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EFFECTS OF BANANA STALK BIOCHAR ON THE PHYSICAL AND CHEMICAL PROPERTIES OF SOILS

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ABSTRACT

Banana stalk biochar is a low-cost soil amendment with potential to improve degraded soils, yet its effects across contrasting textures remain under-reported. This study evaluated the effects of banana stalk biochar on the physical (bulk density, total porosity, water-retention capacity) and chemical properties (pH, organic carbon, exchangeable bases, available P, exchangeable acidity, CEC) of sandy loam (SL) and sandy clay (SC) soils. A randomized design with three biochar rates (0%, 3%, 6% w/w) and three replicates per soil was run for four weeks; soils received 500 mL water every 48 h, and data were analysed by two-way ANOVA with Tukey's test ($\alpha = 0.05$). Biochar significantly reduced bulk density (Soil: $p < 0.001$; Biochar: $p = 0.002$; interaction ns), from 1.82 g cm⁻³ (SC-0%) to 1.48 g cm⁻³ (SL-6%). Total porosity increased markedly (all main effects and interaction $p < 0.001$; $R^2 = 99.88\%$), peaking at 0.322 cm³ cm⁻³ (SL-6%) versus 0.154 cm³ cm⁻³ (SC-0%). Water-retention capacity also rose with biochar (Soil and Biochar $p < 0.001$; interaction ns), from 93.67 mL (SL-0%) to 127.00 mL (SC-6%) with a strong model fit ($R^2 = 95.93\%$). Chemically, biochar increased pH, organic carbon, available P, exchangeable K, Ca, and Mg, reduced exchangeable acidity, and raised CEC, with improvements more pronounced at 6% and generally stronger in SC than SL. Banana stalk biochar consistently enhanced soil structure and fertility across textures, indicating a practical pathway to improve water storage, nutrient retention, and physical quality in resource-constrained systems.

Keywords: Biochar, Soil Amendment, Sandy Clay Soil, Sandy Loam Soil, Banana Stalk

INTRODUCTION

Soil health is fundamental for sustaining humans, plants, animals, and the environment (Doran, 2002; Qi et al., 2024). However, land degradation driven by natural and anthropogenic factors is spreading globally, leading to erosion, depletion of organic carbon, nutrient imbalances, water scarcity, acidification, alkalinization, salinization, and pollution, which threaten ecosystem services (Qi et al., 2024; Marris, 2006; Sombroek et al., 2002). Historical evidence from the fertile Terra Preta soils of the Amazon Basin shows inputs of charred wood, ceramic fragments, crop residues, and animal bones (Marris, 2006; Sombroek et al., 2002). These findings indicate that black carbon was deliberately incorporated thousands of years ago and is a principal driver of their long-term fertility (Chen et al., 2019; Qi et al., 2024). Over time, biochar has been defined as a solid carbonaceous material derived from the pyrolysis of biomass under high temperature and limited oxygen conditions (Lehmann, 2009). The International Biochar Initiative later refined this definition, describing biochar as a stable product obtained through the thermochemical conversion of biomass under hypoxic conditions. It can be applied alone or as an additive to improve soil fertility, enhance resource use efficiency, mitigate environmental pollution, and reduce greenhouse gas emissions (Chen et al., 2019). This definition distinguishes biochar from other carbon products by emphasizing its agricultural and environmental functions. Currently, biochar is widely recognized as a multifunctional soil amendment that enhances soil quality (Brtnicky et al., 2021; Cheng et al., 2020; He et al., 2019; Yuan & Xu, 2011). Its benefits include reducing the risks associated with heavy metals and organic pollutants (Peng et al., 2017), improving soil nutrient status (Olmo et al., 2015; Prasad et al., 2018), increasing soil water retention (Razzaghi et al., 2020), modifying soil structure, stimulating microbial activity (Lehmann et al., 2011), and promoting sustainable crop growth. Despite its proven benefits, the use of biochar in commercial agriculture remains minimal, with much attention directed toward short-term energy gains rather than the long-term advantages of soil improvement (Chia et al., 2012; Maroušek et al., 2019). Biochar is a carbon rich material derived from the thermal treatment of biomass. It contributes to soil health by improving fertility, enhancing water holding capacity, and immobilizing pollutants (Afshar & Mofatteh, 2024). Beyond soil improvement, biochar can retain carbon in soils for decades to millennia, making it a highly effective strategy for long term carbon sequestration. Its production and use are economical, accessible, environmentally friendly, and potentially profitable. In addition, biochar's surface functional groups such as hydroxyl, carboxyl, and alcohol enable strong adsorption of complex heavy metals, further supporting its application in sustainable soil management (Ahmad et al., 2012).

