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ORIGINAL PAPER

Effect of Different Types of Biochar Amendment on Hydraulic Conductivity of Fine-Grained Soils

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Abstract

Biochar has emerged as a promising sustainable soil amendment due to its potential to improve soil structure and enhance stormwater management. However, its effects on saturated hydraulic conductivity (Ksat) and unsaturated hydraulic conductivity (Kunsat) at high suction ranges (i.e., around 100 kPa) remain inconsistent due to variations in biochar properties. This study investigates the influence of nine commercially available wood-based biochars, applied at 3% and 6% rates, on two different fine-grained soils. Laboratory tests included determination of index properties, scanning electron microscopy (SEM), Ksat, and Kunsat of biochar soil mixtures. Ksat was measured using a falling head permeameter, and Kunsat was evaluated through evaporation tests. SEM analysis revealed varied surface structures and pore formations among the biochars, which indicate differences in feedstock characteristics. Results showed that biochar application, especially at 6% reduced bulk density, increased porosity, and improved Ksat and Kunsat in the biochar soil mixtures. Among the biochars tested, three types (Biochar Now Medium, Biochar Now Small, and Char Bliss) were most effective in increasing Ksat for both soils, while certain biochars (Blue Sky and The Anderson) exhibited limited or negligible effects. The primary influencing factors were soil type, biochar type, and application rate. Overall, these findings highlight the potential of biochar amendments to enhance soil infiltration and water retention, which offers practical benefits for managing stormwater runoff in fine-grained soils.

Keywords Biochar · Bulk density · Porosity · Saturated and unsaturated hydraulic conductivity

Background

Biochar is a carbon-rich, highly porous organic material produced through the thermal processing of biomass under limited or no oxygen and can be amended with soil to potentially improve soil health and promote plant growth [1, 2]. Due to its multifunctional characteristics, biochar has the potential for engineered media application, which includes stormwater biofilters, landfill covers, water retention, and infiltration [3–5]. When mixed with soil, it can impact porosity, bulk density, and particle size distribution parameters that directly influence soil hydraulic properties. The functional performance of biochar-soil mixture is mainly governed by properties such as porosity, structural arrangement, carbon content, pH, and surface area, which govern the performance [6–9]. These interactions affect the formation of intra- and inter-particle pores within the Biochar soil matrix, which mainly depends on biochar-soil particle size, and the amount of compaction [10]. The porous nature of biochar results in improved soil structure, which results in

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enhanced total porosity and water retention capacity [11]. A comprehensive review by Blanco-Canqui [11] reported that biochar amendment typically reduces bulk density with an average of 9.2% observed with fine-grained soils. Whereas porosity tends to increase with biochar dosage, with reported average improvements of up to 8.4%.

Biochar feedstock (e.g. softwood, hardwood, sewage sludge, etc.) and production conditions (temperature, oxygen, reactor type, heating time, and rate) govern the properties of biochar [12–14]. Various physical properties of soil, such as pore size distribution, porosity, soil density, soil moisture content, water holding capacity, total porosity, carbon sequestration, nutrient retention, contaminant immobilization, and hydraulic conductivity, can be improved by using biochar in the soil [10, 15]. Ksat is a soil hydraulic property used to evaluate soil drainage and water infiltration capacity [16], and largely depends on soil structure [17]. One of the concerned areas is urban soil, where heavy compaction is given to the soil for load-bearing requirements, leading to poor drainage, filtration of stormwater runoff, and storage. This results in degraded natural soil structure and function, such as infiltration [18–21], and increased stormwater runoff, which causes soil erosion and an altered ecosystem [22], leading to altered hydraulic, vegetative, and physical properties of the roadside soils that cause increased soil bulk density and resistance to root penetration and reduced porosity [23]. Various studies have found that biochar-amended soil can potentially affect the saturated hydraulic conductivity through aggregate stability and changed pore distribution [6, 11, 24]. Studies have found that biochar amendment can increase or decrease the Ksat based on the type of soil, amount, and type of biochar [25, 26]. For example, Hussain et al. [27] found that biochar application of 5% and 10% could increase the saturated volumetric water content by 20–30% in silty sand. The laboratory-conducted data from the study of Lu et al. [28] shows that rice husk biochar improves the expansive clayey soil structure, increases water holding capacity, and has higher available water content when applied in the range of 2–6%. Another study conducted by Bagarello et al. [29] with 1–5% found that the addition of biochar improves soil water transmitting capacity, especially at higher biochar dosage. Several other studies have also reported enhanced Ksat when biochar was applied to the soil [30, 31]. The study of Blanco-Canqui [11] highlights that when biochar is mixed with fine-grained soils such as loam, clay loam, or silty clay loam increases average Ksat by 98%. Studies have also reported reduced or no effect on Ksat in biochar-applied soils [11, 32, 33]. The Kunsat of soil can be defined as the relationship between soil hydraulic conductivity and soil suction or water content [34]. Previous studies have found that the Kunsat effect of biochar is soil-dependent. The study by Wanniarachchi et al. [35] found a reduced effect in loose agricultural loam sand soil. Whereas Villagra-Mendoza and Horn's [36] study showed an increment in Kunsat of sandy loam soil at 2.5% and 5% biochar content; however, no change in silty loam soil at the lower suction range. The study of Kameyama et al. [37] found that the addition of 5% and 10% biochar to the soil results in increased unsaturated hydraulic conductivity.

There remains a lack of systematic research comparing the effects of commercially available biochar types with fine-grained soils under controlled conditions. Research has been done in recent years on agricultural soils [27]. The effects of lower amendment rates (3–6% in this study) across different biochar types on regional soils are rarely studied for geo-environmental applications. These soils are often compacted to achieve structural stability and are subjected to varying weather conditions, including extended dry periods. Biochar amendment can help retain and supply moisture to plants during such dry conditions. The saturated and unsaturated hydraulic conductivity of biochar-amended soil needs to be investigated for potential application to bioengineered soils.

