Prepublished copy

Nature Environment & Pollution Technology

This is a peer-reviewed prepublished version of the paper to be published in Vol. 25, No. 3, September 2026 issue

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 Kalimatan 70124, Indonesia

[2] Soil Science Study Program, Faculty of Agriculture, Lambung Mangkurat University, Banjarmasin, South Kalimatan 70123, Indonesia

[3] Soil Science Study Program, Faculty of Agriculture, Lambung Mangkurat University, Banjarmasin, South Kalimatan 70123, Indonesia

[4] Chemistry Study Program, Mathematics and Natural Science, Lambung Mangkurat University, Banjarmasin, South Kalimatan 70123, Indonesia

† Corresponding author: Author Name; 2241213310057@mhs.ulm.ac.id

Key Words	BTJT characteristics; Bulk density; Porosity; Water retention; Co-inoculated ultisol; Biotron
DOI	https://doi.org/10.46488/NEPT.2026.v25i03.D1883 (DOI will be active only after the final publication of the paper)
Citation for the Paper	Budiono, Ichriani, I., Razie, F. and Sunardi, 2026. Synergy of corn cob biochar modification in improving soil bulk density, porosity and water retention. *Nature Environment and Pollution Technology*, 25(3), D1883. https://doi.org/10.46488/NEPT.2026.v25i03.D1883

Abstract: This study investigates 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, combining biochar, nutrients, and biological agents. The research consisted of two experiments: the first analyzed the morphological characteristics and specific surface area (SSA) of BTJT pores with three inoculation durations (7, 14, and 21 days), while the second examined soil bulk density, porosity, and water retention after BTJT co-inoculation. A completely randomized design (CRD) with five treatments, three replications, and three observation periods was applied. 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 with a 5% error margin. The results indicated that BTJT application at 2 tons per hectare 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 tons/ha for optimal improvement of Ultisol soil quality.

1. INTRODUCTION

Biochar is a fine-textured, porous carbonaceous material produced through the pyrolysis process. BTJT is a composite material combining biochar, nutrients, and biological agents. Previous studies have shown that enriching biochar with organic nutrients consistently improves soil physical quality. BTJT, with its complex and heterogeneous pore structures, functions as a carrier medium capable of combining nutrients and biological agents (Allohverdi et al., 2021; Ben-Noah et al., 2021; Deru et al., 2018). Compared with pure biochar (Sepp et al., 2023; Shaheen et al., 2024), BTJT enhances the soil's ability to retain water, air, and nutrient exchange capacity (Raczka et al., 2021; Robinson et al., 2022; Sachdeva et al., 2019). Furthermore, biochar improves soil aeration, which is essential for microbial activity and plant root development (Quan et al., 2020).

Research on the effectiveness of BTJT in improving the physical properties of Ultisol soils, particularly bulk density (BD), porosity, and water retention, remains limited. This study addresses this knowledge gap by evaluating BTJT's effectiveness as a soil conditioner. The chemical activation process involved lime solution and positive ion activators (catalysts), which are believed to increase pore surface area. The pore spaces serve to store air and water while providing a more favorable habitat for effective microbial consortia (Pandey et al., 2022). The use of unmodified biochar is known to produce varying effects on soil, plants, and microorganisms (Ottani et al., 2022). In line with this, recent studies have shown that the application of biochar as a soil amendment has become an increasing focus of soil and environmental research.

Porosity, water movement, and the availability of spaces between soil particles and pores are crucial physical aspects that support root development. These characteristics are influenced by bulk density, a major soil physical property that reflects the compactness of soil particles within a given volume (Lei et al., 2022; Liao & Thomas, 2019; Liu et al., 2024). Water retention is a soil property that indicates its ability to hold water against gravitational forces (Lani et al., 2023). The volume of water retained in soil represents the actual amount of water available at a given time (Jung et al., 2015; Kiss et al., 2021). Its existence is influenced by soil texture, structure, water-holding capacity, and rainfall. Ultisol soils with clay textures generally have higher water retention than sandy soils because of their smaller particle size and larger surface area. Additionally, the presence of soil organic matter can further enhance water-holding capacity (Jensen et al., 2020).

