Wadi Alshatti University Journal of Pure and Applied Sciences

مجلة جامعة وادي الشاطئ للعلوم البحتة والتطبيقية

Volume 4, No. 1, January-June 2026 Online ISSN: 3006-0877 المجلد 4، الاصدار 1، يناير - يونيو 2026

RESEARCH ARTICLE **SOIL PHYSICS AND BIOCHAR APPLICATIONS**

Influence of Biochar Feedstock and Application Rate on Physical Properties of Sandy Aridisol Soil

Riad O. Eissa[1,*], Khalid A. Elzobair[1], Abdallah Adda[1]

[1]Department of Soil and Water, Faculty of Agriculture, Sebha University, Sebha, Libya

ARTICLE HISTORY
Received 28 March 2026
Revised 15 April 2026
Accepted 02 May 2026
Online 09 May 2026

KEYWORDS
Biochar;
Feedstock type;
Soil bulk density;
Porosity;
Water holding capacity.
Hydraulic conductivity;

ABSTRACT

Biochar is becoming known as an amendment to enhance soil physical properties; however, its efficacy depends on both the type of feedstock and the application rate. The objective of this study was to assess the impacts of the biochar feedstocks (barley residues, sheep manure, woody materials, and chicken manure) and their application rates (1, 3, 5, and 10% w/w) on soil bulk density, porosity, soil water holding capacity, and soil saturated hydraulic conductivity. The results showed that biochar significantly enhanced all measured properties, with statistical analysis confirming highly significant effects of feedstock type, application rate, and their interaction on the studied soil physical parameters ($p < 0.001$). Across feedstocks, soil bulk density decreased approximately from 1.10–1.11 g cm^{-3} in the control to 0.80–0.82 g cm^{-3} with barley residue and sheep manure biochar, representing reductions of about 25–28%, while woody and chicken manure biochars led to smaller reductions (11–19%). Soil porosity increased from 58% in the control to 68–69% with sheep manure and barley residue biochar, corresponding to increases of 17–19%. Water holding capacity increased to 35–39% with most feedstocks, representing increases of 6–18% relative to the control, but reached 47% with barley residue biochar, corresponding to a 42% increase compared with the control. Biochar application rate strongly influenced soil physical properties. Bulk density decreased from 1.12 g cm^{-3} at 0% biochar to 0.83 g cm^{-3} at 5% and 0.78 g cm^{-3} at 10%. Porosity increased from 58% in the control to 66% and 68% at 5% and 10% biochar, respectively. Saturated hydraulic conductivity showed a nonlinear response relative to the control, decreasing by 20–24% at 1–3% biochar rates, but increasing markedly at 5% (52–69%) and remaining elevated at 10% (33–38%). Overall, these results indicate that optimal soil improvement depends on both feedstock selection and biochar application rate, with the greatest benefits achieved with manure and residue derived biochars at 5–10% (w/w).

تأثير نوع المادة الأولية للفحم الحيوي ومعدل إضافته على الخصائص الفيزيائية للتربة الرملية الجافة

رياض عيسى 1،*، خالد الزبير 1، عبدالله آده 1

الكلمات المفتاحية
الفحم الحيوي
المادة الأولية
الكثافة الظاهرية
المسامية
السعة الحقلية
التوصيل الهيدروليكي للتربة

الملخص

يُعدّ الفحم الحيوي (Biochar) من المحسّنات الواعدة لخصائص التربة الفيزيائية، إلا أن كفاءته تعتمد على نوع المادة الأولية ومعدل الإضافة. هدفت هذه الدراسة إلى تقييم تأثير أربعة أنواع من الفحم الحيوي (مخلفات الشعير، روث الأغنام، المواد الخشبية، وروث الدواجن) وبمعدلات إضافة (1، 3، 5، و10% وزن/وزن) على الكثافة الظاهرية، المسامية، السعة الحقلية، والتوصيل الهيدروليكي المشبع للتربة. أظهرت النتائج تحسناً معنوياً في جميع الخصائص المدروسة ($p < 0.001$)، حيث انخفضت الكثافة الظاهرية من نحو 1.10 إلى 0.80–0.82 جم/سم³ عند استخدام مخلفات الشعير وروث الأغنام (انخفاض 25–28%)، مقابل انخفاض أقل مع الأنواع الأخرى (11–19%). كما ارتفعت المسامية 68–69%، وزادت السعة الحقلية حتى 47% مع مخلفات الشعير. كما أثّر معدل الإضافة بشكل واضح، إذ انخفضت الكثافة الظاهرية إلى 0.78 جم/سم³ عند 10%، وارتفعت المسامية إلى 68%. أما التوصيل الهيدروليكي فأظهر سلوكاً غير خطي، حيث انخفض عند المعدلات المنخفضة وارتفع بشكل كبير عند 5–10%. بشكل عام، تعتمد كفاءة تحسين التربة على نوع الفحم الحيوي ومعدل إضافته، مع أفضل النتائج عند استخدام مخلفات وروث الحيوانات بمعدلات 5–10%.

Introduction

Biochar is a carbon rich material produced through the pyrolysis of biomass under oxygen limited conditions. Recently, biochar has gained considerable interest as a sustainable soil amendment [1, 2]. In addition to improving soil quality, biochar has also been widely recognized for its role in carbon sequestration and climate change mitigation through long-term stabilization of organic carbon in soils [1, 3,4]. Its distinct features, such as high porosity, large surface area, and variable nutrient content, lead to improvements in soil structure, water holding capacity, nutrient retention, and mitigation of soil compaction. Several recent studies have

*Corresponding author
https://doi.org/10.63318/waujpasv4i1_49

reported that biochar and other organic amendments can significantly improve aggregate stability, infiltration rate, resistance to surface crusting, and overall soil physicochemical properties, particularly in degraded and coarse-textured soils [5–7]. Among biochar's many soil physical property improvements, the reduction of soil bulk density is very important for improved plant growth and agricultural productivity.

Soil bulk density, which is the mass of oven dried soil in line with unit extent, represents a critical measure of both soil compaction and porosity [8]. High bulk density, which in turn plays a role in root increase, is a factor that can limit plant growth and crop yield. On the other hand, lower bulk density, which is a result of biochar value, displays in a progressed soil structure, improved aeration, and better water retention, which in turn promote root development and microbial activity. Thus, changes in soil porosity induced by biochar can further impact the soil's water retention and movement, thereby affecting both its water holding capacity and saturated hydraulic conductivity [9, 10]. Collectively, these residences govern water availability to flowers, drainage performance and average soil hydraulic functioning [9, 11]. Meta-analytical evidence has further shown that reductions in soil bulk density following biochar application are often accompanied by increases in total porosity and plant available water, although the magnitude of change depends strongly on soil texture and biochar properties [12].