The effect of biochar amendment on soil hydraulic properties is a complex interaction, and the current study addresses these gaps by investigating nine different wood-based biochars of different particle sizes and lower biochar doses amended with two regional fine-grained soils. Both saturated and unsaturated hydraulic conductivities are assessed alongside bulk density, porosity, and SEM analysis. These results will support the selection of appropriate biochar types and dosages for use in different geotechnical applications, especially to improve infiltration in engineered soils in urban areas.

Materials and Methods

Materials

Soil and Biochar

Two different types of soils (NC-X, NC-Y) are used in this study, which are predominantly found in the Piedmont of North Carolina. Soil characterisation shows NC-X and NC-Y as low plasticity clay (CL) and low plasticity silt (ML) soils, respectively, based on the Unified Soil Classification System (USCS). The soils were oven-dried and sieved through a 4.75 mm (#4) standard sieve in the laboratory before the testing. Particle sizes larger than 4.75 mm were discarded to avoid inconsistency in the Ksat measurements. The particle size distribution of NC-X, shown in SI (Fig. 1) and SI (Table 1) below, summarizes the properties of both soil samples. All nine biochars (Wake Field (WF),

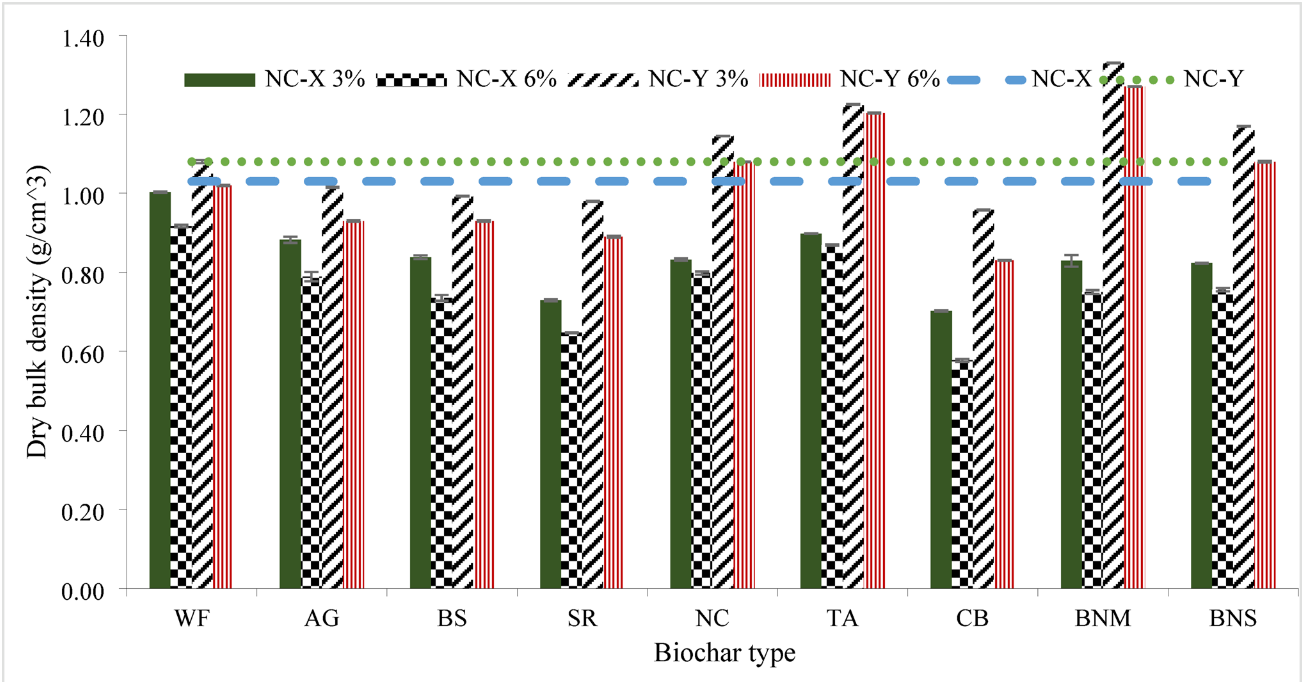

Fig. 1 Dry bulk density of the biochar with the soils at 3% and 6% by weight of the soil

Table 1 Carbon content of biochar and soil

Biochar	Carbon content %
Wake field (WF)	82.4
Aries green (AG)	93.6
Blue sky (BS)	87.1
Soil reef (SR)	88.8
Naked char (NC)	88.6
The Anderson (TA)	81.3
Char bliss (CB)	90.8
Biochar now chip (BNC)	87.1
Biochar now medium (BNM)	87.1
NC-X	38.0
NC-Y	64.7

Aries Green (AG), Blue Sky (BS), Soil Reef (SR), Naked Char (NC), The Anderson (TA), Char Bliss (CB), Biochar Now Medium (BNM), Biochar Now Small (BNS)) used in this study were derived from wood-based feedstocks, including pine, softwood, and wood chips are summarized in SI (Table 2). Biochars were selected based on their suitability for practical implementation and large-scale application from the outcome of this study. The particle size and density of the tested biochar are different. The D50 is the particle size at which 50% of the particles are finer (i.e., pass through).

Biochar Soil Amendment

In all experimental procedures, based on literature, 3% and 6% biochar were used by weight of the soil, which balances performance gains against cost and mixing effort. The soil and biochar were thoroughly mixed in the lab to ensure homogeneity and consistency across all samples. To reflect the practical feasibility of large-scale application of biochar, this study used a slightly lower percentage of biochar amendment, particularly in the context of roadside soils where biochar could be applied over vast areas.