Soil water is bound by capillary and adsorption forces within the soil pores, with bond strength determined by pore size. Soils with micropores retain more water, although only a portion of it is available to plants (Hossain et al., 2020). Factors such as rainfall, surface water infiltration, evaporation, transpiration, evapotranspiration, soil texture, structure, porosity, and water retention collectively determine soil water availability (Harish et al., 2022).

2. MATERIALS AND METHODS

2.1. Research Site Description

The field experiment was conducted in a screen house located at the Agricultural Training Center (*Balai Besar Pelatihan Pertanian*, Binuang), Ministry of Agriculture of the Republic of Indonesia. The coordinates are 3°09′16″ S and 115°05′16″ E, at an elevation of 71.7 m above sea level and approximately 420° from the Earth's horizontal axis. The location can be viewed via Google Maps at: https://maps.app.goo.gl/JmwpHRQWjYsLWiWR9. Laboratory analyses were conducted at several facilities, including the Soil and Fertilizer Laboratory, Particle Material Laboratory, Microbiology Laboratory, and Post-harvest Laboratory. The field experiment was carried out during the rainy season (March–July 2024), while laboratory analyses were conducted from March 2024 to May 2025. Weather conditions during the experimental period can be accessed at https://id.weatherspark.com/y/129103/Cuaca-Rata-rata-pada-bulan-in-Binuang-Indonesia-Sepanjang-Tahun.

2.2. Data Collection

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

The experiment began with the preparation of BTJT samples, each weighing 50 g, with three replications and three treatments involving different soaking (incubation) durations in 2,250 mL of clear $Ca(OH)_2$ solution. The BTJT preparation process included physicochemical, chemical, and biological activation using the prepared materials. Chemical activation (Gao et al., 2025) was conducted by soaking the selected BTJT powder (450–550°C) (Hafeez et al., 2022) in a CaO solution (Geng et al., 2022). The solution was prepared by dissolving 150 g of CaO in 600 mL of distilled water and stirring with a magnetic stirrer for 60 minutes, followed by four activation processes, each using 575 mL of solution (Ferrarezi et al., 2022). The sample was then oven-dried at 105°C for 6 hours (Colucci et al., 2025). The next step was immersion in the best-performing POCH solution for 20 days with three 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 structure and specific surface area analyses were performed using Analytical Scanning Electron Microscopy–Energy Dispersive X-ray (SEM-EDX, JEOL JSM-6510LA) and the Brunauer–Emmett–Teller (BET) method (Chen et al., 2025).

2. **Experiment 2: Soil Quality Characteristics**

This experiment used Ultisol soil samples collected from a depth of 0–20 cm, with each sample weighing 1,000 g, arranged in three replications and five treatments at three observation times. Soil sampling was performed 14 days after co-inoculation with the selected corn cob biochar (BTJ) that had undergone a 7-day inoculation process. The physical characteristics 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 hours (BKT), using both volumetric and gravimetric methods [Libohova et al., 2018]. The parameters PD, KAB, KAV, BD, porosity, and soil water retention were calculated using the following equations:

1. **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. **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) = $[(W_1 - W_2)/(W_2)$ x 100 (Braz et al., 2025)

   Volumetric water content (%) = Water Content (% by weight) x BD (g/cm^3) (Bian et al., 2024)

3. **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)

4. **Porosity (n)**

   n = soil porosity (cm3 cm-1 or %)

   $n = 1 - (\rho particle \times \rho bulk^{-1})$

   $n(\%) = (1 - (\rho particle \times \rho bulk^{-1})) \times 100$

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

   Porosity (%) = (1 - (Bulk Weight / Specific Gravity)) x 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).

2.3. Data Analysis Methods

All statistical analyses were performed using IBM SPSS Statistics version 26.0 and Python (Windows). Analysis of variance (ANOVA) followed by Tukey's post-hoc test at a 5% significance level was used to identify significant differences, interactions between variables, and correlations between BTJT treatments and soil physical properties. OriginPro was used for data visualization, including regression and correlation modeling.