The influence of biochar on soil physical and hydraulic properties is largely governed by the nature of the feedstock and the level of application. [4,5, 13]. Biochars generated from crop residues, animal manures, and woody materials vary greatly in particle density, pore structure, ash content, and mineral composition, resulting in opposing impacts on soil bulk density and pore connectivity [14,15]. For instance, manure derived biochars generally contain higher ash and nutrient concentrations, whereas woody biochars are often characterized by higher fixed carbon content and greater structural stability. Crop residue biochars commonly exhibit intermediate properties, with relatively high surface area and moderate nutrient availability [3, 16]. Comparative studies have shown that manure- and residue derived biochars may yield greater short term improvements in porosity and water retention, whereas woody biochars may contribute more to long-term structural persistence in soil [17, 18]. Likewise, application rate determines the extent to which biochar alters the soil environment, with low rates often producing modest effects, whereas higher rates induce more pronounced changes in porosity, water retention and hydraulic conductivity [10, 19]. Several studies comparing rates from 1 to 10% (w/w) reported that moderate to high rates often result in greater decreases in bulk density and higher water holding capacity, although excessive rates may sometimes reduce hydraulic conductivity depending on pore blockage and particle arrangement [9].

Although biochar has been shown to enhance soil properties, few studies have directly compared the effects of different feedstock types and application rates on soil physical and hydraulic properties under controlled conditions. Most previous studies have focused on either a single feedstock source or a narrow application range, limiting direct evaluation of the interaction between feedstock characteristics and dosage level. Understanding the variations of biochar application is essential for designing strategies tailored to specific soil and crop systems. Therefore, further comparative research is needed to identify the most effective combinations of feedstock type and application rate for optimizing soil physical improvement under specific management conditions. Accordingly, this study aimed to evaluate the impact of biochar produced from barley residues, sheep manure, woody materials, and chicken manure, applied at 1%, 3%, 5%, and 10% (w/w), on the physical and hydraulic characteristics of soil.

Methodology

Soil Collection and Preparation

Soil samples were collected from the Faculty of Agriculture farm, Sebha University (26°58′26″N; 14°26′18″E; 427.22 m above sea level), from the 0–20 cm topsoil layer on 09 September 2025. Immediately after collection, the samples were placed in sealed plastic bags, transported to the laboratory, and air-dried at room temperature for 72 hours before sieving through a 2 mm mesh for subsequent analyses. The soil is classified as sandy, with 88.90% sand, 7.33% silt, and 3.77% clay. All laboratory analyses were conducted in the Soil Physics Laboratory, Faculty of Agriculture, Sebha University.

Biochar Production

Four types of biochar were used in this experiment to evaluate their effects on the soil physical properties and identify the most effective type. The biochar was generated from four different feedstocks at 550 °C using double barrel retort pyrolysis: chicken manure (CM550), sheep manure (SM550), barley residues (BR550), and woody materials (WM550).

Experimental Setup and Design

Each biochar type was incorporated into the soil at four rates: 0% (control), 3%, 5%, and 10% by weight (w/w). The pots were maintained at room temperature (24 ± 2 °C) in a laboratory setting, and soil moisture was kept at 60% of the soil's water holding capacity by watering twice a week. The experiment consisted of three replicates per treatment, resulting in a total of 48 experimental units.

Soil Bulk Density and Porosity Determination

Soil bulk density was measured by the core sampling method. (volumetric cylinder), as shown in Equation (1), while soil porosity was calculated using Equation (2) [20].

$$\rho b = \frac{M_s}{V_t} \quad (1)$$

$$St = \left(1 - \rho_b/\rho_p\right) \text{ x } 100 \quad (2)$$

Where *St* is total porosity (%), ρ_b is bulk density (g cm⁻³) determined as the ratio of oven-dry soil mass (*Ms,* g), to total soil volume (*Vt,* cm³). and ρ_p is particle density (g cm⁻³), commonly assumed as 2.65 g cm⁻³ for mineral soils.

Saturated Hydraulic Conductivity Determination

Saturated hydraulic conductivity (K_s) was determined using the constant-head permeameter method, calculated according to Equation (3) [21].

$$K_s = \frac{V \times L}{A \times T \times H} \quad (3)$$

Where K_s is saturated hydraulic Conductivity (cm/sec), V is the volume of water flowing through the soil sample (cm³), L is the height (Length) of the soil sample (cm), A is the cross-sectional area of the soil sample (cm²), T is the time during which the water volume was collected (seconds), and H is the total hydraulic head (which is the height of the water column above the sample plus the height of the sample itself, measured in cm).

Water Holding Capacity Determination

Volumetric water holding capacity (θv) was determined using a core-based saturation–drainage method following standard soil physical procedures (4) [22]. Soil samples, air-dried and sieved to <2 mm, were placed into cylindrical cores with known internal volumes to ensure consistent bulk density among treatments. Samples were gradually saturated from the base with deionized water for 24 h, ensuring complete soil saturation while reducing air entrapment. After saturation, cores drained freely for 24 h at room temperature to reach approximate field capacity. After drainage, the wet mass of each core was recorded. Samples were then oven-dried at 105 °C for 24 h to constant weight, and the dry mass was measured. Volumetric water holding capacity was calculated as the volume of water retained per unit soil volume and expressed as a percentage, assuming a water density of 1 g cm^{-3}.

$$\theta_v = \frac{W_{wet} - W_{dry}}{V_{core}} x\ 100 \quad (4)$$

Statistical Analysis

Analysis of variance (ANOVA) was conducted using a general linear model in Minitab 19 software [23]. The significance of the effects of biochar feedstock type, application rate (w/w), and their interaction on soil bulk density, porosity, saturated hydraulic conductivity, and water-holding capacity was evaluated at $\alpha \leq 0.05$ using a Completely Randomized Design (CRD). Before performing the two-way ANOVA, the assumptions of normality and homogeneity of variance were tested and confirmed. Significant differences between treatment means were determined using Tukey's test at a 95% confidence level ($p < 0.05$) [24].

Results

Biochar feedstocks and soil bulk density

The results confirmed that biochar feedstock type considerably affected soil bulk density ($p < 0.05$) (Figure 1). Analysis of variance (ANOVA) showed that the differences among treatments were statistically significant. The control treatment (no biochar) exhibited the highest bulk density (1.11 g cm^{-3}). All biochar amended soils showed a significant reduction in bulk density compared with the control. Chicken manure biochar decreased bulk density to approximately 0.99 g cm^{-3}, representing a decrease of about 10.8% relative to the control. A greater reduction was observed with woody biochar (0.90 g cm^{-3}), corresponding to a 18.9% decrease. The most noticeable reductions occurred in soils amended with sheep manure (0.82 g cm^{-3}) and barley residue biochars (0.80 g cm^{-3}), which lowered bulk density by approximately 26.1% and 27.9%, respectively. Tukey's HSD test showed no significant difference between woody and sheep manure biochars, nor between sheep manure and barley residue biochars. Spearman's rank correlation analysis further indicated a strong and significant negative correlation between biochar application rate and soil bulk density ($\rho = -0.851$, $p < 0.05$), confirming that increasing biochar levels reduced soil bulk density. Overall, biochar application significantly improved soil physical condition by reducing bulk density, with stronger effects observed in manure- and residue-based biochars.

Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$).

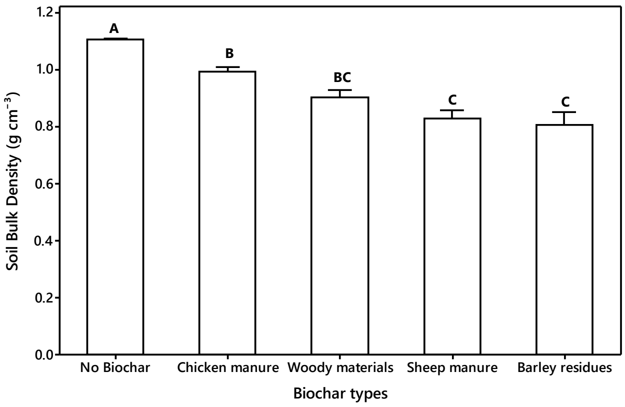

Figure 1: Effects of biochar feedstock type on soil bulk density. Error bars represent ± standard error ($n = 3$).

Biochar feedstocks and soil porosity

Statistical analysis indicated that soil porosity was significantly influenced by the type of biochar feedstock ($p < 0.05$) (Figure 2). Analysis of variance (ANOVA) confirmed that the differences among treatments were statistically significant. The control treatment, which received no biochar, showed the lowest porosity at around 58%. All biochar amended soils showed a significant increase in porosity compared with the control. Chicken manure biochar increased soil porosity to about 62%, representing an increase of approximately 6.9% relative to the control. A greater improvement was observed with woody biochar (65%), corresponding to a 12.1% increase. The highest porosity values were recorded in soils amended with sheep manure (68%) and barley residue biochars (69%), which increased porosity by approximately 17.2% and 19.0%, respectively. Tukey's test indicated no significant differences between woody materials and sheep manure biochars, or between sheep manure and barley residue biochars. Spearman's correlation analysis further revealed a strong and significant positive correlation between biochar application rate and soil porosity ($\rho = 0.761$, $p < 0.05$), while soil porosity was perfectly and negatively correlated with soil bulk density ($\rho = -1.000$, $p < 0.05$). These results demonstrate that biochar incorporation significantly enhances soil pore structure, with the strongest effects observed in residue based biochar.

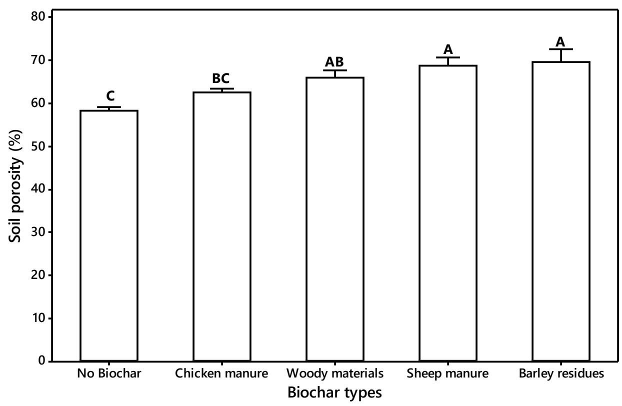

Figure 2: Effects of biochar feedstock type on soil porosity density. Error bars represent ± standard error ($n = 3$). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

Biochar feedstocks and soil saturated hydraulic

conductivity

Soil saturated hydraulic conductivity (K_s) varied significantly among biochar feedstock types (p < 0.05) (Figure 3). ANOVA results confirmed significant variation among treatments. The control treatment (no biochar) exhibited a (K_s) value of 34.5 cm h^{-1}. Application of chicken manure biochar resulted in the lowest (K_s) value (21.8 cm h^{-1}), corresponding to a 36.8% decrease compared with the control. Similarly, woody material biochar reduced (K_s) to 28.6 cm h^{-1}, representing a 17.1% decrease relative to the control. In contrast, sheep manure derived biochar significantly increased (K_s) to 58.4 cm h^{-1}, reflecting a 69.3% increase compared with the control. Barley residue biochar also enhanced (K_s) to 45.9 cm h^{-1}, corresponding to a 33.0% increase, although this increase was not statistically different from either the control or the sheep manure biochar. Spearman's rank correlation analysis further displayed a significant positive correlation between biochar application rate and saturated hydraulic conductivity (ρ = 0.358, $p < 0.05$). In addition, saturated hydraulic conductivity was negatively correlated with soil bulk density (ρ = −0.611, $p < 0.05$) and positively correlated with soil porosity (ρ = 0.611, $p < 0.05$). These results indicate that biochar feedstock type strongly influences soil water transmission, with manure and residue derived biochars enhancing hydraulic conductivity, while chicken manure and woody biochars reduced (K_s) under the conditions of this study.

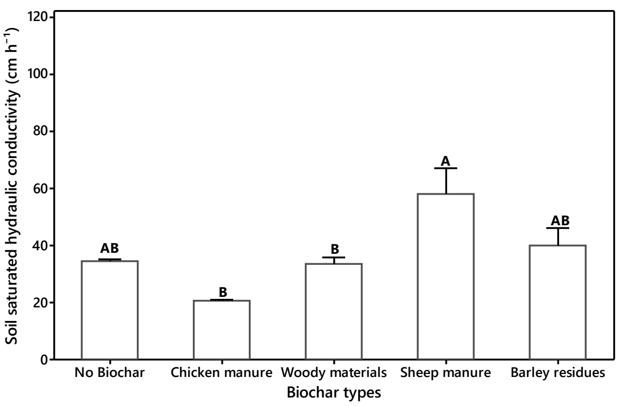

Figure 3: Effects of biochar feedstock type on soil porosity density. Error bars represent ± standard error (n = 3). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

Biochar feedstocks and water holding capacity

The results showed that the type of biochar application significantly affected soil water holding capacity ($p < 0.05$) (Figure 4). ANOVA revealed statistically significant differences among treatments. The control treatment (no biochar) had the lowest water holding capacity at around 33%. Application of chicken manure derived biochar increased water holding capacity to about 35%, resulting in a 6% increase relative to the control. Similarly, woody material biochar raised water holding capacity to approximately 39%, representing an 18% increase compared with the control, while sheep manure biochar resulted in around 37%, reflecting a 12% increase relative to the control. In contrast, barley residue derived biochar significantly enhanced soil water holding capacity, reaching about 47%, which corresponds to a 42% increase compared with the control, and that was significantly higher than all other treatments. Spearman's correlation analysis further revealed a strong and significant positive correlation between biochar application rate and soil water holding capacity (ρ = 0.744, $p < 0.05$). Additionally, water holding capacity was negatively correlated with soil bulk density (ρ = −0.809, $p < 0.05$), and positively correlated with soil porosity (ρ = 0.761, $p < 0.05$) and saturated hydraulic conductivity (ρ = 0.541, $p < 0.05$). These findings indicate that biochar incorporation enhances soil water retention, with the extent of improvement depending on the biochar feedstock type, with barley residue biochar showing the greatest capacity to enhance soil water holding capacity under the conditions of this study.