Physical Properties of the Testing Materials – (Porosity - Bulk Density, Pycnometer Density)

All the biochar and soil samples were oven-dried at 105 °C until a constant weight of the sample was achieved to remove moisture affecting compaction and hydraulic behaviour. Sieve analysis of biochar and soil samples was done by following the standard ASTM D6913/D6913M-17. While the particles smaller than 0.075 mm were analyzed through hydrometer analysis by following ASTM D7928–21. Pycnometer density of biochar and soil samples was conducted for particles smaller than 4.75 mm by following ASTM C136/C136M – 19. The bulk density of all the samples was measured by following ASTM D7263–21 while slightly modifying the procedure. A graduated cylinder of 250 ml with 25 cm height was used, in which the mixture was filled in three layers and compacted under its own weight for a total of 50 times. This simulates light field compaction, such as roadside topsoil, and prevents the crushing of biochar particles or soils used for Best Management Practices (BMPs). The recorded weight and volume were used to calculate the bulk density. Finally, the porosity of the mixture was calculated by using the bulk density and the Pycnometer density of samples, based on Eq. 1 [38].

$$Porosity = 1 - \frac{Dry\ bulk\ density}{Pycnometer\ density} \quad (1)$$

Measurement of Saturated and Unsaturated Hydraulic Conductivity (Ksat & Kunsat)

Ksat was carried out in triplicate by using Ksat® equipment (METER Group, Pullman, WA, USA). Biochar and soil samples were homogenously mixed before the sample preparation to achieve consistency. The control and biochar amended soil samples were prepared by filling the mixture into a standard sampling in three layers and self-weight compaction of 50 times on it. Then the samples were saturated overnight in deionized (DI) water by following the manufacturer's protocol. Finally, Deaired DI water was used to measure the Ksat from the Ksat instrument by the Meter group. The standard protocol provided by the Meter Group was followed for the sample testing. The Ksat device was used to measure Ksat based on Darcy's law using a fully saturated sample by the automated falling head method (ASTM D2434). Then the same sample was transferred to the HYPROP system to measure Kunsat, which assumes negligible volume change during measurement, and derive the soil moisture retention curve. Water content available at a matric potential of -1500 kPa is referred to as the permanent wilting point, the point where no moisture is available for the plants [39]. Kunsat of the samples was analyzed at -100 kPa, which is a comfortable range for most of the plants [40]. It should be noted that soil shrinkage was not explicitly measured in this study, which may introduce some uncertainty due to shrinkage in the estimation of unsaturated hydraulic conductivity. The results of Kunsat were analyzed with HYPROP-FIT (METER group) software.

Surface Morphology Analysis

Scanning electron microscopy (SEM-EDX) was used to carry out surface morphology analysis of biochar and soil samples separately by using a JEOL model 6460LV. Where a small amount of dried biochar and soil samples were adhered to the surface of conductive double-sided tape. Finally, the sample was fixed with the sprayed gold. A random surface part of the biochar samples was observed by operating the SEM multiple times. The selected surface was scanned and photographed for further analysis.

Results and Discussion

Soil Bulk Density

The bulk density of soil is a good indicator of soil health and compaction. The effect of nine different biochar applications at 3% and 6% on the bulk density of both soil types is summarized in Fig. 1. The data show that 6% biochar has a comparatively lower bulk density than 3% biochar. Most of the biochar applications showed lower dry bulk density than the control samples due to biochar's lower density and high porosity, reducing overall mixture density. Whereas NC, TA, BNM, and BNS showed no effect or higher bulk density with NC-Y. NC-X comparatively showed lower dry bulk density than NC-Y, as the particle size was larger. Previous studies have found that different types of biochar and application rates can significantly affect the bulk density of the soil, which aligns with the results of this study. For example, the study by Głąb et al. [41] found that up to a 35% reduction in bulk density of loamy sand was achieved by applying 4% biochar. Also, the bulk density was reduced by 3% in clay loam soil with the addition of 1% biochar [42]. The difference in bulk density, even with the same percentage of biochar, could be due to the type of soil and pyrolysis temperature Herath et al. [30], where they found a 7% and 11% reduction in bulk density with the same biochar produced at 350 °C and 550 °C, respectively. Blanco-Canqui [11] found that biochar application reduces bulk density from 3% to 31%. Whereas, the study of Castellinia et al. [43] found no effect of biochar in clay soil at 1% and 3% application.

Porosity

In contrast to bulk density, biochar application increases the porosity of soil samples. The effect of biochar on soil porosity has been summarized in Fig. 2. Each biochar showed increased porosity with the NC-X and NC-Y, except for TA, BNM, and BNS, with NC-Y either showing no effect or lower porosity. Soil type and texture can alter the porosity of the soil, and usually coarse-textured soil comparatively exhibits higher porosity than fine-textured soils. This confirms the fact that coarse-textured soil (NC-X) shows higher porosity than fine-textured soil (NC-Y). The three mechanisms proposed by Hardie et al. [10] for the increased porosity with biochar application include modification of the pore system by creating more pores, aggregate stability, and pore contribution from biochar with high porosity. A higher application rate of biochar results in increased porosity of the soil, and Fig. 2 shows that 6% biochar content comparatively showed higher porosity than 3% biochar. The increased porosity of the soil highly benefits the productivity of the soil as it affects its hydraulic properties, and it

