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Integrated Effect of Sugarcane Biochar and NPK Fertilizer on Selected Soil Physical and Chemical Properties in A Semi-Arid Agroecosystem of Malumfashi, Katsina State

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Abstract- This study evaluated the integrated effect of sugarcane-derived biochar and NPK fertilizer on selected soil physical and chemical properties in a semi-arid agroecosystem of Malumfashi, Katsina State, Nigeria. A total of 72 soil samples were collected at 0–30 cm depth before and after treatment application and analyzed using standard laboratory procedures. The experiment assessed key soil parameters including soil pH, soil organic matter, organic carbon, total nitrogen, available phosphorus, exchangeable bases, cation exchange capacity (CEC), bulk density, and electrical conductivity. Results revealed that the combined application of biochar and NPK fertilizer significantly improved soil fertility indicators. Soil pH increased from 5.70 to 6.50, while organic matter and organic carbon rose from 0.83% to 1.73% and 0.48% to 0.97%, respectively. Total nitrogen and available phosphorus also increased substantially, indicating enhanced nutrient availability. CEC improved from 1.88 to 3.81 cmol (+)/kg, reflecting better nutrient retention capacity. Bulk density decreased from 1.36 to 1.28 g/cm³, indicating improved soil structure and porosity. Electrical conductivity remained within non-saline limits, confirming no adverse salinity effects. The findings demonstrate that integrating sugarcane biochar with NPK fertilizer enhances soil quality and supports sustainable soil fertility management in semi-arid environments.

Keywords: Biochar, NPK fertilizer, Soil pH, bulk density and Malumfashi

I. INTRODUCTION

Soil fertility decline remains one of the most serious constraints to agricultural productivity in sub-Saharan Africa, particularly in the semi-arid regions of northern Nigeria. In these environments, continuous cultivation, low organic matter inputs, nutrient mining, and high rates of erosion and leaching have contributed to the degradation of soil physical and chemical properties, resulting in reduced crop yields and food insecurity (Lal, 2020). The Sudan Savanna agro-ecological zone, including Malumfashi in Katsina State, is characterized by inherently low soil fertility, low cation exchange capacity, and limited organic matter content, which further exacerbates nutrient deficiencies and limits sustainable agricultural production.

Among the major soil fertility constraints in the region are low nitrogen (N), phosphorus (P) fixation in acidic conditions, poor soil structure, and declining soil organic carbon. These challenges are often intensified by the dominance of sandy loam soils, which have weak nutrient-holding capacity and are highly susceptible to nutrient leaching (Brady & Weil, 2016). As a result, farmers frequently rely on inorganic fertilizers such as NPK to improve crop productivity. However, the sole use of inorganic fertilizers has been shown to be insufficient for long-term soil fertility restoration due to nutrient losses, soil acidification, and declining soil organic matter over time (Vanlauwe *et al.,* 2010).

In recent years, biochar has emerged as a promising soil amendment for improving soil fertility and mitigating soil degradation. Biochar is a carbon-rich product obtained from the pyrolysis of organic materials under limited oxygen conditions. When applied to soil, biochar has been reported to improve soil pH, increase cation exchange capacity, enhance nutrient retention, and promote microbial activity (Lehmann & Joseph, 2015). Additionally, its stable carbon structure contributes to long-term carbon sequestration and improved soil physical properties such as bulk density and water retention (Glaser *et al.,* 2002).

Sugarcane biochar, derived from agricultural waste, presents an environmentally sustainable option for waste management and soil improvement. Its high surface area and porous structure make it particularly effective in retaining nutrients and reducing nutrient losses when combined with mineral fertilizers. The integration of biochar with inorganic fertilizers such as NPK is considered a form of integrated soil fertility management (ISFM), which aims to optimize the efficiency of external inputs while improving soil health and productivity (Biederman & Harpole, 2013). Despite increasing interest in biochar technology, limited empirical studies have evaluated the combined effects of sugarcane biochar and NPK fertilizer on both physical and chemical soil properties in the Sudan Savanna region of Nigeria. Understanding these interactions is critical for developing sustainable soil management strategies tailored to local agro-ecological conditions.

