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# Comparison of Biochar Derived from Slow Pyrolysis of Banana Peels and Bunch Stalks in Agricultural Soil Amendment

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**Keywords:** banana peels, banana bunch stalks, pyrolysis, biochar, soil amendment, crop yield.

**Abstract.** Soil degradation in agriculture represents a significant global challenge, primarily caused by nutrient depletion, erosion, and the loss of organic matter. A potential solution involves amending the soil to improve some properties that impact resistance to erosion, while also enhancing nutrient availability. Biochar has been widely used for soil amendment. This study evaluated the impact of biochar obtained from the slow pyrolysis of banana peels and banana stalks on some soil hydrophysical properties. The parameters assessed were: water retention in coarse-textured soils, swell-shrinkage characteristics in fine-textured soils. The experiment's findings indicated that banana peel biochar (BP) is slightly alkaline with a pH of 9.05. It was also rich in potassium (94.40 mg/kg) and phosphorus (15.20 mg/kg), with a relatively high carbon content (57.20%). In contrast, banana stalk biochar (BS) had a higher pH (9.50), lower carbon content (37.89%), and relatively lower levels of potassium (83.30 mg/kg) and phosphorus (12.80 mg/kg). The fibrous structure of the stalk resulted in a more porous biochar. While banana peel biochar provides immediate nutrients to plants, banana stalk biochar is better suited for moisture retention and long-term carbon storage. Both types of biochar improved water retention, particularly in coarse-textured soils. Notably, banana stalk biochar outperformed banana peel biochar regarding surface area, porosity, cation exchange capacity (CEC), and moisture retention, enhancing the soil's water-holding capacity by up to 30%. This characteristic makes it particularly effective for sandy soils susceptible to water and nutrient leaching. Additionally, banana stalk biochar was more effective in mitigating swell-shrink behavior in fine-textured soils, contributing to greater aggregate stability and reduced volume fluctuations. Amending fine sand with 3% of either biochar type did not significantly enhance total porosity; however, there was a significant increase ($p < 0.001$) in volumetric water content at 0 kPa. The results indicated that BS10% retained the most water, with an $R^2$ value of 0.7599, followed by BP10% at 0.745, demonstrating that higher application rates of biochar correlate with improved water retention. The study also revealed a negative correlation between soil suction and water retention, indicating that as suction levels rise, the soil's ability to retain water decreases. This relationship is vital for agricultural practices, irrigation planning, and understanding soil hydrology. By leveraging these findings, farmers and land managers can optimize irrigation strategies, enhance crop yields, and adapt to changing environmental conditions.

## 1. Introduction

Soil degradation in agriculture is a pressing global issue, driven by factors such as nutrient depletion, erosion, and loss of organic matter. One solution is adding biochar made from different feedstock (including banana peels) to the soil to improve the physico-chemical properties of the soil and help recovery of pore functions [1.] Traditionally seen as waste, banana peels and stalks are now valued for their bioactive compounds. Banana stalks are the long, flexible part that carries the bunch of bananas.

Often called a peduncle, or sometimes an inflorescence stalk [2.]. Banana stalks are now applied in fiber production, bioenergy, and livestock feed. As the world shifts toward sustainability, both banana peels and stalks, when pyrolyzed, offer promising opportunities for economic growth, environmental preservation, soil structure enhancement, and improved water retention [3]. Biochar, a carbon-rich material produced through pyrolysis, offers a sustainable method for enhancing soil health and productivity [4]. Its benefits include improving soil structure and nutrient availability and boosting water retention, while also serving as a carbon sink. As a soil amendment material, biochar has gained significant attention for its role in promoting soil health and addressing climate change by sequestering carbon, improving nutrient retention, and supporting long-term soil sustainability [5].
Pyrolysis, a thermochemical decomposition process for carbon-rich materials, has significant benefits from a sustainability standpoint, utilizing various feedstock while emitting fewer greenhouse gases than conventional incineration [6.]. Since biomass-derived $CO_2$ is re-captured during plant growth, pyrolysis can achieve net-zero emissions. The effectiveness and yield of pyrolysis depend on several operating conditions, primarily temperature, heating rate, and residence time, which dictate product composition. Slow pyrolysis heats materials at rates of 5 - 20°C per minute, lasting from minutes to hours, allowing reactions to reach equilibrium and yielding more solid char products. In contrast, fast pyrolysis, with rates exceeding 1000°C per minute and reaction times as short as two seconds, favors liquid bio-oil production with minimal secondary reaction [7]. These differences in heating rates and time produce distinct product distributions. Biochar from slow pyrolysis also holds potential as a biofuel and soil enhancer [8]. On the other hand, fast pyrolysis is frequently employed for bio-oil extraction, though it also produces biochar suitable for soil amendment and other applications, as demonstrated in studies of rice husk, elm, and meranti wood biochar [9].
The assessment of soil linear shrinkage and cracking, particularly in fine-textured soils, is according to the Atterberg limits, such as the liquid limit (LL), and modulus-based evaluations. These properties are critical in understanding soil behaviour during the wetting and drying cycle, associated with rain and the dry season. Drying results in volume reduction and crack formation, whereas during wetting, the soil expands in volume. The liquid limit relates to the soil's plasticity, while modulus-based approaches evaluate its mechanical response to shrinkage. Water retention is essential in soil, influencing plant health, soil erosion, and water management. Coarse-textured soils, such as those with sand, typically have low water retention, which is particularly problematic for agriculture in arid and semi-arid areas where water is scarce [10, 11]. In agriculture, soil amendments are key to enhancing soil physicochemical properties and fertility, increasing crop productivity, and supporting sustainable practices. Thus, the purpose of this study was to investigate and compare biochar derived from slow pyrolysis of banana peels and banana stalks as soil amendments, focusing on their effects on soil physicochemical properties, including shrinkage and cracking behavior.

## 2. Materials and Methods

### 2.1 Feedstock Selection and Availability in Nigeria

Nigeria is among the top producers of bananas globally. In 2022, the country produced approximately 8.02 million metric tons of bananas, marking an 8.5% increase from the previous year [12.]. This production level positioned Nigeria as the fourth-largest banana producer worldwide. Banana cultivation is predominantly practiced by smallholder farmers in the southern states, including Oyo, Ogun, Osun, Lagos, Delta, and Rivers. These farmers often integrate banana plants into mixed cropping systems, reflecting traditional agricultural practices [13.]. Bananas play a vital role in Nigerian cuisine and daily life. A notable example is "Boli" (also spelled "Bole"), a popular street food consisting of roasted plantain or banana. In southwestern Nigeria, *Boli* is commonly consumed with groundnuts, while in the south-south region, it's often paired with grilled fish. This delicacy is widely sold by street vendors and is integral to local food culture. Despite its prominence, banana cultivation in Nigeria faces several challenges: Banana Bunchy Top Virus (BBTV), limited adoption of improved varieties [14.] , and pest and disease pressure. According to [15.], banana cultivation in Nigeria results in substantial agricultural. residues, notably banana peels and stalks, which have significant potential as feedstock for biochar production that could be used in soil amendment. Nigeria, being one of the leading banana-producing countries, generates considerable quantities of these residues [16.]. Given the country's substantial banana production, large volumes of peels and stalks are discarded annually [17]. Utilizing these residues for biochar production offers a sustainable solution to manage this waste effectively [18.].

