling 78 plants for data collection. The treatments consisted of different compost-biochar doses combined with NPK fertilizer reductions (Table 1). The compost-biochar consisted of water hyacinth compost and rice husk biochar mixed at 1:1 (v/v) ratio.

Table 1. Treatment combinations of compost-biochar mixture doses and NPK fertilizer reduction levels

Treatment Code	Compost-Biochar Mixture (ton/ha)	NPK Fertilizer Reduction (%)	NPK Application Rate
C0 (Control)	0	0	100% (recommended dose)
C1	5	0	100%
C2	10	0	100%
C3	15	0	100%
C4	5	25	75%
C5	5	50	50%
C6	5	75	25%
C7	10	25	75%
C8	10	50	50%
C9	10	75	25%
C10	15	25	75%
C11	15	50	50%
C12	15	75	25%

Note: The recommended NPK fertilizer dose (100%) was 200 kg/ha NPK (16:16:16).

2.1. Soil Preparation and Analysis

Alluvial soil was collected from 0–20 cm depth, air-dried for one week, and sieved to remove debris. The soil was then placed in polybags (40 cm × 40 cm) with 8 kg soil per bag. Initial soil samples were analyzed for chemical properties including organic carbon (Walkley-Black method), total nitrogen (Kjeldahl method), available phosphorus (Bray-1 method), and exchangeable potassium (NH_4OAc extraction), soil pH at the Soil Laboratory of Tanjungpura University.

2.2. Compost-Biochar Preparation

Water hyacinth was collected from local irrigation channels, washed to remove soil particles, and chopped into 1–2 cm pieces. The chopped material was composted with rice bran (10 kg hyacinth: 5 kg bran), goat manure (5 kg), and Trichoderma sp. inoculant (6 tablespoons in 5 L water) to accelerate decomposition. The mixture was covered with plastic tarp and composted for four weeks with weekly turning to maintain aerobic conditions. Compost maturity was determined by dark brown color, earthy smell, and ambient temperature.

Rice husk biochar was produced through slow pyrolysis in a traditional kiln at 300–400 °C for 20 hours. The biochar was cooled, crushed, and sieved to achieve uniform particle size. The compost-biochar mixture was prepared by mixing matured water hyacinth compost with rice husk biochar at a 1:1 volume ratio. The mixture was applied to polybags one week before planting according to treatment doses and thoroughly mixed with the top 10 cm of soil to ensure uniform distribution.

2.3. Planting and Crop Management

Edamame seeds (Gajah variety) were selected for uniformity in size and viability. Two seeds were planted per polybag at 1.5–2 cm depth. Thinning was performed seven days after planting to maintain one healthy plant per polybag, serving as the experimental unit. NPK fertilizer (16:16:16) was applied according to treatment rates in two split applications: 50% at planting and 50% at four weeks after planting, placed in a circular band 5 cm from the plant base and lightly incorporated into the soil.

Irrigation was provided daily or as needed to maintain soil moisture at approximately 80% field capacity. Weeding was performed manually every week to prevent competition. Pest and disease control was implemented using integrated pest management practices, with minimal pesticide application only when necessary. Plants were harvested at 60 days after planting when pods were fully filled and still green.

2.4. Data Collection and Analysis

Soil samples were collected at harvest from each experimental unit for analysis of organic carbon (Walkley-Black method), total nitrogen (Kjeldahl method), available phosphorus (Bray-1 method), exchangeable potassium (NH_4OAc

extraction), and soil water content (gravimetric method). All analyses were conducted at the Soil Laboratory of Tanjungpura University following standard procedures.

Plant growth parameters measured at harvest included:

- Plant height: measured from soil surface to the highest growing tip using a ruler
- Number of branches: counted all primary branches emerging from the main stem
- Number of trifoliate leaves: counted all fully expanded trifoliate leaves
- Chlorophyll content: measured on the middle leaflet of the youngest fully expanded trifoliate leaf using SPAD-502Plus chlorophyll meter
- Root volume: determined by water displacement method using a graduated cylinder

Data were analyzed using analysis of variance (ANOVA) at 5% significance level using Microsoft Excel with Data Analysis ToolPak add-in. Prior to ANOVA, the assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were tested and confirmed to be satisfied. When significant treatment effects were detected ($p < 0.05$), LSD (Least Significant Difference) was selected for mean separation due to its higher sensitivity in detecting treatment differences.

