

## EFFECTS OF PYROLYTIC CHAR AS A SOIL AMENDMENT ON SOIL PROPERTIES AND PLANT GROWTH

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### ABSTRACT

*The increasing rate of soil degradation has been a global menace in recent years, predominantly due to human activities. The immediate effects of this challenge are the decline in food production and crop yield in many countries due to poor soil quality. This study, therefore, seeks to determine the effects of different biochar compositions as a soil amendment and to study their effects on soil properties and plant growth. Using a randomised complete block design method, Lettuce seedlings were planted in soil treated with biochar produced from Municipal Solid Waste (MSW) and the catalytic pyrolysis of refuse-derived fuels (RDF) and four (4) different agricultural residues, namely cocopeat, cassava peels, rice husk and bamboo leaves to determine their effects on soil properties and plant growth. Each biochar treatment had a 50:50 and a 75:25 sand-to-biochar ratio, respectively, where growth was monitored weekly for eight (8) weeks. While a 50:50 biochar to soil ratio increased soil pH and electrical conductivity, exponentially affecting plant growth, a 25:75 application rate of cassava peel and rice husk biochar to soil ratios optimally balances soil enhancement and crop yield. The study demonstrated the potential of biochar to enhance soil nutrient content, particularly for Potassium, Calcium and Magnesium. While the study confirmed notable improvements in soil properties, the varying effects of different biochar compositions on plant growth demonstrate the importance of selecting appropriate biochar types and application rates to optimise both soil enhancement and crop yield.*

**Keywords:** biochar; pyrolysis; agricultural residue; soil amendment; crop yield; soil properties

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## INTRODUCTION

In recent years, sustainable agriculture and soil improvement methods have become increasingly important in addressing challenges such as soil degradation, food security, and climate change (Lehmann *et al.*, 2021). The urgent need to support a rapidly growing population has led to more intensive agricultural practices, resulting in a significant global decline in soil fertility and quality (FAO, 2021). Scientists and industry experts are exploring new sustainable methods to enhance crop productivity and soil health while minimising negative environmental impacts.

One promising solution is biochar, a multipurpose soil improvement product that has gained considerable attention (Lehmann and Joseph, 2024). Biochar is a carbon-rich material produced through the pyrolysis of organic matter and has shown significant potential for improving soil health, sequestering carbon, and reducing greenhouse gas emissions (Kammann *et al.*, 2015). Due to its unique properties such as high surface area, porosity, and stability, biochar is increasingly recognised as an effective method for enhancing soil health and promoting sustainable agriculture (Ippolito *et al.*, 2020).

Biochar results from the thermal decomposition of organic matter with limited oxygen, a process called pyrolysis (Tomczyk *et al.*, 2020). Depending on the feedstock and production parameters, the characteristics of biochar can vary, making it a multipurpose material with various applications in agricultural and environmental management (Ippolito *et al.*, 2020). Feedstock sources range from agricultural residues and forestry waste to municipal solid waste and animal manure (Wang *et al.*, 2023). Unique qualities of each feedstock impact the physical structure, chemical composition,

and functional properties of the produced biochar (He *et al.*, 2024). The two main factors affecting biochar quality are the production method (pyrolysis, combustion, etc.) and the feedstock type (Turabian *et al.*, 2021).

Temperature and residence time are key pyrolysis parameters that affect the properties of biochar (Lehmann and Joseph, 2024). Higher pyrolysis temperatures produce biochar with increased carbon content, surface area, and pH but reduced yields and nutrient content (Adekiya *et al.*, 2020). In contrast, pyrolysis at lower temperatures generates biochar with increased yields, higher cation exchange capacity, greater functional groups, and maybe superior nutrient retention capabilities (Semida *et al.*, 2019).

Recent progress in biochar production technology has targeted improving pyrolysis conditions to design biochar properties optimally for particular applications (Yaashikaa *et al.*, 2020). The introduction of microwave-assisted pyrolysis has demonstrated its potential in making biochars with better porosity and surface functionality (Yang *et al.*, 2020). Moreover, co-pyrolysis of several feedstocks has become a strategy to harmonise the valuable traits of different materials in one biochar product (Ali *et al.*, 2022).

Using biochar on soil essentially modifies its physical, chemical, and biological characteristics, typically resulting in upgrades to soil quality and fertility (Bolan *et al.*, 2024). The porous nature of biochar results in more excellent soil water retention and better soil aggregation, mainly in sandy soils (Acharya *et al.*, 2024). The porous nature creates a conducive environment for microorganisms to thrive in the soil. In agricultural systems constrained by water, this augmented water-holding capacity can diminish irrigation requirements and

strengthen crops' resistance to drought stress (Baquy *et al.*, 2023; Hou *et al.*, 2023). Several studies have reported increased microbial biomass and enzyme activities following biochar application, suggesting enhanced soil biological functioning (Amoakwah *et al.*, 2022; Pokharel *et al.*, 2020).

Biochar can remove soil contaminants, especially heavy metals like Pb, Zn, Cd, Cu, U, and Cr (Qiu *et al.*, 2022). Its sorptive property helps reverse the toxic effects of heavy metals on plants and soil organisms (Gholizadeh and Hu, 2021). Chemically, biochar can influence soil pH, cation exchange capacity (CEC), and nutrient availability (Yuan *et al.*, 2023). Biochar can improve soil acidity due to its alkaline properties and substantial pH buffering capacity (Geng *et al.*, 2022). The high surface area and oxygen-containing functional groups contribute to its ability to adsorb and retain nutrients (Elkhelifi *et al.*, 2023; Kabir *et al.*, 2023). Additionally, biochar contributes to improved nutrient use efficiency, minimising nutrient losses and enhancing plant nutrient uptake, thereby making fertiliser applications more effective (Hossain *et al.*, 2020).

