International Journal of Design & Nature and Ecodynamics
Vol. 21, No. 8, August, 2026, pp. 2361-2368
Journal homepage: http://iieta.org/journals/ijdne

Combined Effects of Young Coconut Waste Biochar, Compost, and Trichoderma on Soybean Growth and Yield Responses in Ultisols

Darusman[1,2], Zaitun[2,3], Abubakar Karim[1], Kiki Surianti[2], Syakur Syakur[1*]

[1] Study Program of Soil Science, Faculty of Agriculture, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[2] Research Center for Biochar and Sustainable Tropical Forests, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[3] Study Program of Agrotechnology, Faculty of Agriculture, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia

Corresponding Author Email: syakur@usk.ac.id

https://doi.org/10.18280/ijdne.210817

Received: 16 June 2026
Revised: 15 August 2026
Accepted: 22 August 2026
Available online: 31 August 2026

Keywords:
biochar, compost, Trichoderma, soybean, Ultisols, young coconut waste

ABSTRACT

This study evaluated the individual and combined effects of young coconut waste biochar, compost, and *Trichoderma* (T) on soybean growth and yield responses in Ultisols. A 2 × 2 × 2 factorial randomized complete block design was used with three replications, resulting in eight treatment combinations and 24 experimental units. Biochar (B) and compost (K) were applied at 0 and 30 t ha^{-1}, while *Trichoderma* was applied at 0 and 3 g plant^{-1}. Plant height was measured at 2, 4, and 6 weeks after planting (WAP), and branch number, fresh biomass, filled pod number, filled pod weight, and seed weight were evaluated. The B × K × T interaction was significant for plant height at 2 WAP, whereas two-way interactions were significant at 4 and 6 WAP. Compost significantly affected branch number at 4 and 6 WAP. The B × K × T interaction was significant for fresh biomass, filled pod number, and filled pod weight, but not for seed weight. B1K1T1 produced the highest filled pod number (60.7 pods plant^{-1}) and filled pod weight (223.7 g plant^{-1}). For fresh biomass, B0K1T1 (242.8 g plant^{-1}) was not significantly different from B1K1T1 (244.3 g plant^{-1}). The responses were therefore dependent on plant growth stage and the parameter evaluated rather than uniformly interactive. These results provide an empirical basis for selecting amendment combinations according to the soybean response targeted under the tested Ultisols conditions.

1. INTRODUCTION

Soybean production on acidic and nutrient-poor soils is constrained by the root environment. Ultisols are highly weathered soils in which acidity and low fertility can limit crop performance. Long-term evidence from Indonesian Ultisols shows that biochar effects can vary with biochar type, application rate, and time after application [1]. Soil amendment strategies therefore need evaluation under defined soil and crop conditions.

Biochar is a carbon-rich product obtained from biomass pyrolysis under limited oxygen. Its effects on soil properties and crop growth depend on feedstock characteristics and production conditions [2]. Green waste biochar has also shown agronomic value as a soil amendment [3]. Young coconut waste is a relevant feedstock for biochar production and agricultural waste valorization [4]. Feedstock-specific studies further show that biochar physicochemical properties vary among agricultural residues [5].

Compost and *Trichoderma* provide functions that differ from those of biochar. Compost supplies organic matter and nutrients, while *Trichoderma* provides a biological component. These inputs may therefore act through complementary processes. Previous soybean research has shown that biochar and compost can affect soil fertility and yield [6]. Studies of biochar-compost combinations report that responses depend on amendment properties and the receiving soil [7, 8].

Biochar-*Trichoderma* interactions are context-dependent and can vary with biochar characteristics, soil conditions, and *Trichoderma* [9]. Recent soybean research has shown that biochar combined with beneficial microorganisms can produce responses that differ from single-amendment treatments [10]. Recent soybean studies also show that *Trichoderma* inoculation can influence soybean growth and yield [11]. In Ultisols, coconut-based bioactive compost containing *Trichoderma* improved several soybean growth variables [12]. These findings support testing the three components together, but they do not establish a universal combined effect.

The ecological relevance of this strategy also relates to agricultural waste management. Converting young coconut waste into biochar creates a potential route for returning a carbon-rich material to agricultural soil. Combining this material with compost and *Trichoderma* links residue utilization with soil amendment and crop production [7, 8, 13]. However, the agronomic value of the combination must be tested under defined soil, amendment, and crop conditions.

Previous studies have examined biochar-compost combinations, biochar with microbial inoculants, and bioactive compost systems. The contribution of the present study is therefore not the first use of these materials together. It is the use of a single 2 × 2 × 2 factorial framework to evaluate young coconut waste biochar, compost, and *Trichoderma* in the same Ultisols-soybean system. This design resolves main effects, two-way interactions, and three-way interactions and allows their consistency to be examined across plant development and yield traits.

2. MATERIALS AND METHODS

Ultisols management requires attention to the interaction between soil constraints and amendment properties. The low pH measured in the experimental soil provides an important context for the amendment treatments. Acidic soils can restrict nutrient availability and alter phosphorus reactions, while low organic C can limit the soil's capacity to maintain a stable supply of nutrients and provide favorable conditions for biological activity [1, 5, 14]. These constraints do not imply that every amendment will produce the same response. They instead support a treatment strategy that tests different amendment functions within the same soil environment.

The biochar component is relevant to this framework because its properties arise from both the original feedstock and the thermal conversion process. Reviews of biochar production show that feedstock kind and pyrolysis temperature can alter ash content, carbon concentration, porosity, surface area, pH, and surface functional groups [4, 5]. These properties influence how a biochar behaves after soil application. The present study therefore treats young coconut waste biochar as a specific material rather than as a generic representative of all biochars.