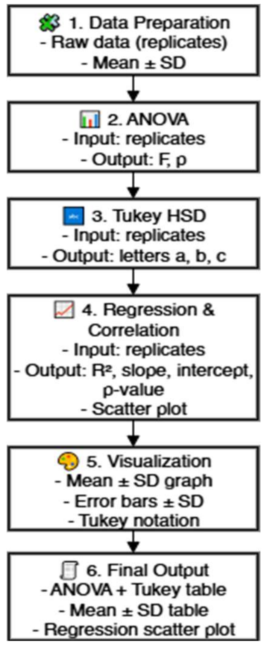
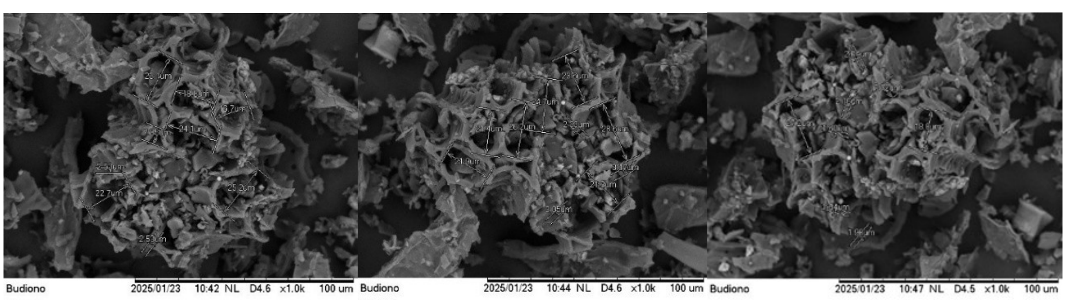


Fig. 1 : Statistical Analysis Flowchart and Visualization

3. RESULTS AND DISCUSSION

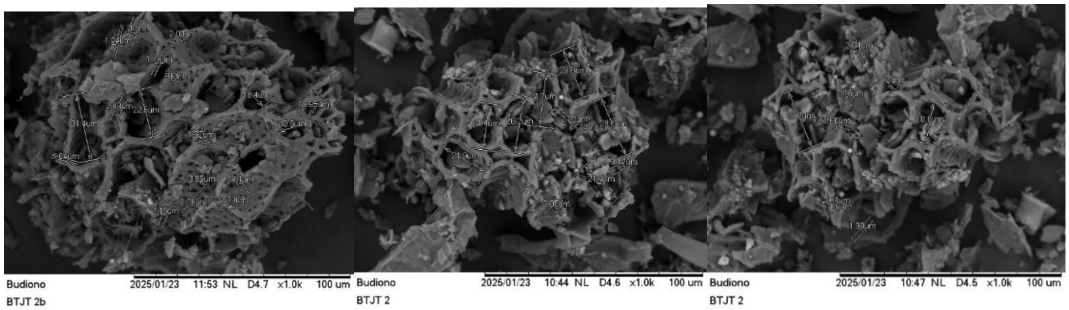
3.1. Experiment 1 Characteristics of BTJT

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 Figures 2–4.



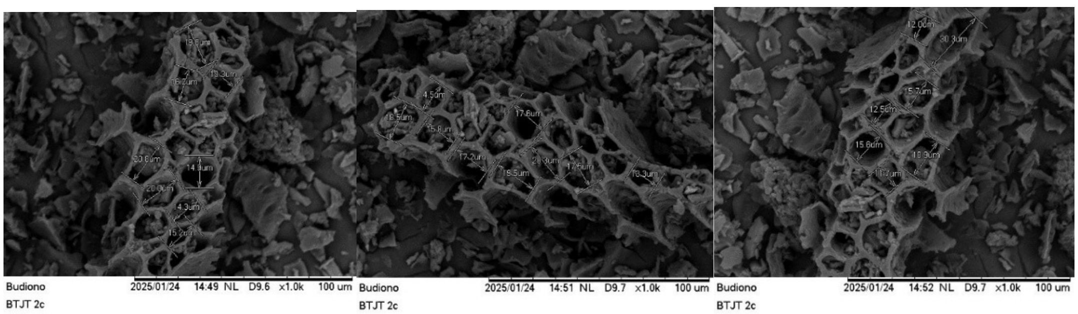
a b c

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



a b c

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

The specific surface area (SSA) of BTJT-7 (with a 7-day co-inoculation duration) showed an optimal average value of 1.63 m²/g, 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 the study. The term "synergistic modification" suggests a substantial enhancement in the biochar's properties, specifically its ability to retain nutrients, water, and support microbial life. However, a BET surface area of 1.63 m²/g 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 m²/g depending on the modification method.