### 2.2 Feedstock Collection and Preparation

A total of 25kg of banana peels and 20kg of banana bunch stalk were collected from roadside roosted plantain sellers and Obaja farms, off Ilesa garage, Akure. These materials were pre-prepared and transported to the laboratory where they were washed and sorted to remove contaminants before sun drying for approximately two months to achieve a moisture content of 3% as shown in Plate 1.

**Plate 1.** Dried feedstock after sun drying.

The moisture content of the banana peels and stalks was calculated using Equation 1. Fresh banana peels and stalks were collected, cleaned, and cut into smaller pieces to ensure uniform drying. A known mass of each sample was weighed using a digital balance. The samples were dried in an oven set at 105°C for 24 hours until a constant weight was achieved. After cooling in a desiccator, the dried samples were reweighed. At 105°C for 24 hours, the moisture content was found to be 20% for banana peels and 23.3% for banana stalks. After the initial moisture content was determined, the banana peels and stalks were sun-dried to 3% moisture content.

$$Moisture\ Content\ (\%) = \frac{W1-W2}{W1} \times 100 \quad (1)$$

Where: W1 is the Initial wet weight of the sample (g), and W2 is the Final dry weight of the sample (g)

### 2.3 Biochar Production

The sun-dried banana peels and banana stalks were pyrolyzed in a muffle furnace (kiln) under limited oxygen conditions in batches. The materials were slowly pyrolyzed at an average temperature of 500°C for 2 hours using a laboratory-scale pyrolyser unit. Slow pyrolysis promotes higher retention of nutrients and the formation of stable carbon structures [19.]. After the biochar (banana peel biochar BPB, banana stalk biochar BSB) was produced in each batch, they were allowed to cool for 4 days, sieved to obtain particles less than 2 mm in diameter, and stored in airtight containers (Plate 2).

### 2.4 Analysis of the Biochar

Proximate and ultimate analysis of sieved biochar was carried out in the Crop, Soil, and Pest Department laboratory of the Federal University of Technology, Akure, to determine the chemical composition and ash content of each biochar (BPB and BSB), offering insight into the quality of the resulting biochar. The micro- Kjeldahl method (AOAC, 1995) was employed to determine nitrogen content. This method consists of three stages: digestion, distillation, and titration. The digestion process involves converting the nitrogen in the sample into ammonium sulphate by boiling it with concentrated sulphuric acid ($H_2SO_4$). The total nitrogen content of the sample was calculated using the formula provided in Equation 2.

$$\%Nitrogen\ (N) = \frac{Titre\ value \times molarity\ of\ HCl}{wt} \times \frac{V1}{V2} \times 100 \quad (2)$$

Where: $V1$ is final volume of the digest, $V2$ is the volume of the digest used in the distillation and $Wt$ is the weight of the sample taken.
The percentage ash content was calculated using Equation 3. The crucibles were then removed from the furnace and transferred into a desiccator to cool before reweighing ($W3$) AOAC, (1995).
Percentage ash content was calculated as Ash

$$(\%) = \frac{W3-W1}{W2-W1} \times 100 \quad (3)$$

Where: $W1$ is the weight of empty crucibles, $W2$ is the weight of crucibles and samples, $W3$ is the weight of crucible and ash samples.
The Walkey-Black method was used for determining the organic carbon content in biochar. The method involves oxidizing organic carbon with potassium dichromate ($K_2Cr_2O_7$) in the presence of sulphuric acid ($H_2SO_4$). Organic carbon content was calculated using Equation 4.
Organic carbon

$$(\%) = \frac{(A - B)(K * V)}{(W - 109)} \quad (4)$$

Where: A is the volume of $K_2Cr_2O_7$, B is the volume of $FeSO_4$, K is the equivalent weight of carbon, V is the volume of Ortho-phenanthroline and W is the weight of sample.
Mineral analysis was conducted on the solution obtained from dry asheing. The minerals analysed included calcium, iron, potassium, zinc, magnesium, and sodium. Phosphorus was determined calorimetrically using the phosphovanadomolybdate method (AOAC, 1995).
The colorimetric determination of phosphorus was done using vanadomolybdate method. The Vanado molybdate solution was prepared from 20 g of ammonium molybdate $(NH_4)_6MO_7.4H_2O$ which was dissolved in 200ml of hot water and cooled. One gram of ammonium metavanadate was dissolved separately in 120ml of water, cooled and 140ml conc. $HNO_3$ was added in a fume cupboard, molybdate solution was gradually added to the vanadate solution and dilute to 1 litre. 10 mm of sample solution was pipetted into 50ml volumetric flask and 10ml of Vanado-molybdate reagent was added with few ml of distilled water mixed and diluted to the volume with water and allowed to stand for 10 minutes. The absorbance of the sample solutions was determined at 470nm and phosphorus content were expressed in mg/100g sample.

**Plate 2.** The biochar produced (a) BPB (b) BSB.

### 2.5 Soil Sample Collection and Preparation

Two soil samples: coarse-textured and fine-textured soil were collected at 0-15cm depths from adjacent farmland for amendment. The samples were transported in a polythene bag to the soil and water laboratory where they were air-dried for a few days and were sieved to eliminate large aggregates and achieve an even distribution of particle sizes. A 2.0 mm sieve (No. 10 mesh) was used for the sandy soil, while a 75µm sieve (No. 200 mesh) was used for the clay soil. After sieving, soil samples were treated with each biochar BPB and BSB at three different rates (3, 5, and 10% w/w) according to literature along with control (no Biochar). Thus, the treatments were BP0, BP3, BP5, BP10, BS0, BS3, BS5, and BS10. 5 replicates of each treatment and control were prepared and stored in a 100cl container for further analysis.

### 2.6 Water Retention Test

Soil moisture retention properties were measured to characterize the effects of biochar on field capacity, wilting point, and plant-available water. The Water Retention Curve (WRC) was determined using the Standard Funnel Test (1986). The WRC illustrates how soil retains water at different suction levels, which is vital for characterizing and understanding some soil-water interaction properties such as field capacity, wilting point, and available water content [20.]. The gravimetric water content (θ) at each suction level was calculated using Equation 4

$$\theta = \frac{\text{mass or water retained}}{Dry\ mass\ of\ soil} \qquad \text{(Hillel 1989)}$$

### 2.7 Determination of Field Capacity, Bulk Density, and Porosity

At a suction of -0, -10,-33 and -100, the filed capacity, bulk density and the porosity of the soil amended were determined using equations 5 – 7

$$Field\ capacity\ (\%) = \frac{(\text{weight of wet soil after drainage}) - (\text{weight of dry soil})}{weight\ of\ dry\ soil} \times 100 \qquad (5)$$

$$Bulk\ density = \frac{\text{Mass of dry soil (g)}}{Volume\ of\ soil\ (\text{cm}^3)} \qquad (6)$$

$$Porosity\ (\%) = \left(1 - \frac{\text{Bulk density}}{Particle\ density}\right) \times 100 \qquad (7)$$

### 2.8 Determination of Soil Linear Shrinkage and Cracking

Linear shrinkage (Equation 8) refers to the percentage reduction in the length of a soil sample as it dries from a plastic state to a completely dry state. The liquid limit (LL), which marks the water content at which soil transitions from a plastic to a liquid state, is often correlated with linear shrinkage, with soils that have high liquid limits typically showing a greater shrinkage potential. Linear shrinkage is directly related to the soil's liquid limit, with higher liquid limit values typically leading to greater shrinkage [21.]. As the soil shrinks, crack formation can be quantified using techniques such as digital image analysis, which assesses crack width, density, and total area [22]. This method offers a more comprehensive understanding of the relationship between the soil's shrinkage properties and its cracking behaviour. For the linear shrinkage measurement, a soil paste was prepared and was filled into a standard shrinkage Mold (140 mm long). The surface was smoothed and allowed to dry at room temperature, then oven-dry it at 105–110°C until constant mass. The final length of the dried sample was measured. Equation 8 can be used to calculate the linear shrinkage.