Therefore, this study investigates the integrated effect of sugarcane biochar and NPK fertilizer on selected soil physical and chemical properties in Malumfashi, Katsina State. The study aims to assess changes in soil pH, organic carbon, nutrient availability, cation exchange capacity, and physical properties such as bulk density, with the goal of providing evidence-based recommendations for improving soil fertility and sustainable crop production in semi-arid agroecosystems.

II. MATERIALS AND METHODS

Study Area

The study was conducted at Faculty of Agriculture Research Farm of Umaru Musa Yar'Aduwa University, located at Layin Minister, Malumfashi Local Government Area, Katsina State, Nigeria. Malumfashi is situate at approximately latitude 11.7929^o N, 7.6168^o E longitude, with a total area of 674 km^2. The soils of the area are predominantly sandy loam to clay loam in texture.

Malumfashi falls within the Sudan Savanna ecological zone, which is characterized by scattered trees, sparse shrubs and grasses. The area experiences a mean annual maximum temperature ranging from 33^o C - 36^o C, with the highest temperatures generally recorded in April. The mean annual minimum temperature ranges between 20^o C - 24^o C, with the lowest temperatures typically occurring in January.

The area receives an annual rainfall of approximately 500 - 800 mm, distributed mainly between May and October over about 75 - 90 rainy days. Rainfall usually peaks in August. The growing season lasts approximately 110 - 130 days, although mild dry spells may occur, particularly during June to July. These climatic conditions influence crop growth and agricultural production in the area (NiMet 2024).

Soil Sampling and Collection

Soil samples were collected both before and after the application of treatments. Prior to treatment application, a total of 36 soil samples were collected at a depth of 0–30 cm across the experimental plots. Following treatment application, the sampling procedure was repeated, yielding an additional 36 soil samples. This resulted in a total of 72 soil samples for the study. All samples were collected from each plot using standard sampling procedures, properly labeled, and stored in clean containers to avoid contamination. The samples were then transported to the laboratory for analysis of selected soil physical and chemical properties following standard procedures outlined by Mylavarapu and Kennelley (2002).

Laboratory Analysis

All collected soil samples were analyzed using standard laboratory methods. Particle size distribution was determined using the hydrometer method as described by Bouyoucos (1992) and modified by Udo *et al.* (2009). Soil pH was measured in both 1:1 soil-to-water and 1:2 soil-to-0.01 M $CaCl_2$ suspensions using a glass electrode pH meter (Jenway, UK, bench-type digital model 3510) following the procedure outlined by Longanathan (1984). Exchangeable acidity was determined by the titration method of McLean as described by Udo *et al.* (2009). The cation exchange capacity (CEC) was calculated as the sum of total exchangeable bases and exchangeable acidity (Udo *et al.,* 2009).

Data Analysis

Descriptive statistics were used to summarize the data obtained from the routine tests. Analysis of variance (ANOVA) was conducted to determine significant differences among treatment means. Where significant differences ($p \leq 0.05$) were detected, means were separated using Tukey's Honestly Significant Difference (HSD) test. All statistical analyses were performed using GenStat (17th edition).

Result and Discussion

The baseline (Table 1) and end-line (Table 2) soil analyses provide a comprehensive evaluation of the integrated effects of sugarcane-derived biochar and NPK fertilizer on selected soil physical and chemical properties in the semi-arid agroecosystem of Malumfashi, Katsina State. The comparative results demonstrate significant improvements in soil fertility indicators, highlighting the effectiveness of combined organic–inorganic nutrient management strategies in enhancing soil productivity in savanna environments.

Soil Reaction (pH), Exchangeable Acidity, and Electrical Conductivity

At baseline, the soil was moderately acidic (pH 5.70), a condition typical of highly weathered tropical soils. Following the application of sugarcane biochar and NPK fertilizer, soil pH increased to 6.50, approaching near-neutral conditions. This improvement is largely attributed to the liming effect of biochar, which contains basic cations (Ca^{2+}, Mg^{2+}, K^{+}) that neutralize soil acidity and reduce exchangeable aluminum toxicity (Lehmann & Joseph, 2015). The slight reduction in exchangeable acidity (Al + H) at end-line further supports the ameliorative role of biochar in acidic soils.

