Available online at:
http://journal.unila.ac.id/index.php/tropicalsoil
DOI: 10.5400/jts.2025.v30i2.85-95

The Influence of Compost and Biochar on the Physico-Chemical Properties of Soil and the Growth of Tomatoes in Sub-Optimal Land

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Received 02 January 2025 Revised 16 January 2025; Accepted 25 March 2025

ABSTRACT

This study seeks to evaluate the effectiveness of coconut shell biochar (CB) and/or Leucaena compost (LC) as ameliorants in improving soil chemical and physical properties, as well as enhancing tomato yields. The goal is to identify the most effective combination of ameliorant formulations that can improve land quality and increase yield of tomato. The study was carried out over a 10-month period, spanning from March 2024 to December 2024. The research method used a Group Random Design, the treatments studied were: A0: no ameliorant + inorganic fertilizer as recommended; A1 : CB 15 Mg ha^{-1}; A2 : LC 15 Mg ha^{-1}; A3 : LC 5 Mg ha^{-1} + CB 10 Mg ha^{-1}; A4 : LC 10 Mg ha^{-1} + CB 5 Mg ha^{-1}. All treatments were repeated 5 times. The data obtained from this study were subjected to statistical analysis and further evaluated using the Duncan's New Multiple Range Test (DNMRT). The findings reveal that applying coconut shell biochar and *Leucaena* compost, whether individually or in combination, markedly enhances the physical properties of the soil. These improvements include reduced bulk density (BD), increased soil organic matter SOM), total porosity (TP), and hydraulic conductivity (HC), as well as better pore distribution and water retention. Furthermore, these treatments resulted in an increase in both the tomato weight per plant and the fresh tomato weight per plot. The most effective combination for maximizing tomato yield was determined to be 10 Mg ha^{-1} of LC combined with 5 Mg ha^{-1} of CB.

Keywords: Biochar, compost, tomato, physic-chemical properties, sub-optimal land

INTRODUCTION

Tomatoes (*Solanum licopersicum*) rank as the second most significant vegetable crop in the global diet, boasting considerable economic and nutritional value (Hasnain et al., 2020). Their culinary versatility and high nutrient content position them as essential among vegetables (Samui et al., 2020). In 2022, global tomato production reached 186.1 million tons, covering an area of 4.7 million hectares (FAOSTAT, 2023). Tomatoes are a rich source of high-quality antioxidants, particularly vitamin C, which is associated with various health benefits, including a reduced risk of heart disease and cancer (Luo et al., 2021 ; Rattanavipanon et al., 2021). The mismanagement and overuse of fertilizers, coupled with suboptimal cultivation techniques, have heightened the vulnerability of tomatoes to adverse environmental conditions, ultimately leading to a decline in yield (Cheng et al., 2021). Consequently, future efforts should focus on developing innovative approaches and technologies that improve agricultural productivity while safeguarding soil health.

In the past two decades, biochar technology has emerged as a promising approach for carbon sequestration in soils. Biochar, a carbon-rich substance created by pyrolyzing biomass in a low-oxygen environment, has gained widespread recognition as a valuable soil amendment in climate-smart agriculture due to its enduring effects and ability to improve soil quality (Yadav et al., 2023). This innovative technology not only helps mitigate climate change but also aligns with circular economy principles by recycling organic residues (Huang et al., 2023; Yang et al., 2023) and enhancing soil fertility (Ding et al., 2016 ; El-Naggar et al., 2019). Meta-analytical studies have demonstrated that biochar application significantly increases crop yields, with an average improvement of 14.5% in field trials (Han et al., 2023), especially in soils with low fertility.

This show the importance of selecting biochar that are specifically suited to the soil conditions and land-use goals before application (Jeffery et al., 2017; Ye, et al., 2020). Biochar's distinctive properties—such as nutrient retention, soil structure improvement, increased water-holding capacity, and enhanced microbial activity also make it an ideal medium for developing enhanced-efficiency fertilizers (Chen et al., 2023).

Among the various innovative approaches, biochar has emerged as a promising strategy for sustainable agriculture due to its significant impact on the physicochemical properties of soil and plant performance (Wu et al., 2019). Biochar, a carbon-rich organic material, is produced by pyrolyzing biomass, including wood, plant residues, and agricultural waste, under high-temperature, low-oxygen conditions (Lee et al., 2023). This method produces a stable carbon structure, yielding a material that serves as an effective soil amendment for improving soil characteristics. As a soil amendment, biochar enhances soil fertility, facilitates plant growth by providing essential nutrients, and improves nutrient retention in the soil (Rosa et al., 2024); Gao et al., 2019). Studies have demonstrated that biochar application can substantially increase tomato yields and enhance fruit nutritional quality, with reported yield improvements of up to 29.55% (Lei et al., 2024). Extensive research has examined the impact of biochar on tomato growth and development, its influence on yield and fruit quality remains variable and, at times, unpredictable. Several studies have attributed significant yield increases to the use of biochar produced from agricultural residues (Li et al., 2021; Zhang et al., 2024; Sayara et al., 2020; Sani et al., 2023).

On suboptimal lands, organic amendments are commonly utilized to increase soil organic matter and improve its physical and chemical characteristics (Garbowski et al., 2023). Among these, compost is recognized as a particularly effective and sustainable option. It increases humus levels, enhances soil fertility, and improves water and nutrient retention, thereby positively influencing soil physical quality (Ampim et al., 2010; Paradelo et al., 2019; Wang et al., 2022). Compost is created through a controlled aerobic, thermophilic decomposition process of organic waste by microorganisms, known as composting. This process stabilizes organic matter and transforms harmful substances into forms that support improved soil conditions for plant growth. Extensive research has documented the benefits of compost on soil physical properties. It promotes soil aggregation and stability (Annabi et al., 2011; Dong et al., 2022 ; Situ et al., 2022), increases total porosity (Arthur et al., 2011; Wallace et al., 2020), and reduces bulk density (McGrath et al., 2020). Compost also optimizes pore size distribution (G³¹b et al., 2020) and enhances water retention capacity (Schmid et al., 2017; G³¹b et al., 2020). Additionally, it enhances soil aeration, reduces compaction, and creates a conducive environment for root growth (Mašková et al., 2021).

This research aims to assess the effectiveness of coconut shell biochar and *Leucaena leucuchepala* biocompost as soil ameliorants in enhancing soil chemical and physical properties, as well as improving crop productivity. The study seeks to identify an optimal combination of ameliorant formulations that can effectively improve soil quality while boosting the growth and yield of tomato.