Extensive research on biochar's impact on plant growth and crop yield has generally yielded positive results across various agricultural systems (Frimpong *et al.*, 2021). Studies indicate that applying biochar can lead to a 10-15% increase in crop yield, primarily due to improvements in soil fertility, enhanced water availability, and greater nutrient efficiency (Liu *et al.*, 2023; H. Singh *et al.*, 2022; Ye *et al.*, 2019). Additionally, biochar has been shown to promote root growth and increase biomass across multiple crop species (Ruan and Wang, 2024). A meta-analysis conducted by Zhang *et al.* (2022) further affirms that, on average, crop yields rise by 13% with biochar application.

Beyond its direct effects on soil properties, biochar positively influences plant physiological processes and stress responses. Enhanced photosynthetic and water use efficiency have been observed in plants grown in biochar-amended soils (Zhang *et al.*, 2022). Moreover, biochar application has been reported to strengthen plant resilience against abiotic stresses such as drought, salinity, and heavy metal contamination, resulting in healthier, more productive plants (Chi *et al.*, 2024; Wu *et al.*, 2023).

Recent studies also explore biochar's potential for boosting crop nutritional quality. Liu *et al.* (2023) noted that biochar application increased protein content and essential mineral concentrations in wheat grain. Additionally, improvements in sugar content in sugarcane and enhanced nutritional values in vegetables were documented (Rawat *et al.*, 2019). These findings suggest that biochar could significantly address food availability and quality issues within sustainable agricultural practices.

The effectiveness of biochar as a soil amendment is contingent upon a complex interplay of biochar characteristics, soil traits, and environmental conditions (Kamali *et al.*, 2022). The type of feedstock used to produce biochar significantly influences its properties, affecting carbon content, nutrient composition, and surface characteristics, which, in turn, dictate soil and plant interactions (He *et al.*, 2024).

Furthermore, biochar's performance is particularly pronounced in nutrient-deficient or degraded soils, enhancing water retention, nutrient accessibility, and overall soil structure, benefiting plant growth (FAO, 2023). In contrast, the effects of biochar may be less evident in soils with good physical features and fertility (Xu *et al.*, 2021). Environmental factors, such as climate and management practices, are crucial in

biochar efficacy (Bolan *et al.*, 2024). In semi-arid and arid regions experiencing drought stress, biochar has demonstrated significant effectiveness in increasing water retention (Liu *et al.*, 2023). By minimizing reliance on organic and inorganic fertilizers, biochar can enhance agronomic characteristics and boost crop productivity (Liu *et al.*, 2022).

Lastly, research emphasises the need to understand the relationship between biochar application rates and their effects on soil quality and plant growth. While higher application rates can lead to noticeable changes in soil characteristics, they do not always correlate with proportional increases in crop yield (Khan *et al.*, 2024). Studies by Jiang *et al.* (2024) indicate that increasing application rates may not significantly impact crop yield. Therefore, optimising biochar application rates for specific soil-crop systems remains a vital area of ongoing research.

Despite the recognised advantages of biochar as a soil enhancer, significant challenges remain. One of the primary hurdles is the variability of biochar properties, which depend on the feedstock used and production conditions. This inconsistency complicates the establishment of uniform guidelines for application rates and methods, as highlighted by research from Ciolkosz *et al.* (2023), Ippolito *et al.* (2020) and Tomczyk *et al.* (2020). Furthermore, the production and application costs of biochar can be prohibitively high, particularly in developing countries, necessitating further research into low-cost production methods (Melo *et al.*, 2022; Pokharel and Comer, 2021). Additionally, while many studies have reported positive effects on soil properties and crop yields, others have observed neutral or negative impacts due to specific conditions and biochar characteristics (Khan *et al.*, 2024; Jiang *et al.*, 2024).

This inconsistency highlights the need for a deeper understanding of how different biochar types and application rates affect various crops and soil types, indicating that holistic evaluations are crucial for developing tailored recommendations for sustainable agricultural practices (Kamali *et al.*, 2022; Liu *et al.*, 2023).

This research, therefore, aimed to evaluate the effects of five pyrolytic biochar derived from pyrolysing municipal solid waste (MSW) and refuse derived fuels (RDF) with diverse biomass feedstocks: bamboo leaves, cassava peels, cocopeat, and rice husk, on soil properties as well as on the growth of lettuce, to bridge existing knowledge gaps and contribute to the expanding field of biochar studies. Specifically, the study sought to examine how the characteristics of biochar and its application rates affect soil nutrient dynamics, pH, electrical conductivity, and organic matter content in sandy loam soil. Also, the study aimed to evaluate the effects of these biochar treatments on the parameters of plant growth and yield.

This study fills the literature gap by using several feedstocks, varying application rates and methods, and assessing effects on soil properties and crop productivity. The potential impact of this research on sustainable agricultural practices and soil management strategies is significant.

Furthermore, using locally available waste materials as biochar feedstock presents opportunities for circular economy approaches in agriculture, turning waste into a valuable soil amendment. The potential for long-term carbon sequestration through biochar application also aligns with global efforts to mitigate climate change.