$$Linear\ shrinkage\ (\%) = \frac{\text{initial lenght} - \text{final lenght}}{initial\ lenght} \times 100 \qquad (8)$$

### 2.9 Data Analysis

Microsoft Excel and ANOVA (Analysis of Variance) was used to analyze the experimental data. The collected data from soil amendment trials involving biochar from banana peels and bunch stalks was computed into Excel spreadsheets. These included parameters such as soil pH, nutrient content (N, P, K), and the linear shrinkage and average cracking width. Excel's built-in functions was used to compute descriptive statistics for each treatment group. For inferential analysis, one-way ANOVA was used, using Excel’s Data Analysis Toolpak to determine whether there were statistically significant differences between the effects of the two types of biochar on soil properties and plant performance. The ANOVA results helped identify if the observed differences between treatments were due to chance or actual variation in biochar efficacy. Where significant differences were found ($p < 0.05$), post-hoc comparisons were considered to further interpret the findings.

## 3. Results and Conclusion

### 3.1 Physicochemical Properties of BPB and BSB

#### 3.1.1 Biochar Properties

As shown in Figure 1, BPB had a pH of 9.05, indicating slight alkalinity, and was rich in potassium (94.40 mg/kg) and phosphorus (15.20 mg/kg). It also had a relatively higher carbon content (57.20%) compared to BSB, as illustrated in Figure 1. In contrast, BSB had a higher pH (9.50), lower carbon content (37.89 %), and reduced levels of potassium (83.30 mg/kg) and phosphorus (12.80 mg/kg) as seen in Figure 1.

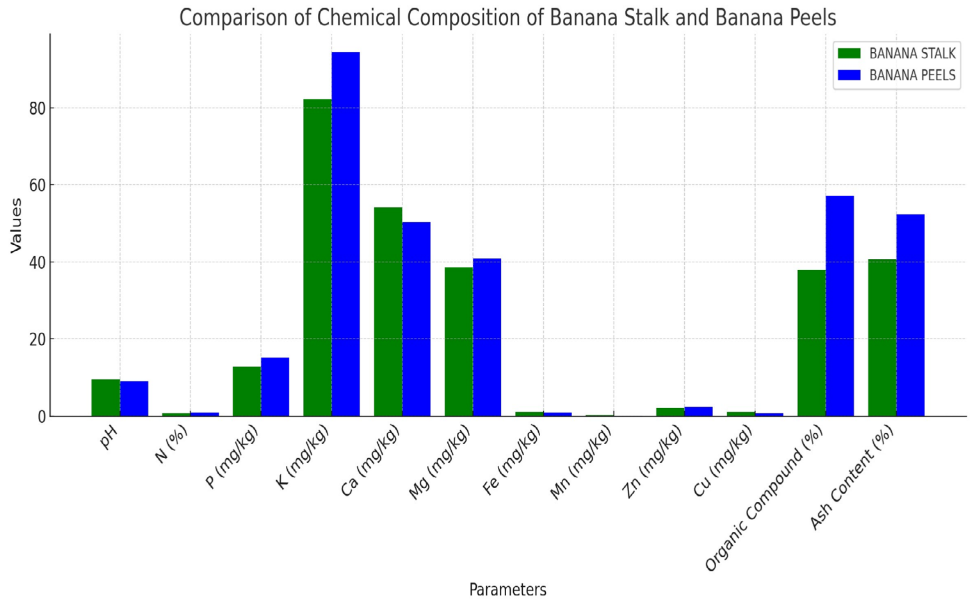



**Fig. 1.** Chemical compositions of the banana peel and banana stalk biochar.

#### 3.1.2 Substrate Properties

Both types of biochar increased soil pH, thereby reducing acidity, with BSB having a more immediate effect on raising pH, which is particularly beneficial for acidic soils. BSB also significantly boosted potassium and phosphorus levels in the soil, enhancing nutrient uptake for plants [23]. BPB had a more immediate impact on nutrient release, whereas BSB contributed to long-term soil conditioning owing to its carbon content and porosity [24.]. In terms of cracking widths, the controls ranged from 0.26 cm to 0.35 cm. The BP3 (Figure 2) displayed slightly smaller cracking widths, between 0.23 cm and 0.30 cm. The BP5 and BP10 series showed progressively lower cracking widths, with the BP10 recording the smallest widths as low as 0.10 cm. The performance of the BP10 indicates superior resistance to shrinkage and cracking, suggesting enhanced durability and stability, which is particularly desirable in materials where controlling shrinkage is critical, such as in concrete or ceramics. The BP5 (Figure 2) moderately improved both shrinkage and cracking compared to the control and BP3, suggesting improved structural integrity relative to the controls. On the other hand, the control and BP3 had higher shrinkage and larger cracking widths, suggesting they are more susceptible to shrinkage-related issues, such as cracking or deformation under certain conditions. Recent studies, such as those by [25.], indicate that incorporating additives like fibre reinforcements, polymers, or pozzolanic materials can significantly reduce shrinkage and cracking. The observed improvements in the BP5 and BP10 (Figure 2) may be linked to such modifications, which help mitigate shrinkage by enhancing internal bonding or minimizing water loss during curing [21; 26.]. Furthermore, BP10's lowered shrinkage and cracking width align with contemporary advancements in sustainable material design, aiming to improve performance under environmental stresses. According to [27], there is a direct relationship between crack width in soil and its structural integrity—wider cracks often indicate weaker, more brittle soil. Therefore, the smaller crack widths observed in BP10 and BS10 samples suggest that these soils have better structural strength, greater durability, and are more resistant to external forces such as weathering or mechanical stress. Figure 3, the C (C1 to C5) shows shrinkage between 6.66% and 8.88%**,** indicating high shrinkage. The BS3 (BS3,1 to BS3,5) has linear shrinkage between 6.36% and 8.70%**,** with results similar to the C. The BS5 (BS5,1 to BS5,5) demonstrates a significant reduction in shrinkage, ranging from 4.17% to 5.22%.