The compost component provides a different material profile. Compost contains organic matter that can decompose and release nutrients over time. The use of compost with biochar can also change the chemical and biological environment of the soil amendment mixture [7, 8]. In a tropical agricultural soil, biochar, compost, and their combination improved several indicators of soil quality and crop performance [7]. These published findings support the rationale for testing compost together with biochar, but they do not predict the response of the present Ultisols-soybean system.

The biological component adds another layer of variation. *Trichoderma* can interact with roots, soil nutrients, and other microorganisms. Soybean studies have shown that selected *Trichoderma* isolates can improve plant growth, including under acidic soil conditions [11]. Biochar may alter the physical habitat in which microorganisms operate because its surfaces and pores can interact with microbial colonization [15, 16]. However, the direction of this interaction depends on the properties of both the biochar and the microbial strain [10]. The present factorial design therefore provides a useful way to test the combined effect without assuming that all three components will act in the same direction.

A further consideration is the temporal scale of amendment effects. Biochar can persist in soil longer than more readily decomposable organic materials, but crop responses can change across growing seasons [1]. Compost, in contrast, is more dynamic because its organic fraction decomposes and releases nutrients. *Trichoderma* responses may also depend on its ability to establish under the prevailing soil and plant conditions. These differences in persistence and biological activity provide a theoretical basis for expecting different responses at early growth stages and at yield formation. The present study tests this temporal pattern by measuring plant height repeatedly rather than relying on a single harvest observation.

The research gap is therefore more specific than the simple absence of studies using these materials. The key unresolved issue is whether the combined application produces the same interaction structure for all soybean responses. A three-way interaction at one growth stage could disappear later. A treatment that increases biomass could have a different effect on pod formation or seed weight. The factorial design can reveal those distinctions because it estimates the main effects and interactions within the same experiment.

The study also has a clear waste-valorization dimension. Young coconut waste can enter a biochar production pathway that returns carbon-rich material to the soil [13]. This approach does not by itself demonstrate a net environmental benefit because the present experiment did not measure waste volume avoided, energy demand, carbon balance, or life-cycle impacts. The appropriate contribution of this study is narrower. It evaluates whether a locally relevant residue-derived biochar can be included in a combined soil amendment strategy without assuming a uniform agronomic response.

The initial soil analysis showed a clay texture (8% sand, 11% silt, and 81% clay), pH(H_2O) 4.72, organic C 0.98%, total N 0.08%, and Bray II extractable P of 0.65 mg kg^{-1}. Exchangeable Ca, Mg, K, and Na were 4.84, 0.71, 0.07, and 0.18 cmol kg^{-1}, respectively. The measured cation exchange capacity (CEC) was 17.20 cmol kg^{-1}, with base saturation of 33.72%. Exchangeable Al and H were 0.40 and 0.24 cmol kg^{-1}, respectively.

2.1 Experimental site and soil

The experiment was conducted as a pot experiment. Laboratory work was carried out at the Soil Physics and Environmental Laboratory, Universitas Syiah Kuala, followed by the experimental phase at the Faculty of Agriculture experimental field. Soil was sampled randomly from 0–30 cm depth, air-dried, crushed, and passed through a 2 mm sieve. A 100 g subsample was used for initial physical and chemical characterization.

The initial soil was clay-textured, with clay content above 40%, pH(H_2O) 4.72, and organic C of 0.98%. These values were used to describe the starting condition of the soil before amendment application.

2.2 Experimental design

The experiment used a 2 × 2 × 2 factorial randomized complete block design with three factors (Table 1). Biochar was applied at 0 and 30 t ha^{-1} (B0 and B1), compost at 0 and 30 t ha^{-1} (K0 and K1), and *Trichoderma* at 0 and 3 g $plant^{-1}$ (T0 and T1). The three factors generated eight treatment combinations. Each combination was represented by three independent biological replicates, giving 24 experimental units. Each pot containing 20 kg of soil and one soybean plant was considered one experimental unit. The experiment was blocked to account for potential spatial heterogeneity. The original experimental record does not document the exact pot positions or randomization sequence, so these details were not reconstructed retrospectively.

Table 1. Experimental design and treatment combinations

(A) Factors and Levels (2 × 2 × 2 Factorial Design)					
Biochar (B)		**Compost (K)**		***Trichoderma* (T)**	
B0	Without biochar	K0	Without compost	T0	Without *Trichoderma*
B1	With young coconut biochar	K1	With compost	T1	With *Trichoderma*

(B) Treatment Combinations (8 Treatments)				
No.	**Treatment Code**	**B**	**K**	**T**
1	B0K0T0	0	0	0
2	B0K0T1	0	0	1
3	B0K1T0	0	1	0
4	B0K1T1	0	1	1
5	B1K0T0	1	0	0
6	B1K0T1	1	0	1
7	B1K1T0	1	1	0
8	B1K1T1	1	1	1

(C) Replication (Three Independent Biological Replicates per Treatment)			
Treatment Code	**Replicate (pot)**		
	R1	**R2**	**R3**
B0K0T0	🪴	🪴	🪴
B0K0T1	🪴	🪴	🪴
B0K1T0	🪴	🪴	🪴
B0K1T1	🪴	🪴	🪴
B1K0T0	🪴	🪴	🪴
B1K0T1	🪴	🪴	🪴
B1K1T0	🪴	🪴	🪴
B1K1T1	🪴	🪴	🪴
24 experimental units = 8 treatments × 3 independent replicates Each pot = one experimental unit			

Note: The experiment used a 2 × 2 × 2 factorial design with biochar (B), compost (K), and Trichoderma (T) at two levels each, producing eight treatment combinations. Each treatment was replicated three times, giving 24 experimental units. Each pot represented one experimental unit. 0 = without, 1 = with.

