Biochar

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Evaluating mechanism and inconsistencies in hydraulic conductivity of unsaturated soil using newly proposed biochar conductivity factor

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Abstract

In the past few decades, numerous studies have been conducted to promote the use of biochar as a soil amendment and most recently, for compacted geo-engineered soils. In general, the definite trends of biochar effects on water retention and fertility of soils have been confirmed. However, the biochar effects on hydraulic conductivity, particularly unsaturated hydraulic conductivity of soil-biochar mix remain unclear, making it difficult to understand water seepage in both agricultural and geo-engineered infrastructures in semi-arid regions. This study examines the unsaturated hydraulic conductivity function derived based on the measurements of soil water characteristic curves of soil with biochar contents of 0%, 5% and 10%. A new parameter "*biochar conductivity factor* (BCF)" is proposed to evaluate the inconsistency in reported biochar effects on soil hydraulic conductivity and to interpret it from various mechanisms (inter- and intra- pore space filling, cracking, aggregation, bio-film formation and piping/internal erosion). The impact of biochar content on unsaturated hydraulic conductivity appears to reduce as the soil becomes drier with minimal effect in residual zone. Qualitative comparison of near-saturated hydraulic conductivity with test results in the literature showed that the BCF is generally higher for smaller ratio of sand to fine content (clay and silt). Moreover, the particle size of biochar may have significant influence on soil permeability. Future scope of research has been highlighted with respect to biochar production for its applications in agriculture and geo-environmental engineering. Long term effects such as root decay and growth, aggregation and nutrient supply need to be considered.

Highlights

1. New biochar conductivity factor (BCF) is defined to explore hydraulic conductivity of biochar amended soils.
2. BCF is generally higher for smaller ratio of sand to fine content (clay and silt).
3. Pore filling, aggregation, bio-film formation and piping in soils due to biochar is discussed.
4. Lack of systematic studies revealing effects of physio-chemical properties of biochar on hydraulic conductivity.

Keywords Biochar conductivity factor (BCF), Unsaturated hydraulic conductivity, Soil water characteristic curve (SWCC), Pyrolysis process

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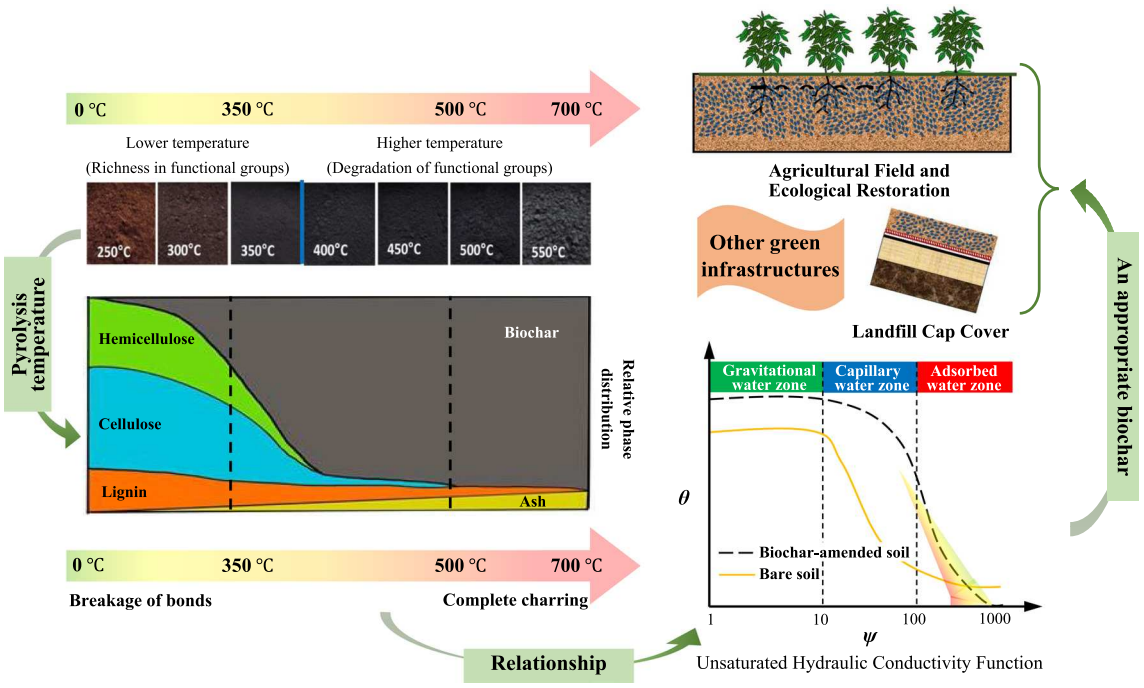
Graphical Abstract



1 Introduction

Biochar is widely recognized as a sustainable solution to improve soil hydrological properties, retention of nutrients in agriculture fields, and improve crop productivity while preserving the ecosystem health (Gámiz et al. 2017; Garg et al. 2020). Biochar is a biomass-derived carbonaceous material produced via the pyrolysis process in the absence or under a limited amount of oxygen. Production of biochar is dependent on the type of feedstock used and the operating conditions such as residence time, temperature, and flowrate of feedstock in the pyrolysis reactor (Meyer et al. 2011). It is well established that changes in pyrolysis temperature affect the pore structure of biochar (Ganesan et al. 2020). Such changes in porosity may subsequently alter the moisture retention properties of soils (Ganesan et al. 2020; Mei et al. 2020). However, past studies on the influence of pyrolysis temperature on moisture retention characteristics of soils have been hitherto neglected.

