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RESEARCH ARTICLE

Effects of biochar application on soil physicochemical properties and maize (*Zea mays L.*) productivity in tropical soils

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ABSTRACT

Biochar is increasingly recognized as a sustainable soil amendment for improving soil fertility and crop productivity in tropical agroecosystems. This study evaluated the effects of biochar application on soil physicochemical properties and maize (*Zea mays L.*) productivity in a tropical soil environment. The experiment was laid out in a randomized complete block design with four biochar rates (0, 5, 10, and 15 t ha^{-1}). Results showed that biochar significantly improved soil physical properties by reducing bulk density (2.56 to 2.27 g cm^{-3}) and increasing total porosity, moisture content, and hydraulic conductivity. Soil chemical properties were also enhanced, with increases in pH (5.2 to 6.7), organic carbon (4.01 to 6.83 g kg^{-1}), total nitrogen (1.46 to 2.17 g kg^{-1}), and available phosphorus (2.57 to 4.10 ppm). Exchangeable bases (Ca, Mg, K, and Na) also improved with increasing biochar rates. Improved soil conditions translated into enhanced maize performance, with increases in plant height, stem girth, cob length, grain yield, and improved reproductive development. The highest performance was consistently observed at 15 t ha^{-1}, although 10 t ha^{-1} also showed substantial agronomic benefits. The study concludes that biochar is an effective soil amendment for improving soil quality and maize productivity in tropical soils, with 10–15 t ha^{-1} recommended for optimal performance. This highlights its potential for sustainable soil management and crop production.

Keywords: Biochar, maize, soil fertility, tropical soils, crop yield, soil amendment.

INTRODUCTION

Sustaining agricultural productivity in tropical regions remains a major challenge due to widespread soil degradation, declining fertility, and low organic matter content (Ibrahim et al. 2021). In Nigeria, continuous cultivation, erosion, and poor soil management practices have led to the deterioration of soil physicochemical properties, particularly in highly weathered soils such as Ultisols and Alfisols (Ding et al., 2016 & Laird, 2021). These soils are typically characterised by low nutrient reserves, high acidity, and weak structural stability, which collectively limit their capacity to support optimal crop growth. Improving soil quality is therefore essential for enhancing crop productivity and ensuring long-term food security (Jeffery et al., 2071 & Ajayi, 2015).

Maize (*Zea mays L.*) is one of the most important staple crops in Nigeria, serving as a major source of food, livestock feed, and industrial raw materials (FAO, 2022). Pandian et al. (2024) report that, despite its economic and nutritional importance, maize yields in Nigeria remain relatively low compared to global averages, largely due to soil fertility constraints and inefficient nutrient management (World Bank 2023). Although inorganic fertilizers are widely used to improve productivity, their continuous application often results in soil acidification, nutrient imbalance, and declining soil health (Palansooriya et al*.,* 2022). This has increased the need for sustainable soil amendment strategies that can enhance soil properties while maintaining crop yield (Ajayi, 2015 & Major et al., 2020).

Biochar, a carbon-rich material produced through the pyrolysis of organic biomass under limited oxygen conditions, has gained considerable attention as a soil amendment for improving soil health and crop performance (Akinyemi et al., 2023). Its unique physicochemical properties, including high porosity, large surface area, and high cation exchange capacity, enable it to enhance nutrient retention, improve soil structure, and increase water holding capacity (Agegnehu et al., 2017). In tropical soils, biochar has been shown to increase soil pH, improve organic carbon content, and enhance the availability of essential nutrients such as nitrogen and phosphorus (Agegnehu et al., 2017).