2.3 Preparation of amendments

The factorial treatment structure allowed the effects of each amendment to be separated from the effects of their combinations. B0K0T0 represented the control condition without the three amendments. The remaining combinations allowed the contribution of each factor and the dependence of one factor on another to be evaluated. The three-replicate structure provided independent biological replication for the treatment comparisons.

The three amendments were introduced at different times before planting. Biochar was incorporated two weeks before planting, compost was applied seven days before planting, and *Trichoderma* was applied immediately before planting. This sequence was retained from the original experiment and is important for interpreting the treatment as a staged amendment system rather than as a single simultaneous application.

Young coconut waste was cut, dried in a greenhouse until relatively dry, and stored under dry conditions. Biochar used in the pot experiment was produced by open pyrolysis under uncontrolled temperature conditions. The combustion temperature was not controlled or directly monitored during production. The carbonized material was crushed, sieved, analyzed for carbon content, and subsequently used as the soil amendment. Proximate analysis and Scanning Electron Microscopy (SEM) were used to characterize the biochar used in the experiment.

Compost was prepared from lamtoro leaves (*Leucaena leucocephala*), trembesi leaves (*Samanea saman*), kirinyuh leaves (*Chromolaena odorata*), and banana peels (*Musa* spp.). The materials were dried to approximately 15% moisture on a dry-weight basis, ground, mixed with EM4 at 30 mL kg^{-1} of material, and turned every two days. The compost was incubated for approximately 21 days, then dried, ground, and sieved through a 4 mm sieve.

Trichoderma was propagated using rice as the growth medium. Rice and rice husk were steamed, cooled under clean conditions, inoculated with the *Trichoderma* starter, and incubated before the resulting inoculum was applied to the soil.

The functional groups of separately prepared young coconut waste biochar samples produced at controlled temperatures of 400 and 800 ℃ were analyzed by Fourier transform infrared (FTIR) spectroscopy using the DRS-8000 method. A Prestige-21 IR spectrometer (Shimadzu Corp.) with a resolution of 4 cm^{-1} was used. The solid sample was mixed with KBr powder at 5–10% sample concentration in KBr and placed on a sample pan. These samples were prepared separately under controlled temperature conditions for comparative characterization. They were not the biochar used in the pot experiment. The applied biochar came from open pyrolysis under uncontrolled temperature conditions and therefore cannot be assigned a specific pyrolysis temperature.

2.4 Planting and observations

Each pot contained 20 kg of soil. Biochar was incorporated two weeks before planting, compost was applied seven days before planting, and *Trichoderma* was applied immediately before planting. One soybean seed of the Anjasmoro variety was planted in each pot at approximately 3 cm depth. Plants were watered twice daily and monitored throughout the experiment.

Plant height was recorded at 2, 4, and 6 weeks after planting (WAP), and branch number was recorded during plant development. Production variables included fresh biomass, filled pod number, filled pod weight, and seed weight per plant.

2.5 Statistical analysis

Data were analyzed using a 2 × 2 × 2 factorial analysis of variance (ANOVA) under a randomized complete block design, with biochar (B), compost (K), and *Trichoderma* (T) as fixed experimental factors. The model evaluated the main effects and the B × K, B × T, K × T, and B × K × T interaction terms: $Y = \mu + Block + B + K + T + B \times K + B \times T + K \times T + B \times K \times T + \varepsilon$, where Y is the measured response, μ is the overall mean, Block represents the blocking component, and ε represents experimental error. When an interaction was significant, interpretation focused on the highest-order significant interaction and the corresponding simple-effect comparisons. Mean separation was conducted using Tukey's honestly significant difference (HSD) test at the 5% significance level. Treatment symbols are B for biochar, K for compost, and T for *Trichoderma*. The experimental record does not document separate formal normality or variance-homogeneity tests; therefore, no specific assumption test is reported.

The interpretation of the interaction terms followed the hierarchy of the factorial model. When a three-way interaction was significant, the response was interpreted within the relevant combinations of biochar, compost, and *Trichoderma*. When the three-way interaction was not significant but two-way interactions were significant, the interpretation focused on the corresponding pair of factors. This approach prevents lower-order main effects from being interpreted independently when a higher-order interaction changes the response pattern.

Because the experiment used three independent replicates per treatment combination, the statistical results are interpreted as evidence for the tested pot conditions rather than as estimates of broad population effects. The limited replication is particularly relevant to higher-order interaction terms, where statistical power is generally lower than for simple treatment comparisons.

3. RESULTS AND DISCUSSION

3.1 Initial soil condition and biochar characteristics

The experimental soil was clay-textured, acidic, and low in organic C, with pH(H_2O) 4.72 and organic C of 0.98%. These conditions indicate a restrictive starting environment for soybean production and provide a relevant basis for evaluating organic and biological amendments. Similar constraints have been reported for soybean production on Ultisols, where soil acidity and low fertility are major limitations [1, 10].