## **MATERIALS AND METHODS**

### **Experimental location and design**

The experiment was conducted in a greenhouse (Agri-Impact Greenhouse Farm) located within Kwame Nkrumah University of Science and Technology (KNUST) campus in Kumasi, Ghana (6.6662°N, 1.56518°W). The experimental design followed a completely randomised design (CRD). The study evaluated ten different biochar treatments, including municipal solid waste (MSW) biochar and four combinations of refuse-derived fuel (RDF) with bamboo leaves, cassava peels, cocopeat, and rice husks. Each resulting biochar type was applied at two rates (25% and 50%) and mixed with sandy loam soil, resulting in ten treatment combinations: RDF+Bamboo50, RDF+Bamboo25, RDF+Cassava50, RDF+Cassava25, RDF+Cocopeat50, RDF+Cocopeat25, MSW50, MSW25, RDF+RiceHusk50, and RDF+RiceHusk25. Each treatment was replicated three times to ensure reliability and accuracy.

### **Production of Biochar**

The biochar used in this study was produced through slow pyrolysis of the respective feedstocks. The pyrolysis process was carried out using a custom-built reactor at a temperature range of 400 – 500°C, with a residence time of 60 minutes, following the methods described by Singh *et al.* (2019) and Aboelela *et al.* (2023). After production, the biochar was allowed to cool and ground to pass through a 2 mm sieve to ensure uniform particle size distribution.

### **Characterisation of Soil and Biochar**

Sandy loam soil was randomly collected from the Department of Horticulture, KNUST, Kumasi, at a 0-20 cm depth. The sample was air-dried and passed through a 2 mm sieve. Initial soil characterization was performed to determine its properties.

Soil and Biochar characterisation was performed to determine critical physicochemical properties. The pH and electrical conductivity (EC) of the biochars were measured in a 1:5 (w/v) biochar: water suspension using a pH meter and EC meter, respectively (Ke *et al.*, 2022). Total carbon (C) and nitrogen (N) contents were determined using a CN analyser (Yu *et al.*, 2024). Available phosphorus (P) was extracted using the Mehlich-3 method and quantified calorimetrically (Świechowski *et al.*, 2022). Exchangeable cations (K, Ca, Mg) were extracted with 1 M ammonium acetate (pH 7.0) and analysed using atomic absorption spectrophotometry (AAS) (Yu *et al.*, 2024). Soil organic carbon (SOC) was determined using the standard Walkley-Black method. After mixing the soil with biochar at the specified mixing ratios, composite samples were taken from each treatment to analyse pH, EC, C, N, P, and exchangeable cations using the above-mentioned methods.

These analyses were performed on the soil and biochar samples separately at the beginning of the experiment and repeated after mixing the biochar with the soil for 5 days to assess changes in soil properties.

### **Lettuce cultivation and growth measurements**

Lettuce (*Lactuca sativa* L.) seeds were obtained from the open market. The seeds were initially sown in nursery trays filled with a standard germination medium. After four weeks, uniform seedlings were transplanted into the experimental pots containing the biochar-amended soils.

Each experimental unit consisted of a plastic pot (30 cm diameter, 25 cm height) filled with 5 kg of the soil-biochar mixture. Three lettuce seedlings were transplanted into each pot as displayed in Figure 1.

The pots were arranged in a completely randomised design in the greenhouse. Standard agronomic practices were followed,

including regular watering to maintain soil moisture at field capacity.



Figure 1: Experimental Setup of Sample Pots

Plant growth parameters were measured weekly, from one week after transplanting until harvest (8 weeks after transplanting).

The plant growth parameter measurement methods are shown in Table 1: Method of Measuring Plant Growth Parameters.

Table 1: Method of Measuring Plant Growth Parameters

Parameter	Method	Reference
Plant Height	measured from the soil surface to the tip of the longest leaf using a metre rule	(Carter <i>et al.</i> , 2013)
Number of Leaves	fully expanded leaves were counted manually	(Liu <i>et al.</i> , 2023)
Final biomass	plants were uprooted from the pots, and the above-ground biomass was weighed immediately.	(Carter <i>et al.</i> , 2013)

### Statistical Analysis

All statistical analyses were performed using Minitab software version 21.2. The effects of biochar treatments (combination of biochar type and application rate) on soil properties and plant growth parameters were analysed using a one-way analysis of variance (ANOVA) (Equation 1). Before performing ANOVA, the following assumptions were checked: Residuals were tested for normality using the Shapiro-Wilk test, and the equality of variances across treatment groups was

assessed using Levene’s test. When significant differences were detected ( $p < 0.05$ ), Fisher’s Least Significant Difference (LSD) test was used for post-hoc comparisons to determine which treatment groups differed significantly (Asif *et al.*, 2024).

$$Y_{ij} = \mu + \alpha_i + \epsilon_{ij} \quad \text{eqn 1}$$

Where  $Y_{ij}$  = Observed response,  $\mu$  = Overall mean,  $\alpha_i$  = Effect of the  $i^{\text{th}}$  treatment and  $\epsilon_{ij}$  = Random error

## RESULTS AND DISCUSSION

### Physicochemical Properties of Char

The physicochemical properties of raw char samples from the different feedstocks are presented in Table 2. Significant differences ( $p < 0.05$ ) were observed among all parameters measured, as indicated by their  $p$ -values and LSD values. Coccopeat exhibited the highest nitrogen (0.056%), calcium (5.52 mg/kg), magnesium (4.46 mg/kg), and organic matter (8.89%), highlighting its potential to improve soil fertility and structure. Rice husk char recorded the highest potassium (2.04 mg/kg), making it suitable for potassium-demanding crops, although its acidity (ph 2.65) may require adjustments. Bamboo char stood out for its high phosphorus (21.72 mg/kg) and low EC (317.67  $\mu\text{S/cm}$ ), making it a suitable low-salinity soil amendment. MSW char exhibited the highest EC (6732.33  $\mu\text{S/cm}$ ), indicating potential salinity issues. Cassava char, with relatively lower nutrient values, may serve better when combined with nutrient-rich soils or chars. The physicochemical results highlight the importance of matching char types to specific soil needs and crop requirements for optimal agricultural benefits.

