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IMMEDIATE AND RESIDUAL EFFECT OF BIOCHAR ON SELECTED SOIL PROPERTIES OF COARSE-TEXTURED-SOIL AND AGRONOMIC PERFORMANCE OF MAIZE

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ABSTRACT

The management of large volumes of abattoir waste generated in Nsukka metropolis has been a serious environmental concern. This study investigated the immediate and residual effects of cow dung biochar on selected properties of coarse-textured soil and agronomic parameters of maize in Nsukka, southeastern Nigeria. The treatments consisted of biochar application rates of 0, 10, 20 and 30 t ha^{-1}, replicated six times in a Completely Randomized Design, with maize (*Zea mays*) as the test crop. Agronomic data (leaf length, leaf width, plant height, plant girth, number of leaves) were collected throughout the 12-week experimental period. Soil samples were collected and analyzed at the end of the study. Both soil and agronomic data were analyzed statistically using the GENSTAT software. The results showed that biochar-amended plots had a significant effect ($P < 0.05$) on most of the soil and agronomic properties evaluated. Soil pH, soil organic matter (SOM), total nitrogen (TN), available phosphorus (P), calcium (Ca), leaf length, leaf width, plant height and number of leaves increased with increasing rates of biochar application in both the 2020 and residual planting seasons. In addition, macro-, micro- and total porosity, saturated hydraulic conductivity, magnesium (Mg), hydrogen (H), cation exchange capacity (CEC), and plant girth significantly increased with increasing biochar application rates during the 2020 planting season only. Aluminum (Al^{3+}) was not significant in either planting seasons. Bulk density decreased with increasing biochar rates in both planting seasons. It can be concluded that cow dung biochar improves both soil properties and maize agronomic performance. Further studies are recommended to determine the optimal minimum application rate, with 10 t ha^{-1} suggested as a potentially effective threshold for improving soil quality and maize productivity.

Keywords: Cow dung biochar, agronomy, soil quality, soil productivity, abbatoir waste, environment.

INTRODUCTION

In the tropics, particularly in Nigeria, soil-related issues are among the major constraints to crop production (Adekiya et al., 2020). Soils in this region commonly exhibit low fertility, acidity, and soil organic matter (SOM), as well as weak soil structure, high susceptibility to erosion, and poor soil moisture storage and retention (Azuka and Ekette, 2024). These challenges are further exacerbated by rapid population growth, food insecurity, increased levels of poverty, agricultural expansion, declining soil quality, nutrient depletion, and other anthropogenic activities, leading to the urgent need for increased and sustainable agricultural production (Oladele and Awodun, 2014). Achieving sustainable agricultural production under these conditions

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is difficult without the use of fertilizers or soil amendments. Biochar, in particular, has been recommended by several authors for improving fertility and crop performance (Ndzeshala et al., 2022; Azuka, 2024).

Biochar is the product of pyrolysis of organic materials in the absence of oxygen or little oxygen and at high temperature (Adekiya et al., 2019). Biochar can be generated from a wide variety of different feedstocks, including organic and inorganic wastes, plant-based materials, and wood-based products. The physicochemical properties of biochar depend on the type of biomass used for pyrolysis conditions, such as charring time, rate and temperature (Mukherjee and Lal, 2013). In addition, the effects of biochar on soil and crop performance vary depending on the agricultural system, crop type, climatic conditions and fertilization (Khan et al., 2024; Leogrande et al., 2024; Pandit et al., 2018). Research interest in biochar has grown rapidly not only because of its potential to support sustainable agricultural production and carbon sequestration, but also due to its ability to enhance soil fertility and improve nutrient retention (Osaji et al., 2017).

Numerous studies, both globally and locally, have reported on the beneficial effects of biochar on soil properties and crop yield. Specifically, biochar has been shown to improve the quality of sandy loam Alfisol by enhancing cocoyam yield, improving soil physical properties and increasing resistance to erosion (Adekiya et al., 2020). Similarly, in the structurally degraded soils of Abakaliki, Southeastern Nigeria, Osaji et al. (2017) and Njoku et al. (2016) reported significant improvements in soil properties and agronomic parameters following biochar application, compared to the control plots. Additionally, biochar amendments have been found to increase soil water holding capacity (Prajakta et al., 2021; Razzaghi et al., 2020), as well as increase soil porosity and infiltration rate (Azuka, 2024; Aslam et al., 2014).