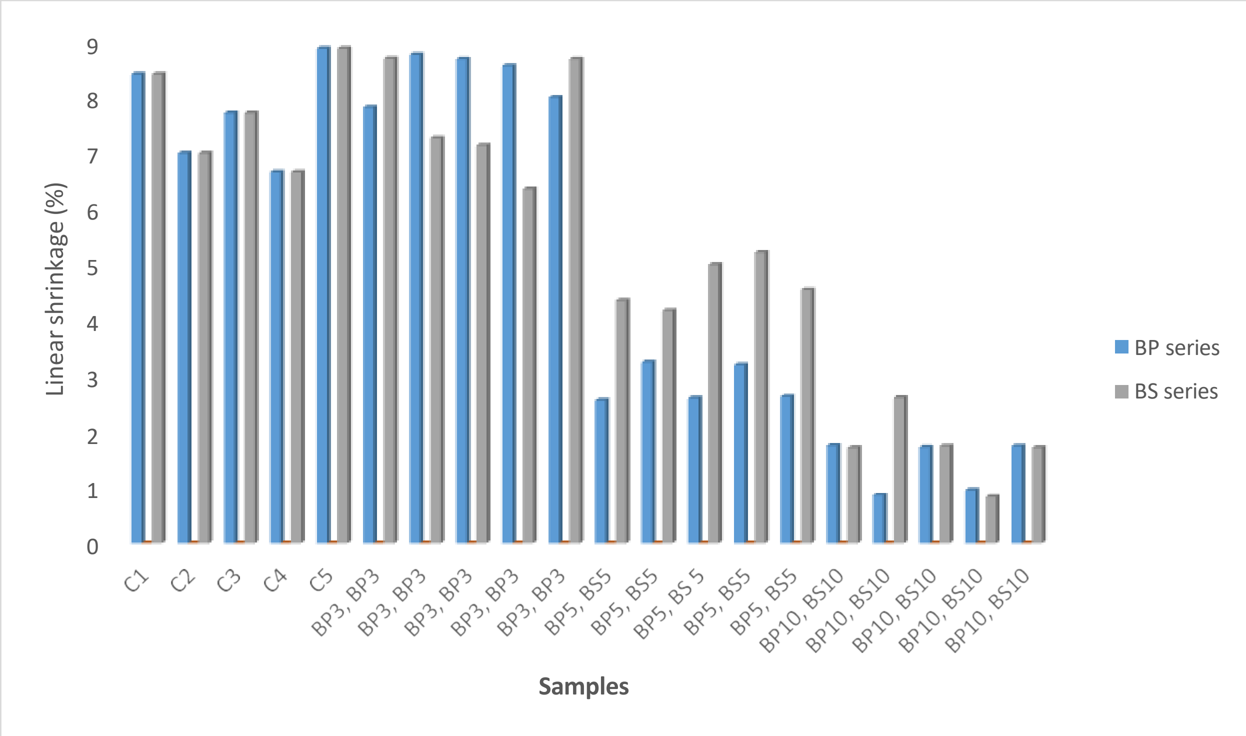



**Fig. 2.** Influence of the control, banana peels, and banana stalks biochar on the linear shrinkage.

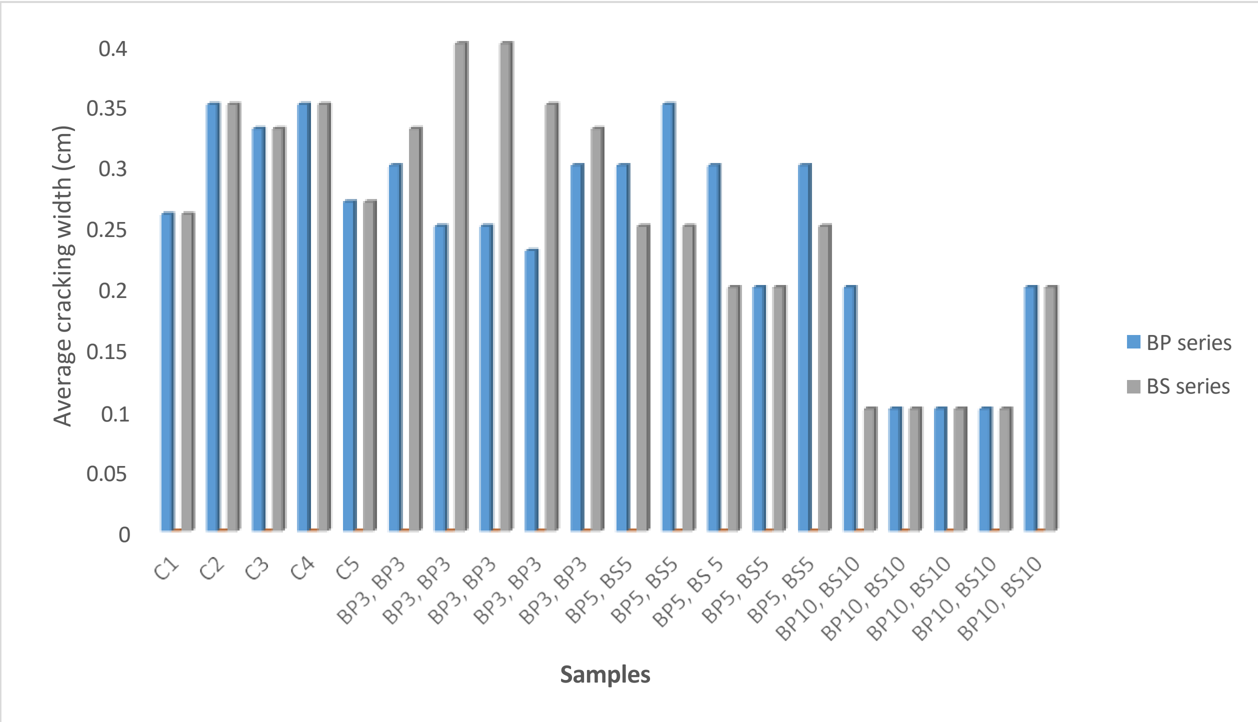



**Fig. 3.** Influence of the control, banana peels and banana stalks biochar on the average cracking width.

### 3.1.3 pH and Electrical Conductivity (EC)

The pH and electrical conductivity (EC) of the banana stalk biochar and the banana peel biochar were 9.50 and 9.05 (Figure 1). The higher pH of banana stalk biochar suggests a better potential as a liming agent, which can help reduce soil acidity and create a more conducive environment for root growth and microbial activity. In terms of electrical conductivity, banana stalk biochar exhibited higher values (1.25 dS/m) compared to banana peel biochar (0.85 dS/m). This indicates that banana stalk would better enhance nutrient retention and cation exchange. A higher EC and cation exchange capacity (CEC) imply that banana stalk biochar can retain more water, while banana peel biochar is better at holding nutrients. This is particularly advantageous in coarse-textured soils that are prone to nutrient leaching. Furthermore, a higher pH contributes to the stabilization of soil structure, enhancing both water infiltration and retention [6, 28.]

### 3.1.4 Moisture Retention Capacity

The addition of the banana stalk biochar in sandy soils enhanced the soil's water-holding capacity by 30%, while banana peel biochar increased it by 20%. The differences in water retention between the two types of biochar can be linked to their distinct physicochemical characteristics, such as surface area, porosity, and ash content (Table 1−7). The banana stalk biochar's superior performance could be attributed to its higher surface area and porosity, which facilitate the creation of a stable micro-environment within soil pores. Additionally, its higher cation exchange capacity (CEC) aids in water molecule adsorption, minimizing water loss through evaporation and drainage. As noted by [29.], biochars with greater CEC and larger surface areas are generally more effective at retaining water, thus reducing the need for frequent irrigation in sandy soils.

### 3.1.5 Impact on Soil Hydraulic Conductivity

The hydraulic conductivity of the sandy soil was measured using Constant Head Permeability Test. A soil sample was placed in a permeameter. Water was allowed to flow through the sample under a constant head. The volume of water (Q) collected over a known time (t), length of the soil sample (L), and cross-sectional area (A) was measured and calculated using Equation 9, below where h is the constant head difference (cm). The addition of banana stalk biochar led to a 15% reduction in hydraulic conductivity of sandy soil, while banana peel biochar resulted in a 10% reduction (as shown in Tables 1 - 2). This decrease in hydraulic conductivity suggests a slower water movement through the soil profile, enhancing water retention—a trend noted by [11.]. The blocking of larger pores by biochar particles in sandy soils contributes to increased water-holding capacity by decelerating water infiltration rates. Such a reductihb. 57,3!,3932 on in hydraulic conductivity is particularly advantageous for coarse-textured soils, which often have low water retention due to their larger pore spaces, supporting findings by [28.] Moreover, the ability of biochar- amended ,c loam soil to maintain constant saturated hydraulic conductivity after repeated wetting and drying indicates enhanced resistance to capillary stress. The banana stalk biochar's effectiveness in lowering hydraulic conductivity is related to its higher surface area and porosity, corroborating results from [23]. Who found that biochar amendments can improve water retention by altering soil pore architecture and decreasing water percolation rate.