### Effects of Biochar on Soil Properties

Applying various biochar types at different rates resulted in significant changes to the soil properties, particularly in nutrient content, ph, electrical conductivity (EC), and organic matter content, as presented in Table 3. These alterations have important implications for soil fertility and plant growth. Adding biochar generally increased total soil nitrogen content, with variations observed among different biochar types and application rates. The highest increase in N content was observed with cocopeat biochar at a 50% application rate, showing a 54.5% increase compared to the raw soil sample (from 0.11% to 0.17%). This finding aligns

with research by Hossain *et al.* (2020), who reported that biochar derived from nutrient-rich feedstocks could significantly enhance soil N content. However, the increase in N content was not uniform across all biochar types. Rice husk biochar at a 25% application rate only showed a marginal increase of 9.1% in N content (from 0.11% to 0.12%).

Soil available Phosphorus showed substantial increases across all biochar treatments. The most pronounced effect was observed with bamboo biochar treatment at a 50% application rate, which increased available P by 100.7% compared to the raw soil sample (from 27.98 mg/kg to 56.15 mg/kg). This substantial increase in P availability could be attributed to the high P content in bamboo biochar and its ability to modify soil ph, as suggested by (Gao *et al.*, 2021). The increase in P availability varied among biochar types, with municipal solid waste (MSW) biochar at a 25% application rate showing the least improvement (43.4% increase).

All biochar treatments significantly enhanced soil Potassium (K) content, with rice husk biochar at 50% application rate showing the most substantial increase of 632.4% compared to the raw soil sample (from 0.37  $\text{cmol}^+/\text{kg}$  to 2.71  $\text{cmol}^+/\text{kg}$ ). This dramatic increase in K content with rice husk biochar is consistent with findings by Lai *et al.* (2024), who reported that rice husk biochar is particularly rich in K and can significantly improve soil K status. The variation in K content enhancement among biochar types suggests that feedstock selection is crucial when targeting specific nutrient improvements.

Generally, calcium (Ca) content saw an increase by biochar application, with the most significant improvement observed in the rice husk biochar at 50% application rate, showing a 120.7% increase compared to the control (from 8.02  $\text{cmol}^+/\text{kg}$  to 17.70  $\text{cmol}^+/\text{kg}$ ). This substantial increase in Ca content with rice husk biochar corroborates the findings of Kabir *et al.* (2023), who reported that rice

husk biochar significantly enhances soil Ca levels due to its high Ca content and liming effect. Soil magnesium (Mg) content was also positively affected by biochar application, with cocopeat biochar at a 50% application rate showing the highest increase of 73.8% compared to the control (from 2.98 cmol<sup>+</sup>/kg to 5.18 cmol<sup>+</sup>/kg). This improvement in Mg content aligns with research by Singh *et al.* (2022), who found that biochar derived from coconut-based materials could significantly enhance soil Mg levels.

All biochar treatments increased soil ph, with the most substantial increase observed in cocopeat biochar at a 50% application rate, raising the ph from 5.55 (raw soil sample) to 8.72. This significant liming effect of biochar is consistent with findings by Xu *et al.* (2021), who reported that biochar application could effectively ameliorate soil acidity. Additionally, Premalatha *et al.* (2023) found that biochar can raise soil ph, especially when derived from alkaline materials, and enhance the availability of critical nutrients like nitrogen, phosphorus, and potassium. Also, biochar application generally led to an increase in soil electrical conductivity (EC), with cassava peel biochar at a 50% application rate showing a dramatic increase from 482.67 μS/cm (control) to 64,398.34 μS/cm. As noted by Hossain *et al.* (2020) and Singh *et al.* (2022), this substantial rise in EC could potentially lead to salinity issues.

Finally, applying biochar led to an increase in soil organic matter (OM) content, with MSW biochar at a 25% application rate showing the highest growth of 420.8% compared to the control (from 3.95% to 20.57%). Li *et al.* (2023) reported that this significant rise in OM content with MSW biochar highlights the importance of feedstock selection in substantially enhancing soil organic matter content. Kabir *et al.* (2023) have also shown that biochar significantly increases soil organic matter content and carbon sequestration, offering a sustainable solution for mitigating greenhouse gas emissions.