The shift toward near-neutral pH enhances nutrient availability, particularly phosphorus and nitrogen, while also promoting microbial activity essential for nutrient cycling (Havlin *et al.,* 2014). Electrical conductivity (EC) remained very low, increasing slightly from 0.015 dS m^{-1} at baseline to 0.04 dS m^{-1} at end-line, indicating that the soil remained non-saline. This confirms that the integrated application did not result in salt accumulation, which is critical for maintaining soil health in semi-arid regions (Rhoades *et al.,* 1992).

Soil Organic Matter, Organic Carbon, and Nitrogen

Soil organic matter (SOM) increased markedly from 0.83% at baseline to 1.73% at end-line, while organic carbon rose from 0.48% to 0.97%. These improvements reflect the contribution of sugarcane biochar as a stable carbon source. Due to its recalcitrant nature, biochar persists in the soil and enhances carbon sequestration, improves soil aggregation, and provides a favorable habitat for soil microorganisms (Glaser *et al.,* 2002; Lehmann *et al.,* 2011).

Total nitrogen also showed a substantial increase from 0.09% to 1.51%, indicating enhanced nitrogen availability and retention. While NPK fertilizer supplies readily available nitrogen, biochar improves nitrogen use efficiency by reducing leaching losses and adsorbing ammonium ions (NH_4^{+}). This synergistic interaction enhances nitrogen retention and availability for plant uptake (Steiner et al., 2007). The observed improvement is particularly significant in semi-arid savanna soils, which are typically characterized by low organic matter and nitrogen deficiency (Lal, 2020).

Available Phosphorus

Available phosphorus increased significantly from 16.4 mg/kg at baseline to 35.9 mg/kg at endline. This increase can be attributed to both direct phosphorus input from NPK fertilizer and the role of biochar in reducing phosphorus fixation. In acidic soils, phosphorus is often immobilized by iron and aluminum oxides; however, biochar can adsorb these compounds, thereby increasing phosphorus availability (Biederman & Harpole, 2013). The elevated phosphorus levels at endline suggest improved nutrient accessibility, which is critical for root development, flowering, and crop yield.

Exchangeable Bases and Cation Exchange Capacity (CEC)

Exchangeable base cations showed notable improvement following treatment. Potassium increased from 0.41 to 0.77 cmol (+)/kg, while calcium remained relatively stable (1.89 to 1.91 cmol (+)/kg), and magnesium showed a slight decrease (1.11 to 1.01 cmol (+)/kg). Sodium decreased significantly from 0.21 to 0.03 cmol (+)/kg, indicating

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reduced risk of sodicity and improved soil structural stability.

Total exchangeable bases increased slightly from 2.16 to 2.24 cmol (+)/kg. More importantly, cation exchange capacity (CEC) increased from 1.88 cmol (+)/kg at baseline to 3.81 cmol (+)/kg at end-line, representing a significant improvement in the soil's nutrient-holding capacity. This enhancement is attributed to the high surface area and porous structure of sugarcane biochar, which increases the number of exchange sites for nutrient retention (Lehmann *et al.,* 2011; Essington, 2015).

Soil Physical Properties: Texture and Bulk Density

Soil texture remained unchanged as loam (sand 44.5%, silt 43.5%, clay 11.9%), confirming that the treatments did not alter the inherent mineral composition of the soil. However, bulk density decreased from 1.36 g/cm³ at baseline to 1.28 g/cm³ at end-line, indicating improved soil structure.

The reduction in bulk density can be attributed to the incorporation of biochar, which increases soil porosity and reduces compaction. Improved soil structure enhances water infiltration, aeration, and root penetration, thereby supporting better plant growth (Abel *et al.,* 2013).