Recent studies in Nigeria have reported significant improvements in soil properties and maize productivity following biochar application (Awwal et al., 2025). For instance, biochar has been shown to reduce bulk density, increase soil porosity, and improve moisture retention, thereby creating favourable conditions for root growth and nutrient uptake (Azuka et al., Ogunlade et al., 2022). In addition, improvements in soil nutrient dynamics and microbial activity have been associated with increased maize growth and yield under biochar-amended soils (Akinyemi et al., 2023 & Oladele et al., 2021). These findings highlight the potential of biochar as a sustainable tool for soil fertility management in tropical agroecosystems. (Mensah et al., 2022 & Liu et al., 2020)

The effectiveness of biochar depends on several factors, including application rate, feedstock type, and soil characteristics (Lehmann et al., 2021 & Sohi, 2020). Moreover, there is limited site-specific information on the combined effects of biochar on soil physicochemical properties and maize productivity under humid tropical conditions in southern Nigeria. This knowledge gap limits the development of practical recommendations for farmers (Glaser et al., & Biederman et al., 2021). Therefore, this study evaluates the effects of different rates of biochar application on soil physicochemical properties and maize (*Zea mays L.*) productivity in tropical soils.

MATERIALS AND METHODS

Study area

The field experiment was conducted at the Delta Steel (DSC) Technical High School Farm, Udu, Delta State, Nigeria, at Latitude 5° 80^{l} and 5° 20^{l} N and Longitude 5° 56^{l} and 5° 53^{l} E of the Greenwich meridian, which falls within the humid environment characterized by heavy annual rainfall of 2768.8mm (NIMET, 2021). The maize was sourced from the Delta State of Agriculture and Rural Development Agency (DARDA). The treated seeds that were used for this experiment were Kapam-6, which is an early-maturing maize. The experiment was laid out in a Randomized Complete Block Design (RCBD) with four treatments and three replications. The treatments consisted of different biochar application rates: B_0 = 0 t ha^{-1} (Control), B_1 = 5 t ha^{-1}, B_2 = 10 t ha^{-1}, B_3 = 15 t ha^{-1}. Each experimental plot measured 3 m × 3 m, with 1 m spacing between plots and 1.5 m between blocks to minimize treatment interference. Biochar was applied uniformly to each plot and incorporated into the topsoil (0–15 cm depth) two weeks before planting to allow stabilization and interaction with the soil. The biochar used in this study was produced from locally available agricultural residues (rice husks and poultry manure) through pyrolysis under limited oxygen conditions at temperatures ranging from 300–500°C. After production, the biochar was air-dried, crushed, and sieved through a 2 mm mesh to ensure uniformity before application. The experimental field was manually cleared, ploughed, and harrowed to obtain a fine seedbed. Maize (*Zea mays L.*) seeds of an improved variety suitable for the agroecological zone were planted at a spacing of 75 cm × 25 cm. Two seeds were sown per hole and later thinned to one plant per stand at two weeks after planting (WAP) to ensure uniform plant population. Weeding was carried out manually at 3 and 6 WAP to reduce weed competition.

The following plant parameters were measured: plant height, stem girth, cob length and grain yield at 4, 6, 8 and 10 weeks after planting; reproductive parameters: Number of days to 50% silking, number of days to 50% tasseling and number of days to 100% silking; and tassel-silking interval. Physicochemical parameters determined are Particle size distribution by hydrometer method (Bouyoucous, 1951). Bulk density (Bd) was determined using the core method, Total porosity (TP) was calculated from bulk density values, Soil moisture content (MC) was determined using the gravimetric method, Saturated hydraulic conductivity (Ks) was measured using standard laboratory procedures, Soil pH (1:2.5 soil–water suspension), Organic carbon (OC) by Walkley–Black method, Total nitrogen (TN) by Kjeldahl method, Available phosphorus (P) by Bray-1 extraction, Exchangeable bases (Ca, Mg, K, Na) using ammonium acetate extraction.

Data analysis

Data collected were subjected to Analysis of Variance (ANOVA) using GenStat eleventh edition for statistical analysis; means were separated using the Least Significant Difference (LSD) at 5% probability level ($p \leq 0.05$). The tasseling–silking interval (TSI) was calculated as: TSI = N50S – N50T by Chukwudi et al. (2021).

RESULTS

Effect of Biochar on Plant Height of Maize

Biochar application significantly ($p \leq 0.05$) increased maize plant height at all sampling periods (Table 1). Plant height rose consistently with increasing biochar rates from 0 to 15 t ha^{-1} across 4, 6, 8, and 10 weeks after planting (WAP). At 10 WAP, the tallest plants (167.81 cm) were recorded at 15 t ha^{-1}, compared to 109.73 cm in the control. Treatments at 5 and 10 t ha^{-1} showed intermediate performance. The improvement in plant height can be attributed to enhanced soil fertility, particularly increased availability of nitrogen and phosphorus, which are essential for vegetative growth. Similar trends have been reported in Nigerian soils where biochar significantly enhanced maize growth (Agbede and Adekiya, 2020; Zubairu et al., 2023).

