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Synergy of Corn Cob Biochar Modification in Improving Soil Bulk Density, Porosity, and Water Retention

Budiono[1]†, Irya Ichriani[2], Fakhrur Razie[3] and Sunardi[4]
[1]Doctoral Program of Environmental Sciences, Lambung Mangkurat University, Banjarmasin, South Kalimantan 70124, Indonesia
[2]Soil Science Study Program, Faculty of Agriculture, Lambung Mangkurat University, Banjarmasin, South Kalimantan 70123, Indonesia
[3]Soil Science Study Program, Faculty of Agriculture, Lambung Mangkurat University, Banjarmasin, South Kalimantan 70123, Indonesia
[4]Chemistry Study Program, Mathematics and Natural Science, Lambung Mangkurat University, Banjarmasin, South Kalimantan 70123, Indonesia
†Corresponding author: Author Name; 2241213310057@mhs.ulm.ac.id

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ABSTRACT

This study investigated the characteristics of modified corn cob biochar (BTJT) and its effects on the physical properties of Ultisol soil co-inoculated with BTJT. The material was produced through a synergistic process involving pyrolysis, activation, and immobilization, which combined biochar, nutrients, and biological agents. The research consisted of two experiments: the first analysed the morphological characteristics and specific surface area (SSA) of BTJT pores with three inoculation durations (7, 14, and 21 days), and the second examined soil bulk density, porosity, and water retention after BTJT co-inoculation. A completely randomized design (CRD) with five treatments, three replicates, and three observation periods was applied. The analytical methods included SEM-EDX and BET, with soil parameters comprising bulk density, water content (% volume and % weight), porosity, and water retention. Statistical analyses were conducted using ANOVA-Tukey tests, regression, and correlation analyses with a 5% error margin. The results indicated that BTJT application at 2 $t.ha^{-1}$ significantly decreased bulk density while increasing soil water content, porosity, and water retention. Overall, the study concludes that the synergistic modification of corn cob biochar effectively enhances soil physical properties, recommending the application of BTJT (biotron) at 2 $t.ha^{-1}$ for optimal improvement of Ultisol soil quality.

1. INTRODUCTION

Biochar is a fine-textured, porous, carbon-rich material produced through pyrolysis. BTJT is a composite that integrates biochar, nutrients, and biological agents. Previous research has demonstrated that enriching biochar with organic nutrients consistently enhances soil quality. Thanks to its complex and heterogeneous pore structures, BTJT functions as a carrier medium capable of binding nutrients and biological agents (Allohverdi et al. 2021, Ben-Noah et al. 2021, Deru et al. 2018). Compared to pure biochar (Sepp et al. 2023, Shaheen et al. 2024), BTJT improves the soil's capacity to retain water, air, and nutrients (Raczka et al. 2021, Robinson et al. 2022, Sachdeva et al. 2019). Additionally, biochar enhances soil aeration, which is vital for microbial activity and plant root growth (Quan et al. 2020).

Research on the effectiveness of BTJT in enhancing the physical properties of Ultisol soils—such as bulk density (BD), porosity, and water retention—is limited. This study seeks to fill this knowledge gap by evaluating BTJT's potential as a soil conditioner. The chemical activation process involves lime solution and positive ion activators (catalysts), which are believed to increase pore surface area. Pore spaces serve as reservoirs for air and water and create a more conducive environment for microbial communities (Pandey et al. 2022). It is also known that unmodified biochar can have diverse effects on soil, plants, and microorganisms (Ottani et al. 2022). Consistent with recent research, applying biochar as a soil amendment has gained increasing attention in soil and environmental studies.

Porosity, water movement, and the availability of space between soil particles and pores are essential physical factors that facilitate root development. These traits are affected by bulk density, a key soil physical property that indicates how tightly soil particles are packed within a given volume (Lei et al. 2022, Liao & Thomas 2019, Liu et al. 2024). Water retention refers to the soil's capacity to hold water against gravity (Lani et al. 2023). The amount of water retained reflects the actual water available at any given moment (Jung et al. 2015, Kiss et al. 2021). This capacity is influenced by soil texture, structure, water-holding ability, and rainfall. Ultisol soils with clay textures typically exhibit higher water retention than sandy soils due to their smaller particle size and greater surface area. Additionally, the presence of soil organic matter can further improve water-holding capacity (Jensen et al. 2020).