Such a low surface area raises questions about 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, water, and facilitate microbial activity. The observed surface area in this study may not be high enough to justify these claims. In this context, it is crucial to emphasize that BET surface area alone cannot fully explain the soil hydraulic effects, such as water retention and nutrient exchange capacity, especially when pore size distribution is not considered. Pore size distribution is a critical factor in determining how well biochar can hold water and support microbial colonization, both of which are vital for improving soil structure and fertility. The manuscript does not provide this 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, the study falls short of providing a complete analysis of the biochar's hydraulic behavior in the soil. Water retention capacity and porosity depend not only on surface area but also on the distribution of pore sizes. Pores of different sizes (micropores, mesopores, and macropores) serve distinct functions in retaining water, air, and facilitating microbial colonization. Smaller pores may retain more water, but the water may not be readily available to plants. Larger pores facilitate air exchange and microbial activity, which are crucial for healthy soil. Without this additional data on pore size distribution, the manuscript's claim of synergistic modification remains unsubstantiated.

In summary, while 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 biochar's role in improving soil physical properties. For a more comprehensive evaluation, the 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 the field. The result as presented in Figure 5.

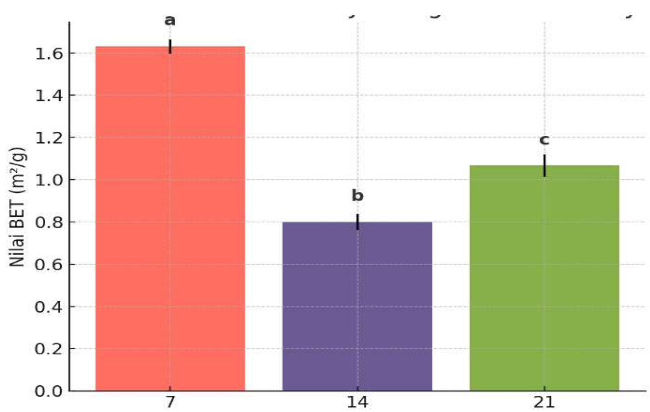


Fig. 5 : Differences in specific surface area (SA) of BTJT at various coinoculation durations

The result from figure 5 chart shows the BET surface area values (in m²/g) 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 m²/g, 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 m²/g, 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, 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 how the inoculation period influences the biochar's surface characteristics, potentially affecting its performance in improving soil properties.

ANOVA analysis revealed a significant difference in specific surface area (SA) among the three BTJT samples ($F = 292.28$; $p < 0.05$). This difference reflects variations in 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 (Siraj Mohammed et al., 2024; 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; C. Wang et al., 2021). This suggests that microbial activity and nutrient availability may fill and cover the biochar pores, thereby markedly reducing the BET value. 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 (L. Wang et al., 2019).

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 Figure 6.

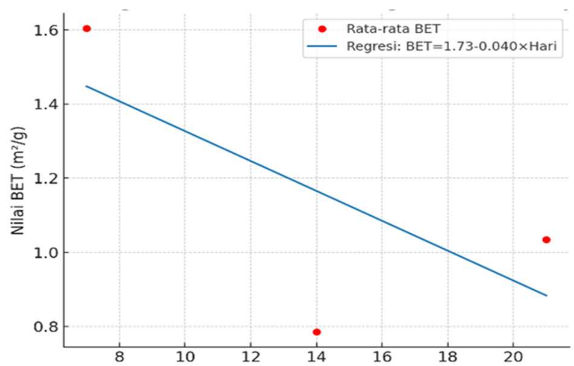


Fig. 6 : Linear regression of the relationship between coinoculation duration and SA in BTJT.

The 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 the 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 ($p < 0.05$).

2. Pearson Correlation

The 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. 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, while at 21 days, the SA increased again but remained lower than that of BTJT-7.