There have been numerous studies on the application of biochar in agricultural soils (Laird et al. 2010; Barnes et al. 2014; Edeh et al. 2020) and, more recently, in compacted geo-engineered soils (Bordoloi et al. 2018; Kumar et al. 2019; Ni et al. 2020). For instance, a study conducted by Kumar et al. (2019) showed that compacted biochar-amended soil decreases erosion on landfill cap covers. Bordoloi et al. (2018) found an improvement in crack resistance due to addition of biochar in compacted soil. Furthermore, enhanced water retention and plant growth were also found due to the presence of biochar in compacted soil (Ni et al. 2020). The positive effects of biochar in terms of water retention, plant growth and crack suppression have been confirmed. However, the influence of biochar on soil hydraulic conductivity or permeability is inconclusive (Blanco-Canqui 2017). Hydraulic conductivity is expressed as the average rate of flow of water through soil pores. Near-saturated hydraulic conductivity indicates rate of flow of water in pores, which are assumed to be filled with water (Das 2019). Whereas, unsaturated hydraulic conductivity indicates water flow rate among inter-connected pores containing water (Thorbjørn et al. 2008). As expected, tortuosity increases due to disconnectivity caused by air filled pores and this phenomenon increases the travle path and hence, reduces the flow rate in an unsaturated soil (Faybishenko 1995).

Several studies have been conducted to analyze the near-saturated hydraulic conductivity of soil mixed with biochar at relatively lower compaction effort (less than 90% degree of compaction) for agricultural purposes (Busscher et al. 2010; Ibrahim et al. 2013; Githinji 2014; Prober et al. 2014; Rogovska et al. 2014; Novak et al. 2016). However, these studies on soil mixed with biochar did not reveal any particular trend with regard to the increase or decrease in the hydraulic conductivity values. For example, some studies have shown enhanced hydraulic conductivity in clayey or loamy soils when mixed with biochar (Prober et al. 2014; Novak et al. 2016), while others have observed lower hydraulic conductivity in sandy or silty sandy soils (Ibrahim et al. 2013; Githinji 2014). Given that the previous studies were conducted under varied soil and testing conditions (in the field or laboratory), a direct comparison is difficult. Furthermore, the authors hypothesized different possible mechanisms such as the pore-space filling effect of biochar into soil, the pore-space filling effect of soil into biochar pores and long-term aggregation (Jien and Wang 2013). To date, only a limited number of studies have investigated hydraulic conductivity over a wide range of suction. Unsaturated hydraulic conductivity is essential to analyze seepage of water during rainfall infiltration and to estimate water balance in slopes and green infrastructure (green roof, biofilters, etc.; Kutílek and Nielsen 1994; Hillel 1998). The effect of biochar on unsaturated hydraulic conductivity, hence, needs to be investigated. Both experimental (instantaneous profile method using 1-D column testing; Ng et al. 2011) and theoretical derivation from soil water characteristic curve (SWCC) (Brooks and Corey 1964) can be adopted for deducing unsaturated soil hydraulic conductivity functions. The former approach is time-consuming and costly, and requires long term measurements. By contrast, the latter approach is relatively easy and has proven to be reliable in deducing hydraulic conductivity for unsaturated soils (Huang et al. 1998; Ni et al. 2020).

The overarching aim of this study is to deduce the unsaturated hydraulic conductivity function of soil based on the measured SWCC at different biochar contents. A new parameter "*Biochar conductivity factor*" (BCF) has been proposed for interpreting near-saturated hydraulic conductivity, which is defined as the ratio of conductivity of soil-biochar mix and bare soil. Comparisons have been made with 148 measured hydraulic conductivity values in the literature. The differences between hydraulic conductivity values have been analyzed with respect to pore-space filling, aggregation and root growth/decay. In addition, the influence of the biochar production process (pyrolysis conditions and feedstock) on the structure of biochar and subsequent hydraulic conductivity has also been discussed.

2 Materials and methodology

2.1 Theoretical framework for estimating unsaturated hydraulic conductivity

Macroscopic models for predicting permeability function are established by assuming fluid-filled pores as bundles of capillary tubes of different sizes. The distribution of the pores that are filled with fluid is determined from SWCC.

In Brooks and Corey (1964), the flow through fluid-filled pores is characterized using Poiseuille equation. Integration across all the pore-water volume expressed by the SWCC can be used to determine hydraulic radius. During the derivation, a tortuosity factor was used to describe the difference between the actual and average pore velocities, and the actual and average pressure gradients. Based on the experimental data obtained by Burdine et al. (1950) and the analytical data of Wyllie and Gardner (1958), the following relationship for tortuosity was put forward.

$$\frac{T_{s=1}}{T_s} = \left[\frac{s - s_r}{1 - s_r}\right]^2 = S_e^2 \tag{1}$$

where T_s represents the tortuosity that is a function of the degree of saturation, and $T_{s=1}$ represents the tortuosity at saturation, S is the degree of saturation and S_r is the residual degree of saturation, and $\frac{s-s_r}{1-s_r}$ is the effective degree of saturation which can be expressed in terms of S_e.