Soil water is held by capillary and adsorption forces within the pores of the soil, with bond strength influenced by pore size. Soils containing micropores tend to retain more water, although only a fraction of this water is accessible to plants (Hossain et al. 2020). Various factors, including rainfall, surface water infiltration, evaporation, transpiration, evapotranspiration, soil texture, structure, porosity, and water retention capacity, govern the availability of soil water. (Harish et al. 2022).

2. MATERIALS AND METHODS

2.1. Research Site Description

The field experiment was conducted in a screen house at the Agricultural Training Center (Balai Besar Pelatihan Pertanian, Binuang) under the Ministry of Agriculture of Indonesia. Its coordinates are 3°09'16" S and 115°05′16″ E, at an elevation of 71.7 meters above sea level and approximately 420° from the Earth's horizontal axis. The site is accessible via Google Maps at: https://maps.app.goo.gl/JmwpHRQWjYsLWiWR9

Laboratory analyses were performed at various facilities, including the Soil and Fertilizer, Particle Material, Microbiology, and Postharvest laboratories. The field experiment is scheduled for the rainy season (March–July 2024), with laboratory analyses spanning from March 2024 to May 2025. Weather conditions during the study period can be viewed at https://id.weatherspark.com/y/129103/Cuaca-Rata-rata-pada-bulan-in-Binuang-Indonesia-Sepanjang-Tahun.

2.2. Data Collection

2.2.1. Experiment 1: Characterization of Modified Corn Cob Biochar (BTJT)

The experiment commenced with the preparation of BTJT samples, each weighing 50 g, utilizing three replicates and three different treatments that involved varying soaking (incubation) durations in 2,250 mL of clear $Ca(OH)_2$ solution. The preparation process included physicochemical, chemical, and biological activation of the materials. Chemical activation (Gao et al. 2025) was executed by immersing BTJT powder (450–550°C) (Hafeez et al. 2022) in a CaO solution. This solution was prepared by dissolving 150 g of CaO in 600 mL of distilled water, stirring it with a magnetic stirrer for 60 minutes, and then conducting four activation cycles, each using 575 mL of solution (Ferrarezi et al. 2022). The samples were oven-dried at 105°C for 6 hours (Colucci et al. 2025). Subsequently, they were immersed in the most effective POCH solution for 20 days, with incubation durations of 7, 14, and 21 days (Carril et al. 2024), followed by air-drying for three days at 25–35°C (Ijam 2024). Morphological and surface area analyses were conducted using Scanning Electron Microscopy–Energy Dispersive X-ray (SEM-EDX, JEOL JSM-6510LA) and the Brunauer–Emmett–Teller (BET) method (Chen et al. 2025).

2.2.2. Experiment 2: Soil Quality Characteristics

This experiment involved collecting Ultisol soil samples from a depth of 0–20 cm, with each sample weighing 1,000 g. The samples were arranged in three replicates and subjected to five treatments at three different observation times. Soil sampling was conducted 14 days after co-inoculation with the selected corn cob biochar (BTJ), which had undergone a 7-day inoculation process. The physical properties of the soil were analyzed for parameters including bulk density (BD) (Braz et al. 2025), volumetric water content (% volume, KAV), gravimetric water content (% weight, KAB), and oven-dry soil weight at 105°C for 24 h (BKT). These measurements were obtained through both volumetric and gravimetric methods (Libohova et al. 2018). The parameters—porosity, soil water retention, PD, KAB, KAV, and BD—were calculated using the following equations.

2.3. Particle Density (PD)

Pparticle (PD) = msoil/ volume of soil solids = particle density ($g.cm^{-3}$), commonly assumed to be 2.65 $g.cm^{-3}$ for mineral soils, representing the density of solid soil particles excluding pore spaces.

2.4. Soil Water Content

For gravimetric water content, the wet soil sample (W_1) was weighed, then oven-dried at 105°C for 24 hours or until a constant weight (W_2) was achieved. The formula used was:

Gravimetric Water Content (%weight) = $[(W_1 - W_2)/(W_2) \times 100$ (Braz et al. 2025)

Volumetric water content (%) = Water Content (% by weight) × BD ($g.cm^{-3}$) (Bian et al. 2024)

2.5. Bulk Density (BD)

Pbulk Bulk density (BD) = bulk density ($g.cm^{-3}$), the ratio of the dry weight of the soil to the total volume of the soil, including the volume of pore space or particles (air and water). Bulk density (BD) = Dry soil weight / Soil volume ($g.cm^{-3}$) (Alkharabsheh et al. 2021)

2.6. Porosity (n)

n = soil porosity (cm^3 cm^{-1} or %)

$$n = 1 - (\rho_{particle} \times \rho_{bulk}\text{-}1)$$

$$n\ (\%) = (1 - (\rho_{particle} \times \rho_{bulk}\text{-}1)) \times 100$$

Porosity (%) = (Void Volume/Total Volume) × 100%.

