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Co-application of kenaf-derived biochar and NPK fertiliser on maize agronomic and soil biological properties in a tropical Alfisol under greenhouse conditions

***,[1]Osunde, O.M., [2]Taiwo, L.B., [3]Fashina, C.D., [1]Olatoberu, F.T., [4]Akintibu, S.T. and [1]Oladimeji, O.J.**

[1]Department of Soil Science and Land Resources Management, Obafemi Awolowo University, Ile Ife, Osun State, Nigeria
[2]Institute of Agricultural Research and Training, Moor Plantation, Ibadan, Obafemi Awolowo University, Ile-Ife, Nigeria
[3]Department of Microbiology, Obafemi Awolowo University, Ile-Ife, Nigeria
[4]Department of Crop Production and Protection, Obafemi Awolowo University, Ile-Ife, Nigeria

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Abstract

Declining soil fertility and excessive inorganic fertiliser use threaten the sustainability of maize production in tropical regions. This study evaluated the co-application of kenaf-derived biochar and NPK fertiliser on maize agronomic performance and soil biological properties in a greenhouse pot experiment at Obafemi Awolowo University, Ile-Ife, Nigeria. Treatments included a control, sole biochar (2.5 and 5 t ha^{-1}), sole NPK (100 kg ha^{-1}), and biochar-NPK co-application (2.5 and 5 t ha^{-1} biochar + 50 kg ha^{-1} NPK) arranged in a completely randomized design with three replicates. Results showed that co-application of 5 t ha^{-1} biochar + 50 kg ha^{-1} NPK significantly ($p < 0.05$) enhanced plant height, stem girth, chlorophyll index, and number of leaves, performing comparably to the full NPK rate. This treatment also significantly increased total heterotrophic bacteria, total heterotrophic fungi, and microbial respiration. Kenaf biochar integration with half-rate NPK offers a viable strategy for sustaining maize productivity while enhancing soil biological health.

Introduction

Global food demand continues to escalate due to rapid population growth, placing tremendous pressure on agricultural systems to increase crop productivity sustainably (Kizito et al., 2019). Maize (*Zea mays* L.) is one of the most widely cultivated cereal crops worldwide, serving as a staple food, livestock feed, and industrial raw material (Naeem et al., 2018). However, maize productivity in many tropical and subtropical regions remains constrained by declining soil fertility, characterized by low organic matter content, poor nutrient retention, and diminished biological activity (Phares et al., 2022). The excessive and continuous application of inorganic fertilizers, while temporarily boosting yields, has been associated with soil acidification, degradation of soil structure, and a reduction in microbial diversity, ultimately undermining the long-term sustainability of cropping systems (Wu et al., 2023). Consequently, there is an urgent need to identify complementary soil management strategies that can sustain crop yields while preserving or enhancing soil health.

Biochar, a carbon-rich solid material produced through the thermochemical decomposition (pyrolysis) of biomass under oxygen-limited conditions, has emerged as a promising soil amendment for addressing these challenges (Khiari et al., 2020). Biochar possesses several unique physicochemical properties, including high porosity, large surface area, elevated cation exchange capacity (CEC), and a recalcitrant carbon structure, which collectively contribute to improved soil fertility and enhanced nutrient cycling

Corresponding author: Tel: +234 8068997476
Email address: mosunde@oauife.edu.ng (O.M. Osunde)
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(Patel et al., 2025; Singh et al., 2025). When applied to soil, biochar has been shown to increase soil organic carbon, improve water-holding capacity, reduce bulk density, and raise soil pH in acidic soils, creating a more favourable environment for root development and nutrient uptake (Pandit et al., 2018; Sharma et al., 2025). Furthermore, the porous architecture of biochar provides suitable microhabitats for soil microorganisms, protecting them from predation and desiccation while supplying carbon substrates and mineral nutrients essential for microbial metabolism (Blackwell et al., 2009; Paz-Ferreiro et al., 2016).

The biological properties of soil, including microbial biomass carbon, enzymatic activities (such as dehydrogenase, urease, and phosphatase), and the population dynamics of bacteria and fungi, are widely recognised as sensitive indicators of soil health and quality (Demisie and Zhang, 2015; Mierzwa-Hersztek et al., 2019). Biochar amendments have been reported to stimulate microbial biomass carbon, enhance dehydrogenase and β-glucosidase activities, and increase bacterial and fungal populations in diverse soil types (Dayoub et al., 2024; Patel et al., 2025). However, the magnitude and direction of these effects depend on biochar feedstock, pyrolysis temperature, application rate, and the inherent properties of the receiving soil (Chintala et al., 2014; Paz-Ferreiro et al., 2016).