The residual effects of previously applied biochar on soil properties and crop yield have been documented in the literature (Leogrande et al., 2024; Rahim et al., 2018; Sara and Shah, 2018). In this sense, it has been reported that agronomic parameters and soil properties were significantly improved in plots that had received biochar, compared to the control plots. Similarly, other studies have reported that water holding capacity, nitrogen (N), phosphorus (P), and potassium (K) levels increased with the use of biochar as soil amendment (Fachini et al., 2021; Prajakta et al., 2021).

In Nigeria, the demand for cereals, particularly maize, is steadily increasingly. Maize serves as a staple food crop, a source of animal fees and raw material for agro-based industries (Ndzeshala et al., 2022). Maize production in Nsukka, Southeastern Nigeria, is a major agricultural activity, with the region experiencing suitable climatic conditions for maize growth. However, the majority of farmers in this region are smallholders who cultivate maize at subsistence level. Most of these farmers use organic manures such as poultry droppings, household refuse, effluents, and pig slurry as fertilizers. Cow dung is rarely used due to its low mineralization rate, highlighting the need to convert it into a more efficient and stable form - biochar. Several studies have demonstrated the positive effects of biochar as an amendment on soil properties and crops yields. However, there is still limited information regarding the persistence and long-term impacts of biochar in tropical soils, particularly its residual impact on soil health and crop performance. Therefore, the present study was designed to examine the immediate and residual effects of biochar on soil properties and the agronomic performance of maize. Specifically, the objective of this study was to assess the effects of biochar on the properties of coarse-textured soil and agronomic performance of maize in Southeastern Nigeria.

MATERIALS AND METHODS

Description of the study area

The study was carried out during the 2020 cropping seasons in the glasshouse of the Department of Soil Science, University of Nigeria, Nsukka. The study area is located within the derived savannah agro-ecological zone of Nigeria (longitude 7°25’20.82”E and latitude 6°51’47.408”N), with an elevation of 436 m above sea level (Fig. 1). The region presents a bimodal rainfall pattern, with peaks occurring from April to July and September to October, separated by a brief dry interval in August, commonly referred to as the ‘August break’. The total annual rainfall is approximately 1600 mm, with relative humidity rarely dropping below 60% (Asadu, 2002). Average minimum and maximum temperatures are about 22 °C and 30 °C, respectively. The soil is very deep, dark-reddish brown at the top layer and reddish in the subsoil. It is sandy in texture, extremely acid, with high bulk density, and low levels of total nitrogen, phosphorus, and exchangeable Ca. It also has low levels of exchangeable Mg, and a very low cation exchange capacity (CEC) based on the classification standards for tropical soils proposed by Enwezor et al. (1989) and Shehu et al. (2015) (Table 1).