Porosity (%) = (1 - (Bulk Weight/Specific Gravity)) × 100%, which requires measuring the bulk density, emphasizing the total volume, including pores, interparticle voids, and soil specific gravity. The specific gravity of soil particles, without considering pores and interparticle voids, is 2.65 (Ahmad et al. 2023).

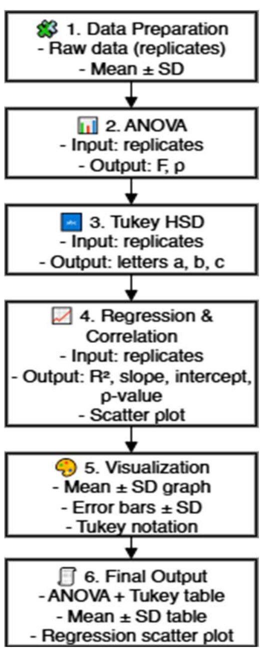


Fig. 1: Statistical analysis flowchart and visualization.

2.7. Data Analysis Methods

All statistical analyses were conducted using IBM SPSS Statistics version 26.0 and Python (Windows) (Fig. 1). An ANOVA was performed, followed by Tukey's post hoc test at a 5% significance level, to detect significant differences, interactions among variables, and correlations between BTJT treatments and soil physical properties. Data visualization, including regression and correlation analyses, was carried out with OriginPro.

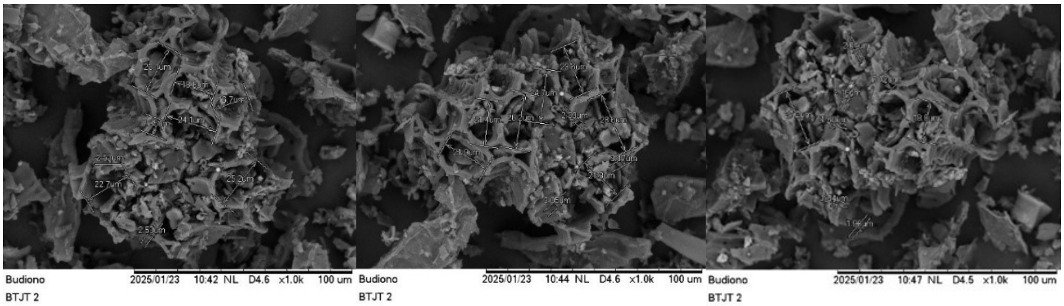
3. RESULTS AND DISCUSSION

3.1. Experiment 1: Characteristics of BTJT

The characterization of BTJT was carried out using Analytical SEM-EDX (JEOL JSM-6510 LA) and the BET method on optimized corn cob biochar (pyrolysis temperature of 450–550°C), which was inoculated in the optimal liquid organic culture (20 days of microbial culture) with incubation periods of 7, 14, and 21 days. The BTJT observation results from three replication points are presented in Figs. 2–4.

The specific surface area (SSA) of BTJT-7 (7-day co-inoculation) showed an optimal average value of 1.63 $m^2.g^{-1}$, which differed from the values observed for BTJT-14 (14-day co-inoculation) and BTJT-21 (21-day co-inoculation). However, it is important to critically assess whether such a low surface area is sufficient to substantiate the claim of "synergistic modification" made in this study. The term "synergistic modification" suggests a substantial enhancement in the biochar properties, specifically its ability to retain nutrients and water and support microbial life. However, a BET surface area of 1.63 $m^2.g^{-1}$ is relatively low compared to most modified biochars reported in the literature, which often show significantly higher values, typically in the range of 20-100 $m^2.g^{-1}$ depending on the modification method.

Such a low surface area raises questions regarding the effectiveness of the modification process in achieving the claimed synergistic effects. Typically, biochar modification aims to enhance the surface area to increase its porosity, which, in turn, improves its ability to adsorb nutrients and water and facilitates microbial activity. The observed surface area in this study may not be sufficiently high to justify these claims. In this context, it is crucial to emphasize that the BET surface area alone cannot fully explain the soil hydraulic effects, such as water retention and nutrient exchange capacity, especially when the pore size distribution is not considered. The pore size distribution



a b c

Fig. 2: BTJT surface structure, 7-day coinoculation duration a) Spot 1 b) Spot 2 c) Spot 3.