MATERIALS AND METHODS

Location and Time

This study was carried out in Tangkit Village, located in Sungai Gelam District of Muaro Jambi Regency, Jambi Province, located at the coordinates 1° 39' 5" S and 103° 41' 33" E, from June 2024 to December 2024. The fieldwork was carried out on the farmland of partner farmers, while soil analysis was performed in the Soil Fertility Laboratory, Faculty of Agriculture, University of Jambi.

Experimental Design, Treatments, and Planting

Coconut shells were sourced from a local coconut plantation and used as feedstock to make biochar. The shells underwent pyrolysis at temperatures ranging from 400 to 450 °C for 4–5 hours in a pyrolyzer under an oxygen-free environment. After the pyrolysis process, the resulting biochar was ground and sieved, with 100% passing through a 40-mesh sieve and 50% passing through an 80-mesh sieve. Leucaena pruning, consisting of leaves and young stalks, were mixed with poultry manure in a ratio of 3:1 (three parts Leucaena pruning to one part poultry manure). Trichoderma and rock phosphate were added to the mixture, which was then composted for one month until it transformed into mature compost, referred to as "Leucaena compost." The finished compost was sieved through a 2-mm and air-dried until fully dried, making it ready for applicatied as organic fertilizer. The dosage and combinations of LC and CB treatments are detailed in Table 1.

In a field trial aimed at evaluating the effects of LC and CB on tomato growth, 10 treatments were applied to plots measuring 3.6 m × 1.2 m, with 1 m spacing between adjacent blocks. The

Table1. Dose ameliorant compost, biochar, and inorganic fertilizer.

Treatment	Compost ($Mg\ ha^{-1}$)	Biochar ($Mg\ ha^{-1}$)	Mineral Fertilizer
A0	0	0	350 kg ha^{-1} Urea, 150 kg ha^{-1} TSP, 150 kg ha^{-1} KCl
A1	0	15	350 kg ha^{-1} Urea, 150 kg ha^{-1} TSP, 150 kg ha^{-1} KCl
A2	15	0	350 kg ha^{-1} Urea, 150 kg ha^{-1} TSP, 150 kg ha^{-1} KCl
A3	5	10	350 kg ha^{-1} Urea, 150 kg ha^{-1} TSP, 150 kg ha^{-1} KCl
A4	10	5	350 kg ha^{-1} Urea, 150 kg ha^{-1} TSP, 150 kg ha^{-1} KCl

treatments consisted of compost and biochar applied either individually or in combination. One week after the application of LC and CB, 30-day-old tomato seedlings were transplanted at a planting density of 65 cm × 60 cm, resulting in 12 tomato plants per treatment plot. Basal fertilizer used at rates of 350 kg ha^{-1} of urea (for nitrogen), 150 kg ha^{-1} of TSP (for phosphorus), and 150 kg ha^{-1} KCl (for potassium). The research was carried out by randomized block design with five replications for each of the ten treatments. Throughout the growing season, the tomato plants were managed with regular irrigation, weeding, and pest control to ensure optimal growth and reliable evaluation of the treatments' effects.

Harvesting was conducted when the tomato plants reached 60 days after planting. For soil analysis, samples were collected from each plot, comprising both disturbed and undisturbed samples to ensure a comprehensive evaluation of soil properties. At the time of harvest, soil samples were analyzed for various characteristics: soil organic matter (SOM) was determined using the dry ash method in a furnace; bulk density was measured using the core sampling method; soil aggregate formation was assessed with a sieve shaker; aggregate stability was evaluated using a wet sieve analyzer; and pore size distribution was analyzed using both pressure plate and pressure membrane apparatuses. The methods employed in this study adhered to the standards established by The Soil Research Institute (2022). Additionally, growth parameters and yield data were collected to assess the effects of the treatments. The statistical analysis was performed using Analysis of Variance (ANOVA) to determine the significance of differences among the treatments. If the calculated F-value exceeded the critical F-value, Duncan's Multiple Range Test (DMRT) at a 5% significance level was used to identify significant differences between the treatment means.

RESULTS AND DISCUSSION

Soil Physical Properties

The results on Table 2, show that the application of coconut shell biochar (CB) and Leucaena compost (LC) significantly influenced soil organic matter (SOM), bulk density (BD), total pore space (TP) , moisture content (WC), and hydraulic conductivity (K). The treatments involving LC and

Table 2 . Effect of biochar and compost application on Organic Materials (OM), Bulk density (BD), Total pore space (TP), Water content (WC), and Hydraulic Conductivity (K).

Treatment	OM (%)		BD ($g\ cm^{-3}$)		TP (%)		WC (%)		K ($cm\ h^{-}$)	
A0	2.40	d	1.34	a	47.12	c	21.42	c	1.84	d
A1	3.61	c	1.28	b	53.14	b	23.72	b	5.28	c
A2	3.92	c	1.23	c	53.71	ab	23.80	b	5.06	c
A3	5.42	b	1.20	cd	54.43	ab	25.30	a	6.63	b
A4	6.10	a	1.19	d	56.53	a	26.32	a	7.11	a

Remark: Values followed by the same lowercase letters within the same column indicate no significant difference, as determined by the DMRT follow-up test at á = 5%. Treatments are defined as follows: A0 = Control, A1 = Coconut Shell Biochar at 10 Mg ha^{-1}, A2 = Leucaena Compost at 10 Mg ha^{-1}, A3 = Combination of Biochar at 10 Mg/ha and Compost at 5 Mg ha^{-1}, A4 = Combination of Biochar at 5 Mg ha^{-1} and Compost at 10 Mg ha^{-1}.

CB, either individually or in combination, resulted in a notable increase in SOM compared to the control (A0). Specifically, the SOM content ranged from 3.61% to 6.1% across treatments (A1 to A4) compared to 2.4% in the untreated control (A0). The highest SOM content was achieved with the simultaneous application of LC10+CB5 Mg ha^{-1}. These findings indicate that increasing the application rates of LC and CB contributes to higher SOM levels. A higher SOM content also signifies elevated levels of C-organic, which aligns with findings from previous studies showing that the application of compost and/or biochar enhances organic matter and C-organic content in soils (Abel et al., 2021; Thapa et al., 2024; Wiskandar & Ajidirman, 2024 ; Larsen et al., 2024; Wang et al., 2024). Ameliorant biochar plays a significant role in enhancing SOM due to its unique properties. Biochar, a carbon-rich material, is highly stable in soil and effectively sequesters carbon over extended periods. Its porous structure facilitates water retention and serves as a habitat for active soil microorganisms, thereby contributing to the accumulation of SOM. This is consistent with previous studies, such as those using palm shell biochar (Endriani & Agus Kurniawan, 2018), compost and biochar derived from plant residues (Feeley et al., 2017) and biochar combined with compost (Ghorbani et al., 2019). These studies demonstrate that incorporating biochar and other ameliorants into soil can significantly increase soil organic carbon content. Furthermore, the hydraulic conductivity (HC) of coarse-textured soils, such as sandy loam, is strongly influenced by SOM, porosity, and BD. Higher SOM reduces BD, resulting in a more friable soil structure that enhances soil hydraulic properties.

