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Effect of Biochar Types on Selected Soil Physical and Chemical Properties on the Growth of Maize

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Authors' contributions

This work was carried out in collaboration among all authors. Authors OSV, SS and MJ developed the concept and designed. Authors OSV and EA carried out the experiment and data collection. Authors SS, AF and MJ implement the software and formal analysis. Authors SS, GJAM, EA, MM and AF, wrote the draft of the manuscript. Authors MM and MJ supervised the manuscript. Authors SS, AF, MJ, and MM authenticate the manuscript. Authors AF, MJ, MM, EA, GJAM, OSV and SS reviewed the manuscript. All authors read and approved the final manuscript.

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Abstract

Biochar amendments can alter soil conditions and crop performance, but their effects may vary with feedstock type. This study evaluated wood-shaving, maize-straw, and charcoal biochars applied at 10 t/ha for their effects on selected soil physical and chemical properties and maize growth at Panderu. The experiment used a split-plot arrangement in a randomised complete block design with four treatments and three replications. Soil pH, cation exchange capacity (CEC), organic carbon, texture, colour, and bulk density were assessed, while maize responses were evaluated using vegetative growth traits. Data were analysed by analysis of variance, least significant difference at the 5% significance level, and correlation analysis. Post-harvest soil pH ranged from 4.69 in the control to approximately 5.00 in the maize-straw treatment. Organic carbon ranged from 2.96% under wood shavings to 3.20% under maize straw, while CEC ranged from 0.41 to 0.82 $cmol^{+}\ kg^{-1}$, with maize straw recording the highest value. Maize growth responses were not uniformly greater under biochar. The control recorded the highest number of leaves (11.1), plant height (75.2 cm), and stem girth (5.87), whereas maize-straw biochar produced the greatest leaf area (199.99 cm^2). Leaf dimensions did not differ significantly among treatments. Overall, the findings show feedstock-specific responses and indicate that maize-straw amendment produced the most favourable short-term changes in the measured soil chemical properties among the amendments tested.

Keywords: Biochar; maize; wood shavings; charcoal; cation exchange capacity; soil organic carbon; bulk density; vegetative growth.

1. Introduction

Soil degradation and declining crop productivity represent persistent challenges in global agriculture, particularly in sub-Saharan Africa and other developing regions where food security remains a critical concern. The intensive use of conventional farming practices, including excessive application of synthetic fertilisers and poor soil management, has led to deteriorating soil health, reduced organic matter content, and compromised soil structure. These factors collectively contribute to decreased agricultural productivity and challenges to environmental sustainability.

Biochar, a carbon-rich solid material produced through the pyrolysis of organic biomass under oxygen-limited conditions, has emerged as a promising soil amendment with the potential to address multiple agricultural and environmental challenges simultaneously. In another field study, the application of biochar (made from cashew-tree wood and pyrolysed at 500 °C) at 30 Mg ha-1 to sandy-loam soil led to a 65% increase in the CEC of the soil (Adekiya *et al*., 2020). The application of biochar to agricultural soils offers the dual benefits of improving soil fertility and contributing to climate change mitigation through carbon sequestration (Sohi, 2012). Biochar is a carbon-rich composite formed by burning biomass in the absence or very limited supply of oxygen. Biochar has the potential to increase soil fertility and is widely recognised as a source of carbon sequestration in soil (Lehmann & Joseph, 2009). Different types of biomass can be used for the preparation of biochar. Commonly used materials include wheat straw, rice husk, wood bark, corn cob, and peanut shell. Mixing biochar into soil is an effective method of enhancing soil carbon storage (Sohi, 2012). Rice-husk biochar can be recycled in a rice-wheat cropping system without damaging soil health (Shackley *et al*., 2012). Biochar has a large surface area, chemical stability, cation exchange capacity, aromatic compounds, and a high carbon content, and it acts as a soil conditioner by improving soil physical, chemical, and biological properties, nutrient and water retention, crop productivity, and crop resistance to various diseases, as proposed by many researchers. Biochar also has the potential to mitigate changes in climate (increasing levels of CO2, methane, and other greenhouse gases) through long-term carbon sequestration and to act as a soil enhancer (Sohi, 2012). Jeffery *et al*. (2017) concluded that biochar addition increased crop yield by an average of 25% in tropical agro-climates, whereas no average yield benefit was observed in temperate agro-climates.

The effectiveness of biochar as a soil amendment depends significantly on several factors, including the type of feedstock used, pyrolysis conditions, application rates, and soil characteristics. Different biochar types, produced from various organic materials such as crop residues, wood waste, and agricultural by-products, exhibit varying properties that influence their effects on soil physical and chemical characteristics. Understanding these variations is crucial for optimising biochar applications in specific agricultural contexts.

Recent synthesis indicates that differences in biochar feedstock and production conditions can influence soil structure, nutrient retention, and water-holding capacity, supporting the need to evaluate biochar types according to their physicochemical characteristics (Hanif *et al*., 2026).

Recent review evidence also supports the use of biochar for improving soil pH and broader soil-health conditions, while noting that its performance varies across soil environments (Okine *et al*., 2026).

A substantial increase in maize yield is particularly expected in regions with high bulk density, as biochar can loosen the soil, and in areas with low soil organic carbon content, which can be enhanced by biochar (Kern *et al*., 2025). Maize, being one of the most important cereal crops globally and a staple food for millions of people, represents an appropriate crop for investigating the potential benefits of biochar. The crop's sensitivity to soil conditions makes it a useful indicator for assessing the effectiveness of different biochar types in improving soil conditions and agricultural productivity.