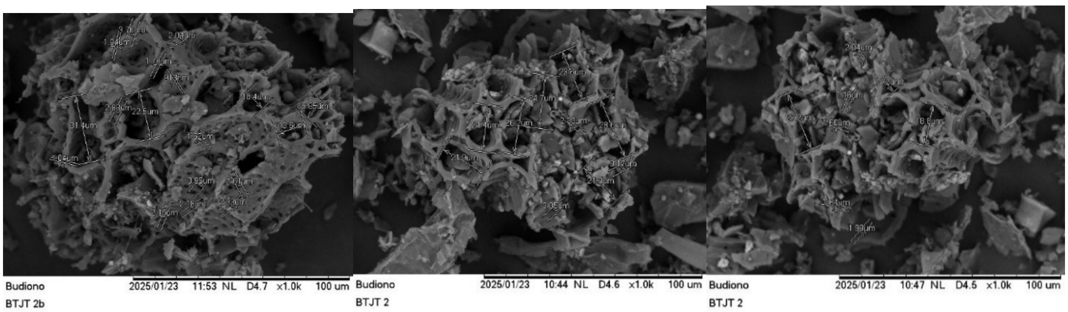


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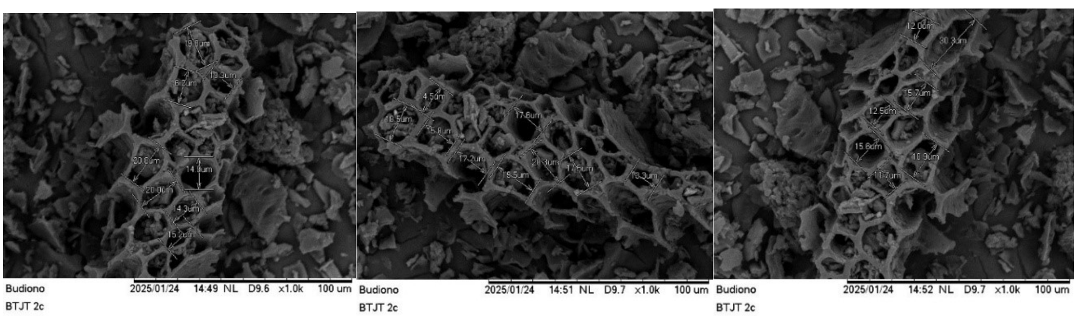
Fig. 3: BTJT surface structure, coinoculation duration 14 days a) Spot 1 b) Spot 2 c) Spot 3.

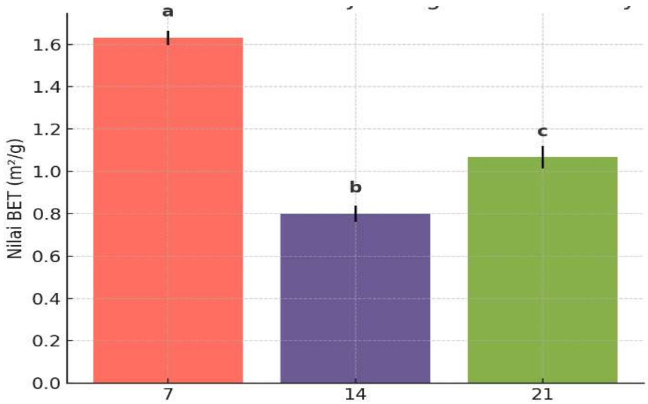


a b c

Fig. 4: BTJT surface structure, coinoculation duration 21 days: a) Spot 1, b) Spot 2, c) Spot 3.

is a critical factor in determining the ability of biochar to retain water and support microbial colonization, both of which are vital for improving soil structure and fertility. The manuscript does not provide these crucial data, which limits the ability to comprehensively evaluate the true impact of BTJT on soil water retention and other physical properties.

