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HYDROLOGICAL PROPERTIES OF AGRICULTURAL SOIL UNDER TREATMENT WITH DIFFERENT LEVELS OF BIOCHAR-BASED NANOPARTICLE

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Abstract

Soil hydrology plays a crucial role in many fields of study, including agriculture, due to the variation in the length of the rainy season brought about by erratic weather patterns. To mitigate crop failure, sustainable and drought-resistant agricultural techniques must be developed. This can be achieved by comprehending the transformative effects of nanoparticles on soil structure, water availability, and nutrient dynamics. Hence, this study aims to explore the impact of biochar-based nanoparticles on the hydrological properties of agricultural soil. Six (6) levels of biochar-based nanoparticles were used as treatments at 0 g, 100 g, 200 g, 300 g, 400 g, and 0 g with constant water supply as control applied to 20 g of soil. The hydrological properties considered are clay flocculation, dispersion ratio, structural stability, void ratio, sodium percentage, and water retention ability, among others, are relevant to agriculture. Biochar addition initially increased soil moisture retention and soil aggregation, but impaired stability at excessive levels due to nanoparticle toxicity. Clay flocculation dramatically improved with 100 g of biochar nanoparticle, yet severely declined beyond 200 g due to toxicity inhibiting natural aggregation. Lower biochar application rates increased aggregate stability compared to control samples, but stability did not increase proportionately as biochar application increased. Compared to higher amounts, the void ratio significantly changed with 100 g biochar addition, .patterns in stability and sodium content indicate biochar nanoparticles profoundly altered soil structure, highlighting the narrow threshold between benefits and ecosystem damage from excessive application. It was concluded that as much as biochar-based nanoparticles can help improve the hydrological properties of the agricultural soil, application beyond 200 g could have a counter effect and hence has to be monitored.

1.0 INTRODUCTION

Climate change has led to erratic rainfall patterns and longer dry spells that threaten agricultural productivity [1]. One proposed mitigation strategy involves applying biochar-based nanoparticles to improve soil moisture retention, nutrient availability, and other physical properties in drought-prone soils [2]. Biochar is produced by pyrolyzing organic materials that are high in carbon, while biochar nanoparticles are synthetically produced in the 1-100 nm size range [3]. The characteristics of biochar nanoparticles depend on the production method, temperature, and source feedstocks [4]. When applied to soil, the nanoparticles can alter important physicochemical properties like porosity, aggregation, and water dynamics [5]. Other studies have shown that

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biochar nanoparticles can improve soil structure and water retention thereby improving crop resistance to water stress [7]. This includes enhanced moisture retention through increased micro and macro-porosity [8] and improved structural stability from higher soil organic matter and aggregation [9]. Yet debates continue over optimal nanoparticle types and application levels to balance intended benefits versus potential toxicity if over-accumulated [10]. Therefore, this study aims to explore how biochar nanoparticles affect key soil hydrological properties like stability, void ratio, clay flocculation, dispersion ratio, and moisture retention in soils. The results will clarify the nanoparticles' effects on soil-water-plant relations to develop more sustainable application techniques for drought-prone regions, with broader implications for climate resilience in vulnerable food systems worldwide [11].

2.0 MATERIALS AND METHODS

2.1 Description of Study Areas

The study was carried out at the teaching and research farm of The Federal University of Technology, Akure (FUTA), Ondo State, Nigeria. The teaching and research farm is located at latitude 7.3072306 and longitude 5.1218411. Being a replication of a drought scenario, this research work needed to be carried out in a controlled environment where it is easier to control the environmental conditions or limit the impact of the environment, such as rainfall. Hence this research was carried out at the screen house at the teaching and research farm. This research was carried out in potting bags arranged in blocks in the screen house.

2.2 Soil Preparation

The soil sample was collected from agricultural land at the FUTA teaching and research farm. The collected soil was then mixed thoroughly with poultry manure at a ratio of 2:1 after which the potting sacks were filled with 20 kg of the mixture of soil and manure. Poultry manure was specifically used in this research because of the nature of the materials used in the production of the nano-milled biochar. The nanoparticles were produced from pyrolysis and milling of sawdust. From the mixture, a composite sample was also collected which was used to carry out a pre-experimental analysis to determine the condition of the soil before adding the treatments.