As proposed by Brooks and Corey (1964), the equation of the relative permeability (k_r) can be written as:

$$k_r = \frac{k(\psi)}{k_s} \tag{2a}$$

$$k_r = \left[\frac{s - s_r}{1 - s_r}\right]^2 \times \frac{\int_0^s \mathrm{d}s/\psi^2}{\int_0^1 \mathrm{d}s/\psi^2} \tag{2b}$$

where $k(\psi)$ means the permeability function and ψ is the soil suction, and k_s means the factor of permeability at saturation. Function of S_e follows SWCC as:

$$s_e = 1 \quad \text{for } \psi \le \psi_{aev} \tag{3a}$$

where ψ_{aev} means the suction that is associated with the air-entry value and

$$S_e = \left[\frac{\psi_{aev}}{\psi}\right]^{\lambda} \quad \text{for } \psi > \psi_{aev} \tag{3b}$$

where λ is the pore-size distribution index and also implies the slope of SWCC on a log–log diagram ($\Delta\log S_e/\Delta\log \psi$). To obtain a bilinear curve on a log–log plot, S_r must be considered as a fitted parameter. In macroscopic models, the effective degree of saturation is generally used to explain "mobile" water phase in the soil, instead of the degree of saturation (Mualem 1986). The relative permeability is replaced by the effective degree of saturation. The relationship of the function is as follow:

$$k_r = S_e^2 \times \frac{\int_0^s ds_e/\psi^2}{\int_0^1 ds_e/\psi^2} \tag{4}$$

Based on the effective degree of saturation given in Eq. (3), the relative permeability can be further simplified as:

$$K_r = S_e^{(2+3\lambda)/\lambda} = S_e^{\delta} \tag{5}$$

where δ is an empirical index.

The relative permeability in terms of suction can be equivalent to the following expression:

$$k_r = 1 \text{for } \psi < \psi_{aev} \tag{6a}$$

$$k_r = \left[\frac{\psi_{aev}}{\psi}\right]^{\eta} \text{for } \psi \geq \psi_{aev} \tag{6b}$$

where the pore-size distribution coefficient, η, is equal to $(2+3\lambda)$.

In the present study, the "macroscopic model" represents the permeability function in terms of degree of saturation (Eq. (5)). Equation (6) has a strong analytical basis and experimental background. Mualem (1978) proposed a macroscopic model by considering the solid surface area in Kozeny's (1927) equation and the hydraulic radius in the Hagen-Poiseuille equation. The equation of the index δ was proposed as follows:

$$\delta = \left(3.0 + 0.015 \int_{\theta_{15atm}}^{\theta_s} \psi d\theta\right) \tag{7}$$

where θ is the volumetric water content.

Many experimental results have shown that the index δ is determined by the pore-size distribution of the porous medium (Huang 1994; Laliberte et al. 1966; Mualem 1978). Consequently, the macroscopic models represented by Brooks and Corey (1964) and Mualem (1978) have found wider applicability than others because the δ index varies due to porous medium pore-size characteristics.

2.2 Experimental programme for determining unsaturated soil water characteristic curve

A series of 1-D column experiments were designed and conducted to measure SWCC for soil modified with biochar. The design and description of the 1-D column (300 mm in diameter and 250 mm in height) can be found in Bordoloi et al. (2018). The particle size distribution of the soils used in the study was 57%, 37% and 6%, for sand, silt and clay, respectively. The soil was classified as sandy loam according to United States Department of Agriculture (USDA) specifications (Soil Survey Staff 2004). The maximum dry density and optimum water content of soil were determined as 1.59 g/c.c. and 16.5%, respectively. The soil was compacted to a bulk density of 1.66 g/c.c. The soil sample was compacted in the 1-D column up to height of 220 mm, and was instrumented with two suction (MPS-6; Decagon devices) and volumetric water content sensors (EC-5, Decagon devices) at a depth of 30 mm from the surface. Both sensors were installed diametrically at opposite ends during compaction. The EC-5 sensors were calibrated for soils at different biochar contents (0%, 5% and 10%). Sensors were calibrated using the approaches proposed by Starr and Paltineanu (2002) and Cobos and Chambers (2010). MPS-6 sensors can be utilized for reliable measurements till 1700 kPa (Saha et al. 2020). The soil sample was prepared in a mold to calibrate the sensors. The sensors were installed in the prepared sample to measure water contents and thereafter, the volumetric water contents were quantified using a small cylinder. The obtained values of volumetric water contents were compared for the calibration. As per study by Kameyama et al. (2014), the effect of biochar type (i.e., pyrolyzed at 400 °C) was found to have almost negligible effect on the calibration results.

The biochar amended soil was subjected to 9 wetting–drying cycles with each cycle consisting of 7 days. Such time period was determined based on negligible change of soil volumetric water content (assuming soil reached residual zone) under drying. The soil suction and volumetric moisture content were simultaneously measured. It should be noted that saturated hydraulic conductivity for soil-biochar mix was determined using mini-disk infiltrometer. Cracks were observed and measured in terms of crack intensity factor (i.e., ratio of total crack area and soil surface area), which is deduced from image processing (Gadi et al. 2017a). It must be noted that minidisk infiltrometer is widely used to measure near saturated hydraulic conductivity. In addition, the theory, working principle and measuring procedure have been explicitly shown in several

earlier studies (Bordoloi et al. 2017, 2019a, b; Gadi et al. 2017a, b). Details of testing procedures for SWCC can be found in Bordoloi et al. (2018) and Gopal et al. (2019), respectively. Brooks and Corey (1964) model (Eq. 5) for relative permeability coupled with Mualem (1978) model (Eq. 7) of hydraulic radius was adopted to deduce relative permeability function. Using near-saturated hydraulic conductivity as measured from mini-disk infiltrometer and obtained relative permeability, unsaturated hydraulic conductivity as a function of soil suction was obtained.