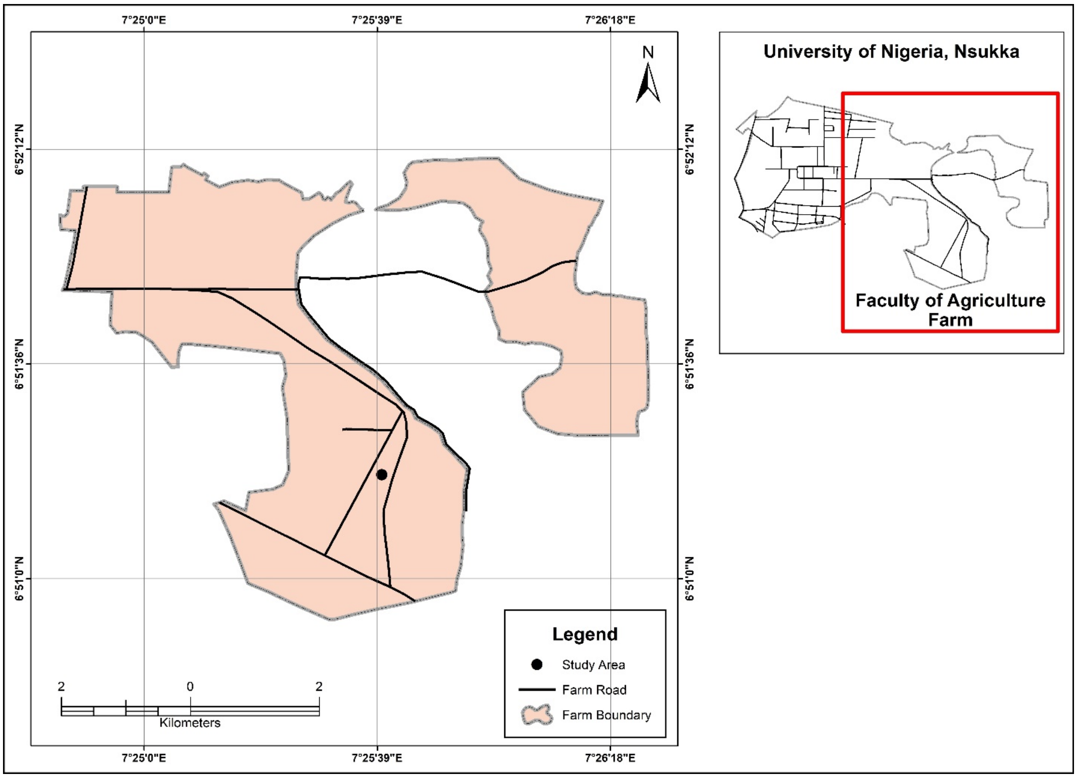

Fig. 1. Map of the University of Nigeria Farm indicating the study area.

Table 1. Properties of the cow dung biochar and soil used in the study.

Test Property	Soil	Biochar
Bulk Density (Mg m^{-3})	1.68	-
Macro porosity (%)	10.72	-
Micro porosity (%)	30.02	-
Total porosity (%)	40.72	-
Hydraulic Conductivity (cm h^{-1})	11.61	-
Mean Weight Diameter (mm)	0.699	-
% Aggregate Stability	17.5	-
pH (H_20)	4.3	8.6
pH (KCl)	4.1	7.6
Soil Organic Carbon (g kg^{-1} %)	11.3	34.23
Total Nitrogen (g kg^{-1} %)	0.08	1.9
Available Phosphorus (mg kg^{-1})	55.9	132.4
Exchangeable Al (mg cmol kg^{-1})	1.4	-
Exchangeable H (mg cmol kg^{-1})	3.6	-
Exchangeable Ca (mg cmol kg^{-1})	0.2	-
Exchangeable Mg (mg cmol kg^{-1})	0.4	-
CEC (cmol kg^{-1})	4.4	-

Biochar source and preparation

The amendment material, cow dung, was sourced locally from the abattoir at Ikpa market, Nsukka, Enugu State, and subsequently converted to biochar through pyrolysis. The pyrolysis process lasted approximately 4-6 hours at a temperature range of 550-600° C. To enhance process efficiency and facilitate a faster biochar production, the cow dung was first air-dried and ground to increase surface area. Pyrolysis was carried out using an improvised kiln of 10 kg capacity, constructed from a cylindrical drum punctured at the sides. The cow dung was poured inside the cylindrical drum, sealed tightly with a lid, and heated over a closed-chamber furnace. During pyrolysis, the drum was continuously rotated to ensure uniform heating. A bright green smoke emitted from the perforations of the drum signaled the completion of the pyrolysis process. Subsequently, the resulting biochar was allowed to cool, crushed, and sieved through a 2 mm mesh for laboratory analysis. Selected properties of both the cow dung biochar and the soil used in the study are shown in Table 1. Generally, the soil presented low permeability (11.61 cm h^{-1}) and moderate porosity. Soil pH was strongly acidic (4.3), whereas structural stability indices, such as aggregate stability and mean weight diameter, as well as available phosphorus (P), soil organic carbon (SOC), and total nitrogen (TN) contents were all very low or poor. Cation exchangeable capacity (CEC) and all exchangeable cations indicated moderate soil fertility, whereas bulk density was high (1.68 Mg m^{-3}), suggesting compaction. In contrast, the cow dung biochar has a slightly alkaline pH and was rich in SOC, N, and P.