Without pore size distribution data, this study falls short of providing a complete analysis of the hydraulic behavior of biochar in soil. The water retention capacity and porosity depend not only on the surface area but also on the distribution of pore sizes. Pores of different sizes (micropores, mesopores, and macropores) serve distinct functions in retaining water and air and facilitating microbial colonization. Smaller pores may retain more water, but this water may not be readily available to plants. Larger pores facilitate air exchange and microbial activity, which are crucial for maintaining healthy soil. Without this additional



Coinoculation duration (days)

Fig. 5: Differences in specific surface area (SA) of BTJT at various coinoculation durations.

data on the pore size distribution, the claim of synergistic modification in this study remains unsubstantiated.

In summary, although the BET surface area is an important metric, it is not sufficient on its own to explain the observed hydraulic effects of BTJT on soil. The lack of data on pore size distribution significantly weakens the argument for synergistic modification, as it is an essential factor in understanding the role of biochar in improving soil physical properties. For a more comprehensive evaluation, this study should include detailed analyses of pore size distribution and its correlation with soil water retention and other key parameters. This would provide a clearer justification for the claims of synergistic effects and strengthen the manuscript's contribution to this field. The result is presented in Fig. 5.

The result from Fig. 5 shows the BET surface area values (in $m^2.g^{-1}$) of BTJT samples with different co-inoculation durations: 7, 14, and 21 days. The chart indicates the following:

1. The BTJT-7 sample, with a 7-day co-inoculation duration, has the highest BET surface area at around 1.63 $m^2.g^{-1}$, significantly higher than the other two treatments. This suggests that the 7-day inoculation period promotes a more open pore structure, increasing the surface area of the biochar.
2. The BTJT-14 sample, with a 14-day co-inoculation duration, shows a much lower surface area, approximately 0.85 $m^2.g^{-1}$, marked with a "b." This indicates that the longer inoculation time may cause the pores to become filled or blocked, reducing the surface area available for adsorption.
3. The BTJT-21 sample, with a 21-day co-inoculation duration, shows a moderate surface area of about 1.1 $m^2.g^{-1}$, marked with a "c." This suggests that after a longer inoculation period, some of the pores may have reopened, increasing the surface area slightly compared to BTJT-14, but still lower than BTJT-7.

The letters "a," "b," and "c" above the bars indicate statistical differences between the treatments. The significant difference in surface area between BTJT-7 and the other two treatments (14 and 21 days) reflects the influence of the inoculation period on the surface characteristics of biochar, potentially affecting its performance in improving soil properties.

ANOVA revealed a significant difference in the specific surface area (SA) among the three BTJT samples ($F = 292.28$, $p < 0.05$). This difference reflects variations in the pore structure resulting from different co-inoculation durations. A higher SA is positively correlated with the number and openness of pores, which potentially enhances the adsorption capacity of biochar (Sizmur et al. 2017).

Extending the co-inoculation duration from 7 to 14 days caused a significant decrease in the SA of BTJT (Sun et al. 2022, Tamburini 2021, Wang et al. 2021). This suggests that microbial activity and nutrient availability may fill and cover the biochar pores, thereby reducing the BET surface area. BTJT with a 14-day co-inoculation duration (BTJT-14) exhibited the lowest and statistically significant BET value compared to both BTJT-7 and BTJT-21. The SA of BTJT-21 increased again, likely due to the reduction in nutrient availability utilized by microbes within the pore spaces that were previously occupied in BTJT-7 (Wang et al. 2019)

3.1.1. Regression Analysis

BTJT-7 demonstrated the highest potential porosity, resulting in relatively greater adsorption capacity for gas molecules and ions in solution (X. Wang et al. 2024). The regression analysis between BET value and co-inoculation duration produced the following equation:

$$\hat{Y} = 0.424x + 0.606$$

With a determination coefficient of $R^2 = 0.732$ and p = 0.003, indicating a significant relationship between the two variables. The relationship between BTJT surface area (SA) and co-inoculation duration is illustrated in Fig. 6.

Regression analysis revealed a moderate negative relationship between co-inoculation duration and specific surface area (SA). Increasing the duration from 7 to 14 days significantly reduced SA, whereas at 21 days, the value increased again, although it remained lower than that observed at 7 days (Wei et al. 2023). The Tukey test results indicated that all three co-inoculation durations produced significant differences in SA ($p < 0.05$).

3.1.2. Pearson Correlation

Pearson correlation analysis showed a very strong positive relationship (r = 0.856) with a coefficient of determination (R^2) of 0.44 and a p-value of 0.052, which was close to being significant at the 5% level.