3 Results and discussions

3.1 Near-saturated hydraulic conductivity and cracking of biochar amended soils

Average near saturated permeability of biochar was found to be $1.27 \pm 0.1 \times 10^{-6}$ m s^{-1} (Gopal et al. 2019). Biochar reduced near-saturated hydraulic conductivity by $39 \pm 2\%$ and $72 \pm 3\%$ at 5% and 10% biochar content (Gopal et al. 2019). Though, it was expected that the presence of biochar may enhance porosity, however, crack suppression phenomenon of biochar also resulted in reduced hydraulic conductivity rate at surface. Peak crack intensity factor in bare soil was found to be $7.1 \pm 0.4\%$. The presence of biochar reduced cracking by $46 \pm 1\%$ and $54 \pm 2\%$, for 5% and 10% amendment ratio, respectively (Gopal et al. 2019). It is known that cracks can significantly increase permeability (Li et al., 2009), as described by the following equation:

$$k^{(s)}(\psi) = k^{(c)}(\psi) + (1 - \mathrm{CIF})k^{(m)}(\psi) \quad (8)$$

where k is hydraulic conductivity and CIF is crack intensity factor. For CIF equivalent to 0, soil can be considered fully uncracked. For this case, permeability of cracked soil is same as that of soil matrix (without crack). For CIF equivalent to 1, the permeability of cracked soil is the same as the permeability of crack matrix.

Sun et al. (2020) analyzed the saturated permeability of low liquid limit clay under influence of biochar at different amendment ratios (0%, 10%, 15% and 20%). It was found from their study that the presence of biochar enhanced permeability of clay. Nuclear magnetic response (NMR) tests confirmed that bi-modal distribution of pure clay was observed under the influence of biochar with relatively higher probable pore size in soil-biochar mix. Recently Zhang et al. (2020) also found that biochar enhanced the swelling ability of soil, which was attributed to the binding of H_2O molecules with C–O–H and –OH groups (Jačka et al. 2018). The moisture retained by the biochar amended soil could be 5% higher than that of bare soil and therefore the saturated hydraulic conductivity was found to decrease in the biochar amended soil (Jačka et al. 2018).

3.2 Normalized soil water characteristic curve and unsaturated hydraulic conductivity function of biochar amended soils

Figure 1a shows the measured SWCCs of bare soil as well as soil amended with 0%, 5% and 10% biochar. It can be observed that near-saturated volumetric water content is significantly higher for biochar amended soils as compared to the bare soil. The difference in volumetric water content retention between them reduces as soil becomes drier. In order to compare efficiency of biochar at different amendment ratios (i.e., 5% and 10%), it may be more suitable to analyze normalized volumetric water content with respect to soil suction (Fig. 1b). It can be observed that the difference between 5% and 10% biochar content on normalized water content was not significant and may lie within error limits of the EC-5 sensor (Fig. 1b), implying that efficiency of biochar content of 5% is already significant as compared to that of bare soil.

Figure 2 shows the variation in estimated unsaturated hydraulic conductivity function. It can be

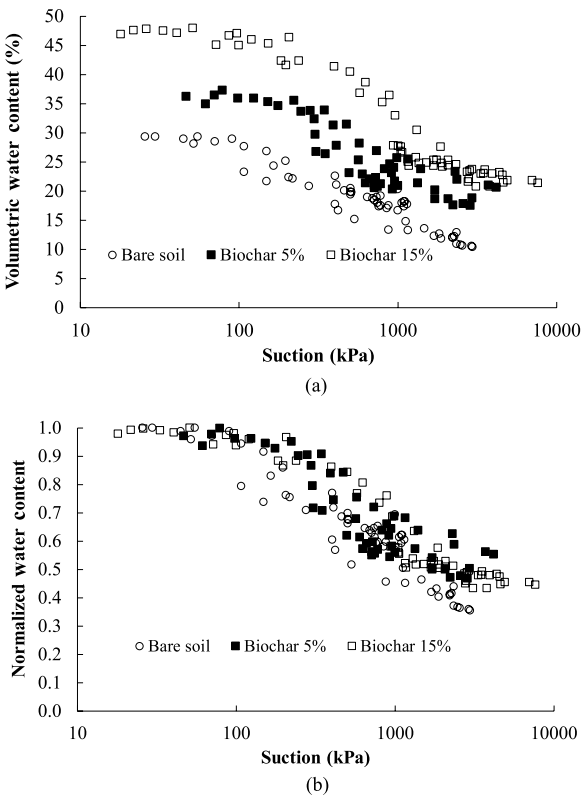


Fig. 1 Relationships of **a** volumetric water contents and **b** normalized water contents with soil suction for bare and biochar amended soils

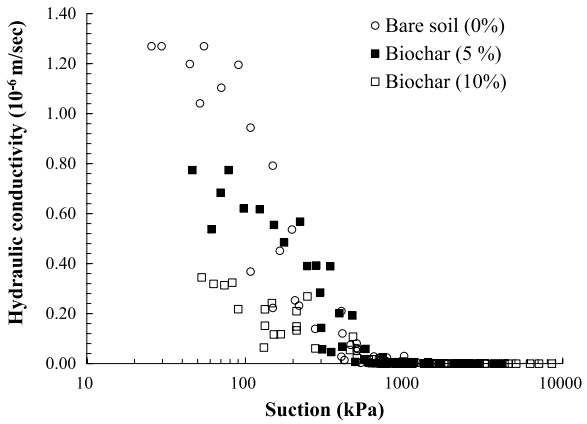


Fig. 2 Deduced unsaturated hydraulic conductivity function for bare and biochar amended soils

observed from the figure that unsaturated hydraulic conductivity for soil-biochar mix remains lower than that of bare soil throughout suction range. The difference in hydraulic conductivity between bare soil and biochar amended soil reduced with suction. There is a limitation in Brooks and Corey (1980) model, which does not capture post residual zone of unsaturated soil (Sillers and Fredlund 2001). Nevertheless, there is a clear tendency of reduction in impact of biochar on permeability of soil in residual zone. It should be noted that such observation is only applicable to one particular soil under given compaction. Further studies are required to obtain more comprehensive view of unsaturated permeability function of biochar amended clay. The following discussion would help to shed more light into possible mechanisms that are likely to influence permeability in biochar amended soils.