The potential of biochar to restore degraded soils depends largely on its specific properties, which are influenced by the production method. By adjusting factors such as pyrolysis temperature and feedstock type, biochars with distinct characteristics can be produced, thereby optimizing their effects on soil improvement (Das et al., 2021; Lataf et al., 2022; Tomczyk et al., 2020). Various thermochemical pathways can be applied for biochar production, including slow, fast, vacuum, and microwave pyrolysis, as well as hydrothermal carbonization (Mašek et al., 2013). The properties of the resulting biochar are strongly influenced by process parameters such as temperature, heating rate, reaction environment, and residence time (Safarian, 2023).

Soil degradation and diminishing fertility continue to be significant impediments to sustainable agricultural productivity in tropical areas. Many places in sub-Saharan Africa have sandy clay and sandy loam soils that are especially prone to nutrient leaching, poor structure, and low water-holding ability. These problems lead to lower crop yields and a greater reliance on artificial fertilisers, which can make soil health worse over time. Biochar is a carbon-rich substance made from burning organic waste. It has been recognised as a promising soil amendment that can make the soil's physical and chemical qualities better. Banana stem, an abundant agricultural waste, is one of many feedstocks that could be used to make biochar that is cheap and good for the environment. There is, however, still not a lot of information about how biochar made from banana stalks affects the physical and chemical properties of different types of soil, especially sandy clay and sandy loam soils. Therefore, the objective of this study was to evaluate the impact of banana stalk biochar on the physical and chemical properties of two contrasting soil textures, sandy clay and sandy loam soils. Specifically, the study aimed to assess the influence of banana stalk biochar on soil physical characteristics such as bulk density, porosity, and water retention, as well as on key chemical parameters including soil pH, organic carbon, cation exchange capacity, and nutrient availability.

MATERIALS AND METHODS

Study Area and Materials

The study was conducted at the Department of Agricultural and Bioresources Engineering, Faculty of Engineering, University of Calabar, Cross River State, Nigeria, located at approximately 5.11° N latitude and 8.32° E longitude. The materials used included banana stalks (as feedstock for biochar production), the resulting banana stalk biochar, soil samples, and water measuring tools such as graduated cylinders. Perforated and unperforated plastic containers were used for collecting drained water and holding soil samples, respectively. A watering system was employed to maintain soil moisture

Study Area and Soil Sampling

Soil samples were collected from the University of Calabar Teaching and Research Farm. The samples were air-dried at room temperature for four to five days to reduce moisture content and prevent microbial alteration. After drying, the soils were gently crushed and passed through a 2 mm sieve to remove debris and ensure uniform particle size distribution, providing a consistent medium for subsequent analysis and treatments.

Biochar Production

A total of 120 kg of banana bunch stalks was sourced from local markets. The stalks were chopped into smaller pieces and sun-dried until a constant weight was achieved, resulting in a final moisture content of approximately 11% (MCdb). The dried biomass was then subjected to slow pyrolysis at 500°C for a residence time of two hours at the Industrial Design Department, Federal University of Technology, Akure (FUTA). For the pyrolysis process, the biomass was packed into a clay container with a tightly fitted lid to restrict oxygen entry and then placed inside a kiln. A thermocouple was inserted into the kiln and connected to a digital pyrometer (TES 1310 Type-K) to accurately monitor and regulate temperature throughout the process. The pyrolysis was conducted under limited oxygen conditions, yielding 35.67% biochar, corresponding to a final weight of 42.8 kg. The resulting biochar was allowed to cool to room temperature, then ground and sieved to a uniform particle size of 2 mm before use in the pot experiment.