Experimental design and field operations

The experiment was laid out in a Completely Randomized Design (CRD) and replicated six times in the glasshouse to assess the effects of biochar on soil properties and agronomic parameters. Biochar was applied at rates of 0, 10, 20 and 30 t ha^{-1} to planting pots, each containing 4 kg of top soil (Table 1) collected from the Department of Soil Science, Research Farm, University of Nigeria, Nsukka, Enugu State, at a depth of 0-20 cm. The soil and biochar were thoroughly mixed and watered to field capacity every two days using 450 mL of water for two weeks prior to sowing, to facilitate the mineralization process. Maize (Oba Super 2) seeds were sown at two seeds per pot and thinned to one seedling per pot one week after germination. NPK 15:15:15 fertilizer was applied to all pots at a rate of 200 kg ha^{-1} two weeks after planting. The pots were watered three times a week and the experiment lasted for 8 weeks. The residual effect of the previous amendments on soil and agronomic parameters was assessed one month after the first trial ended during the same cropping season in order to evaluate crop response to the major nutrients applied previously. All management practices in the first trial, except for the addition of biochar, were repeated for another 8 weeks under similar conditions. At the end of each trial, soil samples (core and auger) were collected from each pot for laboratory analysis.

Determination of soil physical and chemical properties

Soil samples collected pre- and post-harvest at the end of the study were analyzed using the following method. Bulk density was obtained by a cylindrical core method (Blake and Hartge, 1986). Thereafter, the pore size distribution of the soil core was determined using the method described by Flint and Flint (2002). In this method, macroporosity was determined as shown in equation (1) below:

$$\text{Macroporosity} = \frac{\text{Volumetric moisture content of the soil drained at 60 cm (water) tension}}{\text{Bulk volume of soil}} \quad (1)$$

The microporosity was determined as shown in equation (3) below:

$$\text{Microporosity} = \frac{\text{Volumetric moisture content of the soil retained at 60 cm (water) tension}}{\text{Bulk volume of soil}} \quad (2)$$

Total porosity was calculated from bulk density using the formula in equation (3):

$$TP = 100\left(\frac{1 - Bd}{Pd}\right) \quad (3)$$

where Bd = Bulk density, and Pd = Particle density (assumed to be 2.65 g cm^{-3}). Saturated hydraulic conductivity (K_{sat}) was determined by the constant – head perimeter method (Reynolds, 1993b), and calculated using Darcy's equation (4):

$$K_{sat} = \frac{Q}{AT} \times \frac{L}{H} \quad (4)$$

where K_{sat} is the hydraulic conductivity cm hr^{-1}, Q is the steady-state volume of flow (cm^3), L is the length of core sample (cm), A is the cross- sectional area (cm^2), t is change in time interval and H is hydraulic head change (cm). Soil pH was determined using a digital pH meter in a soil solution ratio of 1:2.5 (Mclean, 1982). SOC was determined using the modified Walkley and Black method as described by Nelson and Sommer (1996). TN was determined using the modified kjeldahl digestion procedure (Bremmer and Mulvaney, 1982). Available P was extracted using Bray-2, following the procedure described by Olson and Sommers (1982). The complexometric titration method, described by Chapman (1982), was used to determine Ca and Mg. Exchangeable acidity was determined using the method of McLean (1982), and CEC was determined using the ammonium acetate displacement method as described by Rhodes (1982).

Determination of agronomic parameters

The following agronomic parameters were measured at 2, 4, 6 and 8 weeks after planting: plant height, leaf width, leaf length, plant stem girth, and number of leaves.

Statistical analysis

The soil and agronomic data collected were subjected to analysis of variance (ANOVA) for a Completely Randomized Design (CRD) using GENSTAT software 4.0. Significant differences among means were separated using Fischer's Least Significant Difference (F-LSD) at 5% probability level.

RESULTS

Effect of biochar on soil physical properties

The results presented in Table 2 show the effect of biochar on soil physical properties in the 2020 and residual (second cropping) seasons. In both cropping seasons, bulk density was significantly ($P<0.05$) reduced with biochar amendment, ranging from 1.53 to 1.62 mg m^{-3}. The order of decrease in bulk density was as follows: 0 t ha^{-1} > 10 t ha^{-1} > 20 t ha^{-1} > 30 t ha^{-1}. Macro-, micro- and total porosity, as well as hydraulic conductivity, significantly increased in the 2020 cropping with biochar application, in the following order: 30 t ha^{-1} > 20 t ha^{-1} > 10 t ha^{-1} and 0 t ha^{-1}. However, biochar had no significant effect on these properties in the residual cropping season.