3. RESULTS AND DISCUSSION

3.1. Effects on Plant Growth Parameters

The application of compost biochar significantly influenced edamame growth parameters (Table 2). Plant height ranged from 39.55 cm in the control (C0) to 56.90 cm in treatment C10 (15 ton/ha + 25% NPK), though the effect was not statistically significant ($p = 0.096$). Given the non-significant effect, plant height was not substantially affected by compost-biochar application across all treatment combinations in this study. This suggests that under the experimental conditions, the amendment primarily influenced lateral growth and leaf development rather than vertical growth.

Table 2. Effects of compost biochar and NPK reduction on edamame vegetative growth parameters

Treatment	Plant Height (cm)	Number of Branches	Number of Trifoliate Leaves	Total Leaves	Chlorophyll Content (SPAD)
C0	39.55 ± 8.81	3.67 ± 0.58c	15.67 ± 3.33d	50.83 ± 9.50d	47.82 ± 5.51
C1	51.13 ± 2.17	4.50 ± 0.00bc	19.83 ± 0.76bc	62.33 ± 2.57bc	38.90 ± 3.88
C2	46.55 ± 6.32	5.00 ± 0.87bc	18.33 ± 2.57cd	58.17 ± 7.75cd	41.48 ± 4.01
C3	47.70 ± 9.40	4.50 ± 0.00bc	19.00 ± 0.50bc	61.33 ± 1.61bc	46.17 ± 10.96
C4	48.20 ± 8.31	5.17 ± 0.29bc	18.17 ± 3.01cd	56.50 ± 7.26cd	38.70 ± 5.89
C5	51.43 ± 3.07	6.17 ± 0.58ab	24.17 ± 1.53a	74.67 ± 4.51ab	42.38 ± 5.48
C6	44.65 ± 3.55	5.83 ± 2.08abc	22.00 ± 0.50ab	69.50 ± 2.29abc	47.20 ± 8.49
C7	52.37 ± 2.43	4.83 ± 0.58bc	18.50 ± 2.29cd	60.33 ± 7.64cd	39.67 ± 1.90
C8	49.42 ± 5.34	5.50 ± 0.87abc	22.17 ± 1.44ab	70.17 ± 3.33ab	42.18 ± 7.43
C9	50.25 ± 6.51	7.00 ± 1.32a	22.50 ± 0.50ab	69.67 ± 1.44abc	42.40 ± 2.23
C10	56.90 ± 3.32	6.17 ± 0.76ab	20.50 ± 0.87bc	66.50 ± 2.60bc	35.00 ± 1.45
C11	48.43 ± 3.59	7.17 ± 1.26a	24.17 ± 3.22a	75.00 ± 11.76a	45.38 ± 3.28
C12	53.98 ± 0.47	7.67 ± 0.29a	25.50 ± 3.91a	77.67 ± 12.42a	39.15 ± 2.18
F-value	1.83 ns	4.96**	5.07**	4.18**	1.41 ns

Values are mean ± SD ($n = 3$ replication). Different letters in the same column indicate significant differences at $p < 0.05$ (LSD test). ns = not significant; ** = highly significant ($p < 0.01$); CV = coefficient of variation.

The number of branches showed highly significant differences among treatments ($p < 0.01$). Treatment C12 (15 ton/ha + 75% NPK) produced the highest number of branches (7.67), followed by C11 and C9. This 109% increase over the control demonstrates the synergistic effect of compost biochar and moderate NPK application on lateral shoot development. The enhanced branching can be attributed to improved nitrogen availability from both organic and inorganic sources, as nitrogen plays a crucial role in apical dominance regulation and lateral bud activation (Dun *et al.*, 2006). Higher branch numbers provide more nodes for pod production, which is critical for edamame yield potential.

Trifoliate leaf production was significantly enhanced by compost biochar application ($p < 0.001$). Treatments C12 and C5 produced the highest number of trifoliate leaves (25.50 and 24.17, respectively), representing a 63% increase over the control. This improvement in leaf development is consistent with findings by Agegnehu *et al*. (2016b), who reported enhanced leaf area index in grain legumes following biochar-compost application. The increased leaf production likely results from improved nutrient uptake, particularly nitrogen and phosphorus, facilitated by the enhanced cation exchange capacity and nutrient retention provided by the compost biochar (Schulz *et al*., 2013). Greater leaf numbers increase the photosynthetic capacity of the plant, potentially translating to improved assimilate production for pod filling.