2.3 Treatment Description

The treatment description is given below;
$T1 = 0\ g\ of\ biochar\ nanoparticle\ +\ soil$
$T2 = 100\ g\ of\ biochar\ nanoparticle\ +\ soil$
$T3 = 200\ g\ of\ biochar\ nanoparticle\ +\ soil$
$T4 = 300\ g\ of\ biochar\ nanoparticle\ +\ soil$
$T5 = 400\ g\ of\ biochar\ nanoparticle\ +\ soil$
$T6 = 0\ g\ of\ biochar\ nanoparticle\ +$
$soil\ with\ constant\ water\ supply$

2.4 Experimental Design and Layout

The soil used for this trial was collected from the FUTA farm. A Completely Randomized Design with six treatments replicated three times was employed to give a total of eighteen (18) experimental units. The treatments included six levels of biochar-based nanoparticles (0 g, 100 g, 200 g, 300 g, 400 g, and 0 g with constant water supply as control). About 2 liters of water was applied to all the treatments at the onset of the trial and allowed to incubate for 12 weeks, only treatment six received a regular supply of 2 liters of water every week. At 12 weeks, samples were collected from all the treatments and then analyzed for hydrological properties.

2.5 Preparation of Biochar-based Nanoparticle

The biochar-based nanoparticle was prepared from sawdust through pyrolysis and milling. About 36.5 kg of sawdust collected from a sawmill was pyrolyzed for 6 hours at 389°C when taken with a pyrometer mounted with a thermocouple. After this, the kiln was completely sealed for 12 days to allow for the complete cooling of the materials without oxygen. The pyrolyzed material was opened on the twelfth day at a temperature of 42.8°C when taken with the pyrometer. After the pyrolysis, the material was milled to the nanoscale (1-100 nanometers) using a ball mill.

2.6 Determination of the Dispersion Ratio

The hygrometer method of analysis was used. About 50 g of air-dried soil was measured into a shaking bottle; 100 ml of sodium hexametaphosphate (Calgon) was added and allowed to stand for 30 minutes. The entire contents of the shaking bottles were transferred into 1 L measuring cylinders. Deionized water was added to 80% measure of the cylinder and stirred with a plunger for 30 seconds to bring all material into suspension. The hydrometer reading was taken at 45 sec and 2 hours. The values obtained were used to calculate the percentage of sand, silt, and clay. The process was repeated using deionized water instead of sodium hexametaphosphate (Calgon). The dispersion ratio was then calculated as;

$$\text{Dispersion ratio (\%)} = \frac{\text{Silt+clay dispersion in water}}{\text{Silt+Clay dispersion in calgon!}} \times 100 \qquad (1)$$

2.7 Determination of Aggregate Stability

Soil structural stability indicates the ability of soil to maintain its organization of aggregate when exposed to external factors like water, wind, and erosion. The Wet Sieve Test method was used for the analysis.

2.8 Determination of Moisture Content

The oven-drying method was used for this analysis. About 10 g of the soil sample was put into a weighed foil paper. The foil papers were put into a heated oven and were left in the oven for 24 hours. The soil samples were weighed repeatedly to ensure a constant weight.

After achieving constant weight, the weight was recorded. This was repeated for all the soil samples. The moisture content was then calculated by subtracting the dry weight of the sample from the weight of the initial sample (10 g).

2.9 Determination of Void Ratio

A direct measurement method was used for this procedure. About 20g of Wet soil sample was collected and weighed on a precision balance and recorded as MS1, the sample was oven-dried for 24 hours at a temperature of 105°C to remove all moisture, and the weight was recorded as MS2. From these, the volume of void and volume of solid was calculated which was further used to calculate the void ratio using the formula

$$\mathrm{e} = \frac{\mathrm{Vv}}{\mathrm{Vs}} \tag{2}$$

Where, e = void ratio, Vv = volume of void, and Vs = volume of solid

2.10 Determination of Clay Flocculation

The turbidity method was used for this analysis, a suspension made up of 10 g of soil sample and 100 ml distilled water was prepared, and about 15 ml of the soil suspension was transferred to the spectrometer and measured at the wavelength of 600 nm. This was recorded as the initial turbidity. Five grams of calcium chloride was then added to the suspension which caused the soil solution to form floccs. It was mixed and allowed to settle for another 30 minutes in a granulated cylinder. After 30 minutes, a small aliquot of 10 ml of clear suspension was measured into a spectrometer at a wavelength of 600 nm and recorded as the final turbidity.