Effect of biochar on soil pH, SOC, TN, available P, and CEC

Table 3 shows the effect of biochar on soil pH, SOC, TN, and available P in both the 2020 and residual seasons. In both seasons, biochar significantly ($p < 0.05$) increased the concentrations of OM, TN, available P, and pH, with the highest values being observed with biochar application rates of 30 and 20 t ha^{-1}. Notably, from the 2020 season to the residual effect period (measured days or months after the initial eight weeks of sampling), a gradual decline was observed in OM, TN, and available P, indicating a reduction over time.

Effect of biochar on exchangeable cations and acidity and CEC

The results in Table 4 show the effect of biochar on exchangeable cations, acidity, and CEC. In both seasons, biochar significantly increased the concentrations of Ca^{2+}, with the highest values of 0.64 cmol kg^{-1} at 20 t ha^{-1} treatment and 0.44 cmol kg^{-1} for the 30 t ha^{-1} treatment in the 2020 and residual seasons, respectively. Additionally, biochar significantly improved the concentration of Mg and CEC in the 2020 season, but not in the residual season. Similarly, biochar reduced the H^+ concentration in the 2020 season, with lowest values (2.34 cmol kg^{-1}**)** observed at an application rate of 30 t ha^{-1}. Most of the measured variables decreased from the 2020 season to the residual season.

Table 2. Effect of biochar on soil physical properties in the 2020 and residual cropping seasons.

Biochar	BD (Mg m^{-3})		Macro P (%)		Micro P (%)		TP (%)		Ksat (cm h^{-1})	
(t ha^{-1})	2020	Res	2020	Res	2020	Res	2020	Res	2020	Res
0	1.62a	1.62a	7.76a	7.76a	32.64a	42.64a	40.40a	50.40a	19.7a	11.97a
10	1.58abc	1.61a	9.51bc	98.51a	42.23b	42.23a	51.75b	510.75a	28.8b	11.88a
20	1.56bc	1.60ab	10.01c	78.01a	44.68c	44.68a	54.69b	512.69a	48.5c	14.85a
30	1.53c	1.57b	10.45c	78.45a	45.19c	44.19a	55.64b	512.64a	53.7d	13.37a
$F\text{-}LSD_{0.05}$	0.05	0.03	1.43	NS	1.82	NS	4.29	NS	2.89	NS

Res =residual, NS = not-significant, P = porosity, TP = total porosity, BD = bulk density, Ksat = saturated hydraulic conductivity.

Table 3. Effect of biochar on soil pH, OC, TN and available P in the 2020 and residual cropping seasons.

Biochar	pH (H_2O)		OM (g kg^{-1})		TN (g kg^{-1})		Av. P (mg kg^{-1})	
(t ha^{-1})	2020	Res	2020	Res	2020	Res	2020	Res
0	4.8^a	5.1^a	1.84^a	1.44^a	0.64^a	0.49^a	7053.1^a	50.7^a
10	5.2^b	5.1^a	2.57^b	2.28^b	0.81^b	0.83^b	86.1^b	51.2^a
20	5.6^c	5.4^b	3.23^c	2.68^c	0.85^c	0.88^c	89.2^b	57.5^b
30	5.8^c	5.4^b	3.88^d	2.88^c	0.89^d	0.91^d	93.4^b	62.9^c
F-LSD$_{0.05}$	0.20	0.21	0.401	0.25	0.01	0.11	9.19	3.68

Res =residual, NS = not-significant, P = porosity, TP = total porosity, BD = bulk density, Ksat = saturated hydraulic conductivity.

Table 4. Effect of biochar on exchangeable cations, acidity, and CEC in the 2020 and residual cropping seasons.