3.1.3. Correlation Analysis

Meanwhile, the correlation analysis based on co-inoculation duration revealed a moderate negative relationship (r = –0.66), indicating that increasing the duration from 7 to 14 days significantly decreased the SA value, whereas at 21 days, the SA increased again but remained lower than that of BTJT-7.

3.2. Experiment 2: Soil Characteristics

Physical analysis of soil was conducted under five BTJT dosage treatments: the control without biochar (B0 = 0 $ton \cdot ha^{-1}$), a positive control (B1 = 2.0 $ton \cdot ha^{-1}$ of biotron), and three BTJT treatments (B2 = 1.0 $ton \cdot ha^{-1}$, B3 = 1.5 $ton \cdot ha^{-1}$, and B4 = 2.0 $ton \cdot ha^{-1}$). Each treatment was tested in triplicate. The average data analysis from three observation periods (May, June, and July 2024) showed that the application of BTJT significantly affected soil physical properties. These findings indicate that BTJT, particularly at higher doses, has the potential to be an effective soil amendment for improving land resilience against drought stress. The pores within the BTJT serve as spaces that can hold water, air, and nutrients. Treatments B1 (Biotron) and B4 (BTJT at 2 $t.ha^{-1}$) showed no significant difference, whereas treatments B0, B2, and B3 exhibited significant differences in most parameters, except for bulk density (BD). Previous studies have supported this finding, suggesting that modified biochar possesses pores with larger surface areas. Linear regression analysis has revealed a strong relationship between porosity and soil moisture (Ahmad et al. 2023). Relationship between porosity (%) and gravimetric water content (% by weight). The regression equation obtained was:

$$\hat{Y} = 2.43x + 42.5$$

with a correlation coefficient (r) = 0.849, coefficient of determination (R^2) = 0.721, and p = 6.27×10^{-5}, indicatinghighly significant relationship. Where $\hat{Y}$ = water content (% by weight) and x = porosity (Bian et al. 2024).

Relationship between porosity (%) and volumetric water content (% by volume). The regression equation was:

$$\hat{Y} = 1.87x + 10.54$$

with r = 0.681, $R^2 = 0.463$, and p = 0.0052, showing a highly significant positive correlation between porosity and volumetric water content.

Relationship between porosity (%) and bulk density (BD). The regression equation was:

$$\hat{Y} = 0.0265x + 2.65$$

with r = 0.893, $R^2 = 0.797$, and p = 7.51×10^{-6}, indicating a strong and significant positive correlation. The higher the soil porosity, the greater its water retention capacity.

Relationship Between Bulk Density (BD), Porosity, and Water Retention. Soils with higher bulk density tend

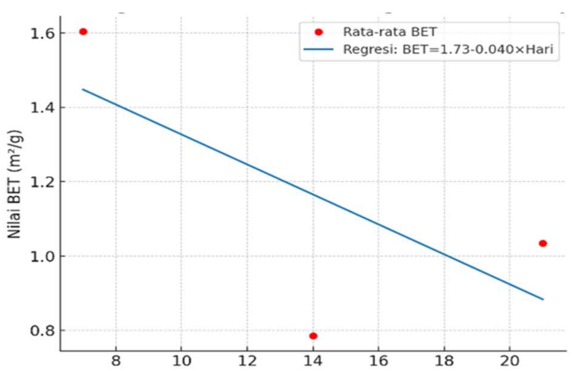


Fig. 6: Linear regression of the relationship between coinoculation duration and SA in BTJT.

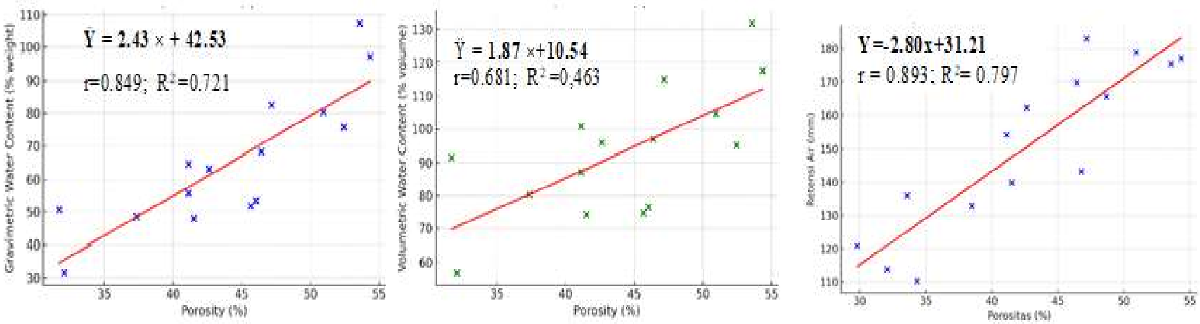


Fig. 7: Relationship of soil porosity with (a) gravimetric water content (% by weight) Vs Porosity, (b) volumetric water content (% by volume) Vs Porosity, (c) Porosity, Retention Vs BD. The red, purple, green, and blue lines show the linear regression equation, while the dots indicate the observed values