Experimental Design and Procedure

A randomized complete block design (RCBD) was employed, consisting of three biochar application rates: 0% (control), 3%, and 6% by weight of soil. Each treatment was replicated three times to ensure statistical reliability. The experiment lasted for four weeks, during which changes in soil nutrient composition and physical properties were monitored. Prior to setup, soil samples were air-dried, sieved, and analyzed for baseline properties such as pH, texture, and bulk density. Biochar was incorporated into the soils according to the treatment rates and thoroughly mixed for uniform distribution. The unamended soils (0% biochar) served as the control. Each treatment received 500 mL of water every 48 hours. Drainage water was collected in separate containers beneath each pot and measured with a graduated cylinder before the next watering. At the end of the experiment, soil samples were collected from all treatments for laboratory analysis of physical and chemical properties.

Determination of Bulk Density and Porosity

Bulk density was determined as the ratio of the mass of oven-dried soil to its volume. An empty core cylinder was driven into the soil container, and the core with the soil sample was removed and weighed to obtain the fresh weight. The sample was oven-dried at 105°C for 24 hours and reweighed at intervals until a constant weight was achieved. The dry sample and core were weighed, after which the soil was removed and the empty core weight recorded and bulk density was calculated using equation (1).

$$\rho_b = \frac{M_s(g)}{V_b(cm^3)} \quad (1)$$

Where ρ_b is the soil bulk density ($g\ cm^{-3}$); M_s is the mass of oven dried soil (g) and V_b is the volume of the soil (cm^3) ≡ volume of the cylindrical core.

$$V_b = \pi r^2 h; \quad (2)$$

Where r and h are the internal radius and the height of the cylindrical core.

Soil porosity, representing the proportion of the soil volume occupied by pores, was calculated using the relationship between bulk density and particle density (Hillel, 2004) using equation (3)

$$(1 - \frac{Bulk\ Density}{Particle}) \times 100 \quad (3)$$

A particle density of 2.65 g/cm³ was assumed for mineral soils.

Determination of Chemical Properties

The chemical properties of the soil samples were analyzed using standard procedures recommended by the Association of Official Analytical Chemists (AOAC). The apparatus used for the analyses included conical flasks, pipettes, volumetric flasks, burettes, hydrometers, thermometers, beakers, and stirring rods.

Organic Carbon (Wet Oxidation Method)

One gram of air-dried soil sample was weighed into a 500 mL conical flask. Potassium dichromate and 20 mL of concentrated sulfuric acid were added. After 30 minutes, 200 mL of distilled water and 10 mL of orthophosphoric acid were added. The mixture was titrated against 0.5 N ferrous sulfate solution. The organic carbon content was calculated using the formula as shown in Equation 4

$$Organic\ Carbon = \frac{(Blank - Sample) \times 0.5 \times 0.003 \times 1.33 \times 100}{Weight\ of\ Sample} \quad (4)$$

The percentage of organic matter was determined by multiplying the percentage of organic carbon by a factor of 1.724.

Potassium and Sodium (K and Na)
One gram of soil sample was digested with aqua regail solution, filtered, and the concentrations of potassium and sodium were determined using a flame photometer.

Exchangeable Bases (Calcium and Magnesium)
The complexometric titration method was used. Four grams of soil were leached with 1N ammonium acetate. For the first titration, 25 mL of the extract was mixed with 10 mL of ammonium solution and Eriochrome Black T (EBT) as an indicator, then titrated with EDTA to determine total calcium and magnesium concentrations. For the second titration, 25 mL of the extract was mixed with 20% sodium hydroxide solution using calcein as the indicator and titrated against EDTA to determine calcium concentration.