Biochar rates and soil bulk density

The results showed that increasing the biochar application rate (w/w %) significantly reduced the soil's bulk density ($p < 0.05$), as shown in Figure 5. ANOVA demonstrated that the application rate had a statistically significant effect. The control treatment (no biochar) recorded the highest bulk density around 1.10 g cm^{-3}, followed by the 1% biochar treatment, around 0.98 g cm^{-3}, representing 10.9% decrease.

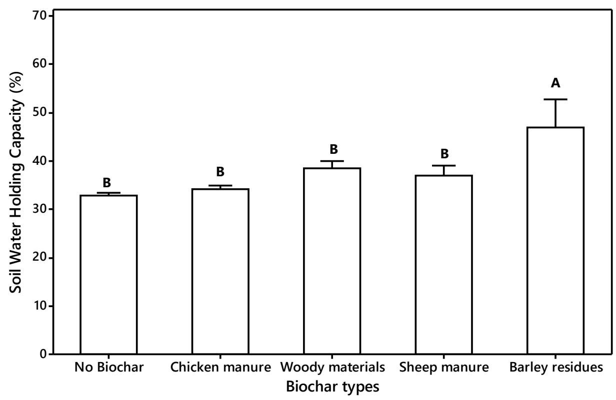

Figure 4: Effects of biochar feedstock type on soil water holding capacity density. Error bars represent ± standard error (n = 3). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

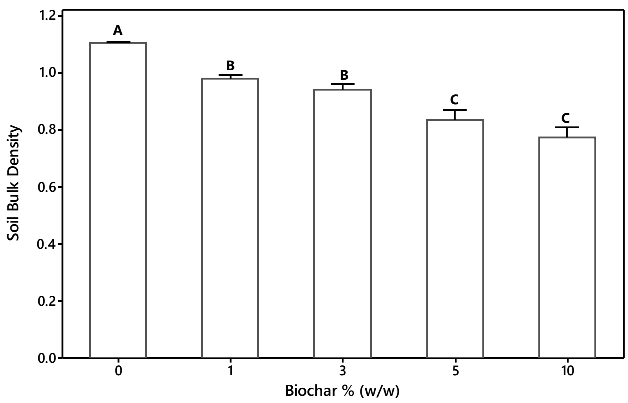

Figure 5: Effects of biochar rates on soil bulk density. Error bars represent ± standard error (n = 3). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

Further decreases were observed: at 3%, about 0.93 g cm^{-3} representing 15.5% reduction. At 5%, around 0.83 g cm^{-3}, corresponding to 24.5% reduction; and at 10% biochar, about 0.76 g cm^{-3}, corresponding to 30.9% reduction relative to the control. Even with the lowest application rate of 1% (w/w), biochar significantly reduced the soil's bulk density compared to the control, and with further reductions observed at a higher rate (10% (w/w)). Results from Spearman's correlation analysis further showed a strong and significant negative correlation between biochar application rate and soil bulk density (ρ = −0.851, $p < 0.05$), indicating that increasing the biochar rate consistently reduced soil compaction. These results indicate that biochar incorporated into the soil improves its physical properties by reducing bulk density as the application rate increases from 0 to 10% (w/w).

Biochar rates and soil porosity

As the rate of biochar application increased ($p < 0.05$), soil porosity consistently increased, as shown in Figure 6. ANOVA indicated significant differences among application rates. The control soil was roughly 58% less porous than all biochar-treated treatments. Even a low biochar rate enhanced porosity, reaching about 62% at 1% and around 64% at 3%, an increase of roughly 6.9% and 10.3%, respectively, compared to the control. At higher application rates, more significant improvements were seen; porosity rose to roughly 68% at 5% and around 71% at 10%, corresponding to 17.2% and 22.4%, respectively, compared with the control. Though the 5% and 10% treatments showed no statistically significant difference, both rates substantially increased porosity compared to the lower rates. Spearman's correlation indicated that increasing biochar application rate significantly increased soil porosity (ρ = 0.761, $p < 0.05$). whereas porosity was inversely related to soil bulk density (ρ = −1.000, $p < 0.05$). With the most notable increases at application rates over 3% (w/w), these findings show that increasing the biochar application rate improves soil porosity.

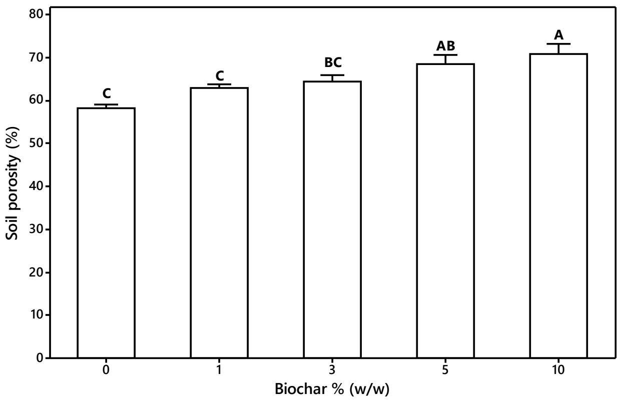

Figure 6: Effects of biochar rates on soil porosity. Error bars represent ± standard error ($n = 3$). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

Biochar rates and soil saturated hydraulic conductivity

Soil saturated hydraulic conductivity (K_s) was significantly influenced by the biochar application rate ($p < 0.05$) as shown in Figure 7. ANOVA results confirmed significant variation among application rates. The control treatment recorded a K_s value of 34.2 cm hr^{-1}. At low application rates, K_s decreased to 26.1 cm hr^{-1} at 1%, which represents a decrease of 23.7% and 27.4 cm hr^{-1} at 3%, corresponding to 19.9% decreases. In contrast, the 5% biochar treatment markedly increased K_s to 52.0 cm hr^{-1}, which corresponds to an increase of 52% relative to the control. A moderate increase was also observed at 10%, where K_s reached 47.2 cm hr^{-1}, which corresponds 38%, although this value was not statistically different from either the control or the 5% biochar treatment. Spearman's analysis showed a significant positive relationship between biochar application rate and saturated hydraulic conductivity (ρ = 0.358, $p < 0.05$). In addition, saturated hydraulic conductivity was negatively correlated with soil bulk density (ρ = −0.611, $p < 0.05$) and positively correlated with soil porosity (ρ = 0.611, $p < 0.05$).