Table 1. Effects of biochar on plant height of maize

Treatments (t/ha)	Plant height (cm)				Stem girth (cm)			
	4WAP	6WAP	8WAP	10WAP	4WAP	6WAP	8WAP	10WAP
0.0	78.10^{c}	87.21^{d}	98.96^{d}	109.73^{d}	1.70^{d}	2.75^{c}	2.83^{c}	2.35^{c}
5t /ha	85.39^{b}	90.65^{c}	112.04^{c}	123.75^{c}	2.71^{c}	2.89^{c}	2.93^{c}	2.41^{c}
10 t/ha	89.12^{b}	97.51^{b}	116.76^{b}	139.02^{b}	3.56^{b}	4.46^{b}	3.36^{b}	3.84^{b}
15 t/ha	93.35^{a}	143.05^{a}	152.09^{a}	167.81^{a}	4.78^{a}	6.96^{a}	7.96^{a}	10.18^{a}

T/ha: Tones per hectare, WAP-Weeks after Planting

Effect of Biochar on stem girth of Maize

Stem girth increased significantly ($p \leq 0.05$) with increasing biochar application rates (Table 1). At 10 WAP, stem girth ranged from 2.35 cm in the control to 10.18 cm at 15 t ha^{-1}. The consistent increase across all sampling periods indicates improved structural growth. The increase in stem girth reflects enhanced cell expansion and structural strength due to improved nutrient supply and water availability. These findings align with reports from tropical agroecosystems where biochar improved maize structural development (Adekiya et al., 2020; Okoro et al., 2024).

Effect of Biochar on grain yield of Maize

Grain yield increased significantly ($p \leq 0.05$) with increasing biochar application (Table 2). At 10 WAP, the highest yield (4.67 t ha^{-1}) was recorded at 15 t ha^{-1}, compared to 1.83 t ha^{-1} in the control. The yield improvement can be attributed to enhanced soil fertility, improved water retention, and better nutrient use efficiency. Biochar application improved soil physical conditions, which enhanced root development and nutrient uptake, and this led to an increase in early flowering and ultimately higher grain yield and improved yield components (Okoro et al., 2024; Dantani et al., 2024).

Table 2. Effects of biochar on grain yield of maize

Treatments (t/ha)	Grain Yield (t ha^{-1})				Cob Length (cm)			
	4WAP	6WAP	8WAP	10WAP	4WAP	6WAP	8WAP	10WAP
0.0	0.21^{c}	0.23^{d}	0.57^{d}	1.83^{d}	6.13^{d}	6.17^{d}	11.12^{d}	11.80^{d}
5t /ha	1.61^{b}	1.71^{c}	2.34^{c}	2.56^{c}	11.21^{c}	12.16^{c}	12.27^{c}	12.28^{c}
10 t/ha	2.61^{a}	2.53^{b}	3.76^{b}	3.84^{b}	12.45^{b}	13.14^{b}	13.61^{b}	15.45^{b}
15 t/ha	2.85^{a}	3.77^{a}	4.91^{a}	4.67^{a}	14.00^{a}	16.32^{a}	18.00^{a}	18.43^{a}

T/ha: Tones per hectare, WAP: Weeks after Planting

Effect of biochar on cob length of maize

Cob length increased significantly with biochar application (Table 2), with values ranging from 11.80 cm in the control to 18.43 cm at 15 t ha^{-1} at 10 WAP. Improved cob development reflects better assimilate production and allocation during reproductive growth. Biochar enhances phosphorus availability, which plays a key role in reproductive development and grain filling. These findings are in line with studies showing improved maize yield components under biochar amendment in tropical soils (Zubairu et al., 2023).