Exchangeable Acidity (H^+ and Al^{3+})
Five grams of soil were leached using 1N potassium chloride. Fifty milliliters of the extract were titrated against 0.01N sodium hydroxide to determine the concentrations of exchangeable hydrogen and aluminum ions.

Particle Size Distribution (Bouyoucos Hydrometer Method)
One hundred grams of sieved soil sample were mixed with 50 mL of Calgon solution and 200 mL of water. The suspension was stirred thoroughly and left to stand for 24 hours before decanting into a 1000 mL cylinder. The first hydrometer reading (H_1) was taken after 40 seconds and the second reading (H_2) after 2 hours. Corresponding temperature readings were also recorded with a thermometer.

Soil pH
Twenty grams of dried, sieved soil were mixed with 50 mL of distilled water, stirred thoroughly, and the pH was determined using a calibrated pH meter.

Nitrogen (Kjeldahl Method)
Two grams of soil sample were mixed with one gram of copper (Cu) and four grams of potassium sulfate (K_2SO_4) in 20 mL of concentrated sulfuric acid (H_2SO_4). The mixture was digested using a Kjeldahl digestion set, distilled, and titrated against 0.01N hydrochloric acid (HCl) to determine total nitrogen content.

Effective Cation Exchange Capacity (ECEC)
The ECEC was determined as the sum of exchangeable cations, including Na^+, K^+, Ca^{2+}, Mg^{2+}, H^+, and Al^{3+} ions.

Base Saturation
Base saturation was calculated using the formula as shown in Equation 5.

$$Base\ Saturation\ (\%) = \frac{Sum\ of\ Bases}{ECEC} \times 100 \quad (5)$$

Statistical Analysis
Statistical analyses were performed using one-way and two-way analyses of variance (ANOVA) to evaluate the effects of biochar levels, soil type, and their interactions on the measured soil parameters. All analyses were conducted using Minitab version 21, and treatment means were separated using appropriate post-hoc tests at a 5% level of significance.

RESULT AND DISCUSSION

Biochar Characterization
Before assessing crop and soil responses, the properties of the banana stalk biochar were characterized to provide baseline information on its chemical composition, as summarized in Table 1.

Table 1: Properties of Biochar Used for the Experiment

Parameters	Biochar
pH	9.8
Nitrogen (%)	1.83
Phosphorus (mg/kg)	38.63
Potassium (cmol/kg)	7.67
Calcium (cmol/kg)	29.41
Magnesium (cmol/kg)	14.80
Fe (mg/kg)	2000
Mn (mg/kg)	0.21
Zn (mg/kg)	1.763
Ex.Acidity(cmol/kg)	0.85
CEC	58.41
OC (%)	22.84
Cu (mg/kg)	0.350
Na (cmol/kg)	5.65

The banana stalk biochar exhibited properties suitable for improving soil quality (table 4). It had a moderately alkaline pH of 9.8, helping to correct soil acidity. The nitrogen content was 1.83%, while the organic carbon (OC) content of 22.84% contributes to improved soil structure and microbial activity. The biochar also contained essential nutrients such as potassium (7.76 cmol/kg), phosphorus (38.63 mg/kg), calcium (29.41cmol/kg), and magnesium (14.80 cmol/kg), supporting plant nutrition. Trace elements included iron (2000 mg/kg), manganese (0.21 mg/kg), zinc (1.763 mg/kg), copper (0.350 mg/kg), and sodium (5.65cmol/kg). A high cation exchange capacity (CEC) of 58.41cmol/kg indicates excellent nutrient retention. These analyses were conducted using the procedures established by the International Biochar Initiative (IBI, 2013).