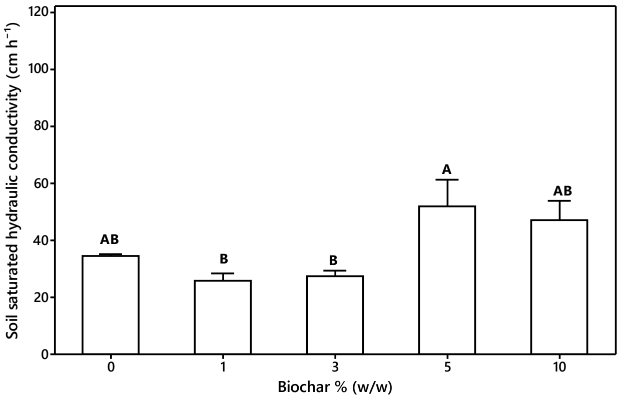

Figure 7: Effects of biochar rates on soil porosity. Error bars represent ± standard error ($n = 3$). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

Biochar rates and soil water holding capacity

The results showed that biochar application rate significantly affected soil water holding capacity (p < 0.05) (Figure 8). Analysis of variance (ANOVA) revealed statistically significant differences among application rates. The control treatment exhibited the lowest water holding capacity (33%).

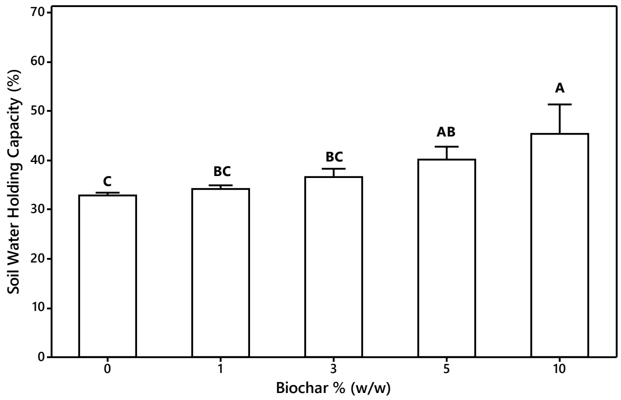

Figure 8: Effects of biochar rates on soil porosity. Error bars represent ± standard error ($n = 3$). Different letters above the bars indicate statistically significant differences among treatments according to Tukey's test ($p < 0.05$)

Application of biochar at 1% resulted in slight increases in water holding capacity, reaching about 34%, representing an increase of 3% relative to the control, while the 3% biochar treatment increased water holding capacity to 37%, corresponding to 12.1% increase. However, these treatments were not significantly different from the control. A further increase was observed at the 5%, where water holding capacity reached 40%, reflecting a 21.2% increase compared to the control. The highest water holding capacity was recorded at the 10% rate, reaching 47%, which represents 42.4% increase over the control, and was significantly greater than in all other treatments. Spearman's correlation analysis further revealed a significant positive relationship between biochar application rate and soil water holding capacity (ρ = 0.744, $p < 0.05$). In addition, water holding capacity was negatively correlated with soil bulk density (ρ = −0.809, $p < 0.05$), and positively correlated with soil porosity (ρ = 0.761, $p < 0.05$) and saturated hydraulic conductivity (ρ = 0.541, $p < 0.05$). Overall, these results demonstrate that biochar incorporation enhances soil water holding capacity, with the magnitude of the improvement increasing with application rate.

Discussion

Effect of biochar feedstock type on soil physical properties

The type of biochar feedstock significantly influenced soil physical and hydraulic properties, namely bulk density, porosity, saturated hydraulic conductivity, and water holding capacity. Soils amended with barley residue and sheep manure biochar showed the strongest improvement, followed by woody and chicken manure biochar. This feedstock-dependent response is consistent with previous studies, which reported that the effects of biochar on soil structure and water dynamics are primarily controlled by feedstock characteristics rather than biochar application alone [9, 16, 25, 26]. These studies also highlight that manure- and residue-based biochars generally show greater effectiveness than woody biochars in improving short-term soil physical quality. However, woody biochar may provide longer-term stability benefits [27–30].

Correlation analysis (Table 1) further helps explain the mechanisms behind these responses. The strong negative correlation between soil bulk density and water holding capacity (ρ = −0.809, $p < 0.001$) indicates that reductions in soil compaction were a key driver of improved water retention. Similar trends have been reported by Acharya et al. (2024) [9] and Alghamdi (2018) [29], who found that biochar-induced reductions in bulk density enhance soil pore space and moisture availability. In this study, manure- and residue-derived biochars were particularly effective, possibly due to their greater ability to modify soil structure.

Similarly, soil porosity was positively correlated with both water holding capacity (ρ = 0.761, $p < 0.001$) and saturated hydraulic conductivity (ρ = 0.611, $p < 0.001$), emphasizing the critical role of pore volume and pore connectivity in regulating soil water storage and transmission. These findings agree with Botková et al. (2023) [26], and Deluz et al. (2025) [31], who reported that improvements in soil hydraulic behaviour are closely linked to increased macro- and mesopore development induced by biochar.

The superior performance of manure- and residue-derived biochar comes from its unique physicochemical properties. These biochars have higher ash and mineral content, lower particle density, and varied, interconnected pores. These features help the biochar form aggregates and create more macropores [9, 16, 29, 32]. However, it should be noted that some studies have reported variability in performance depending on soil texture and application rate, indicating that their effectiveness may be reduced in coarse-textured soils where water retention is already limited [9].

Residue-based biochar, in particular, has been shown to enhance macropore continuity and infiltration, especially in compacted soils, thereby improving both drainage and aeration [25, 33]. In agreement with these findings, the present study suggests that barley residue biochar was especially effective in improving hydraulic conductivity, likely due to its favourable pore network structure.

Manure-derived biochar further contributes oxides and carbonates that facilitate aggregate formation and reduce soil compaction, reinforcing its positive effects on porosity, hydraulic conductivity, and water retention [5, 27, 34]. Nevertheless, some authors have noted potential variability in nutrient composition depending on feedstock source and pyrolysis conditions, which may explain differences among manure biochars [34–36].