Higher water retention capacity is likely due to pore space filling effect of biochar in sand dominated mixture (Jien and Wang 2013). These findings reported in the current study (Fig. 2) are generally opposite to those of soils with lower ratio of sand to fine content (Ibrahim et al. 2013; Githinji 2014). A likely explanation could be that biochar filled the pores of sandy soils, while it was opposite (i.e., clayey particles filling pores of biochar) in case of finer-textured soils. Liu et al. (2016) analyzed the effects of relative particle size of biochar and sand grains on hydraulic conductivity and the authors found that the reduction in hydraulic conductivity was much higher when biochar particles were much finer than sand grains. However, the reduction in hydraulic conductivity was minimal, when biochar particles were coarser or comparable to sand grains, respectively. The decrease of hydraulic conductivity under coarser biochar might be due to bi-modal particle size distribution, resulting in compact packing and enhanced tortuosity.

3.3 Newly proposed biochar conductivity factor (BCF)

Though, qualitatively, the results of near-saturated permeability are consistent with those of Prober et al. (2014) and Novak et al. (2016), it may be difficult to compare since their studies seldom report any cracking effects of biochar. Tables 1, 2 and 3 summarize the near-saturated hydraulic conductivities measured in the literature.

In order to assess biochar effect, a new term "*Biochar Conductivity Factor* (BCF)" is defined. A BCF greater than 1 implies an increase in conductivity due to the influence of biochar, while a BCF less than 1 indicates a reduction in conductivity (see Fig. 3). Studies are categorized based on the reported suction and void ratio/density values (see Table 2) and particle size (see Table 3), which are missing in Table 1. In order to understand soil type effect, a new ratio between sand and fine particles (silt and clay) was defined. The lowerthe ratio, the higheris the fine content and expected lower average pore size. Figure 3a and b shows BCF and its corresponding variation with soil type, respectively and it can be observed that BCF is larger for higher ratio of sand to fine content. BCF factor was enhanced (either less than 1 or greater than 1) under higher biochar content. Glab et al. (2016) investigated the effect of feedstock type (*Miscanthus* and Winter wheat) and particle size on hydraulic conductivity and the authors found that both biochars enhanced conductivity in general; however, the effect of winter wheat feedstock was more significant than that of the *Miscanthus* type (see Table 3).

3.4 Aggregation effect

In contrast to the pore filling and bi-modal particle size distribution effects, Jien and Wang (2013) observed another factor (i.e., aggregation effect; Fig. 3) to be more dominant, while analyzing potential of biochar in a highly weathered soil (i.e., *Typic Paleudults;* Soil Survey Staff (2010)). The authors reported that biochar less than 2 mm in size was able to enhance hydraulic conductivity by almost 1.8 fold in weathered soil containing 43% clay, 40% silt and much lower sand content (i.e., 16%). Biochar could function as a binder, facilitating the connection of microaggregates in the soil to form macroaggregates. It was hypothesized in their study that the oxidized surface of biochar containing hydroxyl (-OH) and carboxylic groups (-COOH) can adsorb soil particles (even clay) to form macroaggregates under low pH environment (i.e., acidic). Jien and Wang (2013) further showed that

Table 1 Review of studies related to near-saturated permeability of biochar amended soils

Reference	Soil type	Biochar type	Biochar content	Suction (initial)	%sand	%silt	%clay	Ratio (sand/(silt + clay))	Hydraulic conductivity of soil (cm s^{-1})	Biochar conductivity factor (BCF)	Maximum dry density (kN m^3)	Saturated water content
Gan et al., (2021)	Clay	Rice straw	0% 5% 10% 15%	–	–	–	–	–	0.000593 0.000523 0.000478 0.000421	**1** **0.88** **0.80** **0.71**	–	39% 48% 52% 54%
Xiao et al. (2016)	Sand	Maize-straw	0 t ha^{-1} (BC0)	10 kPa	–	–	–	–	0.000609 (0–10 cm, 2012) 0.000609(10–20 cm, 2012) 0.000569(0–10 cm, 2014) 0.000411(10–20 cm, 2014)	1 1 1 1	–	47.3% (2012) 47.7% (2014)
			10 t ha^{-1} (BC10)	10 kPa	–	–	–	–	0.001263(0–10 cm, 2012) 0.000907(10–20 cm, 2012) 0.000907(0–10 cm, 2014) 0.000529(10–20 cm, 2014)	**2.07** **1.48** **1.59** **1.28**	–	49.7% (2012) 48.1% (2014)
			20 t h^{a-1} (BC20)	10 kPa	–	–	–	–	0.001799(0–10 cm, 2012) 0.000947(10–20 cm, 2012) 0.001223(0–10 cm, 2014) 0.000709(10–20 cm, 2014)	**2.95** **1.55** **2.14** **1.72**	–	51% (2012) 49.8% (2014)
			30 t $ha^{-}1$ (BC30)	10 kPa	–	–	–	–	0.002236(0–10 cm, 2012) 0.001065(10–20 cm, 2012) 0.001799(0–10 cm, 2014) 0.001124(10–20 cm, 2014)	**3.67** **1.74** **3.16** **2.73**	–	52.3% (2012) 52.2% (2014)
Reddy et al., (2015)	Silty clay soil	Gasifies wood pellets	0%	6.2 kPa	8.35%	91.6%	0%	0.091	4.3×10^{-9}	1	16	20%
			5%	–	10.7%	86.0%	0%	0.12	5.7×10^{-8}	**13.3**	14	20%
Reddy et al., (2015)	Silty clay soil	Gasifies wood pellets	10%	–	9.9%	84.6%	0%	0.117	6.5×10^{-7}	**151.1**	14	20%
			20%	–	11.6%	77.0%	0%	0.151	1.8×10^{-7}	**41.9**	14	20%