Experimental work with maize has shown that biochars derived from different agricultural wastes can produce distinct effects on soil properties and plant growth, reinforcing the importance of feedstock-specific assessment (Qayyum *et al*., 2024).

Applying biochar can alter root morphology, leading to enhanced nutrient uptake, shoot growth, and increased growth and yield because biochar-amended soils showed a larger rhizosphere containing biochar particles, which increased soil N retention, mainly soil-extractable nitrate–N. Although biochar appears to play an important role, less research has examined the appropriate depth of biochar application in soil. The depth of biochar incorporation was positively correlated with the growth of maize plants.

Recent studies have demonstrated that biochar application can significantly influence various soil properties. The results showed that, compared with T0, bulk density (BD) under the T1.5, T3.0, and T4.5 treatments significantly decreased by 11.21%, 16.33%, and 25.57%, respectively, while total porosity (Tp) and saturated hydraulic conductivity (Ks) increased correspondingly (Jin *et al*., 2024). These improvements in soil physical properties were accompanied by enhanced chemical characteristics, including increased pH, cation exchange capacity, and organic carbon content.

A two-year maize study further reported persistent changes in soil physicochemical properties following biochar amendment, indicating that treatment effects may extend across successive cultivation cycles (Wijitkosum *et al*., 2025).

Research gap: Within the context of the present study, evidence remains limited on the comparative effects of wood-shaving, corn-stalk, and charcoal biochars applied at the same rate on selected soil physical and chemical properties and maize vegetative growth.

Objective: Therefore, this study aimed to evaluate the effects of wood-shaving, corn-stalk, and charcoal biochars on selected soil physical and chemical properties and the growth performance of maize.

2. Materials and Methods

2.1 Establishment of Experimental Site

The experimental site was located at the Panderu campus of ETUSL. The area was demarcated, brushed, and cleared manually. The design used was a split-plot arrangement in an RCBD. Twelve plots were laid out in the experimental field, with each plot measuring 2 m x 2 m, with 0.5 m between subplots, 1 m between main plots, and 1.5 m in the alleys. The total experimental area was 352 m². Maize seeds (Western Yellow) were sown at the recommended spacing of 75 cm x 40 cm, with a population of 1,173 plants on 0.0352 ha. Standard agronomic practices such as weeding and pest control were uniformly applied across all plots.

2.2 Biochar Types

Wood Shavings Biochar: Produced by pyrolysing hardwood shavings at temperatures between 300°C and 500°C for 30 minutes.

Corn Stalk Biochar: Created from corn stalk residues using slow pyrolysis at 300°C-500°C for 45 minutes.

Charcoal Biochar: Commercially or locally produced charcoal was converted to biochar via slow pyrolysis at 500°C.

2.3 Plant Material

Certified maize seeds (Western Yellow) were used for planting.

2.4 Treatment Used

A split-plot design with four (4) treatments and three (3) replications was used. Treatments included:

T_0: Control (no biochar)
T_1: charcoal biochar at 10 t/ha
T_2: Corn stalk biochar at 10 t/ha
T_3: Wood shavings biochar at 10 t/ha

2.5 Soil Sampling and Analysis

Soil samples were taken from each subplot and later blended to form a composite sample, which was taken to the laboratory for physicochemical analysis before biochar application and after harvest to assess changes in soil properties.

2.6 Physical Properties

Soil Colour: Assessed using Munsell soil colour charts to document changes due to biochar addition.

Soil Texture: Determined using the hydrometer method to identify sand, silt, and clay fractions.

Bulk Density: Measured using the core method by calculating dry soil mass per unit volume (g/cm³).

2.7 Chemical Properties

Cation Exchange Capacity (CEC): Assessed by ammonium acetate extraction at pH 7.

Soil Organic Carbon (SOC): Determined using the Walkley-Black wet oxidation method.

Soil pH: Measured in a 1:2.5 soil-to-water suspension using a pH meter.

2.8 Data Collection

Plant height (cm): Measured from the soil surface to the tip of the highest leaf using a measuring tape at 3-week intervals until tasselling.

Number of leaves per plant: Counted manually at 3-week intervals until tasselling.

Stem girth: The stem girth was measured using a thread and a ruler at 3-week intervals until tasselling.

Leaf length: The length was measured using a tape measure at 3-week intervals until tasselling.

Leaf width: The leaf width was measured using a tape measure at 3-week intervals until tasselling.

2.9 Data Analysis

Data were subjected to analysis of variance using SAS version 9.4, and mean comparisons were conducted using the least significant difference (LSD) at the 5% significance level. Correlation analyses were also performed to investigate relationships between soil properties and growth parameters.

3. Results and Discussion

3.1 Maize Vegetative Traits

This section presents the analysis of variance (ANOVA) for the effects of biochar treatments on key maize vegetative traits, including number of leaves (MNL), plant height (MPH), stem girth (MSG), leaf length (MLL), leaf width (MLW), and leaf area (MLA).