In contrast, woody biochar, although richer in carbon and more chemically stable, typically has smaller pore sizes and higher particle density. It tends to deliver more limited short-term improvements in soil structure and hydraulic properties [37–39]. However, its high aromatic carbon content contributes to long-term soil structural stability and carbon sequestration, benefits that become more important over longer time scales [40, 41]. This dual behaviour explains why woody biochar is often recommended for carbon management strategies rather than immediate soil physical improvement.

Overall, these findings emphasize the importance of matching biochar feedstock type to specific soil management objectives. Manure and residue-derived biochars are particularly effective for enhancing porosity, infiltration, drainage, and water retention in fine- or compacted-textured soils, whereas woody biochar may be more suitable for long-term carbon stabilization with moderate short-term physical effects. These improvements are interrelated and primarily driven by modifications to soil structure and pore architecture [13, 16, 25, 32,42].

Importantly, compared with previous studies that mainly focused on single feedstock types, this study provides a direct comparative evaluation of multiple biochar sources under the same experimental conditions, allowing clearer interpretation of feedstock-driven differences. Strategic selection of biochar feedstock and appropriate application rate can therefore maximize improvements in soil structure and water dynamics, supporting more sustainable and resilient soil management systems.

Effect of Biochar Rate on Soil Physical Properties

Higher biochar application rates consistently enhanced soil physical and hydraulic properties, as reflected by reduced bulk density and increased porosity, hydraulic conductivity, and water-holding capacity. Soils without biochar showed the poorest physical condition and lowest capacity to retain water, while low application rates produced only minor improvements. In contrast, moderate to high biochar rates led to substantial enhancements in soil structure and water retention, demonstrating a clear rate-dependent response consistent with previous findings [43, 44]. These studies similarly reported that biochar effectiveness increases with application rate up to an optimum threshold, beyond which benefits may plateau or decline.

Correlation analysis (Table 1) provides an important understanding of the mechanisms underlying these responses. the mechanisms underlying these responses. The strong negative association between biochar rate and soil bulk density confirms that increasing biochar application effectively reduces soil compaction. At the same time, positive relationships with porosity and water-holding capacity indicate that biochar-induced structural changes directly increase pore space and soil water storage. The strong relationship between bulk density and porosity further indicates that soil structural loosening improves soil physical quality. These results support the view that biochar primarily

Table 1. Spearman's correlation coefficients (ρ) among biochar application rate (% w/w), soil bulk density, soil porosity (%), water holding capacity (%), and saturated hydraulic conductivity (cm h^{-1})

	Biochar % (w/w)	Soil Bulk Density (g cm^{-3})	Soil porosity (%	K_s (cm hr^{-1})
Soil Bulk Density (g cm^{-3})	-0.851			
	0.000*			
Soil porosity (%)	0.761	-1.000		
	0.000*	0.000*		
K_s (cm hr^{-1})	0.358	-0.611	0.611	
	0.010*	0.000*	0.000*	
Soil water holding capacity	0.744	-0.809	0.761	0.541
	0.000*	0.000*	0.000*	0.000*

*Correlation is significant ($p < 0.05$)

influences soil water dynamics indirectly through modification of soil structure and pore architecture, rather than through direct water adsorption alone.

The observed reductions in bulk density and increases in porosity can be attributed to biochar's low particle density, high internal porosity, and its ability to promote soil aggregation. As reported in previous studies, biochar acts as a physical conditioner that partially replaces dense mineral particles and introduces additional intra- and inter-particle pore spaces within the soil matrix, thereby improving aeration and reducing compaction [42, 44].

At moderate application rates, improvements in saturated hydraulic conductivity were most pronounced, indicating enhanced pore connectivity and macropore continuity that facilitate water movement. However, the tendency of hydraulic conductivity to stabilize or slightly decline at high biochar rates suggests that excessive application may partially obstruct soil pores, particularly when fine biochar particles accumulate and reduce effective pore continuity. Similar limitations at high application rates have also been reported by Zhang et al. (2023) [5] and Acharya et al. (2024) [9], who emphasized that excessive biochar can lead to pore clogging and reduced hydraulic efficiency in some soil systems.

Overall, these results indicate that biochar application rate strongly influences soil physical properties and water movement, but the response is non-linear and rate-dependent. Moderate application rates (around 5% w/w in this study) appear to be most effective for improving soil porosity, water-holding capacity, and hydraulic conductivity, whereas excessively high rates may reduce pore connectivity or partially block flow pathways, limiting improvements in water transmission [5, 9].

When combined with low-density, mineral-rich feedstocks such as manure- and residue-derived biochars, moderate application rates provide a balanced enhancement of soil structure, water retention, and hydraulic performance [9, 46, 47]. These findings reinforce the importance of optimizing both biochar type and application rate to maximize soil physical benefits and support sustainable soil and water management strategies.

Conclusion

The results of this study indicate that biochar effects on soil physical and hydraulic properties are strongly governed by both feedstock type and application rate. Manure and crop residue derived biochars, particularly barley residue biochar, were the most effective in reducing bulk density and improving porosity, water retention, and saturated hydraulic conductivity, mainly due to their favourable pore structure. Optimal improvements were achieved at a moderate application rate (5% w/w), with higher additions showing limited further enhancement of hydraulic conductivity. This may be due to fine particle accumulation and reduced pore connectivity. These findings emphasize the importance of carefully selecting suitable biochar feedstock and application rate to improve soil structure and water flow in managed soils. Long term field studies across diverse soils and climatic conditions are recommended to assess the persistence of these improvements and further clarify the mechanisms of biochar-induced soil structural changes.

Author Contributions: "Eissa: Conceptualization and methodology, writing original draft preparation. Elzobair and Adda: review and editing. Eissa and Adda: Data collection, results analysis and discussion. All authors have read and agreed to the published version of the manuscript."

Funding: "This research received no external funding."

Data Availability: "The data are available from the corresponding author upon request."

Conflicts of Interest: "The authors declare no conflict of interest."