Amelioration using CB and LC reduces soil BD and increase TP. Increasing doses of ameliorants lead to a reduction in soil BD, with the lowest value BD and highest TP observed in the treatment combining BC5+LC10 Mg ha^{-1}. An inverse correlation exists between soil BD and TP, where higher ameliorant applications result in increased pore space. This effect is attributed to the highly porous and lightweight structure of biochar, resembling a sponge, which reduces soil density when incorporated. Similarly, compost contributes to reduced soil BD by enhancing porosity through the expansion of pore spaces. This is due to the produce organic acids by compost, which bind soil particles and create a more porous structure, thereby lowering BD. These findings align with previous studies demonstrating that organic amendments increase total porosity and decrease soil BD (Jabborova et al., 2022; Chen et al., 2018; Le Guyader et al., 2024).

Amelioration with CB biochar and LC compost also increases WC, while lowering K. The water content (WC) of the soil increased from 21.42% in the control treatment to 23.72% (A1), 23.80% (A2), 25.30% (A3), and 26.32% (A4). The soil water content resulting from the application of CB10+LC 5 Mg ha^{-1} and CB5+LC10 Mg ha^{-1} showed no significant differences between the treatments. However, amelioration at a higher dose of 15 Mg ha^{-1} resulted in a higher WC compared to control. The addition of biochar helps increase soil water retention, which in turn enhances soil moisture content, as also reported by (Alotaibi & Schoenau, 2019).

The data presented in Table 3 demonstrates that the application of CB and LC significantly influences hydraulic conductivity (K). The highest K was observed in the treatment plot with CB5+LC10 Mg ha^{-1} (A4), followed by treatments A3, A2, and A1, which were equivalent but significantly lower than the control. The reduction in K is attributed to the fine particles of biochar, which enhance water retention and decrease K. Additionally, LC contributes to the formation of a more friable and stable soil structure, creating pores that effectively retain water, thereby further reducing K. These findings align with the report by Sharma et al., (2021) , which indicates that the application of biochar and compost in coarse-textured soils decreases K while optimizing groundwater content.

Soil Water Retention

Based on Table 3, the application of ameliorants enhances soil water retention by increasing saturated water content (SWC), field capacity water content (FCWC), available water content (AWC), and antecedent water content (AntWC), while simultaneously reducing water content at the permanent wilting point (PWP-WC). These improvements are linked to increased soil porosity and decreased soil BD (as evidenced in Table 2).

The study demonstrated that the combined use of LC and CB significantly enhanced both FCWC and AWC. The treatment with CB5+LC10 Mg ha^{-1} (A4) showed the highest improvement in AWC, following the order A4 > A3 > A2 > A1 > A0. This improvement is attributed to compost's ability to enhance soil aggregate formation, which stabilizes soil structure and increases micropore density. Micropores, typically ranging from 0.2 to 8.6 microns in size, effectively retain water, making it readily available for plants. These findings align with

Table 3. Effect of biochar and compos application on soil water retention, Saturation water content (SWC), Field capasity water content (FC WC), permanent wilting point (PWP-WC) water content. Available water content (AWC), and antecedent water content (AntWC).

Treatment	SWC	(%)	FC WC	(%)	PWP WC	(%)	AWC	(%)	Ant WC	(%)
A0	43.68	a	26.70	a	13.56	a	13.14	e	24.13	d
A1	45.28	b	27.66	b	13.06	a	14.01	d	26.27	c
A2	48.94	c	28.57	c	13.53	a	15.04	c	27.33	b
A3	51.32	d	29.57	d	12.66	a	16.90	b	29.72	a
A4	52.36	e	31.14	e	13.47	a	17.68	a	30.18	a

Remark: The numbers followed by the same lowercase letters in the same column are different based on the results of the DMRT follow-up test at á 5%. A0=control), A1=15 Mg ha^{-1} coconut shell biochar, A2= Leucaena compost 15 Mg ha^{-1}, A3 =a combine of 10 Mg ha^{-1} of biochar and 5 Mg ha^{-1} of compost, A4=combine of 5 Mg ha^{-1} of biochar and 10 Mg of compost, SWC:Saturation Water Content, FC WC : Field Capasity Water Content, WP WC : Wilting Point Water Content, AWC: Available Water Content, Ant WC, Antesedent Water Content

previous studies by Bondì et al. (2024), Ibrahim & Horton, (2021), Sukartono et al. (2023), Le Guyader et al. (2024) which highlighted the positive impact of biochar and compost on soil water retention and availability.

Some Chemical Properties of Soil

The study on Table 4, the use of a biochar and compost mixture, along with their individual applications, significantly raised soil pH. The highest pH was observed in the A4 (CB5+LC10 Mg ha^{-1}), recording a value of 6.19, while the control treatment exhibited the lowest pH at 4.71. Both CB and LC, when applied individually at a rate of 15 Mg ha^{-1}, increased soil pH compared to the control; however, no significant difference was observed between these two treatments. The soil pH of higher can be attributed to the high pH of the LC (8.2), which elevated the soil pH from its initial value of 4.8 to a range of 5.61 to 6.19. During decomposition, compost releases organic acids that bind acid cations, thereby reducing soil acidity.

Additionally, the compost releases simple compounds and alkaline cations that contribute to the increase in soil pH. CB also plays a significant role in raising soil pH. Its porous structure traps cations and releases them into the soil, which helps to reduce the presence of acid cations. Moreover, the recalcitrant nature of biochar further contributes to the increase in soil pH. These findings align with previous studies, which have shown that biochar, due to its recalcitrant nature, and compost, as an organic fertilizer and soil amendment, positively influence the reduction of soil acidity, as evidenced by an increase in soil pH (Mensah & Frimpong, 2018; (Cahyono et al., 2020; Chen et al., 2023; Diri & Kedoneojo, 2024; Sari & Malik, 2023; Calcan et al., 2022).