Table 1. Maize vegetative traits

S/V	DF	MNL	MPH	MSG	MLL	MLW	MLA
REP	2	16.22*	4704.99**	19.29**	336.47ns	0.18ns	7454.85ns
SPLOT	11	15.85*	3943.69**	18.90**	221.77ns	0.45ns	9659.92ns
TRI	2	19.72**	1949.44*	345.83*	345.83*	2.89**	18719.63*
TRI(SPLOT)	12	8.75ns	1179.50ns	3.75ns	191.88ns	1.70*	11734.14ns
Error	522	5.16	719.48	2.81	127.19	0.84	7177.59
Mean		8.71	51.49	4.64	43.59	4.02	182.88
Std Error		0.10	1.21	0.08	0.49	0.04	3.70
Std Dev		2.33	28.09	1.76	11.46	0.93	85.96
CV		26.78	54.56	37.94	26.29	23.06	47.00

Note: S/V = source of variation, DF =degree of freedom, MNL= maize number of leaves, MNP=maize plant height, MSG= maize stem girth, MLL=maize leaf length, MLW=maize leaf width, MLA=maize leaf area, REP=replication, SPLOT=split plot, TRI=treatment, TRI(SLPOT)=treatment in plots, std Dev=standard deviation, std Err=standard error, CV=coefficient of variation

The table above shows that maize number of leaves, plant height, and stem girth were highly significant ($p < 0.01$) among treatments, while leaf length, leaf width, and leaf area did not show significant differences. The significance of the number of leaves (MNL) across treatments indicates that biochar application enhanced vegetative development by stimulating the production of more leaves. This is an important outcome because the number of leaves directly determines the photosynthetic capacity of the crop, which in turn supports biomass accumulation and eventual grain yield.

Plant height (MPH) also responded significantly to biochar treatments, suggesting that biochar amendments improved root-zone conditions that promoted vertical growth. Increased plant height is often associated with improved water retention, reduced soil compaction, and enhanced uptake of macronutrients such as nitrogen and potassium, all of which are facilitated by the porous structure and high cation exchange capacity of biochar. Comparable effects of agricultural waste-derived biochars on maize growth and soil properties have been reported by Qayyum *et al*. (2024).

Similarly, stem girth (MSG) showed highly significant differences among treatments, reflecting the positive impact of biochar on plant structural robustness. A thicker stem provides greater mechanical support, reduces lodging risk, and enhances the translocation of nutrients and water within the plant. Singh *et al*. (2022) reported that biochar can improve soil physical and chemical properties, including soil organic carbon and structural characteristics. The increased girth observed in this study may therefore be attributed to improved soil fertility and reduced bulk density resulting from biochar application.

On the other hand, leaf length (MLL), leaf width (MLW), and leaf area (MLA) were not significantly affected by treatments. This suggests that leaf-size traits are more genetically determined and less responsive to soil amendments than traits such as plant height or stem girth.

The coefficients of variation (CV) ranged between 23% and 54%, with plant height showing the highest variability, indicating that the maize response to biochar was not uniform across all replicates. This variability could be attributed to small variations in soil properties, differences in root penetration, or uneven biochar decomposition within plots. In contrast, lower CV values for leaf traits indicate greater uniformity in these parameters across treatments.

Overall, the results demonstrate that biochar application significantly enhances maize vegetative vigour by improving parameters closely related to growth and structural development, particularly number of leaves, plant height, and stem girth. These traits are important for photosynthetic efficiency, nutrient transport, and plant stability, all of which are precursors of improved grain yield. The lack of significant differences in leaf dimensions suggests that biochar's benefits are more pronounced in structural and physiological traits than in morphological leaf-size traits.

3.2 Maize Growth Parameters

Table 2 presents the correlation coefficients among the vegetative growth parameters of maize under different biochar treatments. The traits examined include number of leaves (MNL), plant height (MPH), stem girth (MSG), leaf length (MLL), leaf width (MLW), and leaf area (MLA). Correlation analysis is important because it helps establish the degree of association between different growth traits, thereby identifying which parameters contribute most to plant performance.

Table 2. Maize growth parameters

	MNL	MPH	MSG	MLL	MLW	MLA
MNL	1					
MPH	0.86**	1				
MSG	0.87**	0.87**	1			
MLL	-0.24**	-0.22**	-0.26**	1		
MLW	-0.24**	-0.26**	-0.24**	0.71**	1	
MLA	-0.29**	-0.28**	-0.29**	0.92**	0.91**	1

*Note: MNL= maize number of leaves, MNP=maize plant height, MSG= maize stem girth, MLL=maize leaf length, MLW=maize leaf width, MLA=maize leaf area.The results show that MNL was strongly and positively correlated with MPH (r = 0.86**) and MSG (r = 0.87**). Similarly, MPH was highly correlated with MSG (r = 0.87**)*

These strong positive associations indicate that, as maize plants produce more leaves, they also tend to grow taller and develop thicker stems. This implies that the enhancement of one trait directly complements the development of others, reflecting overall plant vigour. The findings suggest that biochar not only improves soil properties but also promotes integrated vegetative growth, in which leaf proliferation, vertical growth, and stem strengthening occur simultaneously. Comparable effects of biochar on maize growth and soil properties have been reported by Qayyum *et al*. (2024).

In contrast, leaf length (MLL) exhibited negative correlations with MNL (r = –0.24**), MPH (r = –0.22**), and MSG (r = –0.26**). This negative relationship indicates that plants with more leaves, greater height, and thicker stems tended to have shorter leaves. This trend may reflect a trade-off in resource allocation between leaf expansion and the proliferation of leaf numbers under biochar treatments. Essentially, while biochar stimulated the production of more leaves and stronger plant structures, it did not promote leaf elongation. Similar observations were reported by Blanco-Canqui (2017), who reviewed the effects of biochar on soil physical properties and crop-related responses.