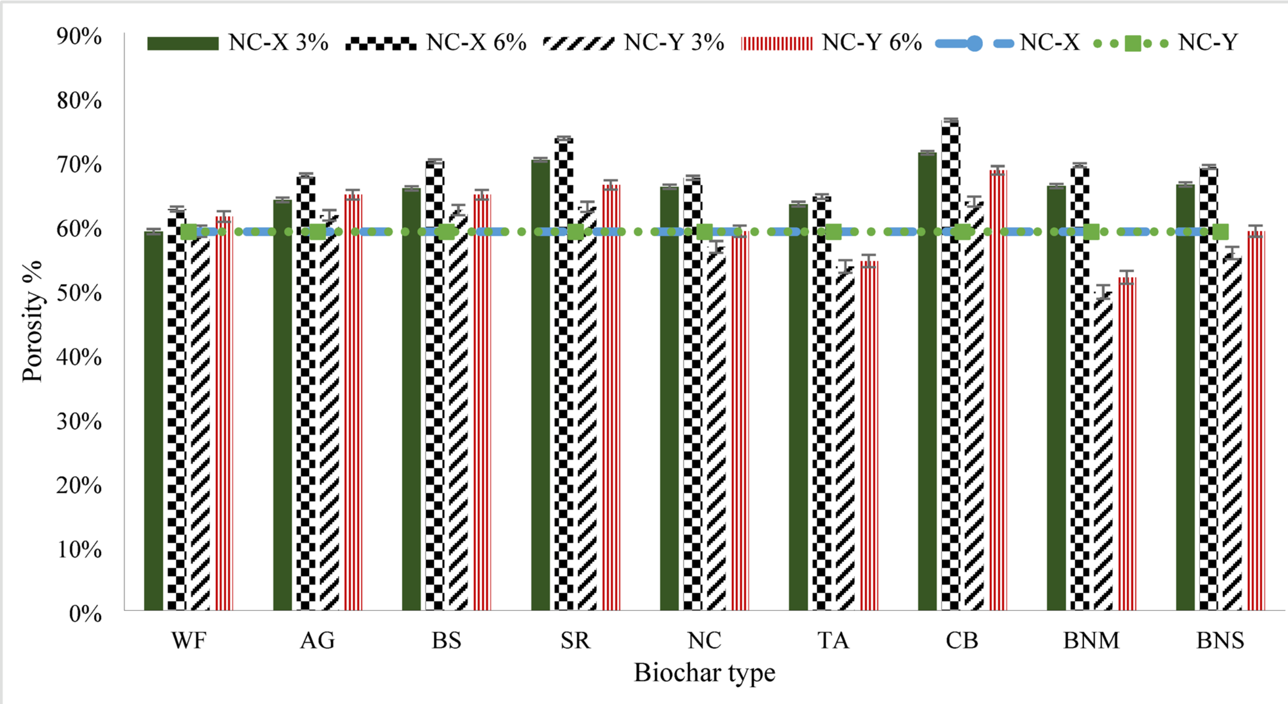

Fig. 2 Porosity of the biochar soil mixture at 3% and 6% biochar content (porosity of NC-X and NC-Y is almost the same)

can help in root growth and microbial activity. These results align with existing literature indicating that higher application rates of biochar can have more pronounced effects on soil properties. For example, the study by Blanco-Canqui [11] shows that biochar application can increase porosity from 14% to 64% by using biochar in the soil. Various other studies have also reported similar findings where biochar improves the porosity of the soil [44, 45]. Ksat and Kunsat are mainly governed by the porosity of the soil [46].

Saturated Hydraulic Conductivity (Ksat)

The addition of biochar to the soil can increase, decrease, or even have no effect on the saturated hydraulic conductivity of the soil. This study has found a similar effect of biochar amendment on soil, and they are summarized in (Fig. 3) and (Fig. 4). Both figures show that the addition of biochar improves Ksat of biochar soil mixture, where 6% biochar amendment significantly ($P < 0.05$) showed better performance than 3%. Figure 3 shows the performance of NC-X, which has comparatively larger particle sizes than NC-Y, where all the biochars increased the Ksat except BS. A similar trend was seen in NC-Y (Fig. 4), where only TA biochar has a reduced effect on Ksat than the control sample. Statistical analysis shows a significant difference ($P < 0.05$) in the Ksat of both soils, where the control Ksat of NC-X is 6.410 cm/hr, which is significantly higher than the 0.147 cm/hr of NC-Y. The improvement with biochar amendment can be attributed to its highly porous structure and low bulk density. Biochars introduce macropores and increase pore connectivity, which facilitates easier flow within the matrix and improves infiltration [47]. SR, CB, and BNM biochars particularly showed enhanced porosity, which is also reflected in the Ksat results, as they showed comparatively better infiltration capacity than others. The porous nature of biochar is further confirmed by SEM analysis, where well-developed, structured pores are observed in biochars like BNM and BNS, which correlates with the improved Ksat found in this study.

The Ksat captures infiltration capacity of biochar samples under saturation during storm events, which is critical for hydrological applications such as stormwater infiltration or retention. Where infiltration of water is primarily controlled by macropores (pores within biochar), that is also known as transmission pores and interpores (pores between biochar and soil particles). The higher the number of these pores, the greater the hydraulic conductivity, as the resistance of the pores will be reduced, which will result in increased flow [48]. The study by Wong et al. [49] found that adding the biochar of 20% by weight of highly compacted Kaolin clay soil resulted in an increment of one magnitude in the saturated hydraulic conductivity of the soil. Another study conducted by Sun et al. [50] with 10%, 15%, and 20% biochar found increased saturated hydraulic conductivity in clay soil. A 29% increase in saturated hydraulic conductivity was observed when 10% biochar was added to the soil