The co-application of biochar with inorganic NPK fertilisers represents a particularly attractive strategy because biochar can enhance the retention and slow release of applied nutrients, thereby improving fertiliser use efficiency and reducing nutrient leaching losses (Peng et al., 2021; Phares et al., 2022). Field studies have demonstrated that the combined application of biochar and NPK fertilisers significantly increased maize grain yield, nitrogen uptake, and nutrient use efficiency compared to the sole application of either amendment (Li et al., 2022; Phares et al., 2022). Phares et al. (2022) reported that the co-application of biochar with half the recommended NPK rate produced grain yields comparable to those obtained with the full NPK rate alone, suggesting that biochar integration could reduce fertiliser input costs without compromising productivity. Similarly, Minhas et al. (2020) observed that biochar at 2 t ha^{-1} combined with half the recommended NP dose improved maize grain yield relative to the full NP dose without biochar, underscoring the synergistic interaction between biochar and inorganic fertilisers.

The choice of feedstock for biochar production is a critical consideration, as it influences the nutrient content, pH, surface area, and functional group composition of the resulting biochar (Khiari et al., 2020; Lompo et al., 2021). Kenaf (*Hibiscus cannabinus* L.) is a fast-growing, high-biomass fiber crop that is increasingly cultivated in tropical regions. Kenaf stems have been shown to possess favourable thermal and chemical properties for biochar production, yielding chars with well-developed microporous structures, high carbon content, and appreciable concentrations of potassium, phosphorus, calcium, and magnesium (Khiari et al., 2020). These attributes suggest that kenaf-derived biochar could serve as an effective soil amendment, supplying essential nutrients and improving soil physical, chemical, and biological conditions. Despite the growing body of literature on biochar–fertiliser interactions in maize systems, little research has specifically examined the effects of kenaf-derived biochar in combination with NPK fertilisers on both maize agronomic performance and soil biological properties.

Therefore, the objective of this study was to evaluate the co-application of kenaf-derived biochar and NPK fertiliser on maize growth parameters and selected soil biological properties.

Materials and Methods

Study area

The study was conducted in the greenhouse and Department of Soil Science and Land Resources Management, Faculty of Agriculture, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria. The soil samples used for the study were collected from the Teaching and Research Farm (T&RF) of the Obafemi Awolowo University, Ile-Ife, Nigeria. The T&RF is situated within the rain forest zone (7°32′–7°33′N, 4°32′–4°34′E). The farm experiences approximately eight months (March-October) of the annual rainfall that is bimodal in distribution patterns with peaks in June and September. It also experiences about four months (November-February) of dry season each year,

though irregularity may occur in the rainfall distribution pattern over the year. The mean annual rainfall is about 1400 mm.

Soil sampling

A bulk soil sample (Iwo series) was taken from a fallow field (0-15 cm) at the Obafemi Awolowo University, Teaching and Research Farm, Ile-Ife, Osun State, Nigeria. To remove the gravel, stones, plant debris, and other unwanted items, the sample was air-dried and sieved through a 2 mm sieve from which subsamples were taken for chemical analyses.

Preparation of kenaf biochar and NPK fertiliser

Kenaf biochar was produced from stems of *Hibiscus cannabinus* obtained from the Institute of Agricultural Research and Training, Ibadan, Moor Plantation, Ibadan, Oyo State, Nigeria. The biomass was cleaned, air-dried, and oven-dried at 105 ℃ for 24 h. Dried stems were chopped (1-3 cm) and pyrolysed in a locally fabricated drum kiln under oxygen-limited conditions at 350-450 ℃ for 2-3 h. The kiln was sealed after carbonisation and allowed to cool, with minimal water applied to prevent ash formation. The resulting biochar was crushed, sieved (<2 mm), and stored in airtight containers before application. The soil culture experiment was conducted in the screenhouse at the Obafemi Awolowo University, Ile-Ife, Nigeria. Five kilograms (5 kg) of topsoil (0-15 cm) were placed into pots and thoroughly mixed with kenaf biochar at equivalent rates. The treatments included: control (soil only), 2.5t ha^{-1} biochar, 5t ha^{-1} biochar, 100 kg ha^{-1} NPK, 2.5t ha^{-1} biochar + 50 kg ha^{-1} NPK and 5t ha^{-1} biochar + 50 kg ha^{-1} NPK. The experimental units were replicated 3 times, resulting in 18 experimental units to ensure the validity and reliability of the results. The amended soils were each transferred into plastic pots (19 and 13 cm upper and lower inner diameters, and 21 cm height)-perforated at the base for free drainage and aeration, replicated thrice, and arranged in a Completely Randomised Design (CRD). Three (3) maize seeds of an early maturing variety (*SC 555*) were planted per pot and later thinned to 2 at two weeks after planting. The plants were allowed to grow for 8 weeks and then terminated.