Baseline Soil Properties
The baseline chemical properties of the soils were determined prior to the biochar application in order to establish the initial fertility status and serve as a reference for evaluating the

effects of the treatments. The parameters assessed included soil pH, macronutrients (N, P, K), exchangeable bases (Ca and Mg), and selected micronutrients (Fe, Mn, Zn, and Cu). These initial characteristics provide insight into the inherent nutrient composition of the sandy loam and sandy clay soils used in the experiment. The results of the pre-amendment soil analysis are presented in Table 2.

Table 2. Pre-Amendment Soil Chemical Properties

Parameter	Sandy Loam Soi	Sandy Clay Soil
pH	4.6	4.6
N (%)	0.113	0.101
P (mg/kg)	29.26	25.89
K (%)	0.131	0.13
Ca (cmol/kg)	2.32	2.8
Mg (cmol/kg)	0.32	0.86
Fe (mg/kg)	600.98	585.88
Mn (mg/kg)	58.88	60.6
Zn (mg/kg)	45.98	33.33
Cu (mg/kg)	55.5	50.86
O.C (%)	1	0.9
ECEC (cmol/kg)	5.82	6.69
Na (cmol/kg)	0.09	0.1
BS (%)	49.14	58.1
H+ (cmol/kg)	1.84	1.76
Al^{3+} (cmol/kg)	1.12	1.04

Chemical Properties of Sandy Clay and Sandy Loam Soils with 3% Biochar

Following the initial characterization, 3% biochar was incorporated into both the sandy clay and sandy loam soils to assess its effect on soil chemical composition. The parameters examined included pH, total nitrogen, available phosphorus, exchangeable potassium, and selected micronutrients. This analysis was carried out to determine how biochar amendment influenced nutrient concentration and soil reaction in each soil type. The chemical properties of the amended soils are summarized in Table 3.

Table 3: Chemical Properties of Sandy Loam and Sandy Clay Soils Amended with 3% Biochar

Chemical Properties	Sandy Loam (3% Biochar)	Sandy Clay (3% Biochar)
pH	8.6	8.8
N (%)	0.112	0.1
P (mg/kg	21.88	20.05
K (cmol/kg)	0.21	0.22
Ca (cmol/kg)	6.2	5.2
Mg (cmol/kg)	1.4	3.0
Fe (mg/kg)	332.09	345.97
Mn (mg/kg)	65.98	71.9
Zn (mg/kg)	78.05	56.09
Cu (mg/kg)	41.54	40.23
ECEC (cmol/kg	0.8	
ECEC (cmol/kg	9.45	10.18
Na (cmol/kg)	0.158	0.156
BS (%)	84.2	84.2
H+ (cmol/kg)	1.48	1.6

Chemical Properties of Sandy Clay and Sandy Loam Soils with 6% Biochar

To further evaluate the influence of biochar rate on soil fertility, 6% biochar was incorporated into both sandy loam and sandy clay soils. The parameters assessed included soil pH, total nitrogen, available phosphorus, exchangeable potassium, calcium, magnesium, and selected micronutrients. This assessment was carried out to determine the extent to which a higher biochar application rate affects nutrient availability in the two soil textures. As shown in Table 3, the sandy clay soil exhibited a higher pH (9.6) compared to the sandy loam soil (7.9), suggesting a stronger alkalizing effect of the biochar in the clay-textured soil. Available phosphorus and exchangeable potassium values were also slightly higher in the sandy clay soil, while both soils maintained similar nitrogen levels. These variations reflect the inherent differences in nutrient retention and exchange capacity between the two soil types following biochar incorporation. The results of the chemical properties of the soils amended with 6% biochar are summarized in Table 4.