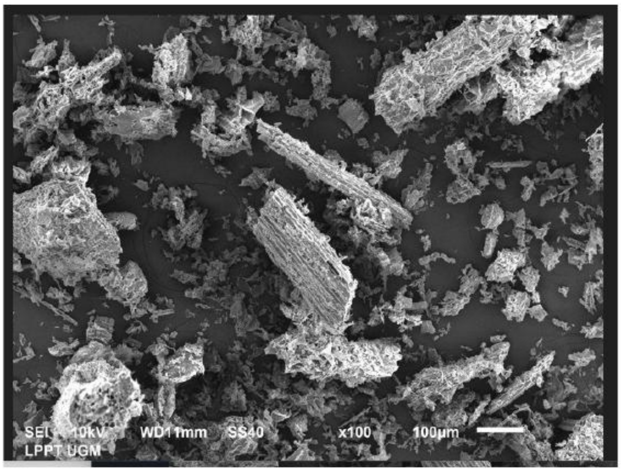

Figure 1. Scanning Electron Microscopy (SEM) image of young coconut waste biochar at 100× magnification

The SEM image (Figure 1) showed a heterogeneous and fibrous surface with visible cavities and irregular spaces. Such features may provide microsites for interactions involving water, nutrients, and microorganisms [15-18]. However, the present study did not directly measure water retention, specific surface area, CEC after amendment, or microbial colonization. These properties therefore remain possible mechanisms rather than measured outcomes.

Proximate analysis showed 5.91% moisture, 16.43% volatile matter, 16.46% ash, and 61.20% fixed carbon in the young coconut waste biochar. These values are reported exactly as provided in the source dataset.

The FTIR spectra (Figure 2) showed differences in the surface functional groups of the separately prepared young coconut waste biochar samples produced at 400 and 800 ℃. The spectra included bands associated with hydroxyl (O–H), aliphatic C–H, carbonyl (C=O), and aromatic structures. Differences in spectral intensity indicate changes in surface functional groups during controlled thermal conversion. Such changes are consistent with the known influence of pyrolysis temperature on biochar surface chemistry and functional groups [5, 14, 18]. These results provide comparative information on temperature-dependent chemical transformation. They do not directly characterize the biochar used in the pot experiment because that material came from open pyrolysis under uncontrolled temperature conditions.

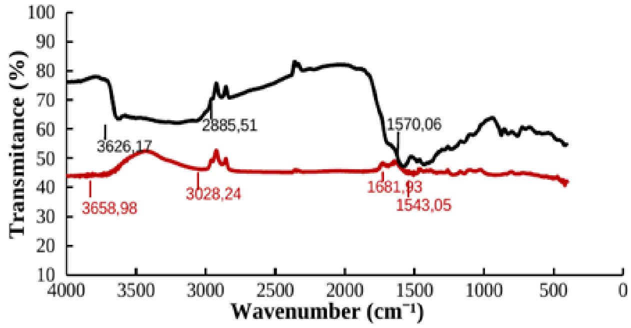

Figure 2. Fourier transform infrared (FTIR) spectra of separately prepared young coconut waste biochar produced under controlled pyrolysis temperatures of 400 ℃ (black) and 800 ℃ (red), compared to show temperature-dependent functional-group changes

The FTIR analysis showed temperature-dependent changes in the functional groups of the separately prepared biochar samples at 400 and 800 ℃ [4, 5]. These samples were not the biochar used in the pot experiment. Therefore, the FTIR results provide comparative information on controlled pyrolysis and should not be interpreted as direct characterization of the applied biochar or as direct evidence for the soybean response.

3.2 Plant height

ANOVA showed that plant height responded differently across growth stages. At 2 WAP, the B × K × T interaction was significant (F = 11.71). Although the F-values for biochar, compost, *Trichoderma*, B × K, and B × T were also above the reported 5% critical value, interpretation at this stage was centered on the significant three-way interaction because the response of each factor depended jointly on the other two factors. The K × T interaction was not significant. At 4 and 6 WAP, the B × K, B × T, and K × T interactions were significant, whereas B × K × T was not (Table 2). Therefore, the interaction structure changed with plant age, supporting a stage-dependent response.

Table 2. F-values for biochar, compost, *Trichoderma*, and their interactions on soybean plant height

Sources	2 WAP	4 WAP	6 WAP
B	13.33	18.90	267.70
K	106.22	132.15	132.65
T	9.15	15.18	56.11
B × K	17.76	24.48*	12.29*
B × T	163.56	221.63*	240.98*
K × T	2.01	11.87*	82.54*
B × K × T	11.71*	3.29	2.20

Note: * identifies the highest-order significant interaction used as the primary basis for interpretation at each growth stage. Other F-values exceeding the reported 5% critical value (4.60) were statistically significant but are not marked with an asterisk. B = biochar, K = compost, T = *Trichoderma*, WAP = Weeks after planting.

The mean plant height that has significant interaction effects at 2, 4, and 6 WAP is shown in Table 3. At 2 WAP, the significant B × K × T interaction indicates that the response of plant height depended on the particular combination of biochar, compost, and *Trichoderma*. The treatment means ranged from 12.6 to 35.1 cm in the reported comparisons. The direction of the response was not uniform across combinations, which is another reason to avoid treating the interaction itself as evidence of universal synergy. At 4 and 6 WAP, the significant two-way interactions show that the effect of one amendment depended on the presence or absence of another amendment, while the three-way interaction was no longer significant. This stage-dependent pattern indicates that amendment effects changed during soybean development. Because the study did not directly measure the underlying soil or microbial processes after amendment application, these processes remain possible explanations rather than demonstrated mechanisms.