Effect of biochar on reproductive characteristics

Biochar application significantly reduced the number of days to tasseling and silking showing in Table 3. The control recorded the longest duration (63.25 days for N50S), while the shortest duration was observed at 15 t ha^{-1} (55.00 days). The tasseling–silking interval (TSI) ranged from 1.98 to 2.92 days and remained relatively stable across treatments, indicating that biochar did not disrupt reproductive structure. These results may be linked to improved nutrient availability and soil moisture status, which accelerate plant metabolic processes. Research has shown that biochar application to the soil enhances nutrient uptake and promotes early flowering in maize (Zubairu et al., 2023; Agbede and Adekiya, 2020).

Table 3. Effect of biochar on reproductive characteristics

Treatments (t/ha)	N50S	N50T	N100S	TSI
0.0	63.25^{a}	61.27^{a}	91.10^{a}	1.98^{d}
5 t/ha	61.16b^{c}	58.31^{b}	89.12^{b}	2.85^{b}
10 t/ha	57.13^{c}	54.21^{c}	85.16^{c}	2.92^{a}
15 t/ha	55.00^{c}	52.35^{d}	83.78^{d}	2.70^{c}

Note: N50%S: Number of days to 50% silking, N50T: Number of days to 50% tasseling, N100S: Number of days to 100% silking, TSI: tassel-silk interval, T/ha: Tones per hectare, WAP-Weeks after Planting.

Table 4. Effects of biochar on soil physical properties

Treatment (t/ha)	Sand (%)	Silt (%)	Clay (%)	Bd (g/cm^{-3})	TP (%)	MC (%)	Ks (cm/s)
0.0	40	39	21	2.56^{a}	50^{d}	1.08^{d}	136.21^{c}
5t /ha	36	43	21	2.51^{ab}	54^{c}	1.31^{c}	142.31^{b}
10 t/ha	38	43	19	2.50^{ab}	58^{b}	1.48^{b}	142.22^{b}
15 t/ha	38	45	17	2.27^{b}	62^{a}	1.68^{a}	375.50^{a}

Note: Bd-Bulk density, TP-Total Porosity, MC-Moisture Content, Ks-Hydraulic Conductivity, T/ha: Tones per hectare, WAP-Weeks after Planting.

Effect of biochar on soil physical properties

Biochar application significantly improved soil physical properties as indicated in Table 4. Bulk density decreased from 2.56 g cm^{-3} in the control to 2.27 g cm^{-3} at 15 t ha^{-1}, while total porosity increased from 50% to 62%. Soil moisture content and hydraulic conductivity also improved with increasing biochar rates. The improvement in soil physical properties is due to the porous nature of biochar, which reduces soil compaction and enhances soil aeration. In Nigerian soils, similar improvements have been linked to increased crop productivity (Akinyemi and Adesina, 2023; Nwite and Alu, 2021).

Effect of Biochar on Soil Chemical Properties

Biochar application significantly ($p \leq 0.05$) improved soil chemical properties (Table 5). A consistent increase was observed in soil pH, organic carbon (OC), total nitrogen (TN), available phosphorus (AP), and exchangeable bases (Ca, Mg, K, and Na) with increasing biochar application rates. Soil pH increased from 5.2 in the control (0 t ha^{-1}) to 6.7 at 15 t ha^{-1}, indicating a strong liming effect of biochar. This rise in pH is particularly beneficial in tropical soils, where acidity often limits nutrient availability. The increase can be attributed to the presence of alkaline ash components in biochar, which neutralize soil acidity. Similar increases in soil pH following biochar application have been reported in Nigerian soils (Zubairu et al., 2023). Soil organic carbon increased significantly from 4.01 g kg^{-1} in the control to 6.83 g kg^{-1} at 15 t ha^{-1}.