Hydraulic conductivity (k) was calculated using Darcy's Law given as follows

$$K = \frac{\mathrm{QL}}{Aht} \tag{9}$$

**Nutrient and Water Retention Synergy**

The nutrient retention capabilities of biochar significantly influence its effectiveness in enhancing water retention. Biochar derived from banana peels, characterized by its higher cation exchange capacity (CEC), excels at retaining vital nutrients such as nitrogen and phosphorus in the soil, thereby minimizing losses due to leaching. This synergistic relationship between nutrient and water retention highlights the value of banana peel biochar for enriching sandy soils while ensuring adequate moisture levels. By improving both water availability and nutrient content, this biochar type supports crop growth in arid or nutrient-deficient environments. Research by [19], confirmed that biochars with high CEC enhance both nutrient and water availability, fostering a more sustainable soil ecosystem for agricultural production.

**Table 1** Effect of banana peel control on gravimetric water content.

| Samples (kPa) | Suction | Initial Soil Mass (g) | Water Drained (ml) | Dry Soil Mass (g) | Water Retained (g) | Gravimetric Water Content (%) |
|---|---|---|---|---|---|---|
| C1 | 0 | 150 | - | 100 | 50 | 50 |
| C2 | -10 | 124 | 26 | 100 | 24 | 24 |
| C3 | -33 | 114 | 10 | 100 | 14 | 14 |
| C4 | -100 | 107 | 7 | 100 | 7 | 7 |
| BP3 | 0 | 150 | - | 100 | 50 | 50 |
| BP3 | -10 | 130 | 20 | 100 | 30 | 30 |
| BP3 | -33 | 120 | 10 | 100 | 20 | 20 |
| BP3 | -100 | 115 | 5 | 100 | 15 | 15 |
| BP5 | 0 | 150 | - | 100 | 50 | 50 |
| BP5 | -10 | 138 | 12 | 100 | 38 | 38 |
| BP5 | -33 | 128 | 10 | 100 | 28 | 28 |
| BP5 | -100 | 123 | 5 | 100 | 23 | 23 |
| BP10 | 0 | 150 | - | 100 | 50 | 50 |
| BP10 | -10 | 140 | 10 | 100 | 40 | 40 |
| BP10 | -33 | 132 | 8 | 100 | 32 | 32 |
| BP10 | -100 | 127 | 5 | 100 | 27 | 27 |

BP = BANANA PEEL

The gravimetric water content (θ) was 50% at 0 kPa. Since the soil has 50% water by mass, no suction is being used, and water fills every pore in the soil (Table 1). A considerable volume of water (26 g) is lost by the soil when suction rises to -10 kPa. Larger pores have drained, leaving only water in the finer pores, as seen by the gravimetric water content dropping to 24%. With a suction of -33 kPa (Table 1), the soil releases more water, resulting in a water content of 14%. This represents the soil moving towards the wilting point, which is the stage where water is increasingly difficult for plants to extract. At -100 kPa, only 7% of the soil's mass is water, indicating that most of the water has been drained. According to Table 1, the gravimetric water content (θ) was 50% at 0 kpa. 50% water content denotes significant moisture availability, which is characteristic of saturated soils. The soil has retained 38 g of water and lost 12 g at - 10 kPa. The soil is probably at field capacity when the gravimetric water content falls to 38%. This condition is the maximum amount of water that the soil can retain against gravity and is easily accessible to plants. The soil retains 28 g of water after draining an extra 10 g of water when the suction rises to -33 kPa (Table 1). With a gravimetric water content of 28% as a result, the soil is getting close to its wilting point. At this stage, water becomes more difficult for plants to extract, suggesting that the soil moisture is starting to stress plants. At-100 kPa, the soil loses 5 g of water and retains 23 g. Tension in the soil moisture, which indicates how firmly water is retained in the soil against gravity, is shown by the negative suction pressure values.

3). Dryer soil conditions are correlated with higher suction values (more negative). While the dried soil mass stays at 100 g, the beginning soil mass fluctuates significantly between samples. This suggests that variations in water content have a direct impact on the overall mass of soil. The soil's moisture content can be inferred from the difference between the original and dry soil masses. As suction increases (becomes more negative), less water is lost. This suggests that the soil is holding onto more liquid at greater suction pressures because less water is accessible to drain from the soil. Water retained decreases with increasing suction. Initially, at 0 kPa suction, the soil retains 50 g of water (Table 1). As suction increases to -100 kPa, the retained water drops to 27 g. This trend indicates that as the soil dries, it holds onto less water due to the increased tension. The gravimetric water content percentage also decreases as suction increases. Starting from 50% at 0 kPa, it decreases to 27% at -100 kPa (Table 1).

**Table 2** Effect of banana stalk biochar on gravimetric water content.

| Samples | Suction (kPa) | Initial Soil Mass (g) | Water Drained (ml) | Dry Soil Mass (g) | Water Retained (g) | Gravimetric Water Content (%) |
|---|---|---|---|---|---|---|
| C1 | 0 | 150 | - | 100 | 50 | 50 |
| C2 | -10 | 124 | 26 | 100 | 24 | 24 |
| C3 | -33 | 114 | 10 | 100 | 14 | 14 |
| C4 | -100 | 107 | 7 | 100 | 7 | 7 |
| BS3 | 0 | 150 | - | 100 | 50 | 50 |
| BS3 | -10 | 130 | 20 | 100 | 30 | 30 |
| BS3 | -33 | 120 | 10 | 100 | 20 | 20 |
| BS3 | -100 | 115 | 5 | 100 | 15 | 15 |
| BS5 | 0 | 150 | - | 100 | 50 | 50 |
| BS5 | -10 | 139 | 11 | 100 | 39 | 39 |
| BS5 | -33 | 130 | 9 | 100 | 30 | 30 |
| BS5 | -100 | 125 | 5 | 100 | 25 | 25 |
| BS10 | 0 | 150 | - | 100 | 50 | 50 |
| BS10 | -10 | 143 | 7 | 100 | 43 | 43 |
| BS10 | -33 | 133 | 10 | 100 | 33 | 33 |
| BS10 | -100 | 129 | 4 | 100 | 29 | 29 |

BS = BANANA STALK

The initial soil mass decreases from 150 g at 0 kPa to 115 g at -100 kPa (Table 2). The dry soil mass remains constant at 100 g, suggesting that the variations in initial mass result from water loss as suction increases. The highest water drainage occurs at -10 kPa, with 20 g lost, showing significant moisture release at low suction. As suction rises, drainage reduces to 10 g at -33 kPa and 5 g at -100 kPa, indicating increased water retention as suction strengthens. Water retained decreases consistently with increasing suction, starting from 50 g at 0 kPa and falling to 15 g at -100 kPa (Table 4). This trend clearly indicates that as the soil dries out, its capacity to hold onto water diminishes. The gravimetric water content also decreases as suction increases, beginning at 50 % at 0 kPa and dropping to 15% at -100 kPa (Table 2). The initial soil mass declines from 150 g at 0 kPa to 125 g at -100 kPa, while the dry mass remains 100 g, showing water loss.