4. Experiment 2 Soil Characteristics

The physical analysis of soil was conducted under five BTJT dosage treatments: the control without biochar (B0 = 0 ton·ha^{-1}), a positive control (B1 = 2.0 ton·ha^{-1} of biotron), and three BTJT treatments (B2 = 1.0 ton·ha^{-1}, B3 = 1.5 ton·ha^{-1}, and B4 = 2.0 ton·ha^{-1}). Each treatment was tested in three independent replications. The average data analysis from three observation periods (May, June, and July 2024) showed that the application of BTJT had a significant effect on soil physical properties. These findings indicate that BTJT, particularly at higher doses, has the potential to be an effective soil amendment in improving land resilience against drought stress. The pores within BTJT serve as spaces that can hold water, air, and nutrients. Treatments B1 (Biotron) and B4 (BTJT at 2 tons/ha) 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 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 $p = 6.27 \times 10^{-5}$, indicatinghighly significant relationship. Where Ŷ = 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 $p = 7.51 \times 10^{-6}$, 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 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 Figure 7.

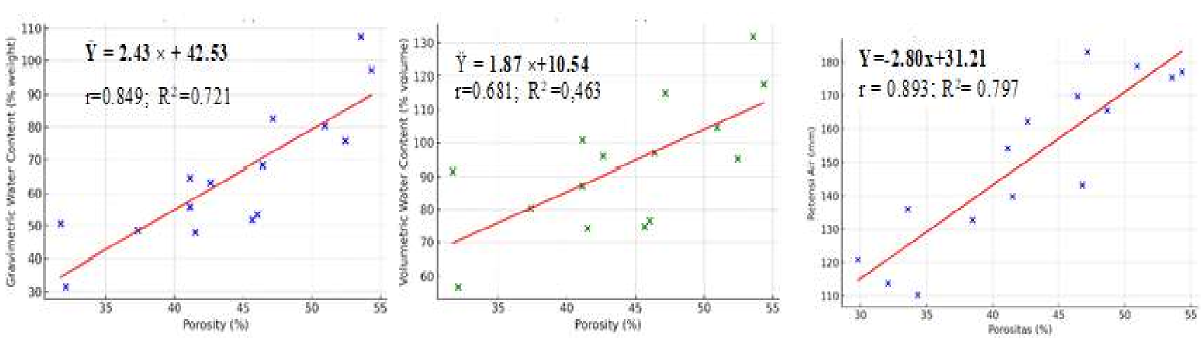


Fig. 7 : Relationship of soil porosity with (a) gravimetric water content (% by weight) Vs Porosity, (b) volumetric water content (% by volume) Vs Porosity, (c) Porosity; Retention Vs BD The red, purple, green and blue lines show the linear regression equation, while the dots indicate the observed values

Bulk density (BD) is a key indicator of soil physical properties that reflects the degree of particle compaction within a given soil volume. High BD values typically reduce porosity, thereby limiting the movement of air and water through the soil. The reduction in porosity caused by 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 pore spaces. These changes not only enhance porosity but also improve the soil's ability to retain water against gravitational forces, leading to more 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 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 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 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 increasing 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 greater pore space available to retain water and nutrients. This aligns with previous research reporting 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. The application of BTJT or Biotron at a dosage of 2 tons/ha 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 ton/ha), BTJT-B3 (1.5 tons/ha), BTJT-B4 (2 tons/ha), and Biotron (2 tons/ha). As the dosage increased, the 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. The relationships among parameters demonstrated moderate to very strong correlations, showing negative interactions with BD and positive interactions with the other parameters. 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..