Table 1 (continued)

Reference	Soil type	Biochar type	Biochar content	Suction (initial)	%sand	%silt	%clay	Ratio (sand/(silt + clay))	Hydraulic conductivity of soil (cm s^{-1})	Biochar conductivity factor (BCF)	Maximum dry density (kN m^3)	Saturated water content
*Ouyang et al. (2013)	Sandy loam soil (SL)	–	0%	–	60%	20%	20%	1.5	0.000667 (Day 1) 0.000706 (Day 20) 0.000719 (Day 60) 0.000744 (Day 90)	1 1 1 1	–	45.4% (Day 1) 45.4% (Day 20) 46.7% (Day 60) 44.6% (Day 90)
Ouyang et al. (2013)	Sandy loam soil (SL)	Dairy manure	2%	–	60%	20%	20%	1.5	0.000719 (Day 1) 0.000878 (Day 20) 0.000886 (Day 60) 0.000784 (Day 90)	**1.07** **1.24** **1.23** **1.05**	–	48.5% (Day 1) 49.5% (Day 20) 49.0% (Day 60) 48.5% (Day 90)
	Silty clay soil (SC)	–	0%	–	6.6%	41.8%	51.6%	0.071	0.000542 (Day 1) 0.000677 (Day 20) 0.000718 (Day 60) 0.000616 (Day 90)	0.81 0.95 0.99 0.82	–	55.0% (Day 1) 55.6% (Day 20) 54.6% (Day 60) 54.1% (Day 90)
	Silty clay soil (SC)	Yairy manure	2%	–	6.6%	41.8%	51.6%	0.071	0.000617 (Day 1) 0.000772 (Day 20) 0.000809 (Day 60) 0.000667 (Day 90)	0.92 **1.09** **1.12** 0.89	–	56.5% (Day 1) 57.0% (Day 20) 55.3% (Day 60) 55.2% (Day 90)
Bohara et al. (2019)	Sandy loam soil	Poultry litter (PL) Pinewood chips (PBC)	0%	5 kPa	64%	25.5%	10.5%	1.78	0.0001558	1	–	–
	–	–	2.5% PL	5 kPa	64%	25.5%	10.5%	1.78	0.0001680	**1.07**	–	–
	–	–	5% PL	5 kPa	64%	25.5%	10.5%	1.78	0.0000875	0.56	–	–
	–	–	10% PL	5 kPa	64%	25.5%	10.5%	1.78	0.0000653	0.41	–	–
	–	–	2.5% PBC	5 kPa	64%	25.5%	10.5%	1.78	0.0003305	**2.12**	–	–

Table 1 (continued)

Reference	Soil type	Biochar type	Biochar content	Suction (initial)	%sand	%silt	%clay	Ratio (sand/(silt + clay))	Hydraulic conductivity of soil (cm s^{-1})	Biochar conductivity factor (BCF)	Maximum dry density (kN m^3)	Saturated water content
	–	–	5% PBC	5 kPa	64%	25.5%	10.5%	1.78	0.0003555	**2.28**	–	–
	–	–	10% PBC	5 kPa	64%	25.5%	10.5%	1.78	0.0005305	**3.4**	–	–
	–	–	2.5% PL + 2.5% PBC	5 kPa	64%	25.5%	10.5%	1.78	0.0001841	**1.18**	–	–
Bohara et al. (2019)	Sandy loam soil	Poultry litter (PL) Pinewood chips (PBC)	5% PL + 5% PBC	5 kPa	64%	25.5%	10.5%	1.78	0.0001322	0.84	–	–
			10% PL + 10% PBC	5 kPa	64%	25.5%	10.5%	1.78	0.0001558	1	–	–
Wong et al. (2018)	Kaolin clay	Peanut shell	0%	–	0%	0%	100%		1.2×10^{-7}	1	–	36%
			5%	–	0%	0%	100%		2.1×10^{-7}	**1.75**	–	39%
			20%	–	0%	0%	100%		1.3×10^{-6}	**10.8**	–	41%
Jien and Wang (2013)	Typic paleudults	Waste wood of white lead trees	0%,	–	16.2%	40.2%	43.6%	0.19	0.00464	1	–	–
			2.5%,	–	–	–	–	–	0.0083	**1.78**	–	–
			5%	–	-	–	–	–	0.0092	**1.92**	–	–
Zhang et al. (2016)	Sand	Wood	0 g kg^{-1}	–	–	–	–	–	0.0136	1	–	–
			7 g kg^{-1}	–	–	–	–	–	0.0136	1	-	–
Zhang et al. (2016)	Sand	Wood	15 g kg^{-1}	–	–	–	–	-	0.0119	0.88	–	–
			25 g kg^{-1}	–	–	-	–	–	0.0118	0.86	–	–
Brockhoff et al. (2010)	Sand	Switchgrass	0%	–	–	–	–	–	0.024	1	–	–
			5%	–	–	–	–	–	0.0155	0.64	–	–
			10%	–	–	–	–	–	0.0147	0.65	–	–
			15%	–	–	–	–	–	0.0081	0.33	–	–
			20%	–	–	–	–	–	0.0043	0.17	–	–
			25%	–	–	–	–	–	0.0018	0.075	–	–
Uzoma et al. (2011)	Sand	Cow manure	0 mg ha^{-1}	–	–	–	–	–	1.96	1	–	–
			10 mg ha^{-1}	–	-	–	–	–	1.83	0.93	–	–
			15 mg ha^{-1}	-	–	–	–	–	1.41	0.71	–	–