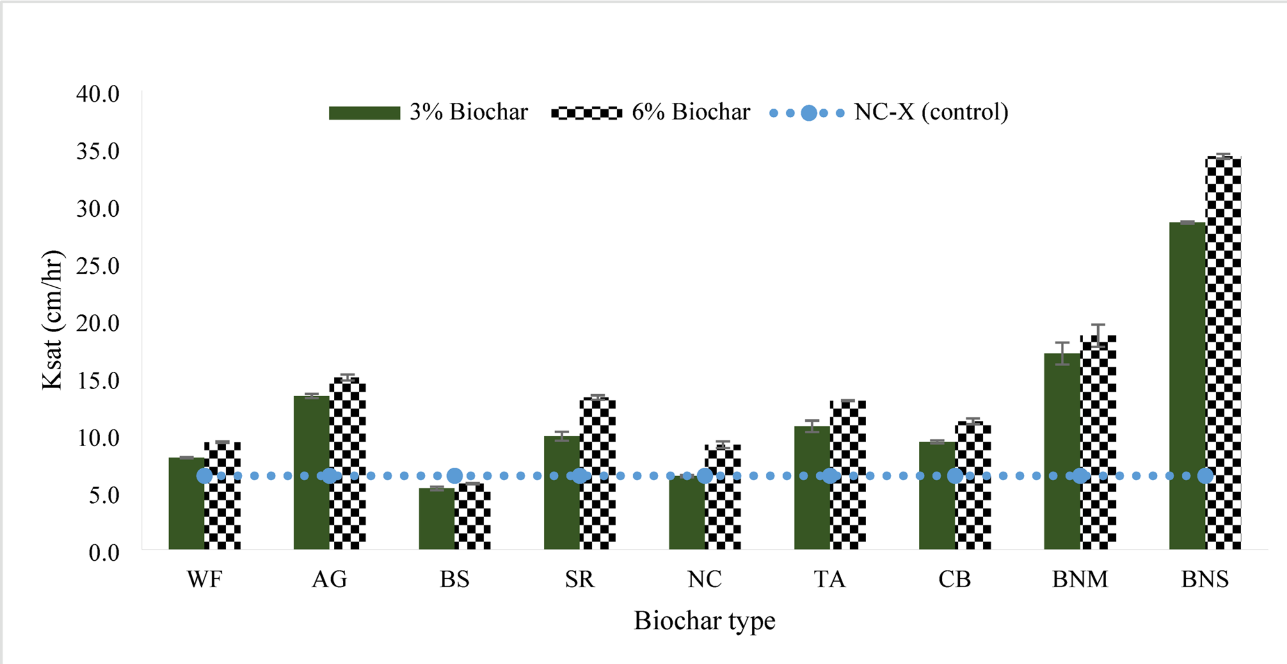

Fig. 3 Effect of biochar on saturated hydraulic conductivity with NC-X

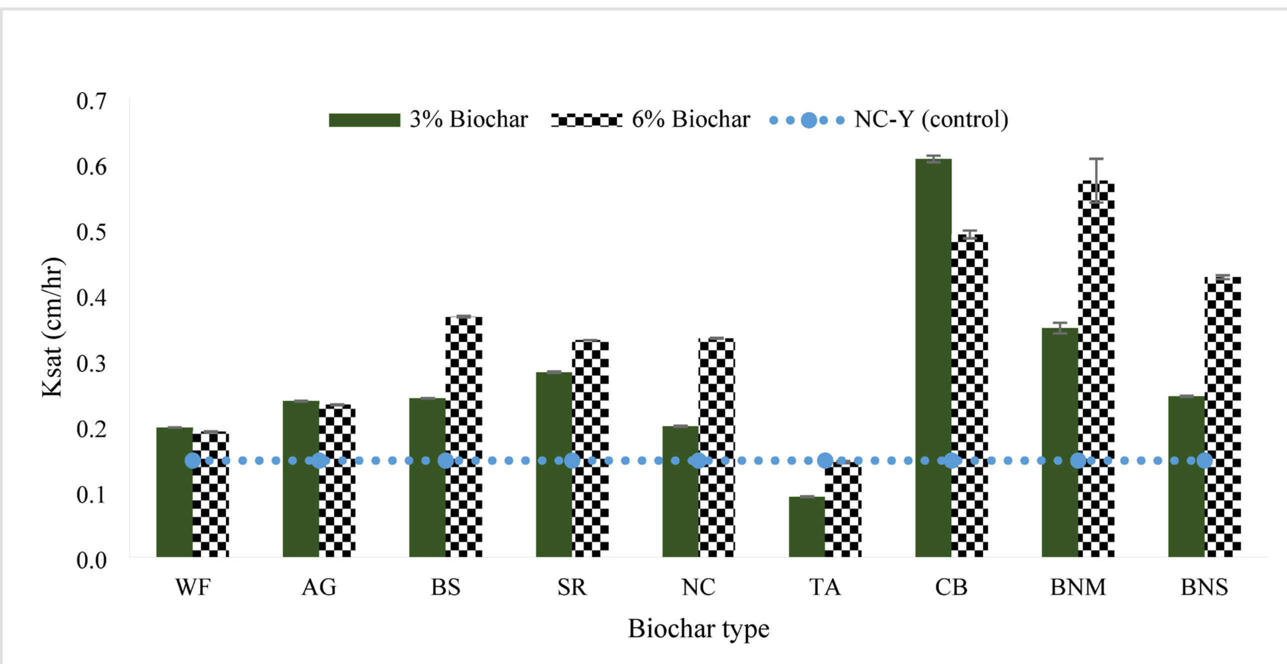

Fig. 4 Effect of biochar on saturated hydraulic conductivity with NC-Y

[51]. On average, the Ksat was increased by 328% in clay-rich soil when biochar was amended with 10% by weight of the soil [52]. The study by Villagra-Mendoza et al. [36] and Alghamdi A.G [53]). found that biochar addition increases the water flow during unsaturated conditions.