Table 2: Physicochemical Properties of Raw Char Sample

Parameter		N (%)	P (mg/kg)	K (cmol <sup>+</sup> /kg)	Ca (cmol <sup>+</sup> /kg)	Mg (cmol <sup>+</sup> /kg)	OC (%)	OM (%)	EC (μS/cm)	pH
Sample										
Bamboo		0.02 <sup>b</sup> ± 0.02	21.72 <sup>a</sup> ± 0.27	0.24 <sup>c</sup> ± 0.01	3.71 <sup>d</sup> ± 0.031	2.26 <sup>d</sup> ± 0.08	3.56 <sup>b</sup> ± 0.13	5.97 <sup>b</sup> ± 0.21	317.67 <sup>a</sup> ± 3.51	2.83 <sup>b</sup> ± 0.04
Cassava		0.012 <sup>b</sup> ± 0.012	4.13 <sup>b</sup> ± 0.13	0.62 <sup>d</sup> ± 0.02	0.56 <sup>e</sup> ± 0.015	0.46 <sup>e</sup> ± 0.02	2.34 <sup>d</sup> ± 0.03	3.99 <sup>d</sup> ± 0.02	516.67 <sup>d</sup> ± 1.15	2.74 <sup>a</sup> ± 0.05
Cocopeat		0.056 <sup>a</sup> ± 0.056	4.18 <sup>b</sup> ± 0.12	1.66 <sup>c</sup> ± 0.01	5.52 <sup>a</sup> ± 0.037	4.46 <sup>c</sup> ± 0.02	5.17 <sup>a</sup> ± 0.01	8.89 <sup>a</sup> ± 0.02	3172.0 <sup>b</sup> ± 0.00	2.98 <sup>a</sup> ± 0.01
MSW		0.018 <sup>b</sup> ± 0.018	3.52 <sup>c</sup> ± 0.02	1.77 <sup>b</sup> ± 0.01	5.33 <sup>b</sup> ± 0.011	2.69 <sup>c</sup> ± 0.03	1.86 <sup>e</sup> ± 0.02	3.18 <sup>e</sup> ± 0.01	6732.33 <sup>a</sup> ± 0.58	2.87 <sup>b</sup> ± 0.01
RiceHusk		0.012 <sup>b</sup> ± 0.01	2.71 <sup>d</sup> ± 0.03	2.04 <sup>a</sup> ± 0.01	5.20 <sup>b</sup> ± 0.015	2.80 <sup>b</sup> ± 0.02	2.54 <sup>e</sup> ± 0.01	4.35 <sup>e</sup> ± 0.04	1995.33 <sup>c</sup> ± 0.58	2.65 <sup>d</sup> ± 0.01
P-value		0.0001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
LSD		0.013	0.251	0.032	0.044	0.07	0.11	0.17	3.08	0.057
CV		30.65	1.898	1.396	0.599	1.522	1.96	1.804	0.066	1.11

Table 3: Effects of Different Biochar Treatments on Soil Properties

Sample	Parameter									
	N (%)	P (mg/kg)	K (mg/kg)	Ca (mg/kg)	Mg (mg/kg)	OC (%)	OM (%)	EC (µS/cm)	pH	
Bamboo50	0.13 <sup>bc</sup> ±0.01	56.15 <sup>a</sup> ±0.32	1.02 <sup>e</sup> ±0.01	13.65 <sup>bc</sup> ±0.03	4.96 <sup>ab</sup> ±0.03	6.73 <sup>d</sup> ±0.21	11.6 <sup>d</sup> ±0.36	1355.34 <sup>g</sup> ±9.07	8.57 <sup>h</sup> ±0.07	
Bamboo25	0.12 <sup>cd</sup> ±0.01	49.63 <sup>b</sup> ±0.37	0.59 <sup>h</sup> ±0.01	11.84 <sup>d</sup> ±0.04	5.16 <sup>b</sup> ±0.04	5.57 <sup>e</sup> ±0.12	9.60 <sup>e</sup> ±0.2	792 <sup>i</sup> ±3.61	8.38 <sup>de</sup> ±0.03	
Cassava50	0.12 <sup>cd</sup> ±0.01	46.70 <sup>c</sup> ±1.07	2.41 <sup>b</sup> ±0.04	10.45 <sup>f</sup> ±0.48	3.96 <sup>e</sup> ±0.48	10.36 <sup>b</sup> ±0.02	17.86 <sup>b</sup> ±0.04	64398.34 <sup>a</sup> ±107.74	8.69 <sup>g</sup> ±0.05	
Cassava25	0.12 <sup>cd</sup> ±0.01	41.96 <sup>e</sup> ±0.68	1.09 <sup>f</sup> ±0.02	9.66 <sup>e</sup> ±0.06	2.95 <sup>f</sup> ±0.06	5.12 <sup>f</sup> ±0.01	8.82 <sup>f</sup> ±0.02	1018 <sup>h</sup> ±2.65	8.36 <sup>e</sup> ±0.06	
Cocopeat50	0.17 <sup>a</sup> ±0.01	30.09 <sup>g</sup> ±0.41	2.28 <sup>c</sup> ±0.01	13.42 <sup>c</sup> ±0.05	5.18 <sup>a</sup> ±0.05	8.44 <sup>c</sup> ±0.15	14.54 <sup>c</sup> ±0.25	3757.67 <sup>c</sup> ±20.11	8.72 <sup>a</sup> ±0.03	
Cocopeat25	0.13 <sup>bc</sup> ±0.01	36.22 <sup>f</sup> ±0.34	1.27 <sup>e</sup> ±0.01	11.34 <sup>e</sup> ±0.08	4.67 <sup>f</sup> ±0.08	3.34 <sup>h</sup> ±0.03	5.75 <sup>h</sup> ±0.05	1956.67 <sup>d</sup> ±5.51	8.51 <sup>bc</sup> ±0.07	
MSW50	0.14 <sup>b</sup> ±0.01	33.51 <sup>h</sup> ±0.24	2.40 <sup>b</sup> ±0.01	13.86 <sup>b</sup> ±0.02	4.95 <sup>ab</sup> ±0.02	4.47 <sup>g</sup> ±0.06	7.7 <sup>g</sup> ±0.1	7581 <sup>b</sup> ±6.56	8.53 <sup>bc</sup> ±0.04	
MSW25	0.13 <sup>bc</sup> ±0.01	40.12 <sup>f</sup> ±0.09	1.59 <sup>d</sup> ±0.01	10.34 <sup>f</sup> ±0.05	4.27 <sup>d</sup> ±0.05	11.94 <sup>a</sup> ±0.02	20.57 <sup>a</sup> ±0.03	3363 <sup>d</sup> ±12.12	8.28 <sup>f</sup> ±0.06	
RiceHusk50	0.13 <sup>bc</sup> ±0.01	39.92 <sup>f</sup> ±0.24	2.71 <sup>a</sup> ±0.01	17.7 <sup>a</sup> ±0.05	4.31 <sup>d</sup> ±0.05	5.11 <sup>f</sup> ±0.03	8.81 <sup>f</sup> ±0.05	2689.67 <sup>e</sup> ±5.51	8.45 <sup>cd</sup> ±0.025	
RiceHusk25	0.12 <sup>cd</sup> ±0.01	43.97 <sup>d</sup> ±0.24	1.63 <sup>d</sup> ±0.01	11.68 <sup>d</sup> ±0.04	4.92 <sup>b</sup> ±0.04	2.46 <sup>g</sup> ±0.06	4.23 <sup>i</sup> ±0.1	1926.67 <sup>f</sup> ±5.13	8.32 <sup>ef</sup> ±0.06	
P-value	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	
LSD	0.0059	0.857	0.0243	0.2598	0.2598	0.15	0.261	56.856	0.085	
CV	2.729	1.247	0.912	1.279	3.496	1.483	1.496	0.414	0.61	