$$\text{Clay Flocculation} = \frac{\text{Final turbidity}}{\text{Initial turbidity!}} \text{ x } 100 \tag{3}$$

2.11 Determination of Sodium Percentage

The summation method was used; 2.5 $grams$ of dry soil was mixed with 10 ml of ammonium acetate in a tube. It was shaken for 30 minutes and spun in a centrifuge to separate liquids. The liquid was carefully poured (with extracted cations) into a flask. The step was repeated 2-3 times with fresh ammonium acetate to ensure complete extraction. The extracted cation in ammonium acetate was transferred into a 100ml granulated cylinder and filled to its mark with water to dilute the extracted cations. The diluted liquid was filtered to remove any remaining soil particles. An AAS instrument was then used to measure the calcium, magnesium, potassium, and sodium in the filtered liquid.

The concentration of each exchangeable base was calculated (mg/L) in the original soil sample. Then the exchangeable hydrogen ion concentration was estimated based on the soil pH. The concentrations of all exchangeable cations were added (including estimated hydrogen) to get the CEC. Then the sodium percentage was calculated using the formula

$$\mathrm{ESP} = \frac{\text{Exchangeable sodium}}{\text{CEC}} \text{ x } 100 \tag{4}$$

2.12 Statistical Analysis

Analysis of variance was employed using MINITAB Statistical Software 17 to analyze collected data. The significant difference test was conducted using Tukey at $p<0.005$ to pinpoint significant differences among treatment means.

3.0 RESULTS AND DISCUSSION

3.1 Pre-Experimental Soil Analysis

The pre-experimental soil analysis is presented in Table 1, the soil was found to have a sand percentage of 62.48, silt of 13.75, and clay of 23.77 consequentially, the soil texture was found to be sandy clay loam. The organic matter content of the soil was moderate with a value of 1.58% and pH was 6.4. Nitrogen content was high (0.18%), phosphorus moderate, and potassium moderate with values of 9.46 ppm and 12.64 $cmol/kg$ respectively. Calcium and magnesium were also moderate having values of 23.88$cmol/kg$ and 14.42$cmol/kg$ respectively. Bulk density was 1.15g/cm and porosity was 43.5%. Generally, the soil can be considered moderately fertile, slightly acidic, and with good drainage.

Table 1: Pre-experimental soil analysis

Parameters	Values
Sand (%)	62.48
Silt (%)	13.75
Clay (%)	23.77
Texture	Sandy Clay Loam
pH	6.4
Organic matter (%)	1.58
Nitrogen (%)	0.18
Phosphorus (ppm)	9.46
Potassium (Cmol/kg)	12.64
Calcium (Cmol/kg)	23.88
Magnesium (Cmol/kg)	14.42
Bulk Density (g/cm^3)	1.15
Porosity (%)	43.5

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3.2 Effect of Biochar-based Nanoparticle on Soil Dispersion Ratio

The effect of biochar-based nanoparticles on the soil dispersion ratio is presented in Table 2. T3 had a significantly higher dispersion ratio of 57.20% compared to other levels of biochar-based nanoparticle application, and T6 ($p<0.05$). T4 (33.10%) and T5 (34.23%) had significantly lower dispersion ratios compared to T1 and T6 ($p<0.05$) both with values of 44.97%. No other significant difference existed between any treatment ($p>0.05$). The high dispersion at T3 ($200\ g$) indicates augmented soil moisture storage and flow. However, as application rates increased ($300 - 400\ g$) dispersion sharply reduced, indicating that biochar nanoparticles could be a good binding agent to reduce soil dispersion, crucial for sustained water transport and erosion control [12].

Table 2: Effect of biochar-based nanoparticle on dispersion ratio

Treatment	Dispersion Ratio (%)
T1	44.97±3.04b
T2	42.60±2.38b
T3	57.20±4.12c
T4	33.10±3.82a
T5	34.23±2.32a
T6	44.97±3.04b

Note: All values are averages of three replicas. This means that according to Tukey test ($P > 0.05$), columns followed by the same letter(s) is not significantly different.