Table 4 shows that the use of CB and LC, both individually and in combination, significantly increases the total organic carbon (TOC) in the soil

Table 4. Effects of biochar and compost application on pH, organic C (OC), N-total, available P, and K-total.

	pH (H2O)		TOC (%)		TN (%)		P-Av (mg kg^{-1})		K (mg $100g^{-1}$)	
A0	4.71	d	1.39	d	0.12	e	8.82	e	9.04	e
A1	5.61	c	2.09	c	0.14	d	12.12	d	12.06	d
A2	5.71	bc	2.27	c	0.17	c	14.61	c	15.81	c
A3	5.84	b	3.14	b	0.20	b	13.83	b	14.79	b
A4	6.19	a	3.54	a	0.24	a	16.21	a	16.52	a

Remark: The numbers followed by the same lowercase letters in the same column are not real based on the results of the DMRT follow-up test at á 5%. A0=control (no treatment), A1=15 Mg ha^{-1} coconut shell biochar, A2= Leucaena compost 15 Mg ha,$^{-1}$ A3 a combination of 10 Mg ha^{-1} of biochar and 5 Mg ha^{-1} of compost, A4=combination of biochar 5 Mg ha^{-1} and compost 10 Mg ha^{-1}, TOC=total organic matter, P-Av=P available.

compared to the control (A0). The application of CB15 Mg ha-1 (A1) did not significantly differ from LC 15 Mg ha-1 (A2), but both were significantly lower than treatments of CB10+LC15 Mg ha-1 and CB5+LC10 Mg ha-1. The highest TOC was observed in the A4 treatment, with a value of 3.54%, while the lowest was recorded in the control (A0) at 1.39%. The TOC increased by 50.36–154.68% compared to no treatment. This increase in TOC is attributed to the decomposition process of compost, which contributes nitrogen (N) to the soil, enhancing the total soil N content.

Additionally, biochar serves as a habitat for soil microorganisms, which further contribute to SOM through their life cycle. Biochar also helps retain N and other nutrients within its porous structure, preventing nutrient loss through leaching and releasing them back into the soil gradually through a slow-release mechanism. These synergistic effects focused on the role of CB and LC in improving SOM and nutrient retention.

The application of CB and LC, significantly increased soil nitrogen (TN) levels. A progressive rise in TN was observed across treatments, following the order: A0 < A1 < A2 < A3 < A4 (Table 4). Similarly, the application of biochar and compost, whether singly or combined, enhanced the availability of phosphorus (P-av) in the soil, with the highest P levels recorded in A4, followed by A2, A3, A1, and A0. A comparable pattern was observed for total potassium (K) content, which was highest in A4, followed by A2, A3, A1, and A0. These improvements in nutrient levels can be attributed to biochar's nutrient-retention capacity and its gradual nutrient-release mechanism, aided by its high porosity, which minimizes nutrient leaching. Compost further contributed to the increased availability of N, P, and K in the soil. These results align with findings from (Larsen et al., 2024, Wang et al., 2024, Ayito et al., 2023, and Sari & Malik, 2023), which also highlighted the beneficial effects of biochar and compost on soil nutrient enhancement.

Growth and yield of tomatoes

The growth rate of tomato from 2 weeks after planting (MST) to 8 weeks after planting is shown in Figure 1. The growth of tomato plants exhibited varying rates of increase, with a noticeable difference in growth observed during the third measurement (4 weeks after planting). At this point, the application of CB5+LC10 Mg ha-1 resulted in the best growth rate, followed by CB10+LC5 Mg ha-1. The growth dynamics of the tomato plants, influenced by the amelioration with biochar and compost, showed significant improvements, particularly between the 3rd and 5th observations (from 4 WAP to 6 WAP). These results suggest that higher doses of biochar and compost have a more pronounced positive effect on tomato plant growth. As previously reported by researchers, compost made from Leucaena leaves can enhance plant growth by optimizing nutrient availability and absorption (Olaifa et al. , 2021; Siregar & Wijayanto, 2024). Composting in tomato cultivation has been

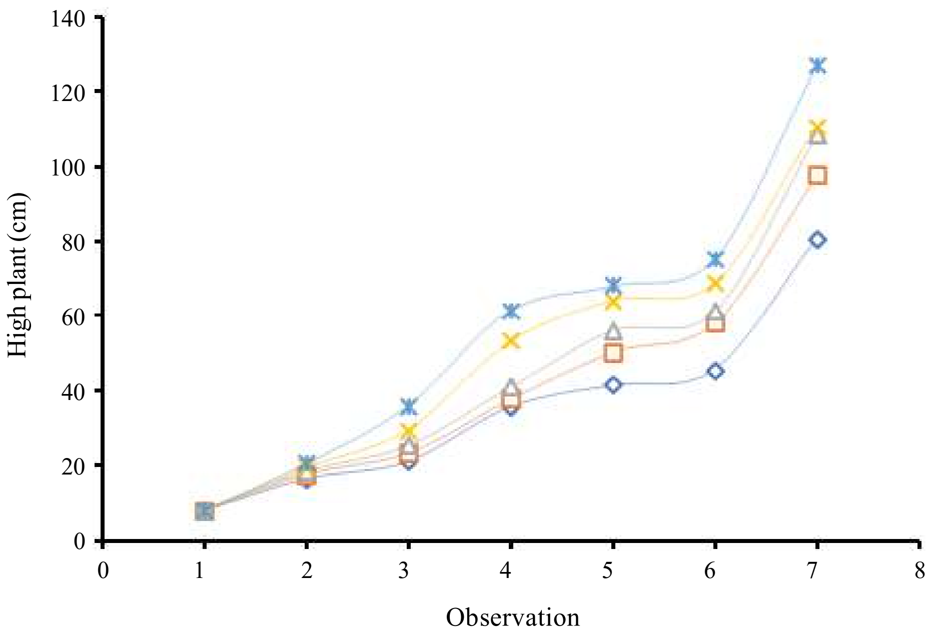

Figure 1. Growth rate of tomatoes due to amelioration of biochar and compost. —◇— : Control, —□— : B15, —△— : C15, —×— : C5B10, —✱— : C10B5.

Table 5. Effect of biochar and compost application on plant height (HP), number of leaves (LN), and weight of tomatoes plant^{-1} (kg) and weigh plot^{-1} (kg).