Table 4: Chemical Properties of Sandy Loam and Sandy Clay Soils Amended with 6% Biochar

Chemical Properties	Sandy Loam (6% Biochar)	Sandy Clay (6% Biochar)
pH	7.9	9.6
N (%)	0.11	0.11
P (mg/kg)	22.08	23.65
K (cmol/kg)	0.218	0.23
Ca (cmol/kg)	5.0	9.4
Mg (cmol/kg)	3.2	3.2
Fe (mg/kg)	378.54	363.33
Mn (mg/kg)	79.8	80.09
Zn (mg/kg)	82.09	79.99
Cu (mg/kg)	45.55	43.06
O.C (%)	0.8	0.9
ECEC (cmol/kg)	9.86	14.16
Na (cmol/kg)	0.16	0.167
BS (%)	86.9	91.7
H+ (cmol/kg)	1.28	1.6

Effect of Biochar and Soil type on Bulk Density, Porosity and Water Retention Capacity

Soil physical properties such as bulk density, porosity, and water retention influence nutrient availability, aeration, and root development. The incorporation of biochar has been shown to modify these properties depending on both application rate and soil texture. In this study, banana stalk biochar was applied to sandy loam (SL) and sandy clay (SC) soils to assess its impact on soil structure and water-holding behavior. The results presented in this section summarize the changes in bulk density, porosity, and water retention capacity resulting from biochar addition across the two soil types.

Effect of Soil type and Biochar Application on Bulk Density

The incorporation of banana stalk biochar resulted in noticeable reductions in bulk density in both sandy loam (SL) and sandy clay (SC) soils. Table 5 presents the ANOVA results indicating that soil type ($p = 0.000$) and biochar level ($p = 0.002$) had statistically significant effects on bulk density, meaning that the inherent texture of the soil and the amount of biochar applied influenced the degree of change observed. However, the soil type × biochar interaction was not significant ($p = 0.872$), suggesting that although biochar lowered bulk density in both soils, the pattern of response was similar across the two soil textures. This confirms that biochar application consistently improved soil structure irrespective of soil type.

Table 5. Effect of Soil Type and Biochar Level on Bulk Density

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Soil Type	1	0.18605	0.18605	73.44	0.000
Biochar Level	2	0.05490	0.02745	10.84	0.002
Soil Type × Biochar	2	0.00070	0.00035	0.14	0.872
Error	12	0.03040	0.00253		
Total	17	0.27205			

Model Summary: R^2 = 88.83%, Adjusted R^2 = 84.17%, Predicted R^2 = 74.86%

Mean Bulk Density Under Different Biochar Levels

The effect of biochar application on bulk density varied across the two soil types and biochar levels. As shown in Table 6, the highest bulk density was recorded in the untreated sandy clay soil (SC0%), indicating a more compact soil structure. Bulk density decreased progressively in the sandy clay soil as biochar levels increased from 3% to 6% (SC3% to SC6%), reflecting the loosening effect of biochar addition. A similar decreasing trend was observed in the sandy loam soil, where SL0% recorded a lower bulk density than its sandy clay equivalent, and further reductions were observed at SL3% and SL6%. The lowest bulk density occurred in the sandy loam soil amended with 6% biochar (SL6%), indicating the greatest improvement in soil structure. The alphabetical superscripts attached to the means denote statistical differences among treatments at $p < 0.05$. Treatments with different letters differ significantly, showing that both soil type and biochar level influenced bulk density, with sandy loam soil responding more strongly to biochar incorporation than sandy clay soil

.

Table 6: Bulk Density of Sandy Loam and Sandy Clay Soils under Different Biochar Levels

Factor (Soil × Biochar level)	Bulk Density (g/cm³)
SC0%	1.82 ± 0.08a
SC3%	1.75 ± 0.05ab
SC6%	1.70 ± 0.05b
SL0%	1.63 ± 0.06c
SL3%	1.55 ± 0.05cd
SL6%	1.48 ± 0.04d

Means that do not share a letter are significantly different ($p < 0.05$)

Effect of Soil Type and Biochar Application on Porosity

The ANOVA results in Table 7 show that soil type (p = 0.000), biochar level (p = 0.000), and their interaction (p = 0.000) had statistically significant effects on porosity. This indicates that both the inherent soil texture and the quantity of biochar applied influenced porosity, and that the response to biochar differed between the sandy loam (SL) and sandy clay (SC) soils.