3.3 Effect of Biochar-based Nanoparticle on Soil Aggregate Stability

The effect of biochar-based nanoparticles on the soil aggregate stability is shown in Table 3. When compared, T6 had the highest aggregate stability among the treatments ($p < 0.05$) with a value of 68.27%. T2 had a significantly higher aggregate stability of 60.30% compared to the remaining four treatments ($p < 0.05$). T1 (no biochar/no water; 38.80±1.83) had the lowest aggregate stability among the treatments ($p < 0.05$). The aggregate stability findings provide insights into the impacts of biochar nanoparticles on soil structure over time. The significantly high stability with $100\ g$ nano biochar agrees with other work of Ouyang et al. [14] that these particles can enhance binding between minerals and organic matter to improve soil aggregation. However, the subsequent decline at higher amounts indicates a fine line between intended benefits and detrimental interference in complex soil systems [15]. This agrees with the work of Gong et al. [18] who stated that excessive nanoparticle accumulation can disturb soil microbiota and overwhelm buffers.

Table 3: Effect of biochar-based nanoparticle on soil aggregate stability

Treatment	Aggregate Stability (%)
T1	38.80±1.83a
T2	60.30±2.46c
T3	45.31±3.20b
T4	42.84±3.4ab
T5	41.21±2.17ab
T6	68.27±1.03d

Note: All values are averages of three replicas. This means that according to Tukey test ($P > 0.05$), columns followed by the same letter(s) is not significantly different.

3.4 Effect of Biochar-based Nanoparticle on Soil Moisture Content

The effect of biochar on the moisture content of the soil for 8 weeks is presented in Figure 1, at week 1, T1 (0.41%) had the lowest moisture content, significantly lower than T3, T4, T5, while T6 (1.87%) recorded the highest moisture content. T4, T3, and T2 were intermediate. At week 2, T1 and T2 had the lowest moisture content of 1.25% and 1.34% respectively, significantly lower than all other treatments. T3 to T6 were not significantly different from each other. At week 3, T1 to T4 were not significantly different while T5 (0.77%) and T6 (1.57%) had higher moisture than the other treatments. At week 4, T1, T2, T5 and T6 were similar. T3 and T4 had higher moisture than T1 and T2. At week 5, T1 (0.58%) and T6 (0.64%) had the lowest moisture content, the other treatments were not significantly different from one other ($p>0.05$). At week 6, T1 with a value of 0.28% had lower moisture than T3, T4, and T5, while T5 (0.40%) and T6 (0.34%) were similar to each other. At week 7, T6 (0.40%) and T1 (0.81%) had lower moisture than the others while the highest moisture was seen in T3, T4, and T5 having a moisture content of 1.08%, 0.92%, and 1.62% respectively.

At week 8, no significant difference existed among the treatments. The moisture patterns over 8 weeks provided insights into the transitional impacts of biochar nanoparticles on key soil hydrological properties. Initially, application at the rate of 400 g increased soil moisture, likely from introduced pores and vast hydrophilic surface area which has been found to improve water retention [8]. This agrees with the findings of Suliman et al [22] and Razzaghi et al. [23] who stated that soil micropore surface area increased with the addition of biochar. However, these enhancements rapidly declined by week 3, suggesting that unchecked biochar nanoparticle interactions with the soil can physically disrupt soil structure despite water capture potential [12]. In contrast, gradual moisture improvements with application rates of 100 and 200 g indicated more stable integration with natural soil structure over time [13]. Biochar-based nanoparticles markedly increased soil water retention for months which according to Gao et al. [8] is linked to expanded surface area and porosity.

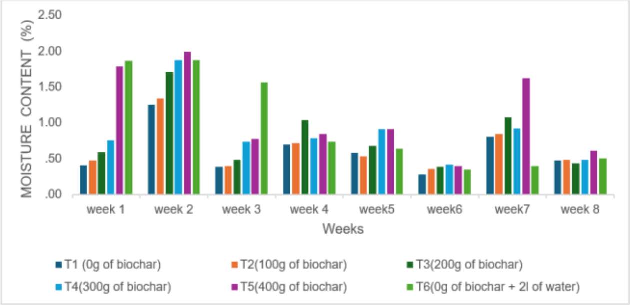

Figure 1: Effect of biochar-based nanoparticle on moisture retention over 8 weeks

3.5 Effect of Biochar-based Nanoparticle on Soil Void Ratio

Table 4 shows the effect of biochar-based nanoparticles on the soil void ratio. T1 with a value of 38.80% had the lowest void ratio out of all treatments while T2 with a value of 60.30% had the highest void ratio out of the biochar nanoparticle treatments. T3, T4, and T5 had intermediate void ratios ranging from 41.21% to 45.31% which was not statistically different from one another but higher than T1 and lower than T2. T6 with a moisture content of 68.27% had the highest void ratio overall. The void ratio is an indicator of soil aeration, with higher ratios providing more air capacity needed by plant roots [10]. Application of biochar nanoparticles increased void ratios creating better soil aeration and pore spaces for proper drainage. This agrees with the works of [16, 17] who stated that the void ratio of soils amended with nanoparticles was increased by 15-25% compared to values for the region's unamended soils, reflecting enhanced porosity from the nanoparticles.

