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Understanding the Potentials of Biochar and Nitrogen Fertilizer on Selected Soil Physical Properties and Maize (*Zea mays*) Performance

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Biochar (BC) application has recently gained attention from researchers due to its promising quality of improving soil properties, including physical qualities, and crop performance. Therefore, this study was conducted to evaluate the effect of biochar in combination with nitrogen fertilizer on

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selected soil physical properties and maize performance through a field experiment at the Teaching and Research Farm of the Federal University of Technology, Minna. The study was a 3 x 4 factorial experiment set up in a randomized complete block design (RCBD) with three levels of biochar (0, 2.5, and 5 t/ha) and four levels of fertilizer (0, 40, 80, and 120 kg N/ha), replicated three times. Analysis of variance (ANOVA) was performed on the obtained soil and plant data, and Least Significant Difference (LSD) was used to distinguish the significant means. The findings showed that the soil bulk density and soil moisture constants (SC, FC, PWP, and AWC) were not significantly affected ($p \geq 0.05$) by the application of fertilizer and BC. The emergence of seedlings was not significantly impacted following the application of BC or fertilizer. Grain yields, stover, and plant height were all significantly ($p \geq 0.05$) impacted following the application of nitrogen fertilizer. Plant height was maximum at 80 and 120kg N/ha application, while the control recorded the shortest plant height. Hence, the application of nitrogen fertilizer increased maize plant height, stover, and grain yields significantly ($p \geq 0.05$). Yet, a more long-term study on BC and N fertilizer needs to be done to better understand their impacts on soil and crop performance.

Keywords: Biochar; fertilizer; soil physical properties; soil bulk density; soil moisture; maize.

1. INTRODUCTION

The world's population has been growing recently, and as the population grows, so does the demand for food. Farmers have embraced intense land cultivation year after year in an attempt to meet the demand of the expanding global population, but this has resulted in a loss of organic matter and nutrient mining, which has lowered the soil quality (Oshunsanya & Aliku, 2012). Among other things, using organic and or inorganic manure and soil amendments such as biochar (BC) can make up for the significant loss of soil nutrients (Kareem et al., 2025). The bush fallow system, which allows arable land to return to fallow after three to four years of continuous cultivation, has been the traditional technique of preserving soil fertility and production in most of the world. However, in order to meet the rising demand for food, the fallow period has been shortened to nearly nothing due to socioeconomic pressures and population growth (Asadu & Unagwu, 2012). Over the years, farmers has popularized the continuous use of inorganic fertilizer in order to improve crop yield, but the risk of soil degradation, increasing cost of procurement, and late supply are some challenges faced by the farmers (Chude et al., 2012).

To combat these threatening challenges, the application of biochar and or fertilizer could be one possible solution to improve the soil quality and crop performance. Biochar, a carbon-rich substance created by heating organic materials in the absence of oxygen, has gained broad recognition for its diverse benefits in agriculture (Jing et al., 2020), It has been effectively used to improve soil health (Zhang et al., 2020), enhance the absorption of nutrients by plants (Liu et al., 2021), reduce the impact of both organic and inorganic pollutants (Fedeli et al., 2022; Zhang et al., 2022), and help crops withstand various environmental stresses (Akhtar et al ., 2015; Ali et al., 2017). Additionally, biochar is known to contribute to higher crop productivity. Notably, when used alongside nitrogen fertilizers, this combination has shown promise in boosting soil nitrogen levels and improving nitrogen use efficiency (NUE), which has drawn significant research interest (Xia et al., 2020; Kumar et al., 2024).

Recently, several studies have shown that biochar can improve soil properties, including physical, chemical, biological, hydrological, and crop performance (Blanco-Canqui, 2017; Bohara et al., 2019; Lehmann & Joseph, 2009; Kareem et al., 2025a; Keller 2023; Liman, 2024a). Although combining nitrogen fertilizers with biochar has been identified as a promising approach to enhance soil properties and boost nitrogen availability for plant uptake (Case et al., 2015; Xu et al., 2012), the results are not consistently positive across all studies (Hossain et al., 2020; Ahirwar et al., 2025). For example, a comprehensive review of 124 studies found that in some cases, biochar application may actually reduce nitrogen retention in soils, resulting in an 11–12% decline in the amount of nitrogen accessible to plants (Gao et al., 2019)

Therefore, this study aims to address the impact of biochar as a sustainable agricultural strategy on soil properties and crop performance along with the use of inorganic fertilizer on maize production and the objectives were to evaluate the effect of biochar in combination with nitrogen fertilizer on (i) soil bulk density, saturation capacity (SC), field capacity (FC), permanent wilting point (PWP), and available water capacity (AWC) (ii) seedling emergence, plant height, stover, and grain yield of maize.