Table 3. Mean plant height under significant interaction effects at 2, 4, and 6 weeks after planting (WAP)

WAP	Interaction	Comparison	Plant Height (cm)
2	B × K × T	B0K0: T0 vs T1	15.7aA vs 25.1bC
2	B × K × T	B0K1: T0 vs T1	28.9aB vs 35.1bD
2	B × K × T	B1K0: T0 vs T1	29.1bB vs 12.6aA
2	B × K × T	B1K1: T0 vs T1	30.1bB vs 21.3aB
4	B × K	B0: K0 vs T1	36.1aA vs 48.9bB
4	B × K	B1: K0 vs T1	36.6aA vs 41.7bA
4	B × T	B0: T0 vs T1	38.3aA vs 46.8bB
4	B × T	B1: T0 vs T1	46.4bB vs 31.8aA
4	K × T	K0: T0 vs T1	39.2bA vs 33.5aA
4	K × T	K1: T0 vs T1	45.5aB vs 45.1aB
6	B × K	B0: K0 vs T1	63.9aB vs 76.2bB
6	B × K	B1: K0 vs T1	53.5aA vs 60.0bA
6	B × T	B0: T0 vs T1	66.8aA vs 73.3bB
6	B × T	B1: T0 vs T1	66.1bA vs 47.3aA
6	K × T	K0: T0 vs T1	65.5bA vs 51.9aA
6	K × T	K1: T0 vs T1	67.4aA vs 68.7aB

Note: Lowercase letters compare T0 and T1 within each B × K combination; uppercase letters compare B0 and B1 within each fixed K × T combination. Different letters indicate significant differences at 5% according to the reported Tukey's honestly significant difference (HSD) test. B = biochar, K = compost, T = *Trichoderma*.

The treatment means at 2 WAP show that the direction of the *Trichoderma* response depended on the levels of biochar and compost. Under B0K1, plant height increased from 28.9 cm without *Trichoderma* to 35.1 cm with *Trichoderma*. Under B1K0, plant height decreased from 29.1 cm without *Trichoderma* to 12.6 cm with *Trichoderma.* This contrast is important because it shows that the effect of a biological amendment cannot be interpreted independently from the chemical and physical amendment context.

The significant B × K × T interaction at 2 WAP should also be separated from the biological concept of synergy. Statistical interaction means that the effect of one factor changes at different levels of the other factors. It does not, by itself, identify the mechanism or demonstrate a positive combined effect. The observed means include both positive and negative changes across treatment combinations. The most defensible interpretation is therefore that the early height response depended on the complete treatment context.

At 4 WAP, the significant B × K, B × T, and K × T interactions indicate that the two-factor relationships became more important than the three-factor relationship. For example, compost increased plant height from 36.1 to 48.9 cm under B0 and from 36.6 to 41.7 cm under B1. The magnitude of the increase was therefore not identical across biochar levels. The B × T interaction also changed direction, with *Trichoderma* increasing height under B0 from 38.3 to 46.8 cm but decreasing height under B1 from 46.4 to 31.8 cm.

At 6 WAP, the same general structure remained. Compost increased plant height from 63.9 to 76.2 cm under B0 and from 53.5 to 60.0 cm under B1. The B × T interaction again showed a different response under the two biochar levels. These results provide evidence under the tested conditions that the interaction structure can change as the crop develops. Because the experiment did not measure root growth or tissue nutrient concentration, the reason for this temporal shift cannot be established from the present data.

3.3 Branch number

Branch number was not significantly affected by any factor or interaction at 2 WAP. At 4 WAP, the overall treatment effect was not significant, but compost showed a significant main effect (F = 7.72). The reported means were 5 branches for K0 and 8 branches for K1. At 6 WAP, the overall treatment effect was significant (F = 4.86), and compost again showed a significant main effect (F = 24.60), with reported means of 12 branches for K0 and 19 branches for K1 (Table 4). No interaction term reached the 5% significance level at either 4 or 6 WAP. Thus, the evidence for branch development is more directly associated with the compost factor than with a synergistic interaction among the three amendments.

Table 4. Mean branch number under the significant compost effect at 4 and 6 weeks after planting (WAP)

WAP	Compost Treatment	Mean Branch Number
4	K0 (0 ton ha^{-1})	5A
4	K1 (30 ton ha^{-1})	8B
6	K0 (0 ton ha^{-1})	12A
6	K1 (30 ton ha^{-1})	19B

Note: K0 and K1 represent compost rates of 0 and 30 t ha^{-1}, respectively. Mean values are the reported marginal means for the significant compost main effect. Different uppercase letters indicate significant differences between compost levels at 5% according to the reported Tukey's honestly significant difference (HSD) test. T0 and T1 are not shown because no K × T interaction was significant.

The branch-number data provide a second example of parameter-specific response. No factor or interaction was significant at 2 WAP, but compost became significant at 4 and 6 WAP. The mean increased from 5 to 8 branches at 4 WAP and from 12 to 19 branches at 6 WAP when comparing K0 with K1. The lack of significant interaction terms indicates that this response did not depend statistically on the biochar or *Trichoderma* levels.

This pattern differs from plant height, where several interactions were significant. The difference emphasizes that plant growth is not a single response variable. Height and branch formation represent different aspects of vegetative development. A treatment can therefore influence one component without producing the same statistical effect on another component.

The compost response is also consistent with the broader evidence that organic amendments can improve crop performance in degraded tropical soils [8]. The present study, however, cannot identify whether nutrient release from compost was the direct cause of the higher branch number. Nutrient concentrations in plant tissue and changes in post-treatment soil fertility were not measured. The result should therefore remain linked to the observed compost factor rather than to an unmeasured mechanism.