Treatment	HP (cm)		LN (Sheet)		Weigh plant^{-1} (kg)		Weigh plot^{-1} (kg)	
A0	80.59	d	30.57	e	1.54	e	18.54	e
A1	97.61	c	38.67	d	2.14	d	25.74	d
A2	108.13	b	48.37	c	2.85	c	34.24	c
A3	110.52	b	58.43	b	2.36	b	28.30	b
A4	126.91	a	70.77	a	3.13	a	37.58	a

Remark: The numbers followed by the same lowercase letters in the same column are different based on the results of the DMRT follow-up test at á 5%. A0=control, A1=15 Mg ha^{-1} coconut shell biochar, A2= Leucaena compost 15 Mg ha^{-1}, A3 a combination of 10 Mg ha^{-1} of biochar and 5 Mg ha^{-1} of compost, A4=combination of biochar 5 Mg ha^{-1} and compost 10 Mg ha^{-1}, HP=high plant, LN=leaf number.

demonstrated to enhance both plant growth and tomato yield (Ainiya et al., 2019). Meanwhile, the incorporation of biochar as a soil amendment significantly improves soil water-holding capacity (Wang et al., 2023; Razzaghi et al., 2020), reduces nutrient leaching, and alleviates soil compaction (Liu et al., 2023; (Bramarambika et al., 2024). These combined effects of LC and CB ensure better conditions for plant growth, contributing to overall improved plant health and productivity.

The application of CB and LC, either individually or in combination, significantly enhanced tomato plant height, leaf number, and fruit weight per plot (Table 5). Applying CB 15 Mg ha^{-1} increased plant height, while the same rate of LC also promoted plant height, with compost demonstrating a greater effect than CB. Interestingly, the use of LC 15 Mg ha^{-1} yielded comparable plant height to the combined application of CB5+LC10 Mg ha^{-1}. The tallest plants, measuring 126.91 cm at eight weeks after planting, were achieved with a treatment combining 5 Mg ha^{-1} of biochar and 10 Mg ha^{-1} of compost. The synergistic effect of biochar and compost is attributed to their ability to enhance soil carbon content, improve soil structure, increase macroporosity, and reduce soil penetration resistance, collectively fostering better plant growth (Anwar et al., 2024).

The application of CB and LC had a beneficial effect on the number of tomato leaves (Table 5). The control treatment (without any amendments) produced an average of 30.57 leaves per plant, whereas the combination of CB5+LC10 Mg ha^{-1} resulted in an increase to 70.77 leaves per plant. This illustrates that the addition of biochar and compost can substantially boost the leaf production of tomato plants.

The application of biochar and compost, either separately or in combination, resulted in a notable enhancement in the fresh fruit weight of tomatoes per plant (Table 5). The highest yield was achieved with a treatment of CB5+LC10 Mg ha^{-1}, producing 3.13 kg of fruit per plant. The control treatment had the lowest fruit weight, at 1.54 kg per plant. Biochar and compost also had a positive effect on the total weight of fresh tomatoes per plot, with the highest yield recorded at 37.58 kg plot^{-1} (A4), compared to 18.54 kg plot^{-1} in the control (A0). Overall, the treatment combining CB and LC yielded the best growth performance in tomato plants, producing the highest plant height, leaf count, fruit weight per plant, and fruit weight per plot. It underscores the potential of biochar and compost, whether applied individually or together, to enhance plant growth. Previous studies have indicated that combining biochar with other organic amendments, such as compost, yields greater benefits for plant development than applying each substance alone (Ayito et al., 2023). Additionally, research has demonstrated that biochar not only accelerates plant growth but also improves the efficiency of fertilizers, particularly when paired with organic fertilizers like compost ((Mensah & Frimpong, 2018)

CONCLUSIONS

The use of CB and LC on sub-optimal land has been shown to improve both soil physic properties and soil chemical characteristics, as well as enhance plant growth and tomato yield. The results from this study indicate that these two soil amendments positively impact soil quality and tomato plant growth performance. The combination of CB and LC provided the best outcomes, significantly increasing plant height, leaf count, fruit weight per plant, and fruit weight per plot. It also contributed to improvements in soil porosity, water retention, soil pore distribution, soil organic matter, and organic carbon content. Additionally, the combination of biochar and compost led to an increase in soil pH and the levels of essential macronutrients such as

N, P, and K. In conclusion, the combination of biochar and compost provides the most effective treatment for improving soil properties and promoting optimal growth and yield of tomatoes.

ACKNOWLEDGMENTS

Thank you to the Ministry of Higher Education, Science and Technology for financing research through the 2024 Fundamental Grant, Thank you to the Rector of the University of Jambi and the Chairman of the Institute for Research and Community Service (LPPM) of the University of Jambi. for his support.

REFERENCES

Ainiya, M., Fadil, M., & Despita, R. (2019). Peningkatan Pertumbuhan dan Hasil Jagung Manis dengan Pemanfaatan Trichokompos dan POC Daun Lamtoro. *Agrotechnology Research Journal*, *3*(2), 69–74. https://doi.org/10.20961/agrotechresj.v3i2.31910

Alotaibi, K. D., & Schoenau, J. J. (2019). Addition of biochar to a sandy desert soil: Effect on crop growth,water retention and selected properties. *Agronomy*, *9*(6), 5–7. https://doi.org/10.3390/agronomy9060327

Ampim, P. A. Y., Sloan, J. J., Cabrera, R. I., Harp, D. A., & Jaber, F. H. (2010). Green Roof Growing Substrates: Types, Ingredients, Composition and Properties. *Journal of Environmental Horticulture*, *28*(4), 244–252. https://doi.org/10.24266/0738-2898-28.4.244

Annabi, M., Le Bissonnais, Y., Le Villio-Poitrenaud, M., & Houot, S. (2011). Improvement of soil aggregate stability by repeated applications of organic amendments to a cultivated silty loam soil. *Agriculture, Ecosystems and Environment*, *144*(1), 382–389. https://doi.org/10.1016/J.AGEE.2011.07.005

Anwar H M; T B Prasetyo; Yulnafatmawita. (2024). Peranan Biochar dan Kompos dalam Meningkatkan Retensi Air dan Produksi Jagung Manis (Zea mays L. var. saccharata) pada Tanah Bertekstur Kasar. *Jurnal Agrikultura*, *35*(2), 238–249. https://jurnal.unpad.ac.id/agrikultura/article/view/53995/23393

Arthur, E., Cornelis, W. M., Vermang, J., & De Rocker, E. (2011). Amending a loamy sand with three compost types: impact on soil quality. *Soil Use and Management*, *27*(1), 116–123. https://doi.org/https://doi.org/10.1111/j.1475-2743.2010.00319.x

Ayito, E. O., John, K., Iren, O. B., John, N. M., Mngadi, S., Heung, B., Abbey, Lord, Agyeman, P. C., & Moodley, R. (2023). Synergistic effects of biochar and poultry manure on soil and cucumber (Cucumis sativus) performance: A case study from the southeastern Nigeria. *Soil Science Annual*, *74*(4), 1–16. https://doi.org/10.37501/soilsa/183903