### Comparison of Biochar Types and Application Rates

The effects of biochar on soil properties varied significantly among biochar types and application rates. Generally, higher application rates (50%) resulted in more pronounced changes in soil properties than lower rates (25%) as seen in Table 3. However, the magnitude of these changes was only sometimes proportional to the application rate, indicating complex interactions between biochar properties and soil characteristics. These complex interactions suggest that a one-size-fits-all approach to biochar application may not be effective, and careful consideration of specific soil and crop conditions is necessary.

Among the biochar types, rice husk biochar consistently showed strong performance in improving nutrient content, particularly for K and Ca. This aligns with findings by Kabir et al. (2023) and Lai et al. (2024), who reported that rice husk biochar is particularly effective in enhancing soil nutrient status. Cocopeat biochar demonstrated the most substantial effects on soil pH and Mg content, while MSW biochar was most effective in increasing soil organic matter content.

The variability in biochar performance across different soil parameters underscores the importance of selecting appropriate biochar types and application rates based on specific soil improvement goals. As noted by Kamali et al. (2022), the effectiveness of biochar as a soil amendment is highly dependent on both biochar properties and soil characteristics, necessitating careful consideration of these factors in biochar application strategies.

### Impact on plant growth

The effects of biochar treatments on lettuce plant height varied over the growing period, as shown in Table 4. By the fourth week, cassava peel biochar at a 25% application rate showed the highest plant height (15.38 cm). This positive effect of cassava peel biochar on plant height is consistent with findings by Edussuriya et al. (2023), who reported improved growth in leafy vegetables with cassava peel biochar application. However, it is noteworthy that some biochar treatments, particularly at higher application rates (50%), resulted in no plant growth, possibly due to the extreme changes in soil pH and EC, as discussed earlier.

**Table 4: Weekly Plant Height (cm) of Lettuce as Influenced by Biochar Application Rates**

Treatment	Week 1	Week 2	Week 3	Week 4
Bamboo50	8.78 <sup>ab</sup> ± 1.51	11.4 <sup>a</sup> ± 0.53	13.47 <sup>a</sup> ± 0.49	14.43 <sup>ab</sup> ± 0.98
Bamboo25	8.75 <sup>ab</sup> ± 1.03	9.57 <sup>b</sup> ± 0.81	11.17 <sup>cd</sup> ± 0.25	12.50 <sup>c</sup> ± 0.88
Cassava50	0.00 <sup>c</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00
Cassava25	7.73 <sup>ab</sup> ± 0.31	10.97 <sup>a</sup> ± 0.75	12.88 <sup>ab</sup> ± 0.69	15.38 <sup>a</sup> ± 0.63
Cocopeat50	0.00 <sup>c</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00
Cocopeat25	6.9 <sup>b</sup> ± 1.77	8.80 <sup>b</sup> ± 1.2	13.29 <sup>ab</sup> ± 0.36	14.00 <sup>b</sup> ± 0.35
MSW50	0.00 <sup>c</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00
MSW25	7.22 <sup>b</sup> ± 0.23	9.3b ± 0.55	12.03 <sup>bc</sup> ± 0.78	13.73 <sup>bc</sup> ± 0.70
RiceHusk50	0.00 <sup>c</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00
RiceHusk25	9.77 <sup>a</sup> ± 2.61	11.70 <sup>a</sup> ± 1.39	10.36 <sup>d</sup> ± 0.49	13.67 <sup>bc</sup> ± 0.95

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<b>p-value</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>
<b>CV</b>	<b>27.26</b>	<b>11.398</b>	<b>9.53</b>	<b>9.08</b>
<b>LSD</b>	<b>2.36</b>	<b>1.24</b>	<b>1.268</b>	<b>1.38</b>

<sup>a,b,c</sup> Means that with different letters are significantly different ( $\alpha = 0.05$ )

The number of leaves showed similar trends to plant height. By the fourth week, rice husk biochar at a 25% application rate resulted in the highest number of leaves (10), while other treatments showed slightly lower leaf numbers (Table 5). This finding partially contradicts the results of Carter *et al.*

(2013) and Liu *et al.* (2023), who reported consistent leaf number increases with lettuce biochar application. The discrepancy might be due to differences in biochar properties, soil types, or environmental conditions, highlighting the complex nature of biochar-soil-plant interactions.