Implications for Soil Fertility Management in Semi-Arid Agroecosystems

The comparative analysis clearly demonstrates that the integrated application of sugarcane biochar and NPK fertilizer significantly improved soil chemical and physical properties in Malumfashi. Key improvements include:

- Increased soil pH toward optimal levels for nutrient availability
- Enhanced soil organic matter and carbon sequestration
- Significant improvement in nitrogen and phosphorus availability
- Increased cation exchange capacity and nutrient retention
- Reduced bulk density and improved soil structure
- Maintenance of non-saline soil conditions

These findings highlight the importance of integrating organic amendments such as biochar with inorganic fertilizers to address soil fertility constraints in semi-arid agroecosystems. The synergistic effects observed in this study align with the principles of integrated soil fertility management, which emphasize the combined use of organic and mineral inputs to achieve sustainable soil productivity (Vanlauwe *et al.,* 2010).

Table 1: Baseline of some Soil physical and chemical analysis of Malumfashi

Soil Parameter	Nutrient Status
pH	5.70
%Organic Matter	0.83
%Organic Carbon	0.48
%Total Nitrogen	0.09
Available Phosphorus mg/kg	16.4
K^+	0.41
Mg Cmol/(+)kg	1.11
Ca Cmol/(+)	1.89
Na Cmol/(+)kg	0.21
Exchangeable Base Cmol/(+)kg	2.16
CEC Cmol/(+)kg	1.88
EC (dSm^{-1})	0.015
Al + H Cmol/(+)kg	0.83
%Sand	44.5
%Silt	43.5
%Clay	11.9
BD g/m^3	1.36
Textural Class	Loam Soil

Key: *CEC= Cation Exchange Capacity, EB= Exchangeable Bases,*
P= PhosphorusK= Potassium, Na= Sodium, BD= Bulk Density

Table 2: Endline Soil Chemical analysis of Malumfashi

Soil Parameter	Malumfashi
pH	6.50
%Organic Matter	1.73
%Organic Carbon	0.97
%Total Nitrogen	1.51
Available Phosphorus mg/kg	35.9
K^+	0.77
Mg Cmol/(+)kg	1.01
Ca Cmol/(+)	1.91
Na Cmol/(+)kg	0.03
Exchangeable Base Cmol/(+)kg	2.24
CEC Cmol/(+)kg	3.81
EC (dSm^{-1})	0.04
Al + H Cmol/(+)kg	0.87
%Sand	44.5
%Silt	43.5
%Clay	11.9
BD g/m^3	1.28
Textural Class	Loam Soil

Key: *CEC= Cation Exchange Capacity, EB= Exchangeable Bases, P= Phosphorus K= Potassium, Na= Sodium, BD= Bulk Density*

III. CONCLUSION

The results of this study demonstrate that the integrated application of sugarcane biochar and NPK fertilizer significantly improves both the physical and chemical properties of soils in the semi-arid environment of Malumfashi, Katsina State. The observed increase in soil pH toward near-neutral levels indicates effective amelioration of soil acidity, thereby enhancing nutrient availability and reducing potential aluminum toxicity.

Substantial improvements in soil organic matter, organic carbon, and total nitrogen highlight the role of biochar as a stable carbon source that enhances nutrient retention and promotes soil biological activity. The marked increase in available phosphorus and cation exchange capacity further confirms the synergistic interaction between biochar and inorganic fertilizers in improving nutrient availability and reducing losses through leaching.
The reduction in bulk density reflects improved soil structure, which enhances water infiltration, aeration, and root penetration critical factors for sustainable crop production in semi-arid agroecosystems. Importantly, the maintenance of low electrical conductivity indicates that the integrated treatment did not induce soil salinity, ensuring long-term soil health.

Overall, the study underscores the effectiveness of integrating organic amendments such as sugarcane biochar with inorganic fertilizers as a sustainable soil fertility management strategy. It is therefore recommended that farmers in the Sudan Savanna region adopt this integrated approach to improve soil productivity, enhance nutrient use efficiency, and ensure long-term agricultural sustainability.

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