The yield-related variables showed stronger treatment responses than most vegetative variables. The three-way B × K × T interaction was significant for fresh biomass, filled pod number, and filled pod weight. In contrast, the three-way interaction was not significant for seed weight, although the main effects of biochar and compost were significant for that variable.

3.4 Yield components and treatment specificity

The yield-related responses provide the clearest evidence that the amendment effects should be interpreted by parameter rather than by a single overall treatment ranking. Fresh biomass, filled pod number, filled pod weight, and seed weight did not show the same statistical pattern. This distinction is important because soybean production involves sequential development from vegetative growth to reproductive formation and seed filling.

The B × K × T interaction was significant for fresh biomass, filled pod number, and filled pod weight. The treatment means show a strong increase across several combinations. B0K0T0 produced 83.5 g plant^{-1} fresh biomass, while B0K1T1 and B1K1T1 produced 242.8 and 244.3 g plant^{-1}, respectively (Table 5). These values show that the presence of compost and *Trichoderma* was associated with much higher biomass than the control under the tested conditions. However, the close values for B0K1T1 and B1K1T1 show that the addition of biochar did not provide a statistically detectable extra increase in fresh biomass when compost and *Trichoderma* were already present.

Table 5. Treatment means for yield-related variables under the three-way interaction

Treatment	Biomass (g plant^{-1})	Filled Pod Number (pods plant^{-1})	Filled Pod Weight (g plant^{-1})
B0K0T0	83.5aA	7.7aA	29.4aA
B0K0T1	135.6bA	15.7bA	58.2bA
B0K1T0	125.1aB	17.0aB	62.6aB
B0K1T1	242.8bC	24.3bC	88.0bC
B1K0T0	194.4aC	28.3bC	106.2bC
B1K0T1	213.7bB	20.0aB	74.3aB
B1K1T0	236.4aD	39.3aD	146.7aD
B1K1T1	244.3bC	60.7bD	223.7bD

Note: For each B × K combination, lowercase letters compare T0 and T1. For each fixed K × T combination, uppercase letters compare B0 and B1. Different letters indicate significant differences at 5% according to the reported Tukey's honestly significant difference (HSD) test.

This result has a direct implication for the interpretation of the complete amendment. The complete combination should not be described as the best treatment for all outcomes. Its advantage was clearer for the pod-related variables than for fresh biomass. This distinction avoids a common problem in multi-factor studies, where a treatment with the highest numerical value for one variable is presented as generally superior without considering other variables.

The filled pod number increased from 7.7 pods plant^{-1} under B0K0T0 to 60.7 pods plant^{-1} under B1K1T1. Filled pod weight increased from 29.4 to 223.7 g plant^{-1} across the same treatments. The significant three-way interaction indicates that these responses depended on the combination of the three factors. The result is consistent with an amendment response that becomes more differentiated during reproductive development. It does not, however, establish which physiological process produced the difference.

The distinction between pod number and seed weight is especially important. The three-way interaction was not significant for seed weight, even though it was significant for filled pod number and filled pod weight. Seed weight was instead associated with significant main effects of biochar and compost. This pattern indicates that pod formation and final seed mass responded differently to the amendment structure. The study therefore supports separate interpretation of yield components rather than treating all yield variables as interchangeable.

The source-sink concept provides a useful theoretical framework for this pattern. During reproductive development, soybean plants partition assimilates between vegetative tissues, pods, and developing seeds. Differences in pod formation can occur without producing the same proportional differences in final seed mass. The present experiment did not measure photosynthetic activity, assimilate transport, seed-filling rate, or tissue nutrient concentrations, so this framework is used only to organize the observed pattern and not to claim a measured physiological mechanism.

From an agronomic perspective, the results support decision-making based on the target parameter. If fresh biomass is the target, B0K1T1 and B1K1T1 provide statistically comparable values. If filled pod number or filled pod weight is the target, B1K1T1 produced the highest observed values. These statements are specific to the measured variables, the tested soil, the tested amendment rates, and the pot conditions.

The statistically significant three-way interaction for fresh biomass, filled pod number, and filled pod weight demonstrates that the amendment combination influenced reproductive and biomass responses more clearly than most early vegetative traits. For fresh biomass, B0K1T1 produced 242.8 g plant^{-1} and was not significantly different from B1K1T1 at 244.3 g plant^{-1}. Under the tested rates, therefore, adding biochar did not provide a statistically detectable additional increase in fresh biomass when compost and *Trichoderma* were already present. In contrast, B1K1T1 produced the highest filled pod number and filled pod weight, at 60.7 pods plant^{-1} and 223.7 g plant^{-1}, respectively. These findings indicate that the response to the combined amendments depended on the specific production trait.

For filled pod number, the B × K × T interaction was significant ($F = 35.00$), and B1K1T1 produced the highest reported value at 60.7 pods plant^{-1}. The same treatment also produced the highest filled pod weight, 223.7 g plant^{-1}, under a significant B × K × T interaction ($F = 12.15$). These findings show that the complete combination was particularly effective for the two pod-related variables measured in this study. However, this result should not be interpreted as evidence that the complete combination was optimal for every soybean response.

Seed weight provides an important contrast. The B × K × T interaction was not significant ($F = 1.40$), and neither B × K, B × T, nor K × T was significant. In contrast, the main effects of biochar ($F = 19.18$) and compost ($F = 12.56$) were significant. Thus, the seed-weight response in this experiment is better described as being associated with the individual biochar and compost factors rather than with their combined three-way interaction.