REFERENCES

1. Ahmad, W., Nepal, J., Zou, Z., Munsif, F., Khan, A., Ahmad, I., Zaheer, S., Khan, M. S., Jadoon, S. A., & Tang, D. (2023). Biochar particle size coupled with biofertilizer enhances soil carbon-nitrogen microbial pools and CO2 sequestration in lentil. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1114728
2. Alkharabsheh, H. M., Seleiman, M. F., Battaglia, M. L., Shami, A., Jalal, R. S., Alhammad, B. A., Almutairi, K. F., & Al-Saif, A. M. (2021). Biochar and its broad impacts in soil quality and fertility, nutrient leaching and crop productivity: A review. Agronomy, 11(5). https://doi.org/10.3390/agronomy11050993
3. Allohverdi, T., Mohanty, A. K., Roy, P., & Misra, M. (2021). A review on current status of biochar uses in agriculture. Molecules, 26(18). https://doi.org/10.3390/molecules26185584
4. Ben-Noah, I., Nitsan, I., Cohen, B., Kaplan, G., & Friedman, S. P. (2021). Soil aeration using air injection in a citrus orchard with shallow groundwater. Agricultural Water Management, 245. https://doi.org/10.1016/J.AGWAT.2020.106664
5. Bian, X., Ren, Z., Zeng, L., Zhao, F., Yao, Y., & Li, X. (2024). Effects of biochar on the compressibility of soil with high water content. Journal of Cleaner Production, 434, 140032. https://doi.org/https://doi.org/10.1016/j.jclepro.2023.140032
6. Braz, G. S., Carvalho, J. do C. L., de Andrade, J. G., Junior, A. T. D., de Lima, R. P., Lima, E. N., Ferreira, O. E., de Oliveira, M. A., Bezerra, A. C. da S., & Machado, A. R. T. (2025). Adsorption of ferrous ions onto phosphoric acid-activated biochar. Desalination and Water Treatment, 321, 100958. https://doi.org/https://doi.org/10.1016/j.dwt.2024.100958
7. Chen, C., Hu, Y., Ge, Y., Tao, J., Yan, B., Cheng, Z., Lv, X., Cui, X., & Chen, G. (2025). Integrated learning framework for enhanced specific surface area, pore size, and pore volume prediction of biochar. Bioresource Technology, 424, 132279. https://doi.org/https://doi.org/10.1016/j.biortech.2025.132279
8. Colucci, G., Stefano, F. Di, Sacchi, F., Licciardello, M., Tonda-Turo, C., Lavagna, L., & Messori, M. (2025). Bio-based polymer composites obtained by vat photopolymerization of photocurable resins modified with biochar as sustainable filler. Composites Part A: Applied Science and Manufacturing, 198, 109102. https://doi.org/https://doi.org/10.1016/j.compositesa.2025.109102
9. Deru, J. G. C., Bloem, J., de Goede, R., Keidel, H., Kloen, H., Rutgers, M., van den Akker, J., Brussaard, L., & van Eekeren,

N. (2018). Soil ecology and ecosystem services of dairy and semi-natural grasslands on peat. Applied Soil Ecology, 125, 26–34. https://doi.org/https://doi.org/10.1016/j.apsoil.2017.12.011

10. Ferrarezi, R. S., Lin, X., Gonzalez Neira, A. C., Tabay Zambon, F., Hu, H., Wang, X., Huang, J.-H., & Fan, G. (2022). Substrate pH Influences the Nutrient Absorption and Rhizosphere Microbiome of Huanglongbing-Affected Grapefruit Plants. Frontiers in Plant Science, Volume 13. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2022.856937
11. Gao, W., Shi, Y., Zhou, Y., Jia, J., & Chen, S. (2025). Biochar with further enhanced properties prepared by acid base combined pretreatment for removal of water pollutants. Scientific Reports, 15(1), 19432. https://doi.org/10.1038/s41598-025-03992-8
12. Geng, N., Kang, X., Yan, X., Yin, N., Wang, H., Pan, H., Yang, Q., Lou, Y., & Zhuge, Y. (2022). Biochar mitigation of soil acidification and carbon sequestration is influenced by materials and temperature. Ecotoxicology and Environmental Safety, 232, 113241. https://doi.org/https://doi.org/10.1016/j.ecoenv.2022.113241
13. Hafeez, A., Pan, T., Tian, J., & Cai, K. (2022). Modified Biochars and Their Effects on Soil Quality: A Review. In Environments (Vol. 9, Issue 5). https://doi.org/10.3390/environments9050060
14. Harish, Kumar, P., Kumar, V., Mishra, R. K., Gwag, J. S., Singh, M. K., Singhal, R., & Mukhopadhyay, A. K. (2022). A novel approach to band gap engineering of Nano-Ca(OH)2: Nanocomposites with Ag2O. Ceramics International, 48(23, Part B), 35771–35787. https://doi.org/https://doi.org/10.1016/j.ceramint.2022.07.136
15. Hossain, M. Z., Bahar, M. M., Sarkar, B., Donne, S. W., Ok, Y. S., Palansooriya, K. N., Kirkham, M. B., Chowdhury, S., & Bolan, N. (2020). Biochar and its importance on nutrient dynamics in soil and plant. Biochar, 2(4), 379–420. https://doi.org/10.1007/s42773-020-00065-z
16. Jensen, J. L., Schjønning, P., Watts, C. W., Christensen, B. T., & Munkholm, L. J. (2020). Short-term changes in soil pore size distribution: Impact of land use. Soil and Tillage Research, 199, 104597. https://doi.org/https://doi.org/10.1016/j.still.2020.104597
17. Jung, K.-W., Hwang, M.-J., Jeong, T.-U., & Ahn, K.-H. (2015). A novel approach for preparation of modified-biochar derived from marine macroalgae: Dual purpose electro-modification for improvement of surface area and metal impregnation. Bioresource Technology, 191, 342–345. https://doi.org/https://doi.org/10.1016/j.biortech.2015.05.052
18. Kiss, T., Fórián, S., Szatmári, G., & Sipos, G. (2021). Spatial distribution of microplastics in the fluvial sediments of a transboundary river – A case study of the Tisza River in Central Europe. Science of The Total Environment, 785, 147306.