Unsaturated Hydraulic Conductivity (Kunsat)

The variation of Kunsat with the different biochar is highlighted in SI (Fig. 2) and (Fig. 3) for NC-X and NC-Y, i.e., the hydraulic conductivity function of both the soils and soils amended with 3% and 6% biochar under drying as well as wetting conditions. Where Kunsat represents flow

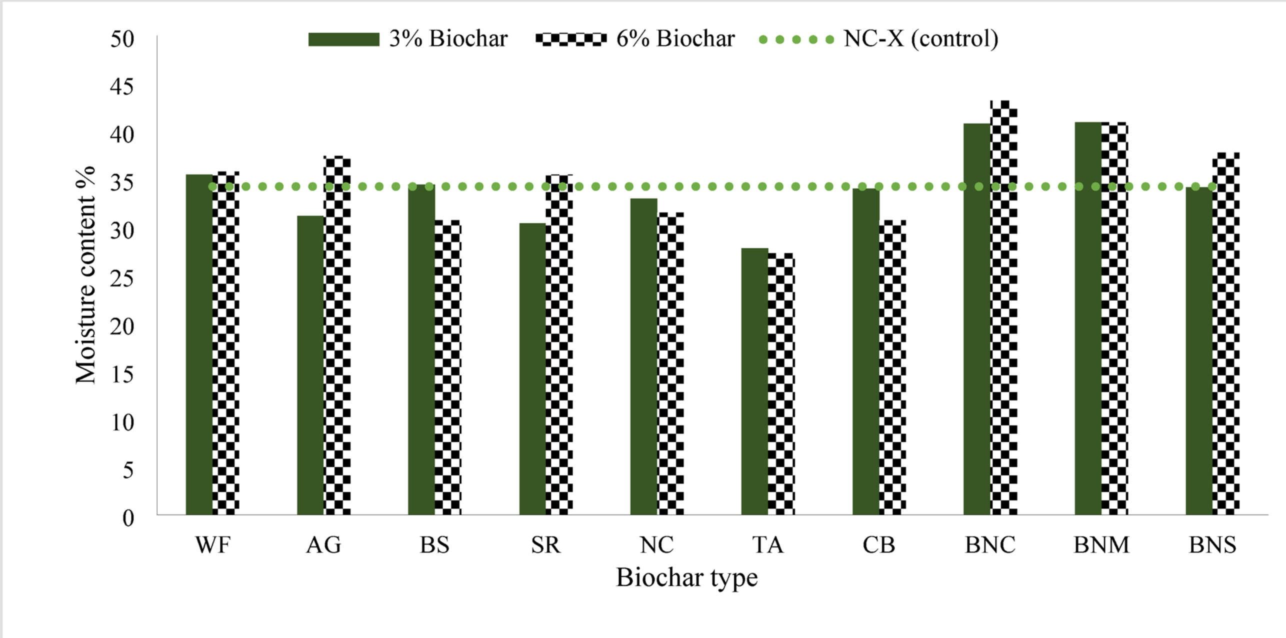

Fig. 5 Moisture content of biochar at 3% and 6% with NC-X

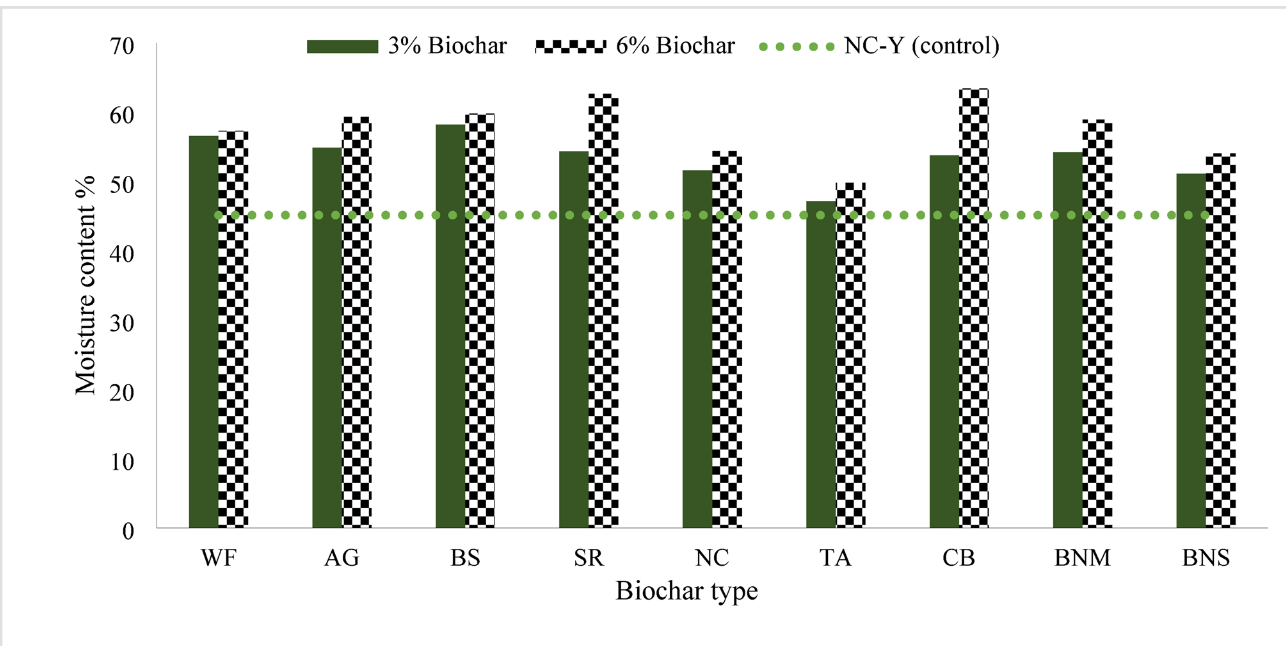

Fig. 6 Moisture content of biochar at 3% and 6% with NC-Y

under unsaturated conditions, which is critical for geotechnical applications such as moisture retention for vegetation. With the increase in suction pressure, the Kunsat reduced in both soils. It has been found that the biochar application increased the Kunsat at a high suction pressure of 100 kPa in both soils and higher biochar content showed higher Kunsat with the majority of the biochar, as shown in (Fig. 5) and (Fig. 6). This can be attributed to the increased pore connectivity and water retention capacities of biochar amendment to soils. The porous structure of biochar adds more micro-pores and mesopores that help in water transmission under unsaturated conditions. This is further explained by SEM analysis that biochar with more defined pore networks improved the continuity of water flow within the biochar soil matrix. However, as the suction pressure increases with time, the biochar dries up more quickly than the control sample, and the performance of both soils was found to be very similar, which can be found in Figs. 2 and 3 of the Supplementary Materials. The reduced Kunsat observed in the biochar-amended soils may also be attributed to changes in pore-size distribution, pore connectivity, and water-retention behavior. It can be inferred from the plotted results that at lower suction pressure, the Kunsat was found to be higher than the soil. In field applications where plants can use available moisture comfortably, which is around 100 kPa, biochar would be effective in providing comparatively higher Kunsat.