On the other hand, leaf length (MLL), leaf width (MLW), and leaf area (MLA) showed very strong positive correlations among themselves, with coefficients ranging from 0.71** to 0.92**. This demonstrates that these traits are interdependent and that increases in one parameter are closely accompanied by increases in the others. For example, plants with longer leaves also tended to have wider leaves and a larger total leaf area. This is logical because leaf length and width together determine overall leaf surface area, which is important for photosynthetic capacity. Such strong interrelationships highlight the importance of leaf morphology in determining photosynthetic efficiency, even though biochar treatments did not significantly alter these parameters, as shown in Table 1.

Taken together, the results of Table 2 suggest that biochar primarily influenced traits related to overall plant vigour, namely leaf number, height, and stem girth, while leaf morphological traits remained strongly interrelated but less responsive to treatments. The strong positive correlations among key vegetative parameters confirm that improvements in soil fertility and structure brought about by biochar application translated into integrated plant growth responses. This implies that, when evaluating the effectiveness of biochar, traits such as leaf number, plant height, and stem girth can serve as reliable indicators of maize performance, while leaf length, width, and area should be considered supportive traits that are more strongly genetically constrained.

3.3 Mean Procedure

This figure illustrates the mean procedure for maize vegetative parameters under different treatments. The graphical trends confirm that biochar treatments significantly influenced plant growth, although the effects varied depending on the parameter measured.

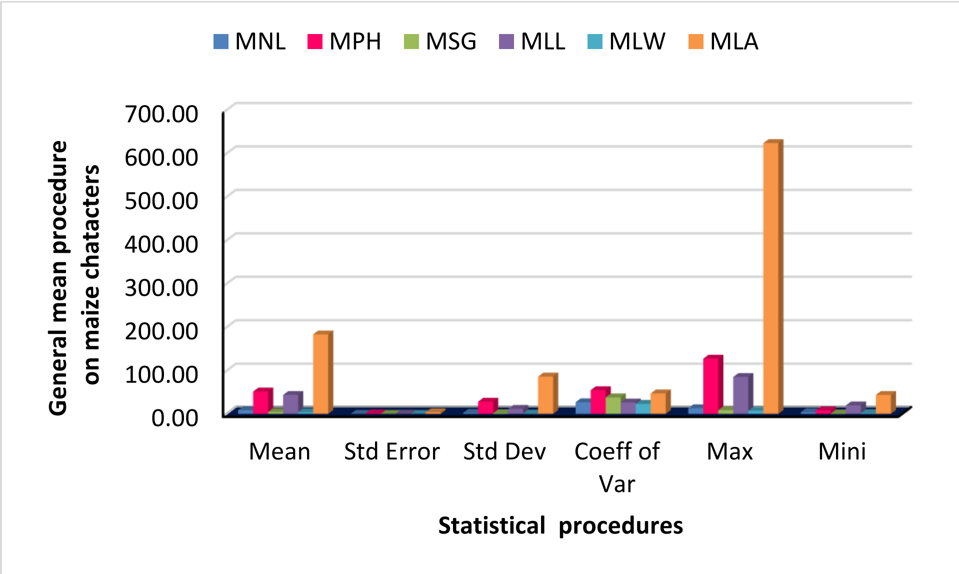

Fig. 1. General mean procedure on maize traits

From the figure, plant height (MPH), number of leaves (MNL), and stem girth (MSG) showed clear differences among treatments, with the control (CON) recording the highest mean values across these parameters. This suggests that, while biochar contributed positively to soil and crop performance, the untreated plots exhibited vigourous growth, possibly due to the inherent fertility of the experimental soil or residual fertility from previous cropping seasons.

Among the biochar treatments, maize stalk biochar (MST) and wood shavings biochar (WSH) supported moderate plant growth, while charcoal biochar (CHA) recorded the lowest values for traits such as plant height and number of leaves. This pattern may be attributed to the nutrient composition and physical properties of the biochar types. Corn stalk biochar is relatively nutrient-rich, providing higher levels of nitrogen, phosphorus, and potassium, which promote vegetative growth. In contrast, charcoal biochar is primarily carbon-dense and less nutrient-rich, which may explain its weaker effect on growth parameters.

In terms of leaf traits (leaf length, leaf width, and leaf area), the figure shows less pronounced differences across treatments, confirming the non-significant variations observed in Table 1. This reinforces the idea that leaf morphology is less sensitive to soil amendments than structural growth traits. Nevertheless, the control and maize stalk biochar treatments maintained slightly higher leaf-area values, which could still contribute to greater photosynthetic potential and improved yield outcomes.

Overall, Figure 1 demonstrates that biochar type plays a crucial role in influencing maize vegetative development. While the control plots unexpectedly showed the highest growth values, maize stalk biochar emerged as the most effective treatment among the biochar types tested, reflecting its higher nutrient content and faster decomposition rate. This suggests that locally available crop residues such as corn stalks can be pyrolysed into biochar and used as soil amendments to support sustainable maize production.

3.4 Mean Separation for Plot

Figure 2 presents the mean separation of split-plot effects on maize vegetative traits, including number of leaves (MNL), plant height (MPH), stem girth (MSG), leaf length (MLL), leaf width (MLW), and leaf area (MLA). The results reveal clear variations among the three split plots (MP1, MP2, and MP3), showing how maize responded under different biochar treatment conditions.

Among the growth traits, MP3 consistently produced the highest values for MNL (9.19), MPH (60.03 cm), and MSG (5.19), significantly outperforming MP1 and MP2. This indicates that maize plants in MP3 developed more leaves, attained greater height, and had thicker stems, reflecting improved vigour and robustness. These improvements suggest that soil conditions under MP3 were more favourable, likely due to enhanced nutrient availability, improved soil aeration, and better water retention promoted by biochar incorporation. Comparable effects of biochar on maize growth and soil properties have been reported by Qayyum *et al*. (2024).