Biochar	Ca^{2+}		Mg^{2+}		Al^{3+} cmol kg^{-1}		H^+		CEC	
(t ha^{-1})	2020	Res	2020	Res	2020	Res	2020	Res	2020	Res
0	0.29a	0.23a	0.66a	0.57a	0.31a	0.33a	3.81a	1.51a	5.16a	4.76a
10	0.50b	0.28a	1.18b	1.08a	0.16a	0.37a	2.38b	1.33a	5.31a	5.27a
20	0.64c	0.34ab	1.36c	1.09a	0.18a	0.48a	2.51b	1.36a	6.18b	5.42a
30	0.63c	0.44ab	1.23bc	1.11a	0.09a	0.49a	2.34b	1.44a	7.53c	6.02a
F-LSD$_{0.05}$	0.11	0.11	0.13	NS	NS	NS	0.37	NS	0.66	NS

Res = residual, NS = not-significant, Ca = exchangeable calcium, Mg = exchangeable magnesium, Al = exchangeable aluminum, CEC = cation exchange capacity.

Effect of biochar on maize growth parameters

The agronomic data on the effect of biochar on maize growth parameters are shown in Table 5. Biochar significantly increased leaf length, leaf width, plant height, plant girth, and number of leaves, with the highest values recorded at the 30 t ha^{-1} application rate in both seasons, while the least values were observed in 0 t ha^{-1}treatment. Biochar increased leaf length by 18-55% at 2-8 weeks after planting in the 2020 season and by 30-93% at 2-8 weeks after planting in the residual season. Plant height was also increased by 90-151% at 2-8 weeks after planting in the 2020 season, and by 80-90% at 2-8 weeks after planting in the residual season. However, in week 6 of residual season, there was no significant effect of biochar on maize growth parameters.

DISCUSSION

Biochar application significantly reduced soil bulk density and increased porosity and hydraulic conductivity. The results of this study corroborate the findings of other researchers, who reported that biochar application led to a decrease in soil bulk density and an increase in porosity (Adekiya et al., 2019; Karim et al., 2020; Nyambo et al., 2018). The decrease in soil bulk density and increase in porosity due to biochar application could be attributed to the relatively lower bulk density of biochar compared to that of the soil (Azuka and Ekette, 2024). Several authors have attributed the decrease in soil bulk density and increase in porosity of biochar-amended soils to the physical dilution effect of biochar and its interaction with soil particles (Lehmann et al., 2011; Alburquerque et al., 2014; Blanco-Canqui, 2017). The extent of such dilution effect can be particularly pronounced when the difference in density of the materials is large (Blanco-Canqui, 2017). Hseu et al. (2014) also attributed changes in soil porosity to the formation of macropores and the rearrangement of soil particles. This was further confirmed by Blanco-Canqui (2017), who reported that biochar application could increase soil porosity by enhancing soil aggregation and reducing soil packing. Due to the high porosity and low bulk density of biochar (Adekiya et al., 2019; Joseph et al., 2010), its application in the soil increases soil porosity and, correspondingly, reduces the soil bulk density (Adekiya et al., 2019; Karim et al., 2020; Nyambo et al., 2018). This

Table 5. Effect of biochar on maize growth parameters in the 2020 and residual cropping seasons.