to exhibit lower porosity and water retention capacity. Relationship between BD and water retention (%). The regression equation was:

$$\hat{Y} = 105.56x + 310.94$$

With $r = -0.893$, $R^2 = 0.797$, and $p = 7.5 \times 10^{-6}$, indicating a strong and significant negative correlation, where increased BD leads to reduced soil water retention.

Relationship between BD and porosity (%). The regression equation was:

$$\hat{Y} = 37.73x + 100$$

Overall, the relationships between porosity, soil water content (both gravimetric and volumetric), BD, and water retention show a consistent and statistically significant pattern, as presented in Fig. 7.

Bulk density (BD) is a key indicator of soil physical properties that reflects the degree of particle compaction in a given soil volume. High BD values typically reduce porosity, thereby limiting air and water movement through the soil. The reduction in porosity caused by a high BD also leads to lower water retention, ultimately decreasing the availability of water for plants. The application of biochar has been shown to lower BD by promoting soil aggregation and creating new pores. These changes not only enhance porosity but also improve the soil's ability to retain water against gravitational forces, leading to optimal water retention (Pandey et al. 2022). Thus, the integration of biochar as a soil amendment plays a strategic role in improving soil physical quality, particularly in Ultisol soils, which are generally characterized by high BD, low porosity, and limited water-holding capacity.

The three graphs present the relationships between porosity (%) and various soil properties: gravimetric water content (% by weight), volumetric water content (% by volume), and water retention (%). The first graph shows a strong positive correlation between porosity and gravimetric water content, with a regression equation of $\hat{Y} = 2.43x + 42.53$ and $R^2 = 0.721$, indicating that higher porosity leads to a greater water content by weight. The second graph, showing porosity and volumetric water content, has a moderate positive correlation ($\hat{Y} = 1.87x + 10.54$, $R^2 = 0.463$), suggesting a weaker relationship, where porosity still influences the volumetric water content but with a lower explanatory power. The third graph shows a very strong positive correlation between porosity and water retention ($\hat{Y} = 2.80x + 31.21$, $R^2 = 0.797$), indicating that soils with higher porosity have a significantly higher water retention capacity. These results collectively underscore the critical role of porosity in determining soil water behavior, with higher porosity generally leading to better water retention, although the strength of the correlation varies across different water content measurements.

This study further shows that an increase in BD is negatively correlated with porosity and water retention, consistent with recent findings that soil physical properties, such as density and porosity, strongly influence the availability of aeration space and soil moisture. From an agronomic perspective, increasing porosity means a greater pore space available to retain water and nutrients. This aligns with previous research, which reported that biochar application improves soil structure, reduces BD, and enhances soil water-holding capacity.

5. CONCLUSIONS

The selected co-inoculation duration for corncob biochar (BTJ) was 7 days (BTJT-7), as it produced the highest specific surface area (SA) of 1.63 $m^2.g^{-1}$. The application of BTJT or Biotron at a dosage of 2 $t.ha^{-1}$ had a significant effect on soil physical characteristics, including moisture content (% by weight and volume), bulk density (BD), porosity, and water retention. The treatment sequence began with the control (B0, without BTJT), followed by BTJT-B2

(1 t.ha^{-1}), BTJT-B3 (1.5 t.ha^{-1}), BTJT-B4 (2 t.ha^{-1}), and Biotron (2 t.ha^{-1}). As the dosage increased, improvements in soil physical parameters became more pronounced. Specifically, the application of BTJT (or Biotron) reduced BD, which correlated with increased soil moisture content, porosity, and water retention capacity of the soil. The relationships among the parameters demonstrated moderate to very strong correlations, showing negative interactions with BD and positive interactions with the other parameters. The continuous application of BTJT or Biotron is expected to enhance the overall soil structural stability and resilience, although further long-term studies are needed to explore the chemical and biological aspects of the soil in greater depth.

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