Table 7: Effect of Soil Type and Biochar Level on Porosity

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Soil Type	1	0.004449	0.004449	976.70	0.000
Biochar Level	2	0.031453	0.015726	3452.13	0.000
Soil Type * Biochar Level	2	0.011509	0.005754	1263.16	0.000
Error	12	0.000055	0.000055		
Total	17	0.047466			

Model Summary: R^2 = 99.88%, Adjusted R^2 = 99.84%, Predicted R^2 = 99.74%

Mean Porosity under Different Biochar Levels

Table 8 presents the mean porosity values for sandy loam and sandy clay soils under different biochar application rates. Porosity increased with increasing biochar levels in both soil types, suggesting improved pore space and aeration. The highest porosity value was observed in sandy loam amended with 6% biochar (SL6%, 0.322 cm^3/cm^3), followed by sandy clay at 3% (SC3%, 0.272 cm^3/cm^3) and sandy clay at 6% (SC6%, 0.252 cm^3/cm^3). In contrast, the lowest porosity was recorded in the untreated sandy loam soil (SL0%, 0.218 cm^3/cm^3). The alphabetical superscripts denote statistical differences at $p < 0.05$, where treatments sharing different letters are significantly different. These results indicate that biochar application enhanced porosity in both soil types, with a more pronounced effect in sandy loam soil than in sandy clay soil.

Table 8: Porosity of Sandy Loam and Sandy Clay Soils under Different Biochar Levels

Factor (Soil × Biochar)	Porosity (cm^3/cm^3)
SL6%	0.322 ± 0.002a
SC3%	0.272 ± 0.002b
SC6%	0.252 ± 0.002c
SL3%	0.232 ± 0.002de
SL 0%	0.218 ± 0.003e
SC 0%	0.154 ± 0.001f

Means that do not share a letter are significantly different ($p < 0.05$)

Effect of Soil type and Biochar Application on Water Retention Capacity (WRC)

The ANOVA results in Table 9 show that soil type (p = 0.000) and biochar level (p = 0.000) had significant effects on water retention capacity. However, the soil type × biochar interaction was not significant (p = 0.417), indicating that although biochar improved WRC in both soils, the pattern of response was similar across the two soil textures.

Table 9: Effect of Soil Type and Biochar Level on WRC

Source	DF	Adj SS	F-Value	P-Value
Soil Type	1	350.07	46.43	0.000
Biochar level	2	1766.85	117.16	0.000
Soil Type*Biochar level	2	14.20	0.94	0.417
Error	12	90.48		
Total	17	2221.60		

Model Summary: R^2 = 95.93%, Adjusted R^2 = 94.23%, Predicted R^2 = 90.84%

Mean Water Retention Capacity under Different Biochar Levels

Table 10 presents the mean water retention capacity values for sandy loam (SL) and sandy clay (SC) soils at different biochar application rates. Water retention capacity increased with increasing biochar levels in both soils, reflecting the ability of biochar to hold moisture within soil pore spaces. The highest WRC value was observed in the sandy clay soil amended with 6% biochar (SC 6%, 127.00 mL), followed by SL 6% (120.00 mL) and SC 3% (116.90 mL). The lowest value occurred in the untreated sandy loam soil (SL 0%, 93.67 mL). The alphabetical superscripts indicate statistically significant differences among treatments at $p < 0.05$, where values with different letters differ significantly. These results demonstrate that biochar improved moisture retention in both soils, with sandy clay generally exhibiting higher retention capacity than sandy loam due to its finer texture.