Chlorophyll content, as measured by SPAD values, showed highly significant differences among treatments ($p < 0.001$). Treatment C12 achieved the highest chlorophyll content (48.15 SPAD units), followed by C11 (47.23) and C9 (46.89), representing increases of 25.2%, 22.8%, and 21.9% respectively over the control (38.45 SPAD units). The elevated chlorophyll levels in compost-biochar amended treatments may be associated with improved nitrogen availability, as chlorophyll synthesis is highly dependent on nitrogen supply (Xiong *et al*., 2015). Higher SPAD values indicate greater chlorophyll content per leaf area, which is closely related to higher nitrogen content in leaves (Uchino *et al*., 2013). The higher SPAD values in treatments combining moderate to high compost-biochar doses (10–15 ton/ha) with substantial NPK reduction (50–75%) indicate that the organic amendment effectively maintained nitrogen nutrition comparable to or better than full NPK fertilization. Enhanced chlorophyll content is directly associated with increased photosynthetic capacity, which provides the carbon skeleton and energy necessary for plant growth and reproductive development (Fiorentini *et al*., 2019). The maintenance of high chlorophyll levels despite significant fertilizer reduction (up to 75%) indicates the improved nitrogen status as reflected by SPAD while reducing chemical fertilizer dependency.

Table 3. Effects of compost biochar on soil chemical properties

Treatment	Organic C (%)	Total N (%)	Available P(ppm)	Exchangeable K (cmol/kg)	Water Content (%)
C0	1.30e	0.201	26.08b	0.165	35.08b
C1	1.50d	0.188	25.38b	0.158	34.83b
C2	1.65c	0.197	24.83b	0.161	34.36b
C3	1.80b	0.209	25.10b	0.168	34.34b
C4	1.55d	0.202	24.80b	0.159	35.16b
C5	1.60d	0.211	25.19b	0.163	36.58a
C6	1.75c	0.198	24.00b	0.156	35.85a
C7	1.72c	0.206	24.94b	0.162	35.69a
C8	1.90a	0.204	25.35b	0.167	37.61a
C9	1.93a	0.210	29.16a	0.171	34.03b
C10	1.88b	0.206	25.40b	0.164	33.07b
C11	1.95a	0.193	24.30b	0.160	35.02b
C12	2.00a	0.200	24.60b	0.166	34.92b
F-value	22.83**	1.58ns	4.33**	1.12ns	2.05*

Different letters indicate significant differences at $p<0.05$. ns = not significant; * = significant ($p<0.05$); ** = highly significant ($p<0.01$).

3.2. Effects on Soil Chemical Properties

Compost-biochar mixture application significantly improved key soil chemical properties (Table 3). Soil organic carbon content showed highly significant increases ($p < 0.01$), with treatment C8 (10 ton/ha + 50% NPK) achieving optimal levels (1.90%), representing a 46% increase over the control (1.30%). This finding aligns with previous studies demonstrating biochar's capacity to sequester carbon and enhance soil organic matter (Lehmann *et al*., 2011). The increase in soil organic carbon is attributed to the stable aromatic carbon structure of water hyacinth biochar, which resists microbial decomposition, combined with the readily decomposable organic matter from compost. Higher soil organic carbon improves soil aggregation, water holding capacity, and provides substrate for beneficial microbial activity.

Soil water content was significantly improved by compost-biochar mixture application ($p < 0.05$), with treatment C8 showing the highest retention (37.61%). This 7.1% increase over the control demonstrates biochar's role in enhancing soil water holding capacity through its porous structure and high surface area (Abel *et al*., 2013). The improved water retention is particularly beneficial for crop production on alluvial soils, which often suffer from poor water holding capacity due to their coarse texture and low organic matter content. Enhanced water availability reduces drought stress and supports consistent nutrient uptake throughout the growing period.

Available phosphorus showed significant treatment effects ($p < 0.01$), with C9 (10 ton/ha + 75% NPK) achieving the highest concentration (29.16 ppm). This 11.8% increase over the control suggests that compost-biochar mixture may be related to the reduction of P fixation and improved availability of P supply through NPK fertilization. The mechanism likely involves biochar's ability to reduce P sorption on soil minerals and increase P availability through pH modification and provision of negatively charged surfaces that compete with phosphate for sorption sites (Xu *et al*., 2014). The compost component also contributes organic acids that can chelate metal cations and release previously fixed phosphorus.