References

[1] S. Shyam, S. Ahmed, and H. Sarma. "Biochar as a Soil Amendment: Implications for Soil Health, Carbon Sequestration, and Climate Resilience." *Discover Soil*, vol. 2, no. 1, pp. 1-22, 2025. https://doi.org/10.1007/s44378-025-00041-8

[2] S. Ziadi, M. Oelbermann, and J. Whalen. "Biochar Amendments for Sustainable Soil Management." *Canadian Journal of Soil Science*, vol. 102, no. 1, pp. vii-viii, 2022. https://doi.org/10.1139/CJSS-2022-0006

[3] F. Marin, et al. "Biochar for Soil Fertility and Climate Mitigation: Review on Feedstocks, Pyrolysis Conditions, Functional Properties, and Applications with Emerging AI Integration." *Agriculture*, vol. 15, no. 22, pp. 2345, 2025. https://doi.org/10.3390/agriculture15222345

[4] T. Ding. "Sustainable Roles of Biochar in Carbon Sequestration and Climate Change Mitigation." *Applied and Computational Engineering*, vol. 180, no. 1, pp. 200-208, 2025. https://doi.org/10.54254/2755-2721/2026.ka27142

[5] C.-A. Zhang, X. Li, Y. Wang, and J. Liu. "Insight into the Soil Aggregate-Mediated Restoration Mechanism of Degraded Black Soil via Biochar Addition: Emphasizing the Driving Role of Core Microbial Communities and Nutrient Cycling." Environmental Research, vol. 228, no. 1, pp. 115895, 2023.

https://doi.org/10.1016/j.envres.2023.115895

[6] Z. Wang, D. Li, H. Jia, and W. Xu. "Biochar Application Influences the Stability of Soil Aggregates and Wheat Yields." *Plant, Soil and Environment*, vol. 70, no. 3, pp. 119-128, 2024. https://doi.org/10.17221/199/2023-pse

[7] F. Firdous, E. Mishra, A. Outhman, and S. Chandel. "Influence of Sewage Sludge Dose on Physicochemical Characteristics of Soil and Productivity of Radish (Raphanus sativus L.)." *Wadi Alshatti University Journal of Pure and Applied Sciences*, vol. 2, no. 2, pp. 6-15, 2024. https://www.waujpas.com/index.php/journal/article/view/68

[8] D. Robinson, et al. "Soil Porosity Prediction Across Europe with a Focus on Soil Particle Density Determination." *International Soil and Water Conservation Research*, vol. 14, no. 2, pp. 100614, 2026. https://doi.org/10.1016/j.iswcr.2026.100614

[9] B. S. Acharya, et al. "Biochar Impacts on Soil Water Dynamics: Knowns, Unknowns, and Research Directions." *Biochar*, vol. 6, no. 1, pp. 1-21, 2024. https://doi.org/10.1007/s42773-024-00323-4

[10] L. Cheng, W. Wang, Z. Yao, X. Liu, D. Zhao, and Y. Wang. "Naturally Deposited Charcoal Enhances Water Retention Capacity of Subtropical Forest Soils." *Forests*, vol. 15, no. 11, pp. 1939, 2024. https://doi.org/10.3390/f15111939

[11] S. Tenodi, S. Maletić, M. Kragulj Isakovski, J. Kruse, and L. Weihermüller. "Impact of Biochar, Compost, and Sludge Amendments on the Soil Water Balance of a Sandy Soil." *Biochar*, vol. 8, no. 1, pp. 1-15, 2026. https://doi.org/10.1007/s42773-025-00509-4

[12] H. Singh, B. Northup, C. Rice, and P. Prasad. "Biochar Applications Influence Soil Physical and Chemical Properties, Microbial Diversity, and Crop Productivity: A Meta-Analysis." *Biochar*, vol. 4, no. 1, pp. 1-17, 2022. https://doi.org/10.1007/s42773-022-00138-1

[13] P. Kuryntseva, K. Karamova, P. Galitskaya, S. Selivanovskaya, and G. Evtugyn. "Biochar Functions Depending on Feedstock." *Agriculture*, vol. 13, no. 10, pp. 2003, 2023. https://doi.org/10.3390/agriculture13102003

[14] S. Lu and Y. Zong. "Pore Structure of Biochars." *Environmental Science and Pollution Research*, vol. 25, no. 30, pp. 30401-30409, 2018. https://doi.org/10.1007/s11356-018-3018-7

[15] K. Jindo, H. Mizumoto, Y. Sawada, M. Monedero, and T. Sonoki. "Physical and Chemical Characterization of Biochars Derived from Different Agricultural Residues." *Biogeosciences*, vol. 11, no. 23, pp. 6613-6621, 2014. https://doi.org/10.5194/bg-11-6613-2014

[16] E. Dheenadhayalan, et al. "Characterisation of Biochar from Agricultural Residues." *Plant Science Today*, vol. 13, no. 1, pp. 1-10, 2026. https://doi.org/10.14719/pst.10352

[17] S. Dimitriadou, E. Isari, E. Grilla, P. Kokkinos, and I. Kalavrouziotis. "Revitalizing Degraded Soils: The Role of Biochar in Enhancing Soil Health and Productivity." *Environments*, vol. 12, no. 9, pp. 324, 2025. https://doi.org/10.3390/environments12090324

[18] V. Lund, R. Salvador, M. Eriksen, M. Hedegaard, and T. Knudby. "Biochar: A Versatile Outcome of Various Biomasses - Benefits and Challenges." *European Journal of Sustainable Development*, vol. 14, no. 3, pp. 225, 2025. https://doi.org/10.14207/ejsd.2025.v14n3p225

[19] G. Li, Y. Chen, X. Chen, B. Zhou, M. Duan, H. Zhu, and G. Shao. "Structural Heterogeneity of Biochar Modulates Soil Hydraulic Properties and Nutrient Migration." *Agronomy*, vol. 15, no. 8, pp. 1830, 2025. https://doi.org/10.3390/agronomy15081830

[20] J. Jabro, W. Stevens, and W. Iversen. "Comparing Two Methods for Measuring Soil Bulk Density and Moisture Content." *Open Journal of Soil Science*, vol. 10, no. 6, pp. 233-243, 2020. https://doi.org/10.4236/ojss.2020.106012

[21] M. Iwanek. "A Method for Measuring Saturated Hydraulic Conductivity in Anisotropic Soils." *Soil Science Society of America Journal*, vol. 72, no. 6, pp. 1527-1531, 2008. https://doi.org/10.2136/sssaj2007.0335

[22] D. Doherty. "Soil Analysis Method Including Saturation/Drying Test Using Undisturbed Core Sample." *U.S. Patent 5672814*, 1996.

[23] Minitab, LLC. *Getting Started with Minitab 19 for Windows*. State College, PA, USA, 2019.