In contrast, MP1 recorded the lowest values for these parameters, with 8.16 leaves, a plant height of 45.07 cm, and a stem girth of 4.12 cm. This indicates weaker plant performance under MP1 conditions, which may be attributed to less efficient soil amendment effects, reduced nutrient release, or higher soil bulk density than in MP3. MP2 showed intermediate results across these parameters, suggesting moderate improvement in plant vigour.

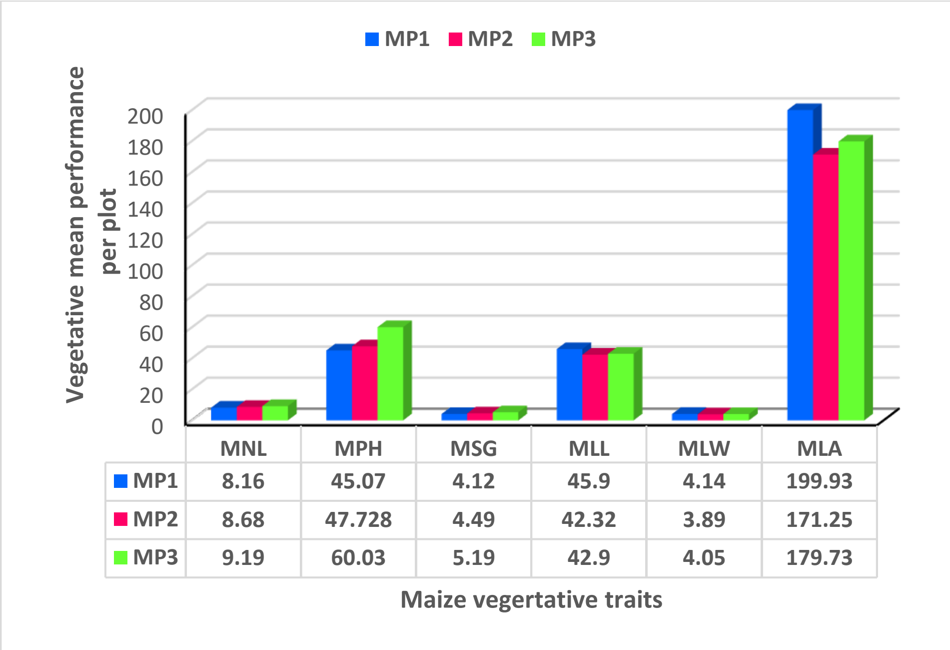

Fig. 2. Maize vegetative growth performance based on plot

Note: MNL= maize number of leaves, MNP=maize plant height, MSG= maize stem girth, MLL=maize leaf length, MLW=maize leaf width, MLA=maize leaf area, MP1=main plot 1, MP2=main plot 2, MP3=main plot 3, SPOLT=split plot

Interestingly, the leaf traits showed an opposite trend. MP1 recorded the highest values for MLL (45.90 cm), MLW (4.14 cm), and MLA (199.93 cm^2), while MP2 and MP3 had lower averages. This suggests that, under less vigourous conditions (as seen in MP1), maize plants compensated for reduced structural growth by producing longer and wider leaves with larger surface areas. On the other hand, in MP3, where plants grew taller and developed more leaves, individual leaves were smaller, highlighting a possible trade-off between leaf size and overall vegetative vigour. This interpretation agrees with the correlation results in Figure 3, which showed negative associations between leaf-size traits (MLL, MLW) and structural traits (MNL, MPH, MSG).

The differences among the split plots therefore indicate that, while biochar application generally promoted maize growth, the specific effects varied depending on how plants allocated resources between structural robustness and leaf development. SPLOT MP3 favoured plant-vigour traits (height, leaf number, and stem thickness), which are important for photosynthetic efficiency and yield potential, whereas SPLOT MP1 promoted larger leaf surfaces, potentially as a compensatory mechanism under less favourable conditions.

Overall, Fig. 3 demonstrates that biochar influenced maize growth differently across split plots, with MP3 emerging as the most favourable environment for strong vegetative growth. This suggests that the choice and management of biochar in split-plot designs can significantly determine how maize allocates resources between structural and leaf development, ultimately shaping productivity outcomes.

3.5 Mean Separation for Treatment

Fig. 3 presents the mean separation of different biochar treatments (TRI) on maize vegetative parameters. The treatments compared were charcoal biochar (CHA), control (CON - no biochar), maize stalk biochar (MST), and wood shavings biochar (WSH). The traits measured included maize number of leaves (MNL), plant height (MPH), stem girth (MSG), leaf length (MLL), leaf width (MLW), and leaf area (MLA).

The results show that the control (CON) produced the highest values for MNL (11.1), MPH (75.2 cm), and MSG (5.87), which were significantly greater than those of all biochar treatments. This indicates that, under the conditions of this experiment, untreated soil supported the strongest vegetative growth. The high performance of the control could be attributed to the inherent fertility of the experimental soil or residual nutrient content that allowed plants to thrive without amendment. This finding suggests that baseline soil properties played a major role in crop performance and may have reduced the observable benefits of biochar in the short term. Singh *et al*. (2022) noted that biochar effects vary with soil conditions and other contextual factors.