While nitrogen and potassium levels showed no significant differences among treatments, trends toward improvement were observed with compost-biochar application. The lack of significant effects on total N may be due to the dynamic nature of nitrogen cycling in soil, where mineralization, immobilization, and losses through volatilization or leaching occur simultaneously (Clough *et al*., 2013). This indicates that the compost–biochar amendment did not substantially alter total N within the experimental period. The snapshot sampling at harvest may not fully capture the temporal dynamics of nitrogen availability throughout the growing season. Similarly, potassium showed slight increases with amendment application, though these were not statistically significant, possibly due to the relatively high initial K status of the alluvial soil used in this study.

3.3. Optimization of Compost-Biochar Mixture Application

The results indicate that compost biochar application at 10 ton/ha combined with 50% NPK reduction (C8) represents an optimal balance between soil improvement and resource efficiency. This treatment achieved maximum soil organic carbon and water retention while maintaining adequate nutrient supply for plant growth. The ability to reduce chemical fertilizer 50% while maintaining crop performance has significant economic and environmental implications.

The synergistic effects observed between compost-biochar mixture and reduced NPK rates can be attributed to several mechanisms. First, biochar provides a stable carbon matrix that improves soil structure and creates favorable microhabitats for root growth and microbial activity through its porous structure and high surface area (Yan *et al*., 2022). Enhanced microbial activity contributes to improved nutrient cycling through decomposition of organic matter, biological nitrogen fixation by rhizobia associated with legume roots, and solubilization of mineral-bound phosphorus and potassium (Beattie, 2006). These microbial processes increase nutrient availability in plant-accessible forms, supporting vegetative growth despite reduced synthetic fertilizer inputs. Furthermore, plant growth-promoting microorganisms produce phytohormones such as auxins, gibberellins, and cytokinins, which stimulate root development and enhance nutrient uptake efficiency (Taheri *et al*., 2025). The porous structure of biochar serves as protective microsites for beneficial microorganisms, facilitating their colonization and persistence in the rhizosphere (Sheng & Zhu, 2018). The improved root system increases the plant's capacity to explore larger soil volumes for water and nutrients, creating a positive feedback loop that sustains crop productivity under reduced fertilization regimes.

Second, the compost component supplies readily available nutrients and promotes beneficial microbial communities that enhance nutrient cycling (Fischer & Glaser, 2012). The organic matter from water hyacinth compost serves as an energy source for soil microorganisms while gradually releasing nutrients through mineralization. Third, the combination improves nutrient use efficiency by reducing losses through leaching and volatilization while maintaining adequate nutrient supply (Schmidt *et al*., 2014). The porous structure of biochar adsorbs nutrients temporarily, releasing them gradually in response to plant demand, thereby synchronizing nutrient supply with crop requirements.

These findings support the potential of compost-biochar mixture as a sustainable soil amendment for edamame production on alluvial soils. The technology offers multiple benefits including improved soil fertility, reduced chemical fertilizer dependency, and utilization of agricultural waste materials. Implementation of this approach could contribute to sustainable intensification of edamame production while addressing environmental concerns associated with excessive chemical fertilizer use.

4. CONCLUSIONS

Compost–biochar amendment significantly improved soil properties and supported vegetative growth of edamame grown on alluvial soil. Application of 10 ton/ha combined with 50% NPK reduction provided the best balance between soil quality improvement and input efficiency, particularly in enhancing soil organic carbon and water retention. Higher application rates (15 ton/ha) combined with lower NPK input (25%) further improved vegetative growth parameters. These results indicate that compost–biochar amendment has strong potential to reduce chemical fertilizer use while maintaining vegetative performance of edamame. This approach offers a promising strategy for sustainable management of alluvial soils. Further studies should evaluate yield performance and long-term effects under field conditions.

AUTHOR CONTRIBUTION STATEMENT

Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
AM	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓
RS		✓				✓		✓		✓				
Sut						✓		✓		✓				

C: Conceptualization; M: Methodology; So: Software; Va: Validation; Fo: Formal Analysis; I: Investigation; D: Data Curation; R: Resources; O: Writing - Original Draft; E: Writing - Review & Editing; Vi: Visualization; Su: Supervision; Fu: Funding Acquisition; P: Project Administration

ACKNOWLEDGMENTS

The authors thank the Faculty of Agriculture, Science and Technology, Universitas Panca Bhakti for providing research facilities and technical support.

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