Determination of microbial respiration (MR)

Microbial respiration was determined for a period of four (4) weeks of sowing through the CO_2 evolved by using the double acid titration method (Anderson, 1982). The content of each vial was taken every two weeks and poured into a 250 ml flask. The unreacted NaOH was first titrated with 0.5 N H_2SO_4 using phenolphthalein indicator to a colourless endpoint. The CO_3^{2-} formed was later titrated using a methyl orange indicator.

The CO_2 concentration was calculated using the following formula:

$$mg\ \frac{C}{100} = Titre \times N\,H_2SO_4 \times \frac{30}{1} \times \frac{12}{60}$$

where, 30 is equivalent to CO_3^{2-} in mg; 12/60 is the ratio of C to the mass of CO_3^{2-}.

Determination of heterotrophic fungi and bacteria

For the enumeration of total heterotrophic fungi, the soil samples were serially diluted using the 100-fold serial dilution according to Osunde et al. (2024). About 0.1 g of the soil sample was added to 9.9 mL of sterile distilled water, which was serially diluted to the 4th test tube. One (1) mL of the serially diluted samples was plated on potato dextrose agar (PDA) supplemented with streptomycin (30 mg L^{-1}) and incubated at 28℃ for 5 days. For the enumeration of total heterotrophic bacteria, one millilitre of each dilution was plated on nutrient agar (NA) and incubated for 18-24 hours at 35 ℃. The colonies were counted based on the rule of significant counting.

The Total Heterotrophic Fungi (THF) were calculated below:

$$THF = \frac{number\ of\ colonies}{dilution\ ratio}$$

The Total heterotrophic Bacteria (THB) were calculated below:

$$THB = \frac{number\ of\ colonies}{dilution\ ratio}$$

Agronomic data collected

Agronomic parameters were assessed during the eight weeks of planting (8 WAP) included plant height, stem girth, chlorophyll index, number of leaves, fresh and dry shoot weights, as well as fresh and dry root weights. Plant height was measured from the soil surface to the apical meristem using a measuring ruler. Stem girth was determined at approximately 2 cm

above the soil surface using a tape rule. The number of fully expanded leaves per plant was counted manually. Leaf chlorophyll content was estimated non-destructively using a SPAD chlorophyll meter (Minolta SPAD-502), with readings taken from the midpoint of the youngest fully expanded leaf and averaged per plant. For biomass determination, sampled plants were carefully uprooted to retain the root system and gently washed under running water to remove adhering soil particles. The shoots were separated from the roots at the collar region. Fresh weights of shoots and roots were recorded immediately using a digital weighing balance. Subsequently, the samples were oven-dried at 65 ℃ to constant weight, after which dry shoot and root weights were recorded.

Data analysis

The data collected were subjected to the ANOVA technique, and means were separated using Duncan's New Multiple Range Test (DNMRT) at 5% probability level with the SAS 9.0 software

Results

The baseline physicochemical properties of the experimental soil before treatment application are presented in Table 1. The soil pH was characterised as slightly acidic, the organic carbon content was low, with moderate levels of available P., total nitrogen, and exchangeable potassium, which are typical of tropical soils with limited inherent fertility.

Table 1: Physical and chemical properties of the experimental soil

Properties	Value
Sand (g kg^{-1})	816
Silt (g kg^{-1})	72
Clay (g kg^{-1})	112
Texture	Loamy sand
pH (0.01 M $CaCl_2$)	4.39
Organic carbon (g kg^{-1})	3.5
Total nitrogen (g kg^{-1})	3
Available P (g kg^{-1})	0.09

The co-application of kenaf-derived biochar and NPK fertiliser significantly ($p < 0.05$) influenced maize agronomic parameters, including plant height, stem girth, chlorophyll index and number of leaves (Tables 2 and 3). The co-application of 2.5t ha^{-1} biochar + 50 kg ha^{-1} NPK, 5t ha^{-1} biochar + 50 kg ha^{-1} NPK, and 100 kg ha^{-1} significantly enhanced plant height, stem girth, chlorophyll index and number of leaves of the maize plant.