Biochar	LL (cm)		LW (cm)		PH (cm)		PG (cm)		NL	
(t ha^{-1})	2020	Res	2020	Res	2020	Res	2020	Res	2020	Res
Week 2										
0	29.44a	12.39a	2.078a	1.40a	18.30a	12.22a	2.19a	0.99a	5.00a	2.44a
10	35.06b	16.76b	2.300b	1.51b	24.74b	16.87b	2.41b	1.20b	5.89b	3.33b
20	38.36c	21.41c	2.333b	1.69c	28.98c	18.32c	2.50bc	1.44c	6.00b	4.00c
30	39.09c	25.91d	2.567c	1.94d	36.62d	23.08d	2.60c	1.63d	5.89b	4.33d
F-LSD$_{0.05}$	3.125	1.311	0.100	0.087	1.979	1.165	0.177	0.061	0.229	0.162
Week 4										
0	55.18a	20.19a	3.19a	1.68a	36.62a	22.33a	2.76a	1.29a	9.44a	4.22a
10	68.92b	23.69b	3.41b	1.90b	52.38b	26.46b	3.70bc	1.54b	10.11ab	5.56b
20	72.03b	28.67c	4.00c	2.12c	62.06c	29.67c	3.47b	1.67c	10.56bc	6.00c
30	85.67c	37.78d	4.66d	2.46d	69.57d	35.77d	3.81c	1.94d	11.44c	6.67d
F-LSD$_{0.05}$	5.530	2.611	0.204	0.119	3.400	2.328	0.306	0.063	0.888	0.281
Week 6										
0	77.74a	27.43a	4.68a	2.13a	64.48a	32.14a	3.59a	1.84a	12.78a	6.67a
10	88.49b	30.44b	5.51b	2.37b	87.97b	40.42b	4.61b	1.92a	14.89bc	7.67b
20	88.31b	35.52c	5.81c	2.68c	100.6c	51.27c	4.41b	2.26a	14.78b	8.44c
30	95.96c	46.04d	6.54d	3.12d	110.9d	60.32d	5.04c	2.57a	15.56c	9.33d
F-LSD$_{0.05}$	3.623	1.979	0.129	0.105	3.100	1.543	0.143	NS	0.688	0.162
Week 8										
0	83.57a	32.30a	5.46a	2.37a	90.29a	39.38a	4.56a	1.97a	16.33a	8.44a
10	98.11b	37.57b	6.62b	2.79b	188.1c	49.21b	5.31b	2.38b	17.44b	9.67b
20	97.94b	46.74c	7.02c	3.13c	165.8b	59.61c	5.30b	2.66c	16.78a	10.33c
30	109.0c	61.87d	7.77d	3.89d	226.5d	72.08d	6.04c	3.14d	19.44c	12.00d
F-LSD$_{0.05}$	3.200	1.711	0.163	0.119	2.758	1.654	0.175	0.087	0.932	0.162

Res = residual, NS = not-significant, LL = Leaf length, LW = Leaf Width, PH = Plant Height, PG = Plant Girth, NL = Number of leaves.

indicates that the biochar porosity is high, and thus its application can decrease bulk density by increasing soil porosity and saturated hydraulic conductivity (Singh et al., 2022; Azuka, 2024). Similarly, Adekiya et al. (2020; 2022) reported significant improvements in soil properties, including decreased bulk density and increased porosity, following biochar application. This improvement was attributed to the porous nature of biochar, which created additional pores in the soil matrix (Azuka, 2024).

Generally, studies have shown that increasing SOC by the addition of organic amendments could significantly decrease bulk density and increase porosity, saturated hydraulic conductivity, infiltration rate and water holding capacity (Azuka and Idu, 2021; Busscher et al., 2011; Zhang et al., 2016). Azuka and Idu (2021) reported that the application of poultry manure and pig slurry led to a decrease in soil bulk density, increased porosity, and improved saturated hydraulic conductivity of the soil.

The soil used for this study was extremely acidic in nature as shown by the presence of acidic cations (Al^{3+}, H^{+}), which are typically dominant in acidic soils (Table 1). Biochar application resulted in an increase in soil pH from very slightly acidic (4.8) to moderately acidic (5.6) in the 2020 season. Similarly, in the residual season, pH remained within the range of 5.1 to 5.4. The increase in soil pH observed in this study corroborated the findings of Lehmann et al. (2003), who reported that biochar typically improves the pH of acidic soils due to the liming effect associated with carbonate salts in the ash component of biochar. Adekiya et al. (2020) also observed a significant increase in soil pH following biochar application in Alfisols in southwestern Nigeria. Additionally, Osaji et al. (2017) reported a similar effect of biochar in increasing soil pH with varying applications rates. In the present study, the results show that the addition of biochar not only increases soil pH but also helps sustain and regulate soil pH. This is important as it helps mitigate excessive buildup of acidity in the soil, thus creating a more favorable environment for plant growth.

The application of different rates of biochar had a significant effect on SOM in the treated plots compared to the control in both cropping seasons. This supports the findings of previous studies that reported that SOM significantly increased with increasing biochar application rates (Angst et al., 2014; Azuka and Ekette, 2024). The results of the present study also agree with the findings of Jien and Wang (2013) and Azuka and Ekette (2024), who observed that biochar addition increases SOM content. The increase in SOM content observed in our study may be attributed to the capacity of biochar to sequester carbon within the soil system (Lehman and Joseph, 2015). However, the effectiveness of biochar in enhancing SOM might not depend solely on its carbon sequestration potential, but also on its ability to create of a favorable environment for the process (Yan et al., 2019).