https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.147306

19. Lani, N. S., Ngadi, N., Mohammed Inuwa, I., Anako Opotu, L., Zakaria, Z. Y., & Haron, S. (2023). A cleaner approach with magnetically assisted reactor setup over CaO-zeolite/Fe3O4 catalyst in biodiesel production: Evaluation of catalytic performance, reusability and life cycle assessment studies. Journal of Cleaner Production, 419, 138329. https://doi.org/https://doi.org/10.1016/j.jclepro.2023.138329
20. Lei, H., Yu, J., Zang, M., Pan, H., Liu, X., Zhang, Z., & Du, J. (2022). Effects of Water-Fertilizer-Air-Coupling Drip Irrigation on Soil Health Status: Soil Aeration, Enzyme Activities and Microbial Biomass. In Agronomy (Vol. 12, Issue 11). https://doi.org/10.3390/agronomy12112674
21. Liao, W., & Thomas, S. C. (2019). Biochar Particle Size and Post-Pyrolysis Mechanical Processing Affect Soil pH, Water Retention Capacity, and Plant Performance. In Soil Systems (Vol. 3, Issue 1). https://doi.org/10.3390/soilsystems3010014
22. Liu, M., Qiao, P., Shan, Y., Zhang, Z., Pan, P., & Li, Y. (2024). Migration and Accumulation Simulation Prediction of PPCPs in Urban Green Space Soil Irrigated with Recycled Water: A Review. Journal of Hazardous Materials, 476, 135037. https://doi.org/https://doi.org/10.1016/j.jhazmat.2024.135037
23. Ottani, F., Parenti, M., Pedrazzi, S., Moscatelli, G., & Allesina, G. (2022). Impacts of gasification biochar and its particle size on the thermal behavior of organic waste co-composting process. Science of The Total Environment, 817, 153022. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.153022
24. Pandey, M., Tirkey, A., Tiwari, A., Pandey, S. K., & Khan, M. L. (2022). Chapter 10 - Microbial interaction of biochar and its application in soil, water and air (J. A. B. T.-M. and M. B. for G. R. Malik (ed.); pp. 185–203). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-323-90452-0.00001-3
25. Quan, G., Fan, Q., Zimmerman, A. R., Sun, J., Cui, L., Wang, H., Gao, B., & Yan, J. (2020). Effects of laboratory biotic aging on the characteristics of biochar and its water-soluble organic products. Journal of Hazardous Materials, 382, 121071. https://doi.org/https://doi.org/10.1016/j.jhazmat.2019.121071
26. Raczka, N. C., Piñeiro, J., Tfaily, M. M., Chu, R. K., Lipton, M. S., Pasa-Tolic, L., Morrissey, E., & Brzostek, E. (2021). Interactions between microbial diversity and substrate chemistry determine the fate of carbon in soil. Scientific Reports, 11(1), 19320. https://doi.org/10.1038/s41598-021-97942-9
27. Robinson, D. A., Thomas, A., Reinsch, S., Lebron, I., Feeney, C. J., Maskell, L. C., Wood, C. M., Seaton, F. M., Emmett, B. A., & Cosby, B. J. (2022). Analytical modelling of soil porosity and bulk density across the soil organic matter and land-use continuum. Scientific Reports, 12(1), 7085. https://doi.org/10.1038/s41598-022-11099-7