Table 2: Effect of co-application of kenaf biochar and NPK fertiliser on plant agronomic parameters

Amendment	Plant height (cm)	Plant girth (cm)	Chlorophyll index	No of leaves
(control)	83.11^{d}	1.49^{ab}	29.39^{b}	11.21^{b}
2.5t ha^{-1} biochar	88.20^{bc}	1.49^{ab}	27.60^{b}	12.29^{a}
2.5t ha^{-1} biochar + 50 kg ha^{-1} NPK	93.02^{a}	1.53^{ab}	31.43^{a}	12.17^{a}
5t ha^{-1} biochar	87.93^{c}	1.46^{b}	29.42^{b}	12.17^{a}
5t ha^{-1} biochar + 50 kg ha^{-1} NPK	90.93^{abc}	1.57^{a}	31.83^{a}	12.67^{a}
100 kg ha^{-1} NPK	92.14^{ab}	1.50^{ab}	31.78^{a}	12.25^{a}

Table 3: Effect of co-application of kenaf biochar and NPK Fertiliser on root and shoot weights

Treatment	Wet root weight (g)	Dry root weight (g)	Wet shoot weight (g)	Dry shoot weight (g)
(control)	22.67^{ab}	12.63^{ab}	55.67^{b}	26.27^{b}
2.5t ha^{-1} biochar	16.33^{b}	8.00^{b}	59.33^{b}	29.07^{b}
5t ha^{-1} biochar	25.33^{ab}	13.71^{ab}	74.00^{ab}	37.20^{ab}
100 kg ha^{-1} NPK	14.33^{b}	7.20^{b}	74.33^{ab}	37.30^{ab}
2.5t ha^{-1} biochar + 50 kg ha^{-1} NPK	34.67^{a}	18.10^{a}	75.33^{ab}	39.97^{ab}
5t ha^{-1} biochar + 50 kg ha^{-1} NPK	35.00^{a}	18.167^{a}	95.00^{a}	47.87^{a}

The co-application of kenaf biochar and NPK fertiliser and their effects on total heterotrophic bacteria (THB), total heterotrophic fungi (THF), and microbial respiration (MR) is presented in Table 4. The THB and THF counts were significantly higher for 5 t ha^{-1} biochar + 50 kg ha^{-1} NPK and 100 kg ha^{-1} NPK. It was observed that the co-application of 5t ha^{-1} biochar + 50 kg ha^{-1} NPK significantly influenced the THB, THF and MR more than other treatments. It was also observed that biochar augmented treatments had a significant influence on MR.

Discussion

The enhanced agronomic performance of maize observed under the co-application of kenaf-derived biochar and NPK fertiliser in this study is consistent with a growing body of evidence demonstrating the synergistic benefits of biochar–fertiliser combinations on crop productivity. The significant increases in plant height, stem girth and chlorophyll index, recorded in the co-applied treatments, can be attributed to the complementary roles of biochar in improving soil physical structure and nutrient retention, while NPK fertiliser supplies readily available macronutrients essential for rapid vegetative growth and reproductive development (Li *et al.*, 2022; Phares *et al*., 2022). Biochar derived from kenaf stems is known to possess a well-developed microporous structure, high carbon content, and appreciable concentrations of potassium, phosphorus, calcium, and magnesium (Khiari *et al*., 2020). This mechanism likely explains the observation that kenaf biochar co-applied with half the recommended NPK rate competes comparably with the full NPK rate alone, a finding with significant economic implications for resource-limited farmers. A similar fertiliser-sparing effect was reported by (Minhas *et al*., 2020b), who demonstrated that biochar at 2 t ha^{-1} combined with half the recommended nitrogen-phosphorus dose improved maize grain yield in loamy soil relative to the full nitrogen-phosphorus dose without biochar. The improvement in plant height and stem girth associated with biochar-amended treatments can further be explained by the role of biochar in reducing soil bulk density, increasing soil porosity and water-holding capacity, and creating favourable conditions for root proliferation and nutrient absorption (Azuka *et al*., 2025; Wu *et al*., 2023). Enhanced root development facilitates greater exploration of the soil volume, thereby improving the uptake of both native and applied nutrients. Pandit *et al*. (2018) similarly reported that biochar addition increased soil moisture and available potassium and phosphorus, with the most pronounced growth benefits occurring under nutrient-stressed conditions, suggesting that biochar is most effective at alleviating nutrient limitations. The significant enhancement of total heterotrophic bacteria (THB), total heterotrophic fungi (THF), and microbial respiration in biochar-amended treatments represents a key finding of this study, as soil biological properties are among the most sensitive indicators of soil health and functional capacity (Mierzwa-Hersztek *et al.*, 2019). The porous structure of biochar provides protected microhabitats that shelter soil microorganisms from desiccation, temperature extremes, and predation, while simultaneously supplying labile carbon substrates and mineral nutrients that stimulate microbial proliferation (Thies and Rillig, 2012; Paz-Ferreiro *et al*., 2016). The higher THB and THF counts observed in the co-application of 5t ha^{-1} biochar + 50 kg ha^{-1} NPK and sole NPK suggest a synergistic interaction whereby biochar creates a favourable physical and chemical microenvironment for microbial colonization, while NPK fertilizer provides the essential nitrogen, phosphorus, and potassium that fuel microbial biosynthesis and energy metabolism.