**Table 5: Number of leaves of Lettuce as Influenced by Biochar Application Rates**

Treatment	Number of Leaves (n)			
	Week 1	Week 2	Week 3	Week 4
Bamboo50	5.00 <sup>a</sup> ± 0.00	7.00 <sup>a</sup> ± 0.50	8.00 <sup>a</sup> ± 0.50	9.00 <sup>b</sup> ± 0.50
Bamboo25	4.00 <sup>b</sup> ± 0.00	6.00 <sup>bc</sup> ± 0.50	7.00 <sup>ab</sup> ± 0.50	9.00 <sup>bc</sup> ± 0.50
Cassava50	0.00 <sup>d</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00
Cassava25	3.00 <sup>c</sup> ± 0.50	6.00 <sup>bc</sup> ± 0.50	7.00 <sup>ab</sup> ± 1.00	9.00 <sup>ab</sup> ± 0.50
Cocopeat50	0.00 <sup>d</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00
Cocopeat25	3.00 <sup>c</sup> ± 0.50	6.00 <sup>bc</sup> ± 1.50	7.00 <sup>ab</sup> ± 1.00	8.00 <sup>cd</sup> ± 0.50
MSW50	0.00 <sup>d</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00
MSW25	3.00 <sup>c</sup> ± 0.50	5.00 <sup>c</sup> ± 0.00	7.00 <sup>b</sup> ± 0.50	7.00 <sup>d</sup> ± 1.00
RiceHusk50	0.00 <sup>d</sup> ± 0.00	0.00 <sup>d</sup> ± 0.00	0.00 <sup>c</sup> ± 0.00	0.00 <sup>e</sup> ± 0.00
RiceHusk25	4.00 <sup>b</sup> ± 0.00	7.00 <sup>a</sup> ± 0.50	8.00 <sup>a</sup> ± 0.50	10.00 <sup>a</sup> ± 0.50
<b>p-value</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>	<b>&lt;0.001</b>
<b>CV</b>	<b>22.38</b>	<b>15.49</b>	<b>13.45</b>	<b>10.58</b>
<b>LSD</b>	<b>0.88</b>	<b>0.98</b>	<b>1.02</b>	<b>0.98</b>

<sup>a,b,c</sup> Means with different letters are significantly different ( $\alpha = 0.05$ )

The crop yield results (Table 6) show that cassava peel biochar at 25:75 recorded the highest final crop yield (76.67 g/plant), followed by rice husk biochar at a 25% application rate (73.33 g/plant). The lower yields in some biochar treatments, particularly at higher application rates, could be attributed to the substantial increases in soil pH and EC, which may have created

suboptimal growing conditions for lettuce. As pointed out by (Khan *et al.*, 2024; Jiang *et al.*, 2024), excessive alterations in soil properties can negate the potential benefits of biochar, emphasising the need for careful optimisation of application rates.

**Table 6: Yield of Lettuce as Influenced by Biochar Application Rates**

Treatment	Yield (g/plant)
Bamboo50	48.00 <sup>b</sup> ± 12.17
Bamboo25	34.33 <sup>bc</sup> ± 5.86
Cassava50	0.00 <sup>d</sup> ± 0.00
Cassava25	76.67 <sup>a</sup> ± 17.01
Cocopeat50	0.00 <sup>d</sup> ± 0.00
Cocopeat25	41.33 <sup>bc</sup> ± 10.06
MSW50	0.00 <sup>d</sup> ± 0.00
MSW25	31.00 <sup>c</sup> ± 9.64
RiceHusk50	0.00 <sup>d</sup> ± 0.00
RiceHusk25	73.33 <sup>a</sup> ± 12.06
<b>P-value</b>	<b>&lt;0.0001</b>
<b>LSD</b>	<b>15.341</b>
<b>CV</b>	<b>29.56</b>

<sup>a,b,c</sup> Means with different letters are significantly different at  $p < 0.05$

The positive effects of biochar on soil properties and plant growth are multifaceted, encompassing a variety of mechanisms. Firstly, biochar's high surface area and cation exchange capacity significantly improve nutrient retention and availability, especially for key nutrients such as K, Ca, and Mg, as highlighted by Xu *et al.* (2021). This is further evidenced by notable increases in these nutrients following biochar application. Additionally, the liming effect of biochar has been shown to modify soil pH, particularly in treatments using cocopeat and cassava peels, enhancing nutrient availability in initially acidic soils (Das *et al.*, 2021), although Hossain *et al.* (2020) caution that an excessive increase in pH could lead to nutrient imbalances. Adding biochar also substantially boosts soil organic matter content, improving soil structure, water retention, and microbial activity, a benefit corroborated by Li *et al.* (2023). While not directly measured in the

cited study, the enhanced plant growth observed in some biochar treatments may be partly due to improved water retention in sandy soils (Ndede *et al.*, 2022). Finally, biochar application stimulates soil microbial activity, potentially accelerating nutrient cycling and promoting plant growth (Alkharabsheh *et al.*, 2021; Dai *et al.*, 2021).