2. METHODOLOGY

2.1 Experimental Site

A field experiment was carried out at the Teaching and Research Farm Gidan Kwano Campus of Federal University of Technology Minna, Nigeria. The study area is located between latitude 9° 30´ 30.10´´ and longitude 6° 27´ 2.00 ´´ at elevation ranging from 190 to 216 m above sea level in the Southern Guinea savanna zone of Nigeria (Liman et al., 2025; Odofin, 2017). The study location is also sub-humid with average annual rainfall of 1,284 mm from April to October and a district dry season of about 5 months occurring from November to March with an average temperature of about 33°C (Ojanuga, 2006).

2.2 Experimental Design and Treatments

The study was a 3 × 4 factorial experiments laid out in a randomized complete block design (RCBD) with three levels of biochar (0, 2.5, and 5 t/ha) and four levels (0, 40, 80, and 120 kg N/ha) of N fertilizer (urea) replicated three times. The N fertilizer was applied by side placement at 2 and 6 weeks after sowing (WAS). A total of 36 plots were used in the study, measuring 4 × 4 m each and the plots were separated by a buffer of 1 m, while the replicates were 3 m parts

2.3 Biochar Production and Application

The biochar used in this study was produced from camel foot (*Poliostigma reticulatum*) and bilinga (*Nauclea spp*). These shrubs were sourced from neighboring fallow lands. The feedstock was sun-dried for a week and later converted to biochar by heating using the traditional earthen mound kiln method in the absence of oxygen at a temperature of about 400°C within the kiln. The produced biochar was broadcast on each plot following the application rate, and it was incorporated into the soil manually using hoe two weeks before seed sowing. Two maize seeds of Oba super II variety were planted per hole at a depth of about 3 cm with a spacing of 75 × 25 cm intra and inter row spacing on ridges made manually using hoe. At 2 WAS, seedlings were thinned to one plant per stand. Weeding was done manually using hoe and rake at 2 and 6 WAS.

2.4 Initial Soil Characteristics

Prior to planting, soil samples were collected at random from five locations at the experimental plots at a depth of 0 to 15 cm. Collected samples were mixed to form a composite soil sample where a sub sample was taken, air dried, crushed, and sieved through a 2 mm screen to extract fine particles. Following the International Institute of Tropical Agriculture (IITA, 2012) standard routine procedure, the sieved soil samples were examined for standard soil physical and chemical properties. The hydrometer method was used to determine the particle size distribution. The Walkley-Black method was used to determine the organic carbon content (Nelson & Sommers, 1996) and the pH of the soil was measured at a 1:2 soil-water ratio using a glass electrode pH meter (Basso et al., 2012). The Bray P-1 method was used to estimate the amount of phosphorus, micro-Kjeldahl procedure was used to calculate the total nitrogen, and 1 NNH_4OAC buffer at pH 7.0 was used to extract the exchangeable bases including Ca^{2+}, Mg^{2+}, K^+, and Na^+ respectively. K^+ and Na^+ were estimated using a flame photometer, whereas Ca^{2+} and Mg^{2+} in the extract were measured using an atomic absorption spectrophotometer (Kareem et al., 2025a). Using phenolphthalein indicator, exchangeable acidity (Al^{3+} and H^+) was extracted using 1 N KCl and measured by titration with 0.5 N NaOH. Effective cation exchange capacity (ECEC) was calculated by adding all the exchangeable bases and exchangeable acidity.