The observed responses should be interpreted within the scope of the experiment. The study used three independent replicates for each treatment, one soybean variety, one Ultisol, and pot conditions. This scope limits statistical power for higher-order interactions and limits direct extrapolation to other soils, varieties, amendment rates, or field conditions. The experiment also did not measure post-treatment soil pH, organic C, nutrient availability, CEC, water retention, microbial biomass, microbial colonization, or enzyme activity. Therefore, changes in these properties cannot be attributed directly to the treatments from the present dataset.

The same scope applies to the soil interpretation. The initial soil values were measured before amendment application. They describe the starting environment but do not show how the treatments changed soil pH, carbon, nutrient availability, CEC, or water relations. Published studies have documented such soil changes after biochar and compost application [5, 7, 19], but those published measurements cannot be substituted for measurements in the present experiment.

The three independent replicates provide treatment replication, but they also limit the precision of estimates for complex interactions. This is particularly relevant when a three-way interaction is interpreted at several developmental stages. The present study therefore reports significant interactions where the analysis supports them and avoids converting non-significant interactions into biological claims.

The pot scale also limits extrapolation. A pot experiment controls the soil volume and plant density more closely than a field trial, but it cannot reproduce all sources of field heterogeneity. The present results should therefore be treated as evidence under controlled pot conditions. Field studies with repeated seasons are needed to determine whether the same response pattern persists under practical production conditions.

Finally, the experiment did not measure the biological establishment of *Trichoderma* or the interaction between *Trichoderma* and the biochar surface. The literature provides a rationale for such interactions [9, 11, 15, 16], but the present dataset contains no microbial abundance, colonization, or activity measurements. This limitation is important because it prevents a direct attribution of the observed plant responses to microbial mechanisms.

The baseline soil properties provide the initial chemical context for interpreting the amendment response. The soil was strongly clay-dominated (81% clay) and had a measured pH(H_2O) of 4.72, organic C of 0.98%, total N of 0.08%, Bray II extractable P of 0.65 mg kg^{-1}, and CEC of 17.20 cmol kg^{-1}. Because these measurements were taken before treatment application, they describe the starting condition rather than treatment effects. Post-harvest changes in these properties were not measured in the present experiment.

The biochar characterization provides supporting context for interpreting the agronomic responses. The SEM image of the applied biochar showed a heterogeneous and fibrous surface with visible cavities. The FTIR analysis, conducted on separately prepared samples produced at controlled temperatures of 400 and 800 °C, showed temperature-dependent differences in surface functional groups. The FTIR results therefore describe comparative chemical changes during controlled pyrolysis and should not be treated as a direct measurement of the uncontrolled pyrolysis conditions used to produce the biochar applied in the pot experiment. Because soil water retention, post-application nutrient availability, CEC after amendment, microbial biomass, microbial colonization, and enzyme activities were not directly measured, these properties are considered possible mechanisms rather than demonstrated causes of the observed soybean responses.

Biochar characterization helps explain why production conditions matter when interpreting the treatment response. The proximate analysis of the applied biochar showed 61.20% fixed carbon, together with 16.46% ash and 16.43% volatile matter. These measurements describe the material used in the pot experiment. They do not, however, provide a direct estimate of soil carbon persistence or nutrient release after application.

The SEM image adds structural information. The heterogeneous fibrous surface and visible cavities are compatible with porous biochar structure reported for other biomass-derived materials [11, 15]. Such structures can provide surfaces for water, dissolved compounds, and microorganisms. The present study did not quantify surface area, pore-size distribution, water retention, or microbial colonization. The SEM evidence therefore supports discussion of potential physical habitat but not a direct claim of improved soil physical or biological function.

The FTIR comparison requires a separate interpretation. The 400 and 800 °C samples were prepared under controlled conditions and differed in surface functional groups. Pyrolysis temperature is known to affect carbonization and surface chemistry [4, 5]. The observed spectral differences are therefore consistent with the broader theory of thermal transformation of biomass. They cannot be assigned directly to the open-pyrolysis material used in the pot experiment.

This distinction also affects how the FTIR findings should be used in relation to the agronomic data. The FTIR results cannot explain why a particular treatment produced a specific soybean response because the applied biochar did not have a controlled production temperature. The most defensible use of the FTIR results is to document that thermal conversion can alter the functional groups of young coconut waste biochar and to identify a basis for more controlled future experiments.

4. CONCLUSIONS

The combined application of young coconut waste biochar, compost, and *Trichoderma* produced different responses among soybean growth and yield parameters under the tested Ultisols conditions. A significant B × K × T interaction occurred for plant height at 2 WAP, while two-way interactions occurred at 4 and 6 WAP. Compost significantly affected branch number at 4 and 6 WAP. The B × K × T interaction was significant for fresh biomass, filled pod number, and filled pod weight, but not for seed weight. B1K1T1 produced the highest filled pod number (60.7 pods $plant^{-1}$) and filled pod weight (223.7 g $plant^{-1}$). For fresh biomass, B0K1T1 (242.8 g $plant^{-1}$) was not significantly different from B1K1T1 (244.3 g $plant^{-1}$). Thus, the observed amendment responses varied with plant growth stage and the parameter evaluated.

ACKNOWLEDGMENT

The authors would like to express their gratitude to the Institute for Research and Community Service (LPPM), Universitas Syiah Kuala, for providing research funding through the PP Research Grant Scheme (Grant No.