Table 4: Effect of co-application of kenaf biochar and NPK on THB, THF and MR

Treatment	THB	THF	MR (mg C/100g)
5t ha^{-1} biochar + 50 kg ha^{-1} NPK	6.40a	4.37a	7.85a
100 kg ha^{-1} NPK	6.35a	4.33a	5.8bc
2.5t ha^{-1} biochar	5.62b	4.27ab	6.75ab
5t ha^{-1} biochar	5.43b	4.15ab	6.73ab
2.5t ha^{-1} biochar + 50 kg ha^{-1}NPK	5.39b	4.12ab	6.58ab
(control)	4.15c	3.86b	4.93bc

This observation aligns with the findings of Phares et al. (2022), who reported that the co-application of biochar and NPK fertilizer significantly increased bacterial and fungal populations, microbial biomass carbon, and basal respiration rates in maize-cultivated soils. Similarly, Lu et al. (2026) demonstrated in a three-year field experiment that the combined application of biochar (16 t ha^{-1}) and nitrogen fertiliser (150 kg ha^{-1}) increased the relative abundance of Proteobacteria and enhanced enzyme activities associated with carbon and nitrogen cycling. The elevated microbial respiration rates observed in the co-applied treatments further confirm the stimulatory effect of kenaf biochar on soil microbial metabolic activity. Microbial respiration reflects the overall rate of organic matter decomposition and nutrient mineralisation in soil, and its enhancement indicates a more biologically active and functionally diverse soil ecosystem (Demisie and Zhang, 2015). The high organic carbon present in freshly applied biochar likely served as an initial energy source for heterotrophic microorganisms, triggering a positive priming effect on native soil organic matter decomposition (Dayoub et al., 2024). Although the present study focused on microbial counts and respiration rather than individual enzyme assays, the overall pattern of enhanced biological activity is consistent with the emerging consensus that biochar–fertilizer combinations stimulate multiple dimensions of soil biological function.

Conclusion

The co-application of kenaf-derived biochar and NPK fertiliser improved maize growth performance and soil biological properties under greenhouse conditions. Among the treatments evaluated, 5 t ha^{-1} kenaf biochar + 50 kg ha^{-1} NPK consistently gave the best overall response, producing the highest wet and dry root weights, shoot biomass, total heterotrophic bacteria, total heterotrophic fungi, and microbial respiration. It also significantly enhanced plant height, stem girth, chlorophyll index, and number of leaves, with performance comparable to the sole application of 100 kg ha^{-1} NPK. These findings indicate that integrating kenaf biochar with half the recommended NPK rate can sustain maize growth while improving soil microbial activity in a tropical Alfisol. Therefore, the combined use of 5 t ha^{-1} kenaf biochar with 50 kg ha^{-1} NPK shows strong potential as an efficient soil fertility management option for maize production. However, as this was a short-term greenhouse study, treatment adjustment, field-scale validation across multiple cropping seasons and soil types is recommended to confirm the durability and broader applicability of these benefits.

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