2.5 Soil Properties

Following the termination of the field trial, soil samples were collected at random from each plot to determine the soil bulk density (Blake & Hartage, 1986; Kareem et al., 2025b) and soil moisture constants, inclusive of saturation capacity (SC), field capacity (FC), permanent wilting point (PWP), and available water capacity (AWC). For the SC, the collected soil samples were placed in a ring which one end was covered with a piece of cloth, saturated with water, and left to sit for 24 hours. After 24 hours, the rings were transferred into an empty bowl, water was added to the bowl so that the rings were not submerged. The saturated samples were weighed, after which they were oven-dried at 105°C for 48 hours to constant weight. SC was then calculated using

$$SC = \frac{m1-m2}{m2-m3} \times 100$$

Where;

m1: mass of saturated soil + core ring,
m2: mass of oven-dried soil + core ring,
m3: mass of empty core ring

FC and PWP were calculated using the saturation water percentage-based model reported by Mbagwu and Mbah, (1998).

FC = 0.79 (SC) – 6.22 (r = 0.972)

PWP = 0.51 (SC) – 8.65 (r = 0.949)

AWC = difference between FC and PWP

The bulk density (BD) was calculated using the oven-dried soil sample in the formula below

$$BD = \frac{m1-m2}{\pi r^2 h}$$

Where;

m1: mass of oven dry soil + core ring
m2: mass of empty core ring
r: internal radius of the core sample
h: height or length of core sampler

2.6 Crop Parameter

The number of seedling emergence per plot was counted 2 WAP in percentage. Ten maize plants per plot were sampled for plant height at 16 WAP using a measuring tape from the ground to the tip of each plant. At crop maturity, cobs from the inner rows were harvested, sun-dried (with a moisture level of 13 – 14 %), threshed, and used for estimating grain yield per plot. Following crop harvest, stover yield was calculated. After shelling, leaves, stems, husk, and cobs were also weighed.

2.7 Statistical Analysis

All collected data were subjected to ANOVA using the General Linear Model (GLM) in SAS V 9.0. The Shapiro-Wilk test was done to check for normality of data. Levene's test was done to check for equality of variance. When the Global F value at a probability level of 5% ($p \geq 0.05$) was found to be significant, means were separated using least significant difference (LSD).

3. RESULTS AND DISCUSSION

3.1 Initial Soil and Biochar Characteristics

From the analysis of the study area's initial soil (0 – 15 cm depth) characteristics, the soils were classified as sandy loam. The water's pH (5.4) was acidic. Both organic carbon and total nitrogen (3.80 and 0.11 g/kg) were low. The accessible phosphorus (6.89 mg/kg) and ECEC (10.09 cmol/kg) were low as well. The levels of exchangeable bases, including calcium, magnesium, potassium, and sodium, ranged from 0.26 to 6.00 cmol/kg (Table 1). According to another study, a typical savanna soil has these characteristics (Lawal et al., 2013, 2014; Afolabi et al., 2014). Table 2 displays the distinctive properties of the biochar with a high C:N ratio of 70.5 which is in line with those created by other authors (Fagbenro et al., 2013; Fagbenro et al., 2018) from sawdust and Gliricidia.

Table 1. Soil characteristics prior to planting

Soil Properties	Values
Sand (g/kg)	792
Silt (g/kg)	33
Clay (g/kg)	175
Textural Class	Sandy Loam
pH (H2O)	5.4
Organic Carbon (g/kg)	3.8
Total Nitrogen (g/kg)	0.11
Available Phosphorus (mg/kg)	6.89
Exchangeable Bases (cmol/kg)	
Ca	6.0
Mg	2.53
K	0.35
Na	0.26
Exchangeable Acidity (cmol/kg)	1.02
ECEC	10.09

ECEC: Effective cation exchange capacity

Table 2. Chemical Properties of the biochar

Parameter	Value
pH (H_2O)	8.3
Organic Carbon (%)	63.5
Total Nitrogen (%)	0.9
Phosphorus (%)	1.7
Ca (%)	3.54
Mg (%)	3.08
K (%)	2.74
CEC (cmol/kg)	96.09

Table 3. Main effects and interactions of biochar and nitrogen fertilizer on selected soil physical components

	BD (g/cm^3)	SC (g/g)	FC (g/g)	PWP (g/g)	AWC (g/g)
Biochar (BC) (t/ha)					
0	1.59	0.22	0.12	0.05	0.08
2.5	1.61	0.22	0.11	0.03	0.08
5	1.59	0.22	0.11	0.03	0.09
SE ±	0.05	0.01	0.01	0.01	0.01
Fertilizer (kg N/ha)					
0	1.61	0.22	0.11	0.05	0.08
40	1.56	0.22	0.12	0.04	0.08
80	1.58	0.23	0.12	0.03	0.09
120	1.62	0.21	0.11	0.03	0.08
SE ±	0.05	0.01	0.01	0.01	0.01
Interaction					
Fertilizer × BC	ns	ns	ns	ns	ns