Table 4: Effect of biochar-based nanoparticle on void ratio

Treatment	Void Ratio (%)
T1	38.80±1.83a
T2	60.30±2.46d
T3	45.31±3.20c
T4	42.84±3.39bc
T5	41.21±2.17ab
T6	68.27±1.03e

Note: All values are averages of three replicas. This means that according to Tukey test (P > 0.05), columns followed by the same letter(s) is not significantly different.

3.6 Effect of Biochar-based Nanoparticle on Soil Clay Flocculation

The effect of biochar-based nanoparticles on the soil clay flocculation is captured in Table 5. T2 with a value of 6.39% had significantly higher clay flocculation compared to all other treatments ($p < 0.05$) while T3 (3.74%) recorded significantly lower clay flocculation than all other treatments ($p < 0.05$). T4 (4.86%), T5 (4.76%), and T6 (4.70%) had significantly higher clay flocculation than T1 (4,26%) ($p < 0.05$). There were no significant differences between T4, T5, and T6 ($p > 0.05$). The significant differences in clay flocculation point to a potent impact of biochar nanoparticles influencing soil colloid interactions. The increase in flocculation with 100 g nano biochar is due to enhanced clay binding capacities [18]. However, the sharp decline at the application rate of 200 g suggests potential toxicity thresholds that can hinder natural clay interactions [19]. Notwithstanding, the fact that higher rates caused less harm suggests some normalization over time is possible.

Table 5: Effect of biochar-based nanoparticle on clay flocculation rate

Treatment	Clay Flocculation (%)
T1	4.26±0.05b
T2	6.39±0.06d
T3	3.74±0.09a
T4	4.84±0.14c
T5	4.76±0.18c
T6	4.70±0.15c

Note: All values are averages of three replicas. This means that according to Tukey test (P > 0.05), columns followed by the same letter(s) is not significantly different.

3.7 Effect of Biochar-based Nanoparticle on Soil Sodium Percentage

Table 6 presents the effect of biochar-based nanoparticles on the soil sodium percentage. T3 (11.66%) and T4 (11.61%) had significantly higher sodium percentages than all other treatments ($p < 0.05$). T2 (8.26%), T5 (8.36%), and T6 (8.43%) had significantly higher sodium percentages than T1 with a sodium percentile of (6.48%) ($p < 0.05$) without any difference existing between them ($p > 0.05$). Biochar-based nanoparticle incorporation significantly increased the sodium content of soils from $100 - 400\ g$ rates compared to control. It can be theorized that the rise in sodium may increase dispersion and deteriorate structure [20]. However, sodium substantially declined at the highest 400 g rate, likely pointing towards a threshold where excess sodium is precipitated under alkaline conditions also induced by high biochar rates [21]. Hence further work needs to be done on this.

Table 6: Effect of biochar-based nanoparticle on sodium percentage

Treatment	Sodium percentage (%)
T1	6.48±0.34a
T2	8.26±0.21b
T3	11.66±0.1c
T4	11.61±0.2c
T5	8.36±0.18b
T6	8.43±0.32b

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Note: All values are averages of three replicas. This means that according to Tukey test (P > 0.05), column followed by the same letter(s) is not significantly different.

4.0 CONCLUSION

The study revealed that biochar-based nanoparticles can profoundly influence key soil hydrological properties, but only within narrow concentration ranges. Moderate application of biochar increased moisture storage, flow dynamics, and clay flocculation through expanded surface area and binding sites. However, excessive accumulation impaired stability, aggregation, and cation balances from unchecked nanoparticle interactions and toxicity. The significant moisture, dispersion, stability, and sodium fluctuations demonstrate precarious transitional thresholds between improving versus disrupting natural soil systems. While prudent use of biochar nanotechnology could sustainably enhance agriculture, strict validation is imperative before field applications given the extremely fine line between benefits and toxicity.

5.0 CONFLICT OF INTEREST

The authors declare no conflict of interest financial or otherwise.

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