Bondì, C., Castellini, M., & Iovino, M. (2024). Temporal variability of physical quality of a sandy loam soil amended with compost. *Biologia*, *0123456789*. https://doi.org/10.1007/s11756-024-01637-1

Bramarambika et al. (2024). The Effect of Coconut Shell Biochar on the Growth and Yield of Chilli (Capsicum annum L.) in Acidic Alfisols Soil. *Journal of Advances in Biology & Biotechnology*, *27*(7), 203–211. https://doi.org/OI: 10.9734/jabb/2024/v27i7980

Cahyono et al. (2020). Effect of Compost on Soil Properties and Yield of Pineapple (Anana Cumosus L. MERR.) on Red Acid Soil, Lampung, Indonesia. *International Journal of GEOMATE*, *19*(76), 33–39. https://doi.org/ttps://doi.org/10.21660/2020.76.87174

Calcan, S. I., Pârvulescu, O. C., Ion, V. A., Rãducanu, C. E., Bãdulescu, L., Madjar, R., Dobre, T., Egri, D., Mo, A., Iliescu, L. M., & Jerca, I. O. (2022). Effects of Biochar on Soil Properties and Tomato Growth. *Agronomy*, *12*(8), 25–27. https://doi.org/10.3390/agronomy12081824

Chen, X., Li, L., Li, X., Kang, J., Xiang, X., Shi, H., & Ren, X. (2023). Effect of Biochar on Soil-Water Characteristics of Soils: A Pore-Scale Study. *Water (Switzerland)*, *15*(10), 1–16. https://doi.org/10.3390/w15101909

Chen, Y., Gel, Y. R., Lyubchich, V., & Nezafati, K. (2018). Snowboot: Bootstrap Methods for Network Inference. *The R Journal*, *10*(2), 95–113. https://journal.r-project.org/archive/2018/RJ-2018-056/index.html

Cheng M, H Wang, Junliang F, Y Xiang, Z Tang, S. P. H. (2021). Effects of nitrogen supply on tomato yield, water use efficiency and fruit quality: A global meta-analysis. *Scientia Horticulturae*, *290*(15 Desember 2021). https://doi.org/https://doi.org/10.1016/j.scienta.2021.110553

Ding, Y., Liu, Y., Liu, S., Li, Z., Tan, X., Huang, X., Zeng, G., Zhou, L., & Zheng, B. (2016). Biochar to improve soil fertility. A review. *Agronomy for Sustainable Development*, *36*(2). https://doi.org/10.1007/s13593-016-0372-z

Diri, K. H., & Kedoneojo, A. T. (2024). Evaluating the impact of poultry manure variants and swine manure on soil chemical properties and growth of maize (Zea mays). *Asian Journal of Agriculture*, *8*(1), 1–9. https://doi.org/10.13057/asianjagric/g080101

Dong, L., Zhang, W., Xiong, Y., Zou, J., Huang, Q., Xu, X., Ren, P., & Huang, G. (2022). Impact of short-term organic amendments incorporation on soil structure and hydrology in semiarid agricultural lands. *International Soil and Water Conservation Research*, *10*(3), 457–469. https://doi.org/10.1016/j.iswcr.2021.10.003

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., Zimmerman, A. R., Ahmad, M., Shaheen, S. M., & Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, *337*, 536–554. https://doi.org/10.1016/J.GEODERMA.2018.09.034

Endriani & Agus Kurniawan. (2018). Konservasi Tanah dan Karbon Melalui Pemanfaatan Biochar Pada Pertanaman Kedelai. *Jurnal Ilmiah Ilmu Terapan Universitas Jambi*, *2*(2), 93–106. https://doi.org/https://doi.org/10.22437/jiituj.v2i2.5980

FAOSTAT. (2023). FAO STAT Statistik Database Commodities by country. *FAO of United Nation*, 1–6. https://www.fao.org/faostat/en/#rankings/commodities_by_country

Feeley, K. J., Stroud, J. T., & Perez, T. M. (2017). Most 'global' reviews of species' responses to climate change are not truly global. *Diversity and Distributions*, *23*(3), 231–234. https://doi.org/10.1111/ddi.12517

Gao, S., DeLuca, T. H., & Cleveland, C. C. (2019). Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of the Total Environment*, *654*, 463–472. https://doi.org/10.1016/J.SCITOTENV.2018.11.124

Garbowski, T., Bar-Michalczyk, D., Charaziñska, S., Grabowska-Polanowska, B., Kowalczyk, A., & Lochyñski, P. (2023). An overview of natural soil amendments in agriculture. *Soil and Tillage Research*, *225*(January), 1–10. https://doi.org/10.1016/j.still.2022.105462

Ghorbani, M., Asadi, H., & Abrishamkesh, S. (2019). Effects of rice husk biochar on selected soil properties and nitrate leaching in loamy sand and clay soil. *International Soil and Water Conservation Research*, *7*(3), 258–265. https://doi.org/10.1016/J.ISWCR.2019.05.005

G³¹b, T., ¯abiñski, A., Sadowska, U., Gondek, K., Kopeæ, M., Mierzwa-Hersztek, M., Tabor, S., & Stanek-Tarkowska, J. (2020). Fertilization effects of compost produced from maize, sewage sludge and biochar on soil water retention and chemical properties. *Soil and Tillage Research*, *197*(March), 1–11. https://doi.org/10.1016/j.still.2019.104493

Han, M., Zhang, J., Zhang, L., & Wang, Z. (2023). Effect of biochar addition on crop yield, water and nitrogen use efficiency: A meta-analysis. *Journal of Cleaner Production*, *420*, 138425. https://doi.org/10.1016/J.JCLEPRO.2023.138425

Hasnain, M., Chen, J., Ahmed, N., Memon, S., Wang, L., Wang, Y., & Wang, P. (2020). The effects of fertilizer type and application time on soil properties, plant traits, yield and quality of tomato. *Sustainability (Switzerland)*, *12*(21), 1–14. https://doi.org/10.3390/su12219065

Huang, K., Zhang, J., Tang, G., Bao, D., Wang, T., & Kong, D. (2023). Impacts and mechanisms of biochar on soil microorganisms. *Plant, Soil and Environment*, *69*(2), 45–54. https://doi.org/10.17221/348/2022-PSE

Ibrahim, A., & Horton, R. (2021). Biochar and compost amendment impacts on soil water and pore size distribution of a loamy sand soil. In *Soil Science Society of America Journal* (Vol. 85, Issue 4). https://doi.org/10.1002/saj2.20242