Table 1 (continued)

Reference	Soil type	Biochar type	Biochar content	Suction (initial)	%sand	%silt	%clay	Ratio (sand/(silt + clay))	Hydraulic conductivity of soil (cm s^{-1})	Biochar conductivity factor (BCF)	Maximum dry density (kN m^3)	Saturated water content
			20 mg ha^{-1}	–	–	–	–	–	1.27	0.64	–	–
Tian et al. (2015)	Sand	Peanut shell	0 g kg^{-1}	–	–	–	–	–	0.00033	1	–	–
			50 g kg^{-1}	–	–	–	–	–	0.000056	0.169	–	–
			100 g kg^{-1}	–	–	–	–	–	0.0000278	0.084	–	–
			150 g kg^{-1}	–	–	–	–	–	0.0000278	0.084	–	–
Jačka et al. (2018)	Sandy loam	Grape stalks	0% (wt.)						0.0000478	1	–	–
			2% (wt.)						0.0000475	0.996	–	–
			5% (wt.)						0.0000456	0.954	–	–
	Sandy loam with kaolin clay (20% mix)	Grape stalks	0% (wt.)						0.00000913	1	–	–
			2% (wt.)						0.00000885	0.968	–	–
			5% (wt.)						0.00000348	0.381	–	–

Bold letter (1 < biochar conductivity factor) implies that permeability of soil-biochar mix is either equal or greater than bare soil

Table 2 Review of studies related to near-saturated permeability of biochar amended soils (cont.) (*Suction, void ratio/dry density and saturated water content are not reported)

Reference	Soil type	Biochar type	Biochar content	%sand	%silt	%clay	Ratio (sand/(silt + clay))	Hydraulic conductivity of soil (cm s^{-1})	Biochar conductivity factor (BCF)
Lim et al. (2016)	Coarse sand	Hardwood	0 g kg^{-1}	–	–	–	-	0.0069	1
			10 g kg^{-1}	–	–	–	–	0.00194	0.28
			20 g kg^{-1}	–	–	–	–	0.00089	0.12
			50 g kg^{-1}	–	–	–	–	0.00029	0.04
Lim et al. (2016)	Fine sand	Hardwood	0 g kg^{-1}	–	–	–	–	0.00299	1
			10 g kg^{-1}	–	–	–	–	0.00194	0.64
			20 g kg^{-1}	-	–	–	–	0.00155	0.51
			50 g kg^{-1}	–	–	–	–	0.00043	0.14
Ibrahim et al. (2013)	Sandy loam	Wood	0 g kg^{-1}	–	–	–	–	0.00136	1
			5 g kg^{-1}	–	-	–	–	0.00133	0.97
			10 g kg^{-1}	–	–	–	–	0.00125	0.91
			15 g kg^{-1}	–	–	–	–	0.00119	0.87
			20 g kg^{-1}	–	–	–	–	0.00114	0.83
Ajayi and Horn (2016)	Fine sand	Columns	0 g kg^{-1}	–	–	–	–	0.0098	1
			20 g kg^{-1}	–	–	–	–	0.00744	0.75
			50 g kg^{-1}	–	–	–	–	0.00433	0.44
			60 g kg^{-1}	–	–	–	–	0.00222	0.23
Tian et al. (2015)	Silt loam	Peanut shell	0 g kg^{-1}	–	–	–	–	0.000002	1
			50 g kg^{-1}	–	–	–	–	0.0000027	**1.35**
			100 g kg^{-1}	–	–	–	–	0.0000069	**3.45**
			150 g kg^{-1}	–	–	–	–	0.0000086	**4.3**
Herath et al. (2013)	Silt loam	Corn stover	0 mg ha^{-1}	–	–	–	–	0.0028	1
			11.3 mg ha^{-1}	–	–	–	–	0.0037	**1.32**
			10.0 mg ha^{-1}	–	–	–	–	0.0067	**2.39**
Ajayi and Horn (2016)	Silty clay loam	Wood	0 g kg^{-1}	–	–	–	–	0.000026	1
			20 g kg^{-1}	–	–	–	–	0.000033	**1.26**
			50 g kg^{-1}	–	–	–	–	0.0000425	**1.63**
			60 g kg^{-1}	–	–	–	–	0.0000467	**1.79**
Asai et al. (2009)	Clay loam	Wood	0 mg ha^{-1}	–	–	–	–	0.000164	1
			4 mg ha^{-1}	–	–	–	–	0.000247	**1.50**
			8 mg ha^{-1}	–	–	–	–	0.000214	**1.3**
			16 mg ha^{-1}	–	–	–	–	0.000453	**2.76**
Lim et al. (2016)	Clay	Hardwood	0 g kg^{-1}	–	–	–	–	0.000286	1
			10 g kg^{-1}	–	–	–	–	0.0004	**1.39**
			20 g kg^{-1}	–	–	–	–	0.000514	**1.79**
			50 g kg^{-1}	–	–	–	–	0.000283	**0.98**
Sun et al. (2020)	Low liquid limit clay	Rice straw	0%	–	–	–	–	$2.96*10^{-8}$	1
			5%	–	–	–	–	$6.7*10^{-8}$	**2.2**
			10%	–	–	–	–	$8.20*10^{-8}$	**2.77**
			15%	–	–	–	–	$1.17*10^{-7}$	**3.95**
			20%	–	–	–	–	$1.35*10^{-7}$	**4.56**
Yaghoubi (2011)	Silty clay	Wood pellets	0%	8.3%	58.6%	33%	0.0906	$4.30*10^{-9}$	1
			5%	10.7%	51.4%	34.5%	0.12456	$5.70*10^{-8}$	**13.26**