Among the biochar treatments, MST and WSH showed moderate performance. Maize stalk biochar (MST) recorded 8.93 leaves, a plant height of 52.22 cm, and a stem girth of 4.71, while wood shavings biochar (WSH) recorded 8.84 leaves, a height of 53.62 cm, and a stem girth of 4.74. These values were statistically similar and suggest that both feedstocks contributed modest improvements to maize growth compared with charcoal biochar, although the values remained lower than those of the control. The relatively better performance of MST can be attributed to its higher nutrient content, particularly nitrogen and potassium, which are essential for vegetative development. This aligns with Blanco-Canqui (2017), who noted that biochar effects vary with feedstock and soil conditions.

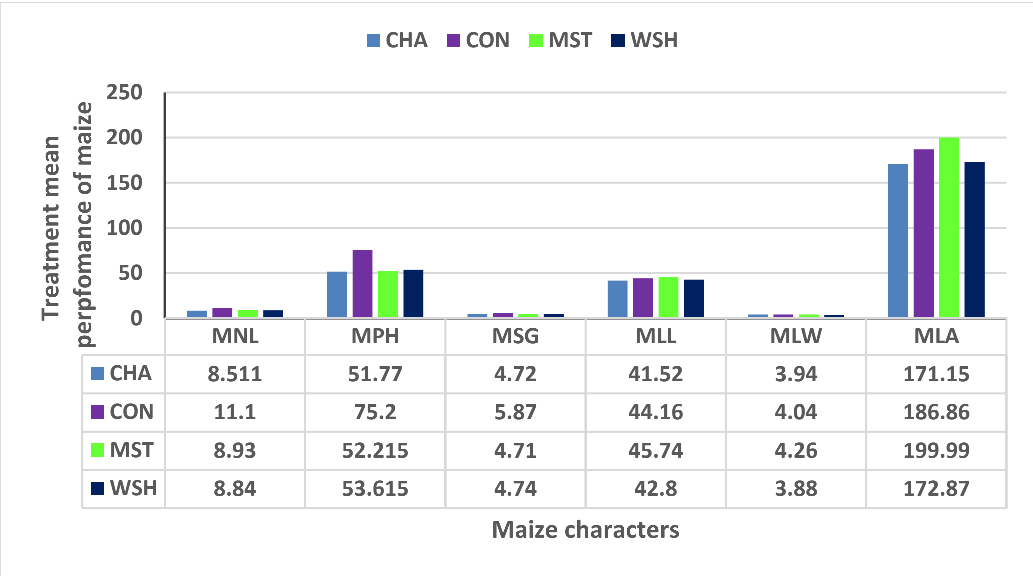

Fig. 3. Mean separations for treatment on maize characters

Note: MNL= maize number of leaves, MNP=maize plant height, MSG= maize stem girth, MLL=maize leaf length, MLW=maize leaf width, MLA=maize leaf area, CHA=charcoal, CON=control, MST=maize straw, WSH=wood shaving.

Charcoal biochar (CHA) recorded the lowest values among treatments, with 8.51 leaves, a plant height of 51.77 cm, and a stem girth of 4.72. This reflects the fact that charcoal biochar is carbon-dense but contains fewer nutrients than biochars derived from crop residues. As such, it primarily improves soil structure and water retention but contributes little directly to nutrient supply, explaining its weaker effect on growth parameters.

For the leaf traits (MLL, MLW, MLA), differences among treatments were not statistically significant. All treatments, including the control, produced comparable values for leaf length (41.52–45.74 cm), width (3.88–4.26 cm), and area (171.15–199.99 cm²). This result suggests that leaf-size traits are less responsive to biochar application and are more strongly influenced by genetic factors than by soil amendments. Qayyum *et al*. (2024) similarly reported variable maize growth responses among different agricultural waste-derived biochars.

Overall, the results of Table 3 indicate that biochar treatments influenced maize vegetative growth differently depending on feedstock type. While the control unexpectedly outperformed all treatments in terms of structural growth (height, leaf number, and stem girth), maize stalk and wood shavings biochar supported moderate growth, and charcoal biochar was the least effective. The lack of significant differences in leaf morphology suggests that biochar's primary benefits lie in improving general plant vigour rather than altering leaf-size traits. These results highlight the importance of considering both soil fertility status and biochar feedstock type when evaluating biochar's effectiveness as a soil amendment.

Table 3. Mean separation for SPLOT

SPLOT	MNL	MPH	MSG	MLL	MLW	MLA
MP1	8.16c	45.07b	4.12c	45.90a	4.140a	199.93a
MP2	8.68b	47.728b	4.49b	42.32b	3.89b	171.25b
MP3	9.19a	60.03a	5.19	42.90b	4.05ab	179.73b

Note: MNL= maize number of leaves, MNP=maize plant height, MSG= maize stem girth, MLL=maize leaf length, MLW=maize leaf width, MLA=maize leaf area, MP1=main plot 1, MP2=main plot 2, MP3=main plot 3, SPOLT=split plot

3.6 Soil Chemical and Physical Properties

3.6.1 Pre-Soil Test

3.6.1.1 Soil pH

The analysed soil exhibited a pH of 4.91, classifying it as strongly acidic. Such acidity typically limits the availability of key macronutrients (notably phosphorus, calcium, and magnesium) and can increase the solubility of potentially toxic elements such as aluminium. This leads to stunted plant growth, poor root development, nutrient deficiencies, and reduced soil microbial activity. It also contributes to environmental issues such as soil degradation, reduced crop yields, and increased heavy-metal uptake by plants.

3.6.1.2 Cation Exchange Capacity (CEC)

The cation exchange capacity (CEC = 1 cmol kg^{-1}) is low to moderate, consistent with sandy soils and indicating limited nutrient retention. The CEC of 10 cmol/kg is a moderate value, indicating the soil's average ability to hold and exchange positively charged nutrient ions. Soils with higher clay or organic matter contents have higher CEC values; therefore, this moderate CEC reflects the combination of sandy texture and good organic carbon content. This capacity affects nutrient retention and supply to plants.