Jabborova, D., Annapurna, K., Azimov, A., Tyagi, S., Pengani, K. R., Sharma, P., Vikram, K. V., Poczai, P., Nasif, O., Ansari, M. J., & Sayyed, R. Z. (2022). Co-inoculation of biochar and arbuscular mycorrhizae for growth promotion and nutrient fortification in soybean under drought conditions. *Frontiers in Plant Science*, *13*(July), 1–9. https://doi.org/10.3389/fpls.2022.947547

Jeffery, S., Abalos, D., Prodana, M., Bastos, A. C., Van Groenigen, J. W., Hungate, B. A., & Verheijen, F. (2017). Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, *12*(5). https://doi.org/10.1088/1748-9326/aa67bd

Larsen, J., Rezaei Rashti, M., Esfandbod, M., & Chen, C. (2024). Organic amendments improved soil properties and native plants' performance in an Australian degraded land. *Soil Research* , *62*(4). https://doi.org/10.1071/SR22252

Le Guyader, E., Morvan, X., Miconnet, V., Marin, B., Moussa, M., Intrigliolo, D. S., Delgado-Iniesta, J., Girods, P., Fontana, S., Sbih, M., Marin, B., Delgado-Iniesta, M. J., Fontana, S., Boumaraf, B., Tirichine, A., Kavvadias, V., & Gommeaux, M. (2024). Influence of Date Palm-Based Biochar and Compost on Water Retention Properties of Soils with Different Sand Contents Date Palm-Based Biochar and Compost on Water Retention Properties of Soils with Different Sand Contents Influence of Date Palm-Based Bioch. *Forest*, *15*(2), 304. https://doi.org/10.3390/f15020304ï

Lee, J. M., Jeong, H. C., Gwon, H. S., Lee, H. S., Park, H. R., Kim, G. S., Park, D. G., & Lee, S. Il. (2023). Effects of Biochar on Methane Emissions and Crop Yields in East Asian Paddy Fields: A Regional Scale Meta-Analysis. *Sustainability (Switzerland)*, *15*(12), 19–21. https://doi.org/10.3390/su15129200

Lei, Y., Xu, L., Wang, M., Sun, S., Yang, Y., & Xu, C. (2024). Effects of Biochar Application on Tomato Yield and Fruit Quality: A Meta-Analysis. *Sustainability (Switzerland)*, *16*(15), 1–19. https://doi.org/10.3390/su16156397

Li, S., Zhu, X., Chen, Y., & Liu, D. (2021). PAsso: an R Package for Assessing Partial Association between Ordinal Variables. *The R Journal*, *13*(2), 239–252. https://journal.r-project.org/archive/2021/RJ-2021-088/index.html

Liu, X., Ren, X., Dong, J., Wang, B., Gao, J., Wang, R., Yao, J., & Cao, W. (2023). Preparation and physicochemical properties of biochar from the pyrolysis of pruning waste of typical fruit tree in north China. *BioResources*, *18*, 8536–8556. https://doi.org/10.15376/biores.18.4.8536-8556

Luo, J., Ke, D. and, & He, Q. (2021). Dietary Tomato Consumption and the Risk of Prostate Cancer: A Meta-Analysis. *Frontiers in Nutrition*, *8*(May). https://doi.org/10.3389/fnut.2021.625185

Mašková, L., Simmons, R. W., Deeks, L. K., & De Baets, S. (2021). Best Management Practices to Alleviate Deep-Seated Compaction in Asparagus (Asparagus officinalis) Interrows (UK). *Soil and Tillage Research*, *213*(May). https://doi.org/10.1016/j.still.2021.105124

McGrath, D., Henry, J., M, R., & W, C. (2020). Compost improves soil properties and tree establishment along highway roadsides. *Urban Forestry & Urban Greening*, *55*(November 2020). https://doi.org/https://doi.org/10.1016/j.ufug.2020.126851.

Mensah, A. K., & Frimpong, K. A. (2018a). Biochar and/or Compost Applications Improve Soil Properties, Growth, and Yield of Maize Grown in Acidic Rainforest and Coastal Savannah Soils in Ghana. *International Journal of Agronomy*, *2018*. https://doi.org/10.1155/2018/6837404.

Mensah, A. K., & Frimpong, K. A. (2018b). Biochar and/or Compost Applications Improve Soil Properties, Growth, and Yield of Maize Grown in Acidic Rainforest and Coastal Savannah Soils in Ghana. *International Journal of Agronomy*, *2018*. https://doi.org/10.1155/2018/6837404.

Olaifa K.A , Olaitan, A.O, Agbeja A.O, Adesokan F. B , Sulaiman , O. N and Onifade, A. . (2021). Influence of Different Compost on The Early Growth of Detarium microcarpum Guill & perr Seedling. *Journal of Research in Forestry, Wildlife & Environment*, *13*(1), 67–74.

Paradelo, R., Basanta, R., & Barral, M. T. (2019). Water-holding capacity and plant growth in compost-based substrates modified with polyacrylamide, guar gum or bentonite. *Scientia Horticulturae*, *243*, 344–349. https://doi.org/10.1016/J.SCIENTA.2018.08.046.

Rattanavipanon, W., Nithiphongwarakul, C., Sirisuwansith, P., Chaiyasothi, T., Thakkinstian, A., Nathisuwan, S., & Pathomwichaiwat, T. (2021). Effect of tomato, lycopene and related products on blood pressure: A systematic review and network meta-analysis. *Phytomedicine*, *88*, 153512. https://doi.org/10.1016/J.PHYMED.2021.153512.

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, 114055. https://doi.org/10.1016/J.GEODERMA.2019.114055.

Rosa, D., Petruccelli, V., Iacobbi, M. C., Brasili, E., Badiali, C., Pasqua, G., & Di Palma, L. (2024). Functionalized biochar from waste as a slow-release nutrient source: Application on tomato plants. *Heliyon*, *10*(8), e29455. https://doi.org/10.1016/J.HELIYON.2024.E29455.

Rosland Abel, S. E., Kheang Loh, S., Abdul Wahab, N., Masek, O., Tanimu, M. I., & Bachmann, R. T. (2021). Effect of Operating Temperature on Physicochemical Properties of Empty Fruit Bunch Cellulose-Derived Biochar. *Journal of Oil Palm Research*, *33*(4), 643–652. https://doi.org/10.21894/jopr.2021.0007.

Samui, I., Skalicky, M., Sarkar, S., Brahmachari, K., Sau, S., Ray, K., Hossain, A., Ghosh, A., Kumar, M., Bell, R. W., Mainuddin, M., Brestic, M., Liu, L., Saneoka, H., Raza, M. A., Erman, M., & Sabagh, A. E. L. (2020). Yield response, nutritional quality and water productivity of tomato (Solanum lycopersicum L.) are influenced by drip irrigation and straw mulch in the coastal saline ecosystem of Ganges delta, India. *Sustainability (Switzerland)*, *12*(17). https://doi.org/10.3390/SU12176779.