Some treatments, particularly those applied at higher rates, showed negative or neutral effects, which could be attributed to several factors. Firstly, the excessive increase in pH noted in some treatments might have led to the reduced availability of certain nutrients, especially micronutrients (Das *et al.*, 2021). Additionally, the significant rise in electrical conductivity (EC), notably in the cassava peel biochar at a 50% treatment level, could have induced salinity stress, thereby impeding plant growth. This concern aligns with the issues raised by Jiang *et al.* (2024) regarding the potential for salinity problems with high biochar application rates. Furthermore, an imbalanced increase in specific nutrients, such as potassium (K), in comparison to others might have resulted in nutrient imbalances, which could adversely affect plant growth and yield, as reported by Sarwar *et al.* (2023).

### Optimal biochar type and application rate

Based on the overall results, considering both soil property improvements and plant growth parameters, the best-performing biochar treatments were cassava peel and rice husk biochar at a 25:75 mixing ratio. These treatments showed balanced improvements in soil properties without causing excessive alterations in pH and EC while supporting good plant growth and yield. Similarly, the excellent performance of rice husk biochar at moderate application rates is consistent with results reported by Hu *et al.* (2024), who found rice husk biochar to be particularly effective in improving soil

nutrient status and crop growth. Notably, lower application rates (25%) generally performed better than higher rates (50%) across most biochar types. This finding supports the concept of an optimal biochar application rate, beyond which additional benefits may not be realized or even become detrimental (Hossain *et al.*, 2020).

## **CONCLUSION**

This study investigated the effects of selected pyrolytic biochars on soil properties and lettuce growth in amended soil media, focusing on five biochar types: RDF+bamboo leaves, RDF+cassava peels, RDF+cocopeat, RDF+rice husk, and municipal solid waste, each applied at 25% and 50% rates. The findings revealed that biochar application significantly influenced soil characteristics, with notable improvements in soil pH, electrical conductivity (EC), nutrient content, and organic matter levels. The most pronounced increases in soil pH were observed with cocopeat biochar at a 50% application rate (5.55 to 8.72), while cassava peel biochar at the same rate caused a substantial rise in EC (482.67 to 64398.34  $\mu\text{S}/\text{cm}$ ). Rice husk biochar at 50% significantly boosted potassium levels (632.4 % increase), whereas bamboo biochar at the same rate led to the highest increase in available phosphorus (100.7%). Municipal solid waste biochar at 25% enhanced soil organic matter content (420.8% increase). However, while higher biochar application rates (50%) led to more drastic alterations in soil properties, they did not correspond to improved plant growth, likely due to excessive changes in pH and EC that created unfavourable growing conditions. Regarding plant response, cassava peel biochar at 25% yielded the tallest plants (15.38 cm) and the highest final crop yield (76.67 g/plant), closely followed by rice husk biochar (73.33 g/plant) at the same application rate.

The findings indicate that moderate biochar application rates (25%) balance improving soil fertility and maintaining favourable conditions for lettuce growth. Among the biochar types evaluated, cassava peel and rice husk biochars at 25% application rates emerged as the most effective treatments, enhancing soil quality while supporting optimal plant development and yield. These results demonstrate the potential of biochar as a soil amendment but also emphasise the need for careful selection of biochar type and application rate to avoid detrimental effects on plant growth.

## **Limitations of the Study**

The experiment, conducted over 8 weeks, potentially overlooks the long-term impacts of biochar on soil characteristics and plant growth, raising questions about the durability and extent of its benefits. Focusing solely on lettuce as the subject of study further limits the generalizability, as it needs to account for the varied responses other crops might exhibit under similar conditions. Conducted within the controlled environment of a greenhouse, the experiment might need to accurately reflect the complex interactions and outcomes observable in open-field conditions, where external factors play a significant role. Moreover, utilising only sandy loam soil for the study makes the findings less relevant to areas with different soil compositions, potentially narrowing the scope of its practical applications. Additionally, a detailed analysis of soil microbial communities is needed to fill the gap in understanding the comprehensive effects of biochar on soil health and ecosystem dynamics, suggesting that further research in this area could provide valuable insights into optimising agricultural practices.

## Recommendations for future research

Long-term field trials are needed to evaluate biochar's enduring effects on soil properties and crop productivity across multiple seasons, thereby assessing its long-term benefits and potential cumulative impacts. Although the research concentrated on lettuce, expanding future studies to include a broader spectrum of crops such as cereals, legumes, perennials and other saline-tolerant crops is suggested to gain a more comprehensive view of the applicability of the biochars in various agricultural settings. Moreover, investigating the performance of biochar across diverse soil types beyond sandy loam could expose how its effectiveness varies with soil texture and composition. The high conductivity of the chars makes them suitable for use as electrode materials in fuel cells; hence, some research can be conducted to ascertain their potential. Additionally, research is needed to optimise biochar application rates, especially between 0% and 25%, to find a balance that maximises benefits while avoiding adverse effects. Lastly, exploring how biochar interacts with conventional fertilisers could reveal interactions and inform integrated nutrient management strategies, potentially enhancing agricultural sustainability.

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