[24] G. Fernandez. "Residual Analysis and Data Transformations: Important Tools in Statistical Analysis." *HortScience*, vol. 27, no. 4, pp. 297-300, 1992. https://doi.org/10.21273/HORTSCI.27.4.297

[25] S. Bhat, et al. "Application of Biochar for Improving Soil Properties: A Systematic Review." *Sustainability*, vol. 14, no. 17, pp. 11104, 2022. https://doi.org/10.3390/su141711104

[26] N. Botková, et al. "Impact of Biochar Particle Size and Feedstock Type on Hydro-Physical Properties of Sandy Soil." *Journal of Hydrology and Hydromechanics*, vol. 71, no. 4, pp. 1-12, 2023. https://doi.org/10.2478/johh-2023-0030

[27] B. Thapa, R. Awal, and A. Fares. "Improving Soil Health Through Manure and Biochar Amendments Under Climate-Smart Agriculture." *Soil Science Society of America Journal*, vol. 89, no. 5, pp. 1-15, 2025. https://doi.org/10.1002/saj2.70129

[28] S. Sapkota, B. Sharma, and R. Ghimire. "Enhancing Carbon Stability in Arid Soils Through Biochar Amendment: Insights from a Long-Term Soil Incubation Study." *Carbon Management*, vol. 16, no. 1, pp. 1-12, 2025. https://doi.org/10.1080/17583004.2025.2602999

[29] A. Alghamdi. "Biochar as a Potential Soil Additive for Improving Soil Physical Properties—A Review." *Arabian Journal of Geosciences*, vol. 11, no. 24, pp. 1-16, 2018. https://doi.org/10.1007/s12517-018-4056-7

[30] K. Tang. "Biochar Amendments for Soil Restoration: Impacts on Nutrient Dynamics and Microbial Activity." *Environments*, vol. 12, no. 11, pp. 425, 2025. https://doi.org/10.3390/environments12110425

[31] T. Wen, X. Chen, Y. Luo, L. Shao, and G. Niu. "Three-Dimensional Pore Structure Characteristics of Granite Residual Soil and Their Relationship with Hydraulic Properties Under Different Particle Gradation by X-Ray Computed Tomography." *Journal of Hydrology*, vol. 618, no. 1, pp. 129230, 2023. https://doi.org/10.1016/j.jhydrol.2023.129230

[32] S.-H. Jien. "Physical Characteristics of Biochars and Their Effects on Soil Physical Properties." In: *Biochar from Biomass and Waste, Elsevier*, pp. 21-35, 2019. https://doi.org/10.1016/B978-0-12-811729-3.00002-9

[33] S. Chowdhury, et al. "Improving Stormwater Infiltration with Biochar." *Journal of Environmental Management*, vol. 360, no. 1, pp. 121032, 2024. https://doi.org/10.1016/j.jenvman.2024.121032

[34] T. Rahman, A. Jim, J. Joardar, N. Sonia, M. Islam, and M. Halder. "Pig Manure Biochar Enhances Soil Organic Carbon, Aggregate Stability, and Microbial Biomass in the Clay Soil of Bangladesh." Plant Science Today, vol. 12, no. 2, pp. 1-10, 2025. https://doi.org/10.14719/pst.3760

[35] A. Freitas, V. Nair, and W. Harris. "Biochar as Influenced by Feedstock Variability: Implications and Opportunities for

Phosphorus Management." *Frontiers in Sustainable Food Systems*, vol. 4, no. 1, pp. 1-12, 2020. https://doi.org/10.3389/fsufs.2020.510982

[36] İ. Omotade, S. Momoh, B. Oluwafemi, and E. Agboola. "Comparative Analysis of Nutrients Composition in Biochar Produced from Different Feedstocks at Varying Pyrolysis Temperature." *Eurasian Journal of Environmental Research*, vol. 3, no. 2, pp. 64-70, 2020. https://doi.org/10.35208/ert.747833

[37] A. Ahmed, J. Kurian, S. Satyanarayana, and V. Raghavan. "Impact of Wood-Derived Biochar on the Hydraulic Characteristics of Compacted Soils." *International Agrophysics*, vol. 35, no. 2, pp. 167-177, 2021. https://doi.org/10.31545/intagr/135898

[38] J. Pranagal, P. Oleszczuk, D. Tomaszewska-Krojańska, P. Kraska, and K. Różyło. "Effect of Biochar Application on the Physical Properties of Haplic Podzol." *Soil & Tillage Research*, vol. 174, no. 1, pp. 92-103, 2017. https://doi.org/10.1016/j.still.2017.06.007

[39] L. Esmaeelnejad, M. Shorafa, M. Gorji, and S. Hosseini. "Impacts of Woody Biochar Particle Size on Porosity and Hydraulic Conductivity of Biochar-Soil Mixtures: An Incubation Study." Communications in Soil Science and Plant Analysis, vol. 48, no. 14, pp. 1710-1718, 2017. https://doi.org/10.1080/00103624.2017.1383414

[40] S. Li, W. Wei, and S. Liu. "Long-Term Organic Amendments Combined with Nitrogen Fertilization Regulates Soil Organic Carbon Sequestration in Calcareous Soil." *Agronomy*, vol. 13, no. 2, pp. 291, 2023. https://doi.org/10.3390/agronomy13020291

[41] J. Gamage, P. Voroney, A. Gillespie, A. Lo, and J. Longstaffe. "Evidence for the Formation of Fused Aromatic Ring Structures in an Organic Soil Profile in the Early Diagenesis." *Scientific Reports*, vol. 13, no. 1, pp. 1-12, 2023. https://doi.org/10.1038/s41598-023-39181-8

[42] R. Yoganivashini, et al. "Carbon Sequestration Potential of Biochar for Sustainable Agriculture." *Plant Science Today*, vol. 12, no. sp3, pp. 1-10, 2025. https://doi.org/10.14719/pst.8918

[43] C. Librici, et al. "Dose-Dependent Effects of Biochar on Soil Revealed by Fast Field-Cycling (FFC) NMR: From Molecular Water Dynamics to Soil Functionality." *Magnetic Resonance in Chemistry*, vol. 64, no. 3, pp. 349-364, 2026. https://doi.org/10.1002/mrc.70077

[44] M. Zachovalova, J. Šimečková, V. Vlček, S. Hejduk, and J. Jandak. "Effect of Biochar Application Rate on Physical and Hydro-Physical Properties of a Dystric Cambisol." *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis*, vol. 70, no. 1, pp. 19-29, 2022. https://doi.org/10.11118/actaun.2022.002

[45] L. Toková, D. Igaz, J. Horák, and E. Aydin. "Effect of Biochar Application and Re-Application on Soil Bulk Density, Porosity, Saturated Hydraulic Conductivity, Water Content and Soil Water Availability in a Silty Loam Haplic Luvisol." *Agronomy*, vol. 10, no. 7, pp. 1005, 2020. https://doi.org/10.3390/agronomy10071005

[46] M. Lebrun, M. Aguinaga, and Z. Zahid. "Manure–Biochar Blends Improve Soil Water Retention." *Soil Use and Management*, vol. 40, no. 4, pp. 1-12, 2024. https://doi.org/10.1111/sum.13135

[47] S. Mensah, A. Simpson, and E. Sabi. "Impact of Biochar Application on Soil Physical and Biogeochemical Characteristics: A Review." *Applied and Environmental Soil Science*, vol. 2025, no. 1, pp. 1-12, 2025. https://doi.org/10.1155/aess/3734167