72/UN11.2.1/PT.01.03/PNBP/2023).

REFERENCES

[1] Cornelissen, G., Jubaedah, Nurida, N.L., et al. (2018). Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol. Science of the Total Environment, 634: 561-568. https://doi.org/10.1016/j.scitotenv.2018.03.380

[2] Premalatha, R.P., Poorna Bindu, J., Nivetha, E., et al. (2023). A review on biochar's effect on soil properties and crop growth. Frontiers in Energy Research, 11: 1092637. https://doi.org/10.3389/fenrg.2023.1092637

[3] Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A., Joseph, S. (2007). Agronomic values of greenwaste biochar as a soil amendment. Australian Journal of Soil Research, 45(8): 629-634. https://doi.org/10.1071/SR07109

[4] Tomczyk, A., Sokołowska, Z., Boguta, P. (2020). Biochar physicochemical properties: Pyrolysis temperature and feedstock kind effects. Reviews in Environmental Science and Bio/Technology, 19: 191-215. https://doi.org/10.1007/s11157-020-09523-3

[5] Ding, Y., Liu, Y.G., Liu, S.B., et al. (2016). Biochar to improve soil fertility. A review. Agronomy for Sustainable Development, 36: 36. https://doi.org/10.1007/s13593-016-0372-z

[6] Barus, J., Dermiyati, Sudarsono, H. (2016). Soil chemical properties and soybean yield due to application of biochar and compost of plant waste. Journal of Tropical Soils, 21(1): 1-7. https://doi.org/10.5400/jts.2016.v21i1.1-7

[7] Agegnehu, G., Bass, A.M., Nelson, P.N., Bird, M.I. (2016). Benefits of biochar, compost and biochar-compost for soil quality, maize yield and greenhouse gas emissions in a tropical agricultural soil. Science of the Total Environment, 543: 295-306. https://doi.org/10.1016/j.scitotenv.2015.11.054

[8] Wu, H.P., Lai, C., Zeng, G.M., et al. (2017). The interactions of composting and biochar and their implications for soil amendment and pollution remediation: A review. Critical Reviews in Biotechnology, 37(6): 754-764. https://doi.org/10.1080/07388551.2016.1232696

[9] Paveen, P., Kataoka, R., Kumar, V. (2026). Omics-informed insights into biochar–*Trichoderma* interactions in plant–soil systems: Mechanisms of defense and context-dependent responses. World Journal of Microbiology and Biotechnology, 42: 219. https://doi.org/10.1007/s11274-026-04950-w

[10] Cui, X., Bi, Y.H., Wang, L.D., et al. (2026). Biochar and *Trichoderma* viride co-application boosts industrial soybean performance under continuous cropping stress via rhizosphere metabolic reprogramming. Industrial Crops and Products, 247: 123573. https://doi.org/10.1016/j.indcrop.2026.123573

[11] Bononi, L., Chiaramonte, J.B., Pansa, C.C., Moitinho, M.A., Melo, I.S. (2020). Phosphorus-solubilizing *Trichoderma* spp. from Amazon soils improve soybean plant growth. Scientific Reports, 10: 2858. https://doi.org/10.1038/s41598-020-59793-8

[12] Suryani, R., Setiawan, S., Astar, I. (2025). Application of coconut waste-based bioactive compost charcoal and incubation time to improve soybean plant growth on Ultisol soil [in Indonesian]. Agrologia: Jurnal Ilmu Budidaya Tanaman, 14(2): 125-136. https://doi.org/10.30598/agrologia.v14i2.21814

[13] Anwar, K., Mahidin, Ramli, I., et al. (2025). Waste to a value-added material: Production of biochar from young coconut waste. International Journal of Design & Nature and Ecodynamics, 20(12): 2821-2829. https://doi.org/10.18280/ijdne.201208

[14] Silva, R.W., Loquez, M.H.R.S., Paquini, L.D., et al. (2025). Role of biochar in phosphorus sorption and availability in acidic soil. Communications in Soil Science and Plant Analysis, 56(14): 2149-2165. https://doi.org/10.1080/00103624.2025.2492223

[15] Jaafar, N.M., Clode, P.L., Abbott, L.K. (2015). Soil microbial responses to biochars varying in particle size, surface and pore properties. Pedosphere, 25(5): 770-780. https://doi.org/10.1016/S1002-0160(15)30058-8

[16] Wong, J.W.C., Ogbonnaya, U.O. (2021). Biochar porosity: A nature-based dependent parameter to deliver microorganisms to soils for land restoration. Environmental Science and Pollution Research, 28: 46894-46909. https://doi.org/10.1007/s11356-021-14803-8

[17] Yang, C.D., Liu, J.J., Ying, H.C., Lu, S.G. (2022). Soil pore structure changes induced by biochar affect microbial diversity and community structure in an Ultisol. Soil and Tillage Research, 224: 105505. https://doi.org/10.1016/j.still.2022.105505

[18] Dai, Z.M., Xiong, X.Q., Zhu, H., et al. (2021). Association of biochar properties with changes in soil bacterial, fungal and fauna communities and nutrient cycling processes. Biochar, 3: 239-254. https://doi.org/10.1007/s42773-021-00099-x

[19] Major, J., Rondon, M., Molina, D., Riha, S.J., Lehmann, J. (2010). Maize yield and nutrition during 4 years after biochar application to a Colombian savanna oxisol. Plant and Soil, 333: 117-128. https://doi.org/10.1007/s11104-010-0327-0