Sani, J. E., Moses, G., & Musa, S. (2023). Physicochemical evaluation of coconut shell biochar remediation effect on crude oil contaminated soil. *Cogent Engineering*, *10*(2). https://doi.org/10.1080/23311916.2023.2269659.

Sari, W. K., & Malik, P. A. (2023). The effects of application of biochar from oil palm empty fruit bunches on chemical properties of ultisols and the growth of cacao seedlings. *Kultivasi*, *22*(2), 157–167. https://doi.org/10.24198/kultivasi.v22i2.46525.

Sayara, T., Basheer-Salimia, R., Hawamde, F., & Sánchez, A. (2020). Recycling of organic wastes through composting: Process performance and compost application in agriculture. *Agronomy*, *10*(11). https://doi.org/10.3390/agronomy10111838.

Schmid, C. J., Murphy, J. A., & Murphy, S. (2017). Effect of tillage and compost amendment on turfgrass establishment on a compacted sandy loam. *Journal of Soil and Water Conservation*, *72*(1), 55–64. https://doi.org/10.2489/jswc.72.1.55.

Sharma, P., Abrol, V., Sharma, V., Chaddha, S., Srinivasa Rao, C., Ganie, A. Q., Ingo Hefft, D., El-Sheikh, M. A., & Mansoor, S. (2021). Effectiveness of biochar and compost on improving soil hydro-physical properties, crop yield and monetary returns in inceptisol subtropics. *Saudi Journal of Biological Sciences*, *28*(12), 7539–7549. https://doi.org/10.1016/j.sjbs.2021.09.043.

Singh Yadav, S. P., Bhandari, S., Bhatta, D., Poudel, A., Bhattarai, S., Yadav, P., Ghimire, N., Paudel, P., Paudel, P., Shrestha, J., & Oli, B. (2023). Biochar application: A sustainable approach to improve soil health. *Journal of Agriculture and Food Research*, *11*, 100498. https://doi.org/10.1016/J.JAFR.2023.100498.

Siregar, A. P., & Wijayanto, N. (2024). The Response of giving Gamal, Calliandra, and Lamtoro leaves compost fertilizer to Stevia plant (Stevia rebaudiana Bertoni) growth. *IOP Conference Series: Earth and Environmental Science*, *1315*(1). https://doi.org/10.1088/1755-1315/1315/1/012008.

Situ, G., Zhao, Y., Zhang, L., Yang, X., Chen, D., Li, S., Wu, Q., Xu, Q., Chen, J., & Qin, H. (2022). Linking the chemical nature of soil organic carbon and biological binding agent in aggregates to soil aggregate stability following biochar amendment in a rice paddy. *Science of the Total Environment*, *847*(November), 1–11. https://doi.org/10.1016/j.scitotenv.2022.157460.

Sukartono, Dewi, R. A. S., Bakti, A. A., & Kusumo, B. H. (2023). Dynamic of Change in Soil Physical Properties and SoyBean Growth through The Application of Biochar on Lombok Vertisols. *Jurnal Biologi Tropis*, *23*(1), 237–245. https://doi.org/10.29303/jbt.v23i1.4590.

Thapa, R. B., Coupal, R. H., Dangi, M. B., & Stahl, P. D. (2024). An Assessment of Plant Growth and Soil Properties Using Coal Char and Biochar as a Soil Amendment. *Agronomy*, *14*(2), 1–13. https://doi.org/10.3390/agronomy14020320.

Wallace, D., Almond, P., Carrick, S., & Thomas, S. (2020). Targeting changes in soil porosity through modification of compost size and application rate. *Soil Research*, *58*(3), 268–276. https://doi.org/10.1071/SR19170.

Wang, D., Lin, J. Y., Sayre, J. M., Schmidt, R., Fonte, S. J., Rodrigues, J. L. M., & Scow, K. M. (2022). Compost amendment maintains soil structure and carbon storage by increasing available carbon and microbial biomass in agricultural soil – A six-year field study. *Geoderma*, *427*, 116117. https://doi.org/10.1016/J.GEODERMA.2022.116117.

Wang, J., Zhang, B., Wang, J., Zhang, G., Yue, Z., Hu, L., Yu, J., & Liu, Z. (2024). Effects of Different Agricultural Waste Composts on Cabbage Yield and Rhizosphere Environment. *Agronomy*, *14*(3), 1–18. https://doi.org/10.3390/agronomy14030413.

Wang, L., Leghari, S. J., Wu, J., Wang, N., Pang, M., & Jin, L. (2023). Interactive effects of biochar and chemical fertilizer on water and nitrogen dynamics, soil properties and maize yield under different irrigation methods. *Frontiers in Plant Science*, *14*(September), 1–15. https://doi.org/10.3389/fpls.2023.1230023.

Wiskandar, & Ajidirman. (2024). Effect of biochar and Tithonia compost on physical properties of post-coal mining soil. *Journal of Degraded and Mining Lands Management*, *11*(3), 5829–5838. https://doi.org/10.15243/jdmlm.2024.113.5829.

Wu, Z., Zhang, X., Dong, Y., Li, B., & Xiong, Z. (2019). Biochar amendment reduced greenhouse gas intensities in the rice-wheat rotation system: six-year field observation and meta-analysis. *Agricultural and Forest Meteorology*, *278*, 107625. https://doi.org/10.1016/J.AGRFORMET.2019.107625.

Yang, M., Chen, L., Wang, J., Msigwa, G., Osman, A. I., Fawzy, S., Rooney, D. W., & Yap, P. S. (2023). Circular economy strategies for combating climate change and other environmental issues. *Environmental Chemistry Letters*, *21*(1), 55–80. https://doi.org/10.1007/s10311-022-01499-6.

Ye, L. , Arbestain, M.C., Shen, Q., Lehmann, J., Singh, B., Sabir, M. (2020). *Biochar effects on crop yields with and without fertilizer: A meta analysis of field studies using separate controls.., 2019. Soil Use Manag. 36(1),*. https://doi.org/https://doi.org/10.1111/sum.12546.

Zhang, P., Li, M., Fu, Q., Singh, V. P., Du, C., Liu, D., Li, T., & Yang, A. (2024). Dynamic regulation of the irrigation–nitrogen–biochar nexus for the synergy of yield, quality, carbon emission and resource use efficiency in tomato. *Journal of Integrative Agriculture*, *23*(2), 680–697. https://doi.org/10.1016/J.JIA.2023.06.006.