28. Sachdeva, V., Hussain, N., Husk, B. R., & Whalen, J. K. (2019). Biochar-induced soil stability influences phosphorus retention in a temperate agricultural soil. Geoderma, 351, 71–75. https://doi.org/https://doi.org/10.1016/j.geoderma.2019.05.029

29. Sepp, S.-K., Vasar, M., Davison, J., Oja, J., Anslan, S., Al-Quraishy, S., Bahram, M., Bueno, C. G., Cantero, J. J., Fabiano, E. C., Decocq, G., Drenkhan, R., Fraser, L., Garibay Oriel, R., Hiiesalu, I., Koorem, K., Kõljalg, U., Moora, M., Mucina, L., … Zobel, M. (2023). Global diversity and distribution of nitrogen-fixing bacteria in the soil. Frontiers in Plant Science, Volume 14. https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1100235

30. Shaheen, J. F., Eniola, J. O., & Sizirici, B. (2024). Adsorption of ibuprofen from aqueous solution by modified date palm biochar: Performance, optimization, and life cycle assessment. Bioresource Technology Reports, 25, 101696. https://doi.org/https://doi.org/10.1016/j.biteb.2023.101696

31. Siraj Mohammed, A., Ramaya Ancha, V., & Mekbib Atnaw, S. (2024). Optimization of biodiesel production from Croton Macrostachyus seed oil with calcium oxide (CaO) catalyst and Characterization: Potential assessment of seed and kernel. Energy Conversion and Management: X, 24, 100791. https://doi.org/https://doi.org/10.1016/j.ecmx.2024.100791

32. Sizmur, T., Fresno, T., Akgül, G., Frost, H., & Moreno-Jiménez, E. (2017). Biochar modification to enhance sorption of inorganics from water. Bioresource Technology, 246, 34–47. https://doi.org/https://doi.org/10.1016/j.biortech.2017.07.082

33. Sun, M., Liu, X., Shi, K., Peng, F., & Xiao, Y. (2022). Effects of Root Zone Aeration on Soil Microbes Species in a Peach Tree Rhizosphere and Root Growth. In Microorganisms (Vol. 10, Issue 10). https://doi.org/10.3390/microorganisms10101879

34. Tamburini, D. (2021). Analytical pyrolysis applied to the characterisation and identification of Asian lacquers in cultural heritage samples – A review. Journal of Analytical and Applied Pyrolysis, 157, 105202. https://doi.org/https://doi.org/10.1016/j.jaap.2021.105202

35. Wang, C., Huang, R., Sun, R., Yang, J., & Sillanpää, M. (2021). A review on persulfates activation by functional biochar for organic contaminants removal: Synthesis, characterizations, radical determination, and mechanism. Journal of Environmental Chemical Engineering, 9(5), 106267. https://doi.org/https://doi.org/10.1016/j.jece.2021.106267

36. Wang, L., Wang, Y., Ma, F., Tankpa, V., Bai, S., Guo, X., & Wang, X. (2019). Mechanisms and reutilization of modified biochar used for removal of heavy metals from wastewater: A review. Science of The Total Environment, 668, 1298–1309. https://doi.org/https://doi.org/10.1016/j.scitotenv.2019.03.011

37. Wang, X., Chen, Z., Wang, C., & Zhang, L. (2024). Ultrahigh and kinetic-favorable adsorption for recycling urea using

corncob-derived porous biochar. Scientific Reports, 14(1), 8131. https://doi.org/10.1038/s41598-024-58538-1

38. Wei, B., Peng, Y., Lin, L., Zhang, D., Ma, L., Jiang, L., Li, Y., He, T., & Wang, Z. (2023). Drivers of biochar-mediated improvement of soil water retention capacity based on soil texture: A meta-analysis. Geoderma, 437, 116591. https://doi.org/https://doi.org/10.1016/j.geoderma.2023.116591
39. Xu, T., Xi, J., Ke, J., Wang, Y., Chen, X., Zhang, Z., & Lin, Y. (2023). Deciphering soil amendments and actinomycetes for remediation of cadmium (Cd) contaminated farmland. Ecotoxicology and Environmental Safety, 249, 114388. https://doi.org/https://doi.org/10.1016/j.ecoenv.2022.114388