Means with no letters down the column for each factor are not significantly different (p ≥ 0.05); ns: Not significant; SE ±: Standard error; SC: saturation capacity; FC: field capacity; PWP: permanent wilting point; AWC: available water capacity; BD: bulk density

Table 4. Main Effects and Interactions of Biochar and Nitrogen Fertilizer on growth and yield components

	Seedling emergence (%)	Plant height (cm)	Stover yield (t/ha)	Grain yield (t/ha)
Biochar (BC) (t/ha)				
0	81	184.03	3.75	1.28
2.5	81	173.79	4.10	1.27
5	80	177.22	4.31	1.36
SE ±	1.58	4.46	0.32	0.12
Fertilizer (kg N/ha)				
0	81	134.09c	2.08c	0.12d
40	82	178.82b	3.95b	1.13c
80	79	198.98a	4.90ab	1.70b
120	80	201.45a	5.28a	2.26a
SE ±	1.82	5.15	0.37	0.14
Interaction				
Fertilize × BC	ns	ns	ns	ns

Means with no letters down the column for each factor are not significantly different (p ≥ 0.05); ns: Not significant; SE ±: Standard error; SE ± = Standard error, ns = not Significant

3.2 The Main Effect of Biochar and N Fertilizer on Soil Physical Properties

The soil bulk density and moisture constants (SC, FC, PWP, and AWC) were not significantly affected (P ≥ 0.05) by the application of fertilizer and biochar (Table 3). This may be associated with the application rates of biochar used. According to other research (Githinji, 2013; Liman, 2024a), increasing the rate of biochar application also resulted in a considerable decrease in bulk density since biochar has a very high porosity and increases the pore volume when utilized in soil. This finding is consistent with that of Njoku et al. (2015), who also found that soil physical characteristics were similarly unresponsive to varying amounts of biochar application.

3.3 The Main Effect of Biochar and N Fertilizer on Maize Growth and Yield Parameters

The application of biochar and fertilizer did not significantly impact the emergence of seedlings (Table 4). However, the application of fertilizer had a significant impact on maize grain yields, stover, and plant height (Table 4), respectively. Compared to 40 kg N/ha, which gave the shortest plant height, 80 and 120 kg N/ha produced taller plants. The stover yield of 120 kg N/ha was the greatest and did not differ significantly from that of 80 kg N/ha. Additionally, there was no significant difference in stover yield between 80 and 40 kg N/ha, but a significant difference between 40 and 120 kg/ha was recorded (Table 4). As the level of fertilizer application increases, so does the grain yield, which may be explained as a result of the fertilizer application rates leading to grain yield and robust growth of maize (Asai et al., 2009; Babatola et al., 2006; Zhang et al., 2011; Fagbenro et al., 2018). Further, the application of biochar had no significant impact on the plant height, stover, and grain yield (Table 4). Similar results were reported from other studies (Zhang et al., 2011; Fagbenro et al., 2018; Liman et al., 2024b), and they linked the reasons to soil type, crop type, climate, and chemical and physical properties of the biochar used. Another study by Kareem et al. (2023), reported that biochar had no significant effect on cucumber yield or growth. They (Kareem et al., 2023) ascribed the cause to the soil's CEC content. In a similar vein, Keller et al. (2023), found no increase in pinto bean and sorghum sudan yield following the application of biochar. Another similar outcome after the application of fertilizer and biochar was also reported by Kareem et al. (2025b), while other studies have reported the negative effect of biochar application on crop yield (Chan et al., 2007; Asai et al., 2009).

4. CONCLUSION

The application of biochar and N fertilizer did not appear to impact the soil's physical characteristics. However, the N fertilizer application greatly increased the maize plant height, stover, and grain yield, even when the N fertilizer application was at a lower level, suggesting that at a lower level of fertilizer application, crop improvement will be enhanced, noting that higher application gave greater performance. Further, more long-term research will be needed to better understand the effect of biochar and fertilizer on soil physical properties.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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