Considering the type of soil tested, NC-Y exhibited higher Kunsat as compared to NC-X due to the pronounced effect of biochar, as the soil has lower organic content, especially with CB, BNM, and BNS biochars. Several studies have explored the influence of biochar on Kunsat [35–37]. However, due to variations in biochar type, content, and soil properties, a comprehensive study is still needed to establish a clearer understanding. The results from this study show that most of the biochar amendments resulted in higher Kunsat compared to the control samples with all the biochar for NC-Y soil at both application rates. Whereas BS, TA, and CB biochar did not show improvement for NC-X soil. Moreover, the evaluated result showed that 6% biochar applications were found to have higher Kunsat at lower suction pressure. This also follows the fitted results. Whereas, mixed results were observed with NC-X and NC-Y towards the higher suction pressure (drying stage).

Electron Microscopy Analysis of Biochar

The SEM provides the real, three-dimensional, and high-resolution structure of the biochar [10]. The SEM photographs of all the biochar samples are shown in (Fig. 7) and the soil samples in (Fig. 8). It has been found that the surface structure of each biochar differs, as well as the number of surface pores and mesh formation. The difference in each biochar could be attributed to the fact that the feedstock of each biochar is different, and also to the production temperature. The current study correlated SEM-EDX analysis with the Ksat and Kunsat.

A large number of macropores on all the biochar surfaces can be seen except the TA biochar and soil samples, which do not show the presence of cell walls as well as macropores. While most of the biochar shows cracks on the surface and profile, BS and BNS do not show any sign of cracks. Only WF biochar was found to have a disorder of the pore structure; the rest of the biochar showed stratification and

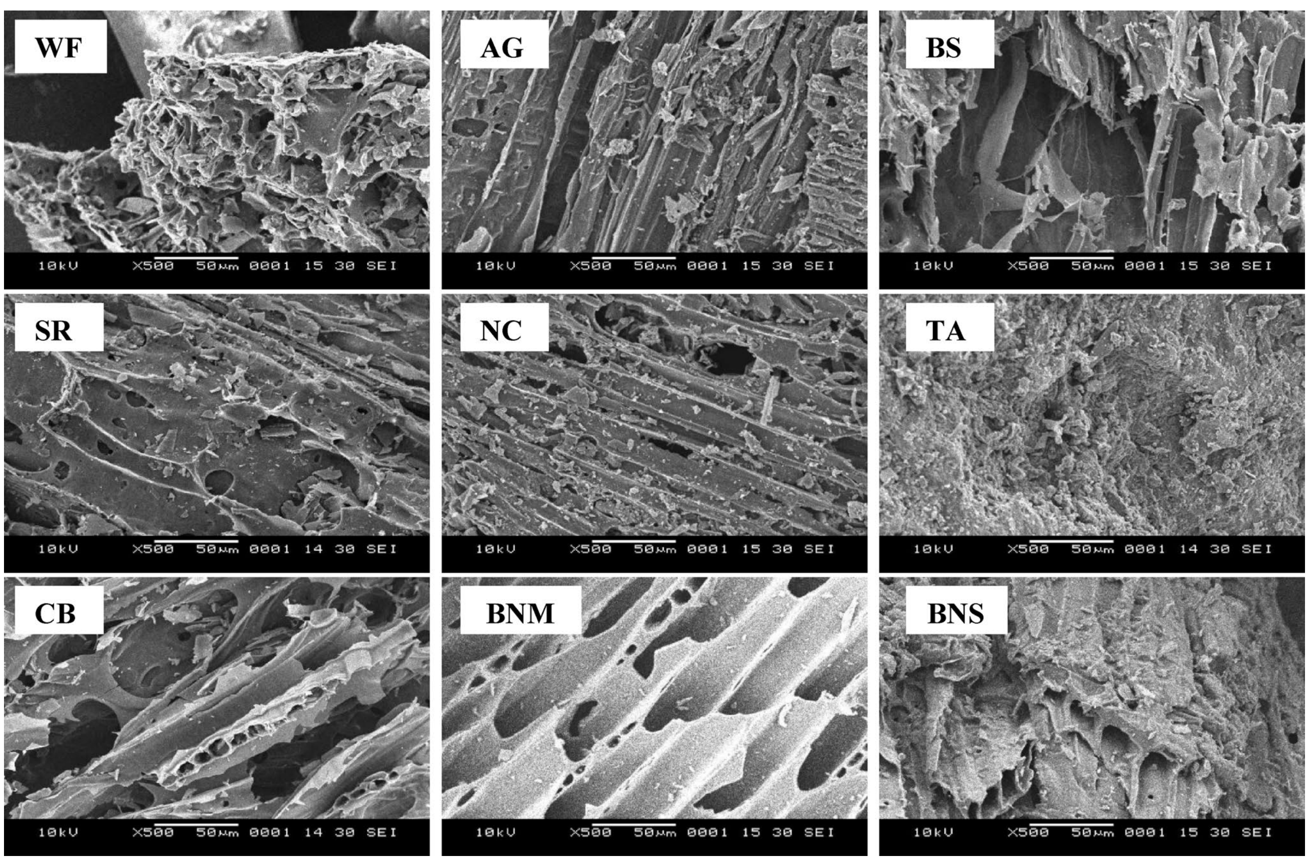

Fig. 7 Scanning electron microscope of the biochar particles with scale bar on each panel. The images of all biochar were recorded at 10 kV current probe, with identical magnification of each pair