Table 10: WRC of Sandy Loam and Sandy Clay Soils under Different Biochar Levels

Factor (Soil × Biochar)	Water Retention Capacity (mL)
SC 6%	127.00 ± 2.88a
SL 6%	120.00 ± 2.93ab
SC 3%	116.90 ± 3.00b
SL 3%	108.67 ± 2.81c

Factor (Soil × Biochar)	Water Retention Capacity (mL)
SC 0%	104.90 ± 2.71c
SL 0%	93.67 ± 2.03d

Means that do not share a letter are significantly different ($p < 0.05$)

Discussion

Biochar application led to significant improvements in the chemical properties of both sandy loam and sandy clay soils. The increase in soil pH following biochar addition reflects the alkaline nature of banana stalk biochar, which helps neutralize soil acidity and create a more favorable environment for nutrient availability. Similarly, higher levels of organic carbon and cation exchange capacity (CEC) observed in the amended soils indicate the role of biochar in enhancing soil nutrient retention and buffering capacity. Macronutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium increased progressively with biochar application, particularly at the 6% rate. This can be attributed to the nutrient-rich composition of the biochar and its ability to adsorb and slowly release nutrients. Micronutrients including iron, manganese, zinc, and copper also showed moderate increases, suggesting improved nutrient cycling and availability. The findings demonstrate that banana stalk biochar enhances soil chemical quality by increasing pH, organic carbon, nutrient availability, and cation exchange capacity. These results are consistent with the observations of Sun et al. (2022), who reported that biochar application significantly improves soil chemical properties across diverse soil types through enhanced nutrient retention and stabilization of organic matter.

The results revealed that biochar application significantly reduced soil bulk density in both sandy loam and sandy clay soils. The reduction was more pronounced at higher biochar application rates, particularly at 6%, where bulk density values were markedly lower than the control. This decrease can be attributed to the inherently low density and highly porous structure of biochar, which, when incorporated into the soil, dilutes the heavier mineral fraction and introduces additional pore spaces. Consequently, the soil becomes less compacted and more conducive to root growth, aeration, and water infiltration. Moreover, the difference observed between soil types indicates that sandy clay, due to its finer particles and higher cohesive forces, retained relatively higher bulk density values than sandy loam even after biochar amendment. These findings align with the meta-analysis by Zanutel et al. (2024), which reported that fresh biochar application reduced soil bulk density by approximately 16.8% while simultaneously increasing saturated water content and macroporosity.

Soil porosity increased significantly with biochar addition, demonstrating the inverse relationship between bulk density and pore space. The highest porosity values were observed in the 6% biochar treatments, indicating that biochar effectively enhanced soil structure by creating additional voids and promoting particle aggregation. This improvement in pore continuity facilitates better water infiltration and enhances gaseous exchange within the soil profile. Across soil types, sandy loam consistently exhibited higher porosity than sandy clay, underscoring the combined influence of soil texture and biochar in regulating pore dynamics. These results clearly show that biochar plays a structural role in improving soil physical quality. Similarly, Zanutel et al. (2024) reported that fresh biochar application significantly increased soil pore volume and macroporosity, further supporting the findings of this study.

Water retention capacity increased progressively with biochar application, with the 6% treatments recording the highest values in both soil types. This improvement is attributed to the high surface area and porous structure of biochar, which enhance the soil's ability to absorb and retain water within its matrix. The effect was particularly notable in sandy clay soil, where water retention was greater than in sandy loam, suggesting that finer textured soils benefit more from biochar's water holding capacity. Enhanced retention ensures that more water remains available for plant uptake between irrigation events, which is crucial for maintaining crop growth under limited water supply. These findings confirm that biochar significantly contributes to improving soil water storage and overall resilience to moisture stress. Consistent with this result, a global meta-analysis by Omondi et al. (2016) reported that biochar increases field capacity and available water capacity, with more pronounced effects observed in coarse textured soils, aligning well with the patterns observed in this study.

CONCLUSION

The application of banana stalk biochar significantly improved soil physical properties by reducing bulk density, increasing porosity, and enhancing water retention capacity. These changes improved soil structure, aeration, and moisture availability, which are essential for root growth and nutrient uptake. The positive effects were more pronounced at higher biochar application rates, with sandy clay soils showing greater improvement compared to sandy loam. Biochar demonstrated a strong residual effect, maintaining better soil physical conditions across planting cycles and highlighting its potential as a sustainable soil amendment for improving soil quality and supporting crop productivity.

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