3.6.1.3 Organic Carbon

An organic carbon content of 4.7% is relatively high, indicating a good presence of organic matter, which enhances soil structure, moisture retention, and microbial activity. The 4.70% organic carbon content signifies an amount that positively influences soil structure, water-holding capacity, nutrient cycling, microbial diversity, and soil fertility, all of which are important for sustainable agriculture and environmental benefits. Organic carbon is a primary component of soil organic matter and greatly influences many soil properties and ecological functions.

3.6.2 Bulk Density

The bulk density results for the soil layers are 1.25 g/cm^3 for Layer A, 1.69 g/cm^3 for Layer B, and 2.10 g/cm^3 for Layer C.

Layer A (1.25 g/cm^3): This value indicates a relatively loose soil with good porosity and aeration. Bulk densities below 1.3 g/cm^3 are typical of surface soils rich in organic matter and are favourable for root penetration, water infiltration, and microbial activity.

Layer B (1.69 g/cm^3): This higher value suggests moderate compaction and lower porosity than Layer A. Bulk densities above 1.6 g/cm^3 often begin to restrict root growth and reduce soil aeration, indicating that this subsurface layer might limit root expansion and water movement.

Layer C (2.10 g/cm^3): A bulk density above 2.0 g/cm^3 is very high and is typical of compacted or mineral soil layers with very low porosity. Such densities severely inhibit root growth, water infiltration, and gas exchange, often indicating a compacted subsoil or bedrock layer.

3.6.3 Soil Texture

Soil texture analysis (75% sand, 7% silt, and 18% clay) places the soil in the sandy-loam category. This texture provides good drainage and ease of tillage but has a limited capacity to retain water and nutrients. The soil contains 4.70% organic carbon, a relatively high value that reflects substantial organic matter inputs, which in turn enhance soil structure, microbial activity, and nutrient-holding capacity.

3.6.4 Soil Colour

The soil colour results are reported using the Munsell colour notation system, a scientific method of describing soil colour by hue (basic colour), value (lightness), and chroma (colour intensity).

Layer A: 7.5R 3/2 (Dusky Red)

Hue (7.5R): A red hue indicating the presence of iron oxide, which is common in well-drained soils.

Value (3): A low value, meaning that the soil is quite dark, likely due to some organic matter or moisture.

Chroma (2): Low chroma indicates dullness, associated with some moisture retention or partial saturation. Overall, dusky red suggests a moderately oxidised soil with some moisture and organic content typical of surface horizons.

Layer B: 7.5R 6/2 (Pale Red)

Hue (7.5R): The same red hue, indicating the presence of iron oxide.

Value (6): A higher value means that it is much lighter or paler than Layer A.

Chroma (2): Low chroma again indicates a dull colour, suggesting some moisture or lower oxidation intensity.

Pale red indicates a subsoil with less organic matter and more weathered, oxidised mineral content than the surface layer. The soil is likely less moist or lower in organic content.

Layer C: 5FR 6/8 (Reddish Yellow)

Hue (5FR): Intermediate between red and yellow hues, typical of iron-oxide minerals such as goethite and hematite.

Value (6): A pale or light soil colour.

Chroma (8): Very high chroma, showing a bright, intense colour typical of well-oxidised and well-drained mineral soil.

Reddish yellow colour suggests that the deepest layer is mineral-rich and highly oxidised, with low moisture and organic content. Such bright colours are typical of subsoil or parent material not affected by organic matter.

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No.	Parameters	Units	Control	Charcoal	Maize Straw	Wood Shaving
1	pH		4.693	4.84	5.001	4.84
2	Organic Carbon	%	3.08	3.12	3.20	2.96
3	CEC	cmol+/kg soil	0.41	0.55	0.82	0.50
4	Colour		Dark Grey (10 YR 4/1)	Very dark greyish brown (10YR 3/2)	Very Dark Brown (10YR 2/2)	Dark greyish brown (10YR 4/2)
5	Texture		Sandy loam	Sandy loam	Sandy loam	Sandy loam
Bulk density g/cm³					Layer A	1.68
					Layer B	2.04

Sign...............................
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Njala University: *A rural public university for excellent research and teaching in Sierra Leone.*

Fig. 4. Post-harvest soil laboratory analysis showing the effects of control, charcoal, maize straw, and wood-shaving amendments on soil pH, organic carbon, cation exchange capacity, soil colour, texture, and bulk density

The literature reviewed includes multiple relevant scientific studies and articles discussing soil properties - pH, organic carbon, cation exchange capacity (CEC), soil colour, texture, and bulk density - in relation to biochar and organic amendments such as maize straw and wood shavings.

3.7 Post-Soil Analysis

The results indicate that the soils across all treatments were generally acidic, with pH values ranging from 4.69 in the control to 5.00 in the maize-straw-amended soil. Hazelton and Murphy (2016) describe soil pH as an important indicator for interpreting soil chemical conditions. The slightly higher pH observed in the maize straw treatment suggests that organic materials can help buffer soil acidity through decomposition and the release of basic cations (Agegnehu *et al*., 2016). Similarly, soils amended with charcoal (biochar) and wood shavings also recorded higher pH values than the control, although the increase was less pronounced. This rise in pH with biochar amendment is consistent with studies demonstrating that biochar can neutralise soil acidity. Biochar contains alkaline minerals, such as oxides and carbonates of calcium, magnesium, potassium, and sodium, which dissolve and neutralise hydrogen ions in acidic soils, thereby increasing pH. The extent of the pH increase depends on the feedstock used for biochar production and the pyrolysis temperature, with wood-based biochars tending to have higher pH values. Maize straw, as a fresh organic amendment, may also raise pH due to the mineralisation of its organic compounds and the release of basic cations during decomposition.