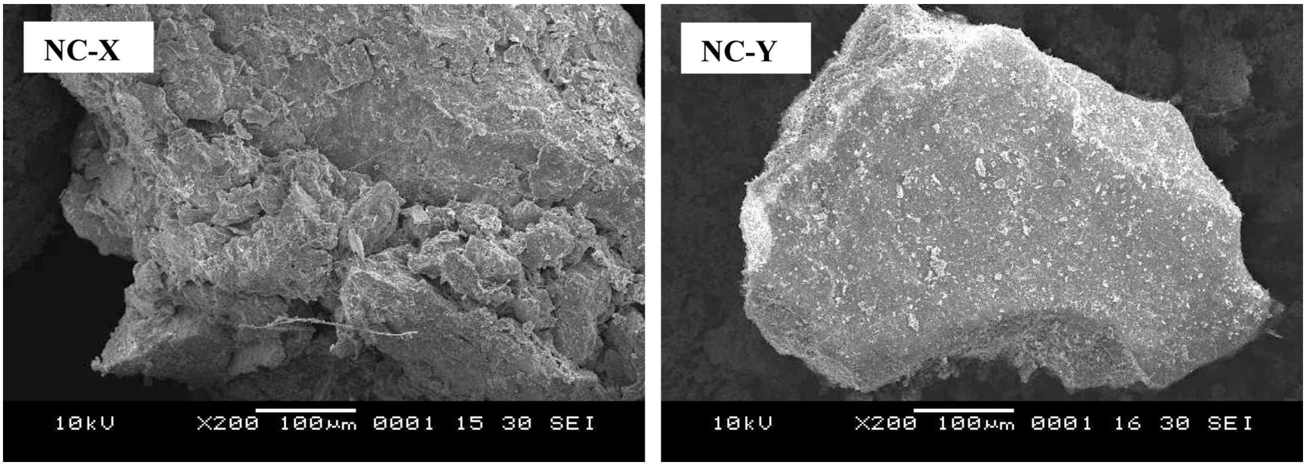

Fig. 8 Scanning electron microscope of both soils' particles with the scale bar on each panel. The images of both soils were recorded at a 10 kV current probe, with identical magnification of each pair

a similar order of the pore structure. The study of Ma et al. ([54]) found ubiquitous biochar cracks, and this study found the same with most of the biochar; however, BS and BNS had the least pore cracks. Intense water flux can be facilitated with macropores through their inner caliber, resulting in a higher infiltration rate of the water, which has been found with the Ksat test results [55]. This research found that the SEM method might not be efficient in finding the different elements of the biochar. However, with the help of EDX, the carbon (C) of biochar was analyzed and is summarized in Table 1. Where the carbon content of biochar is significantly ($P < 0.05$) higher than that of soil samples.

The Applicability and Limitations of This Research

It would be difficult to compare the laboratory findings of this study with the field experiments, as a standard laboratory protocol was followed, where soil samples were homogeneously mixed and packed. Also, the tests did not consider the interaction of the soil with the surroundings and long-term field behavior. For example, the swelling effects of the soil in the field conditions would be different than lab conditions; it is restricted by the plates and walls of the sampling ring. Moreover, compared to lab conditions, homogenous biochar soil mixture application would be impossible [56]. Mechanical tillage will help achieve homogeneous biochar application. The effects of individual biochar properties were not evaluated separately; therefore, the observed hydraulic responses should be interpreted as the combined effect of multiple biochar characteristics. Overall, the available studies show that the application of biochar to fine-grained soil usually improves the Ksat properties of the soil. However, the efficiency greatly varies with the biochar type, application rate, and soil type. The long-term impact of biochar still needs to be explored, especially in the field of applied biochar.

Conclusions

This study investigated the effect of biochar application on bulk density, porosity, and both Ksat and Kunsat of two distinct soils. The results highlight that biochar performance varies significantly depending on biochar type, application rate, and soil type. Overall, most biochars improved soil properties, with 6% application consistently showing better performance than 3%. The effects of biochars were more pronounced in the coarser soil (NC-X), where reductions in bulk density and increases in porosity were observed. The findings also demonstrate substantial enhancement in hydraulic conductivity; however, variations exist depending on biochar characteristics. These results emphasize the importance of selecting appropriate biochar types and application rates for optimizing soil performance.

- Biochar amendment reduced bulk density by up to 28% and increased porosity by up to 36%, with more pronounced effects in NC-X soil.
- Application of 6% biochar consistently performed better than 3% across most measured properties.
- Ksat improved by up to 5-fold in NC-X and over 4-fold in NC-Y soils, whereas Kunsat increased by up to 26% (NC-X) and 40% (NC-Y).
- Biochar performance varied by biochar type, where BNM, BNS, and CB showed better improvements, while TA biochar showed limited effects.
- Differences in pore structure and morphology observed through SEM analysis were qualitatively associated with variations in hydraulic behavior among the biochars.

This research contributes valuable insights into the potential of biochar as a filter medium to improve soil properties and address issues such as poor drainage and soil compaction. Moreover, the study acknowledged the complexity of the interaction between biochar and soil, emphasizing the need for further exploration of the long-term impacts of biochar amendments, especially in field conditions. The results emphasize the importance of considering biochar type and application rate for fine-grained soils in optimizing the efficacy of biochar amendments for sustainable soil management.

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Author contributions Mohammad Khalid: Conceptualization, Methodology, Formal Analysis, Data Curation, Visualization, Writing – original draft.Michael Unduebor: Conceptualization, Methodology, Formal Analysis, Review – review andediting.Jacelyn Rice-Boayue: Conceptualization, Resources, Project Administration, Fundingacquisition, Writing – Review and Editing.Mariya Munir: Conceptualization, Resources, Supervision, Project Administration, Fundingacquisition, Writing –Review and Editing.

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Data Availability Some or all data, models, or code that support the findings of this study are available from thecorresponding author upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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