Similarly, the improvement in SOM resulting from biochar application also led to higher concentrations of N and available P in the biochar-amended plots in both seasons. The ability of biochar to improve soil nutrient levels, especially N and P, can be attributed to its high carbon content, large specific surface area, porosity, and abundance of negatively charged surface functional groups. In acidic soils, where P is typically fixed by aluminum (Al^{3+}) and iron (Fe^{3+}) ions, biochar increases P availability by raising soil pH, thereby reducing the solubility of Al^{3+} and Fe^{3+} and adsorbing these cations to prevent P fixation. These attributes contribute to increased soil N and P availability, as well as reduced nutrient leaching, which significantly enhance soil fertility (Singh et al., 2022; Chan and Xu, 2009). This aligns with the results of the residual study, which showed that N and P levels remained higher in the previously biochar-amended plots compared to the untreated control. According to Oladele et al. (2024) and Azuka and Ekette (2024), biochar-amended soils retained more N and P from the total N and P input, indicating that biochar could serve as a valuable soil amendment for mitigating N and P leaching and enhancing nutrient use efficiency.

In the present study, biochar significantly improved exchangeable cations and CEC and reduced the exchangeable hydrogen concentrations in the 2020 cropping season. Similar improvements in soil exchangeable cations and CEC, along with a corresponding reduction in exchangeable acidity or H^+ concentration, have been reported by other researchers (Faloye et al., 2024; Liang et al., 2006). These improvements can be attributed to the presence of basic cations in biochar, which are released into the soil upon application, making them more available to plants.

Liang et al. (2006), Sohi et al. (2010), and Jones et al. (2012) attributed the significant increases in Ca^{2+}, Mg^{2+}, and CEC in biochar-amended plots to the presence of cation exchange sites and carboxyl groups on the surface of biochar particles after microbial degradation. The result of the residual study further demonstrated a continued enhancement of basic cations and CEC even without additional applications of biochar or fertilizer. This finding is consistent with the results of Kongthod et al. (2015), who emphasized the role of biochar's surface charge density in nutrient retention. Other studies have also demonstrated that biochar possesses negatively charged surfaces, which improve and enhance its cation adsorption capacity (Lou et al., 2016). These factors enhance soil cation exchange capacity with a high potential to reduce the leaching of essential cations while increasing the availability of the nutrient in the soil (Agbede and Oyewumi, 2022).

The results of the present study showed that the improvements in soil properties following application of biochar enhanced the agronomic parameters of maize, including leaf length, leaf width, plant height, plant girth, and number of leaves, compared to the control. The findings corroborated those of Major et al. (2010), who reported that biochar can enhance plant growth by improving soil nutrient availability. Other studies have also attributed the positive effects of biochar on agronomic parameters to improved nutrient retention, reduced soil acidity, and increased levels of base cations, CEC and available P (Agegnehu et al., 2017; Osaji et al., 2017). In a recent experiment, Adekiya et al. (2019) applied biochar at rates of 0, 25 and 150 t ha^{-1} using radish as a test crop and observed increased leaf weight, root length, root weight, and root girth. Furthermore, Agbede et al. (2020) reported that biochar application significantly improved soil properties due, which in turn improved the agronomic parameters of cocoyam.

CONCLUSIONS

The results of our study showed that improvements in soil properties due to biochar application led to enhanced agronomic performance in maize. These improvements in both soil and crop were more pronounced with increasing biochar application rates in both the 2020 and residual cropping seasons compared to the control. The greenhouse experiment yielded promising preliminary results regarding soil and maize responses to biochar application rates. The study concludes that biochar application significantly improves key soil properties, which are critical for improved agronomic productivity, with the 30 t/ha rate showing the most substantial effects across both cropping cycles. However, field experiments are required to evaluate and quantify the long-term soil and agronomic benefits of biochar applications on the coarse-textured soils of Southeastern Nigeria.

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