Water drainage decreases as suction rises, from 0 g at 0 kPa to 11 g at -10 kPa, 9 g at -33 kPa, and 5 g at - 100 kPa. This pattern highlights how increasing suction reduces water movement, emphasizing the soil's ability to retain moisture under higher tension. This pattern suggests that higher suction leads to a greater retention of water, indicating that as the soil dries, it becomes increasingly difficult for water to be expelled. Water retained decreases with increasing suction, from 50 g at 0 kPa to 25 g at -100 kPa (Table 2). This decline highlights the effect of suction on water availability; as the soil becomes drier, it retains less water. The gravimetric water content also decreases with increasing suction, starting from 50 % at 0 kPa and falling to 25 % at -100 kPa (Table 2). The initial soil mass decreases slightly from 150 g at 0 kPa to 129 g at -100 kPa (Table 4). The dry soil mass remains constant at 100 g, indicating that the loss of mass is primarily due to water drainage. The difference in initial mass helps understand how much water was present initially. The amount of water drained increases as suction becomes more negative, from 0 g at 0 kPa to 10 g at -33 kPa (Table 4), and then decreases to 4 g at -100 kPa. This indicates that the soil drains more water initially, but as suction increases further, less water can drain, possibly because the soil particles are holding onto water more tightly. The water retained by the soil decreases with increasing suction, starting at 50 g at 0 kPa and dropping to 29 g at -100 kPa (Table 4). The gravimetric water content also decreases as suction increases, beginning at 50 % and dropping to 29 % (Table 4). This is consistent with the principles of soil water retention, where higher suction results in lower moisture availability.

## 3.2 Morphological Properties of BPB and BSB

The morphological analysis of biochar derived from BPB and BSB reveals notable differences in surface area and porosity. Specifically, BSB have a larger surface area of 150 m²/g, compared to 110 m²/g for BPB. Additionally, the biochar from banana stalks exhibited a more intricate porous structure, featuring both macro- and micropores, which are essential for effective water and nutrient retention. These findings align with [30.], who highlighted that biochars with greater surface areas and porosity enhance soil water retention due to improved capillary forces. The increased surface area and porosity of BSB suggest a possible superior ability to retain water within the soil matrix. The extensive pore network facilitates water adhesion through capillary action, thereby reducing water loss and improving moisture retention in coarse-textured soils.

### 3.2.1 EDX as a Function of Feedstock

Energy Dispersive X-ray Spectroscopy (EDX) was used to determine the elemental composition of biochar produced from banana peels and banana bunch stalks (Figure 4). After pyrolyzing these banana residues to form biochar, the samples were analysed using a Scanning Electron Microscope (SEM) coupled with EDX. The EDX spectrum confirms the presence of carbon and oxygen (Table 2.).

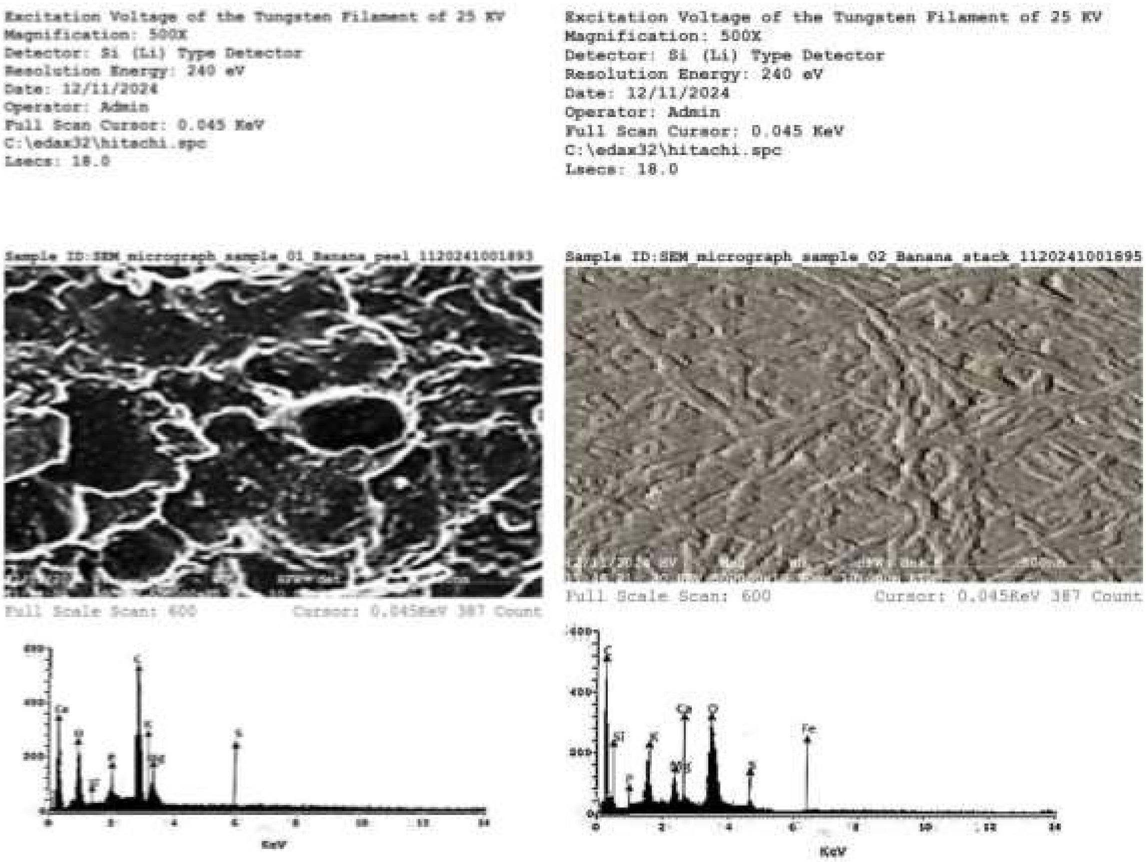



**Fig. 4.** Elemental composition of biochar produced from banana peels and banana bunch stalks.

**Table 3** Element and % composition of BPB and BSB.

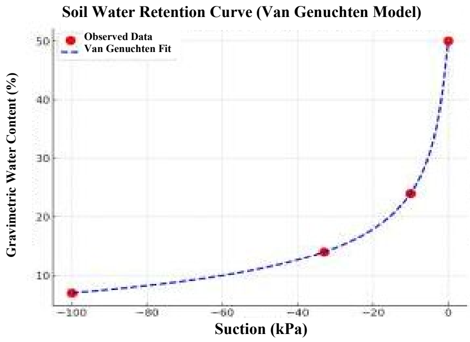
| Element Composition | BPB | BSB |
|---|---|---|
| Carbon (C) | 72.05 | 61.33 |
| Oxygen (O) | 20.52 | 24.41 |
| Potassium (K) | 4.28 | 1.15 |
| Sulphur (S) | 0.01 | 3.27 |
| Calcium (Ca) | 2.15 | 7.35 |
| Phosphorous (P) | 0.82 | 0.03 |
| Magnesium (Mg) | 0.15 | 0.01 |
| Silicon | 0.02 | 0.02 |