The organic carbon (OC) content ranged from 2.96% in the wood-shaving treatment to 3.20% in the maize-straw treatment, showing a modest change in soil organic matter following the addition of organic residues. Organic carbon is a vital indicator of soil fertility because it enhances soil structure, water-holding capacity, and nutrient retention (Lehmann & Joseph, 2015). The relatively higher OC under maize straw is consistent with the broader role of organic inputs in supporting soil carbon and nutrient processes (Lehmann & Joseph, 2015). Conversely, the slightly lower OC in the wood-shaving treatment could be attributed to the slow decomposition rate and high carbon-to-nitrogen (C:N) ratio of woody materials, which may temporarily immobilise nitrogen during decomposition (Agegnehu *et al*., 2016). This fresh organic matter serves as a substrate for soil microorganisms, enhancing carbon pools and nutrient cycling. Biochar's contribution to organic carbon is more recalcitrant; it adds stable carbon fractions that are resistant to microbial decomposition, enhancing long-term carbon sequestration. Although the increase relative to the control is small, biochar's carbon benefits are often realised over longer timescales. The slightly lower organic carbon with wood shavings may be due to the slower decomposition rate and lower nutrient content of the woody material, resulting in comparatively less organic carbon accumulation in the short term.

The cation exchange capacity (CEC) values ranged from 0.41 cmol⁺ kg⁻¹ in the control to 0.82 cmol⁺ kg⁻¹ in the maize-straw treatment. Although these values are relatively low for agricultural soils, they are typical of coarse-textured sandy loams that contain limited clay and organic matter (Hazelton & Murphy, 2016). The higher CEC values in the maize-straw- and charcoal-amended soils demonstrate the positive influence of organic materials on nutrient-holding capacity. As noted by Chan *et al.* (2008), biochar can alter soil chemical properties and nutrient availability. Higher CEC improves soil nutrient-buffering capacity, reducing nutrient leaching and improving availability to plants. This is important in sandy-loam soils, such as that in this study, which naturally have lower nutrient retention. The moderate increase from wood shavings is consistent with its lower SOC contribution and slower decomposition.

Soil colour ranged from dark grey (10 YR 4/1) in the control to very dark brown (10 YR 2/2) in the maize-straw-amended soil. Darker colours are often associated with higher organic matter content and improved soil structure. All treatments exhibited a sandy-loam texture, a characteristic that partly explains the soils' low CEC and relatively high bulk density. The darkening observed with biochar and maize straw amendments is linked to increased organic matter accumulation, which darkens soil through humus formation. Biochar's intense black colour contributes to the very dark hue following amendment. Maize straw decomposition enhances organic matter, while wood shavings, despite adding organic material, impart less intense darkening because of slower breakdown. Colour changes may also indicate changes in soil condition and organic matter status. The Munsell colour system values further quantify the visual changes observed and align with the effects of organic amendments.

The bulk density values for Layer A (1.68 g cm^{-3}) and Layer B (2.04 g cm^{-3}) indicate moderate to high soil compaction. Bulk densities above 1.6 g cm^{-3} can restrict root penetration and reduce water infiltration, particularly in sandy soils. The higher bulk density observed in the B horizon suggests limited root growth and poor aeration, conditions that could reduce the effectiveness of organic amendments in improving soil productivity.

Overall, the results show that the maize-straw treatment performed best, producing noticeable improvements in soil pH, organic carbon, and CEC compared with the control and other amendments. These findings are consistent with previous studies suggesting that organic and carbon-rich amendments can influence soil fertility and related properties (Glaser *et al*., 2002). However, the persistently low pH values observed across all treatments indicate that liming would still be necessary to correct soil acidity effectively and optimise nutrient availability for maize production.

4. Conclusion

The study results provide clear evidence that the organic amendments - charcoal (biochar), maize straw, and wood shavings - substantially improve key soil physical and chemical properties in acidic sandy-loam soils. Each amendment enhanced soil health in a different way.

Charcoal effectively increased soil pH, helping to ameliorate the acidic soil environment, while also contributing stable organic carbon and supporting long-term soil carbon sequestration.

Maize straw produced the most significant increases in organic carbon and cation exchange capacity (CEC), indicating its value as a fresh organic input that rapidly enhances nutrient retention and availability.

Wood shavings led to moderate improvements in pH, organic carbon, and CEC, reflecting their slower decomposition but useful contribution to soil organic matter and structure.

All amendments darkened soil colour, indicating greater organic matter content and soil fertility. Soil texture remained sandy loam, which is appropriate for many cropping systems, while bulk density data from the control suggest that organic amendments are likely to reduce compaction and improve porosity.

5. Limitations

This study was conducted at one experimental site, used one biochar application rate (10 t/ha), and included three replications. The reported crop response is based mainly on vegetative traits and post-harvest soil properties, so it does not establish the persistence of treatment effects over multiple seasons or across contrasting soils.

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Declaration of AI Use

This manuscript was prepared through the intellectual contributions of the author(s) to the study design, data analysis, interpretation of results, and scholarly content. Grammarly and ChatGPT were used solely to assist with grammatical refinement and reference formatting during manuscript revision. The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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