Table 5. Effects of biochar on soil chemical properties

Treatments (t/ha)	pH	OC (g/kg)	TN (g/kg)	AP (ppm)]	Exchangeable bases Ca (cmol/kg)	Mg (cmol/kg)	K (cmol/kg)	Na (cmol/kg)
0.0	5.2	4.01^{c}	1.46^{c}	2.57^{c}	2.54^{b}	1.61^{c}	1.49^{a}	1.13^{d}
5 t/ha	5.8	5.92^{b}	1.83^{b}	2.66^{c}	2.73^{b}	1.79^{b}	1.51^{b}	1.15^{c}
10 t/ha	6.3	6.21^{ab}	1.91^{b}	2.87^{b}	2.96^{a}	1.82^{a}	1.53^{b}	1.20^{b}
15 t/ha	6.7	6.83^{a}	2.17^{a}	4.10^{a}	2.98^{a}	1.87^{a}	1.57^{a}	1.35^{a}

OC-Organic Carbon, TN-Total Nitrogen, AP-Available Phosphorous, Ca-Calcium, Mg-Magnesium, K-Potassium, Na-Sodium, T/ha: Tones per hectare, WAP-Weeks after planting

The highest value was statistically similar to 10 t ha^{-1} (6.21 g kg^{-1}), but significantly higher than lower treatments. This increase reflects the high carbon content and stability of biochar, which contributes to long-term carbon sequestration and improved soil structure. Total nitrogen followed a similar trend, increasing from 1.46 g kg^{-1} in the control to 2.17 g kg^{-1} at 15 t ha^{-1}. The increase in nitrogen content may be due to improved nitrogen retention and reduced leaching losses, as biochar enhances soil cation exchange capacity. These findings are consistent with reports from studies where biochar improved soil nitrogen status (Okoro et al., 2024). Available phosphorus showed a marked increase with biochar application, rising from 2.57 ppm in the control to 4.10 ppm at 15 t ha^{-1}. The significant increase at higher application rates suggests reduced phosphorus fixation and improved availability under less acidic conditions. Enhanced phosphorus availability is crucial for root development and reproductive growth. Exchangeable calcium increased from 2.54 cmol kg^{-1} in the control to 2.98 cmol kg^{-1} at 15 t ha^{-1}, with 10 and 15 t ha^{-1} showing similar values. Magnesium also increased significantly from 1.61 to 1.87 cmol kg^{-1} across treatments. These increases indicate improved base saturation and soil fertility status. Exchangeable potassium and sodium also increased with biochar application. Potassium rose from 1.49 cmol kg^{-1} in the control to 1.57 cmol kg^{-1} at 15 t ha^{-1}, while sodium increased from 1.13 to 1.35 cmol kg^{-1}. The increase in these bases reflects the nutrient-rich nature of biochar and its ability to supply and retain essential cations in the soil. Overall, the significant improvement in soil chemical properties observed in this study demonstrates the effectiveness of biochar in enhancing soil fertility. These improvements are in agreement with findings by Agbede and Adekiya (2020), who reported that biochar is an effective soil amendment for improving soil chemical fertility and sustaining agricultural productivity in tropical agroecosystems.

CONCLUSION

The study demonstrated that biochar application significantly improved soil physicochemical properties and maize (*Zea mays L.)* productivity under tropical soil conditions. Both soil physical and chemical properties responded positively to increasing biochar rates. Bulk density decreased, while total porosity, moisture retention, and hydraulic conductivity increased progressively, indicating better soil structure and water infiltration into the soil. Similarly, soil chemical properties including pH, organic carbon, total nitrogen, available phosphorus, and exchangeable bases were enhanced, reflecting improved fertility status of the soil. The improvements in soil quality translated into better crop performance. Maize growth parameters such as plant height and stem girth increased consistently with biochar application. In addition, biochar accelerated reproductive development by reducing days to tasseling and silking while maintaining a stable tasseling–silking interval. The yield and yield components, including grain yield and cob length, were significantly enhanced, with the highest values recorded at 15 t ha^{-1}. In other words, the results show that biochar is an effective soil amendment for improving soil health and maize productivity in tropical agroecosystems. It can therefore be concluded that biochar application offers a sustainable strategy for restoring degraded soils and enhancing maize production in tropical soils.

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AUTHORS' CONTRIBUTIONS

All the authors contributed equally to this research work.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ETHICAL APPROVAL

Not applicable.

CONSENT FOR PUBLICATION

Not Applicable

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AVAILABILITY OF DATA AND MATERIALS

All datasets analyzed and described during the present study are available from the corresponding author upon reasonable request.

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