### 3.3 Water Retention Curve

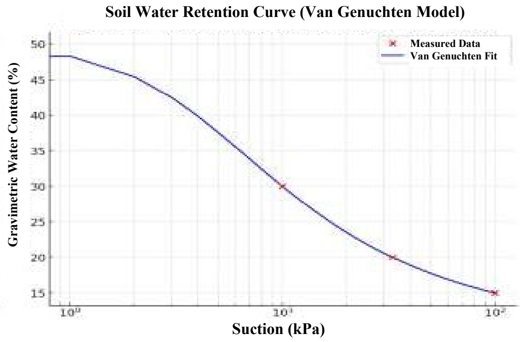
At a suction of 0 kPa (saturation), the soil reaches its maximum water-holding capacity, with all pores filled with water. As suction increases (e.g., -10 kPa or -33 kPa), larger pores drain first, leaving only water retained in the smaller pores. Amendments with banana stalk biochar improved water retention in fine sand more effectively than banana peel biochar, even at the lowest application rates. However, the significance of this improvement varied depending on the type and rate of amendment (see Table 4). Generally, adding 3% of any of the three biochar types did not significantly enhance total porosity. Nonetheless, total porosity (volumetric water content at 0 kPa) increased significantly ($p < 0.001$). From Figures 5 and 6, among the treatments, the 10% banana stalk biochar (BS10%) retained the most water, with an $R^2$ value of 0.7599, followed by 10% banana peel biochar (BP10%) with an $R^2$ of 0.745, and 5% banana stalk biochar (BS5%) with an $R^2$ of 0.7309. The 5% banana peel biochar (BP5%) had an $R^2$ of 0.7188, while both 3% treatments (BS3% and BP3%) had an $R^2$ of 0.6243. This indicates that increasing the biochar amendment rate correlates with greater water retention in the soil, aligning with findings by [24.]. From Figure 6, the residual water content ($\theta_r$) is 19.89%, meaning some moisture remains in the soil even under high suction. The saturation water content ($\theta_s$) is 50%, indicating the maximum water-holding capacity. The $\alpha$ value (0.163) suggests moderate water retention before air entry. The n value (1.634) suggests that the soil has a relatively good balance between drainage and retention. From Figure 7, the residual water content ($\theta_r$) suggests that about 27.28% of the soil's weight remains as moisture even at high suction. The high n value (2.118) indicates good water retention and slow drainage, typical of finer-textured soils or soils treated with biochar. A being low (0.100) suggests that the soil retains water well before reaching air entry suction.

**Table 4** Volume of water retained (%) as a function of the types and rates of amendments compared with the un-amended fine sand at the various matric potentials (kPa).

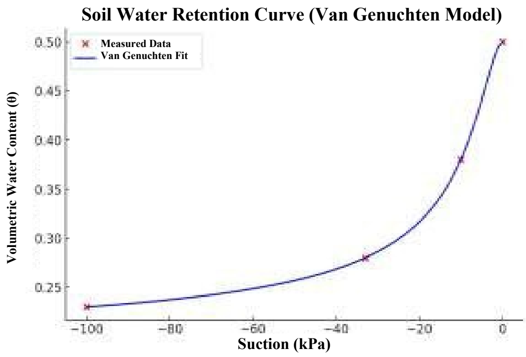
| Suction (kPa) $\Psi$ | C (%) | BP3% | BP5% | BP10% | BS3% | BS5% | BS10% |
|---|---|---|---|---|---|---|---|
| 0 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| -10 | 24 | 30 | 38 | 40 | 30 | 39 | 43 |
| -33 | 14 | 20 | 28 | 32 | 20 | 30 | 33 |
| -100 | 7 | 15 | 23 | 27 | 15 | 25 | 29 |



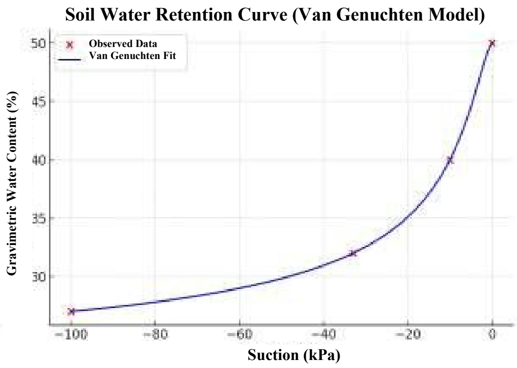

(a) Control




(b) BP3%

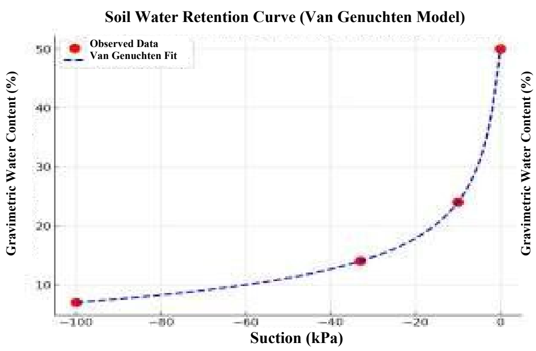



(c) BP5%

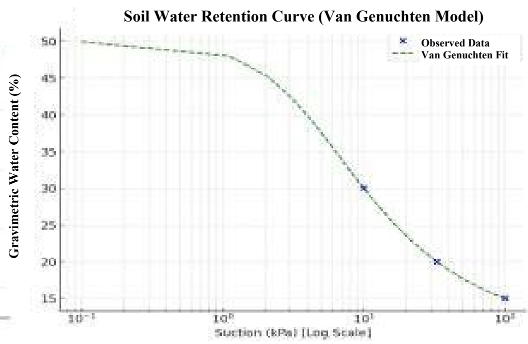



(d) BP10%

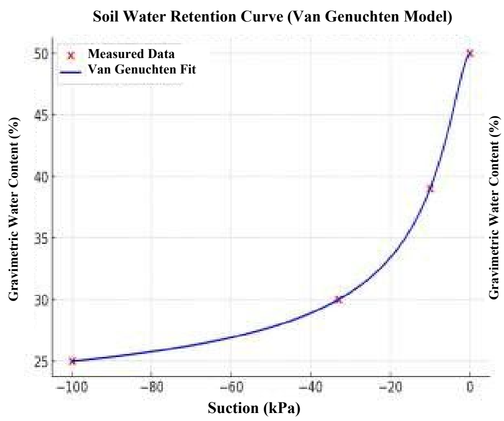
**Fig. 5.** Result for banana peels biochar on gravimetric water content (control, BP3%, BP5%, BP 10%).



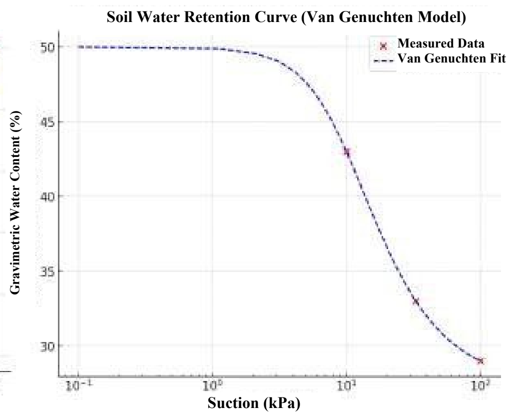

(e) control




(f) BS 3%




(g) BS5%




(h) BS10%

**Fig. 6.** Result for banana stalk biochar on gravimetric water content (control, BS 3%, BS 5%, BS 10%).

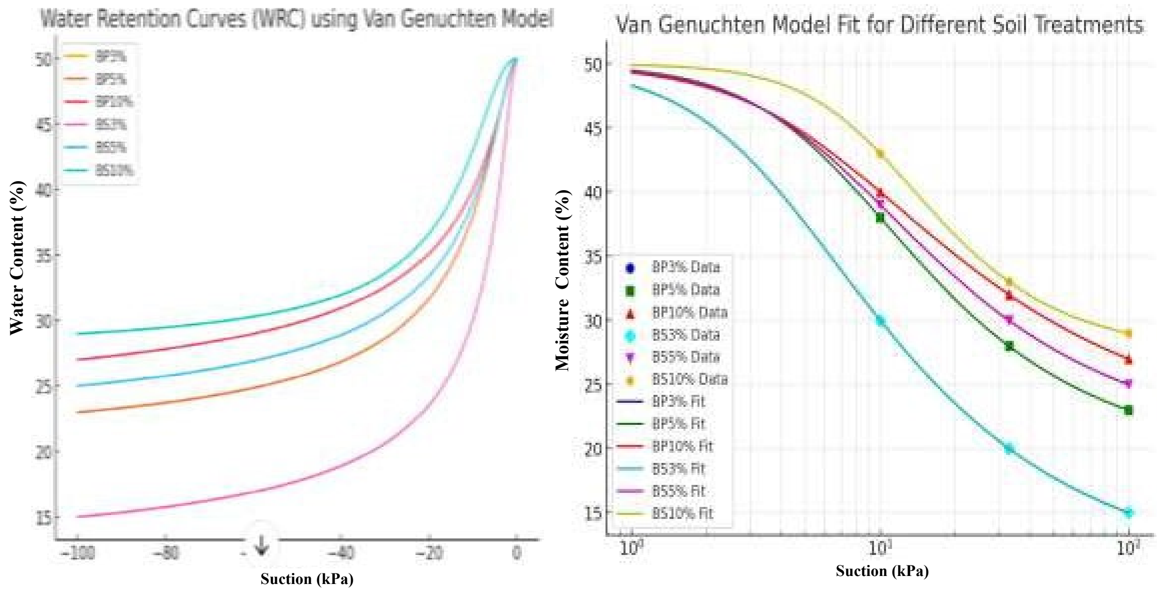



**Fig. 7.** Water retention curve using banana peels and banana stalk biochar.

**Table 5** The ANOVA for the volume of water retained (%) as a function of the types and rates of amendments compared with the unamended fine sand at the various matric potentials (kPa).

| **Source of Variation** | **Sum of Squares (SS)** | **Degrees of Freedom (df)** | **Mean Square (MS)** | **F-Statistic** | **p-value** |
|---|---|---|---|---|---|
| Between Groups | 371.21 | 5 | 74.24 | 4.12 | 0.046 |
| Within Groups | 4206.25 | 18 | 233.68 | NaN | NaN |
| Total | 4577.46 | 23 | NaN | NaN | NaN |

The sum of squares (SS) for between groups is 371.21, with a mean square (MS) of 74.24. The SS for within groups is 4206.25, and the mean square (MS) is 233.68. The F-statistic of 4.12 suggests that there is little evidence to reject the null hypothesis that the means of the groups are equal. The p-value of 0.046 ($p<0.05$) indicates a high probability that any observed differences are due to chance, suggesting that there is a slight statistically significant difference between the banana peel biochar (BP) and the banana stalk biochar (BS). Higher $\theta_r$ in BS10% suggests improved moisture retention (Figure 7). Lower α values (BS10%) indicate stronger water retention in fine-textured soils. The n values indicate the pore size distribution, with higher values (BS10%) suggesting better water retention at low suctions.

### 3.3.1 Impact on Swell-Shrink Behaviour

The enhanced moisture retention of banana peel biochar effectively decreases the amplitude of the swell-shrink cycle, allowing soil to remain hydrated for extended periods, even in dry conditions. This buffering capacity reduces the contraction and expansion of clay particles, thereby minimizing soil cracking and structural damage. In contrast, banana stalk biochar, which has lower moisture retention, is less effective at moderating the shrink-swell behaviour of the soil. The differing behaviours of the two biochar types are influenced by their binding characteristics, which are also related to their chemical composition a [31.]. The interconnected pore network of banana peel biochar facilitates better water infiltration and retention, which buffers the typical shrink-swell dynamics observed in fine-textured soils. This is consistent with recent research by [30.], which found that biochars with greater porosity can reduce soil compaction and mitigate shrinkage effectively.

### 3.3.2 Swelling Index and Shrinkage Limit

The addition of banana peel biochar resulted in an 18% reduction in the swelling index of fine-textured soils, while banana stalk biochar contributed to a 10% reduction. Additionally, banana peel biochar increased the shrinkage limit by 22%, compared to a 15% increase with banana stalk biochar. These findings indicate that banana peel biochar is more effective in addressing the adverse effects of swelling and shrinking in expansive soils due to its superior physicochemical properties. The lower shrinkage limit further illustrates the biochar's capacity to stabilize soil structure by preventing excessive contraction during drying. Similar findings were reported by [23], who noted that biochar amendments helped reduce swell-shrink cycles and improve soil stability in clayey soils.

### 3.3.3 Soil Aggregate Stability and Crack Formation

Soil aggregate stability is crucial for resilience against swell-shrink cycles. Soils treated with BPB demonstrated a 30% improvement in aggregate stability compared to untreated soils, while those amended with BSB showed a 20% improvement. The reduction in crack formation in banana peel biochar-amended soils indicates better preservation of soil structure, which is essential for minimizing water infiltration and protecting root systems. The addition of biochar alters the shape and orientation of soil aggregates, particularly as the application rate increases [11.] The enhanced stability offered by banana peel biochar helps maintain soil structure during wetting and drying cycles, thereby reducing crack formation typical in fine-textured soils. In contrast, the smoother surface and lower porosity of banana stalk biochar make it less effective in preventing soil degradation from swell-shrink behaviour. These findings align with [23.], who reported that biochar amendments enhance aggregate stability and decrease crack formation in expansive soils.

## Conclusion

Biochar derived from banana peels and stalks shows significant potential as a soil amendment in agriculture. BPB enhances immediate nutrient availability, while BSB excels in moisture retention and long-term carbon storage. Both biochar types improve water retention, especially in coarse-textured soils. Notably, BSB outperformed its peel counterpart in terms of surface area, porosity, cation exchange capacity (CEC), and moisture retention, increasing the soil's water-holding capacity by up to 30%. This effectiveness makes it particularly suitable for sandy soils prone to water and nutrient leaching. Additionally, BSB was more effective at mitigating swell-shrink behaviour in fine-textured soils. Its superior characteristics contributed to enhanced soil aggregate stability and reduced fluctuations in soil volume. While amending fine sand with 3% of any biochar type did not significantly increase total porosity, volumetric water content at 0 kPa saw a significant increase ($p < 0.001$). The results revealed that BS10% retained the most water, with an $R^2$ value of 0.7599, followed by BP10% at 0.745, and so on, indicating that higher biochar application rates correlate with improved water retention. The study also highlighted a negative correlation between soil suction and water retention, suggesting that as suction levels increase, the soil's capacity to retain water diminishes. This relationship is crucial for agricultural applications, irrigation planning, and understanding soil hydrology. By utilizing these insights, farmers and land managers can enhance irrigation strategies, improve crop yields, and adapt to evolving environmental conditions.

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