Table 2 (continued)

Reference	Soil type	Biochar type	Biochar content	%sand	%silt	%clay	Ratio (sand/(silt + clay))	Hydraulic conductivity of soil (cm s^{-1})	Biochar conductivity factor (BCF)
			10%	9.9%	47.6%	37.0%	0.11702	$6.50*10^{-7}$	**151.16**
			20%	14.2%	50%	28.5%	0.18089	$1.80*10^{-7}$	**41.86**
Wong et al. (2018)	Kaolin clay	Peanut-shell	0%	–	–	–	–	$1.20*10^{-7}$	1
			5%	–	–	–	–	$2.10*10^{-7}$	**1.75**
			20%	–	–	–	–	$1.30*10^{-6}$	**10.8**
Barnes et al. (2014)	Sand	Mesquite wood	0%	–	–	–	–	$2.90*10^{-4}$	1
			10%	–	–	–	–	$2.30*10^{-5}$	0.07
	Clay-loam (poor drainage)	Mesquite wood	0%	–	–	–	–	$3.20*10^{-6}$	1
			10%	–	–	–	–	$1.20*10^{-5}$	**3.75**

Bold letter (1 < biochar conductivity factor) implies that the permeability of soil-biochar mix is either equal or greater than that of bare soil

mucilage produced by microbial activity and hyphae in the interface between soil and biochar particles tended to bind micro-aggregates to form macro-aggregates in biochar amended soils. In their study, porosity tended to decrease due to enhanced macro-aggregate formation at relatively higher biochar addition (i.e., 5%).

As also suggested in Fig. 4, aggregation can also happen due to presence of humus formed (due to root growth and decay) that is more likely to happen in long term. Plant residues naturally are broken down in long term (more than 10 years) to form humus. As compared to natural biomass decomposition, biochar is relatively far more stable (O/C ratio of less than 0.2 can have expected half-life over 1000 years; Wani et al., 2020). Biochar aggregation is more likely to occur in the long term in the field. There is aging effects that could oxidize functional groups at biochar surface, thus leading to higher water retention (Aller et al., 2017; Wang et al., 2019). Further systematic studies are needed to analyse long term effects of biochar on water retention taking aggregation, biomass decomposition and aging of biochar into account.

3.5 Wettability

Wettability is indicated by hydrophilicity (contact angle < 90°) or hydrophobicity (contact angle > 90°). Minimum biochar pore diameter (D) that can retain water is determined as:

$$D = \frac{4\gamma\cos\theta}{\rho_w g h} \tag{9}$$

where γ refers to surface tension at room temperature (0.072 N m^{-1}) and θ is the contact angle between the biochar surface and water–air interface. A lower contact angle implies a larger D. This indicates that even larger pores of biochar can retain water. There is a dearth of information on the contact angle of biochar and how this can influence the hydraulic properties of soils. Das and Sarmah (2015) reported that hydrophobicity of biochar produced at low pyrolysis temperature is temporary and contact angle tends to reduce under wetting. They hypothesized that under water, aliphatic functional groups that are responsible for hydrophobicity are likely to be displaced, which can further enhance the affinity of the biochar for water. Recent studies (Mei et al. 2020; Ganesan et al. 2020) also showed that pyrolysis temperature could affect porosity as well as hydrophobicity of biochar, which can influence its cracking and water retention property. The authors concluded that biochar from plant waste (water hyacinth/algae) was found to retain more water than that from animal waste (pig manure, poultry litter), which could be attributed to higher porous structure of biochar from plant waste. Therefore, in addition to relative physical structure of biochar and soil, it is important to consider other factors such as feedstock type, pyrolysis temperature, pH and cracking of soil. These factors can affect hydrophilicity, aggregation and water retention phenomenon and hence, hydraulic conductivity of soil-biochar mix. Therefore, suffice it to say that porosity of biochar alone is not the driver that determines the soil hydraulic conductivity values upon biochar addition. The physio-chemical and biological interactions between biochar, soil, and water need to be considered.

3.6 Influence of biochar production process on soil permeability and water retention control

Figure 5 shows the conceptual framework on how biochar production process (feedstock type and pyrolysis

Table 3 Review of studies related to near-saturated permeability of biochar amended soils considering particle size and biochar type effect (Glab et al., 2016)

Reference	Soil type	Biochar type	Particle size of biochar (μm)	Biochar content	% sand	% silt	% clay	Ratio (sand/(silt + clay))	Hydraulic conductivity (cm s^{-1})	Ratio of Conductivity	Saturated water content (%)
Glab et al. (2016)	Loamy sand	–		0%	81%	14%	5%	4.26	0.00133	1	32
		Winter wheat	0–500	0.5%	–	–	–		0.001282	0.96	37
		Winter wheat	0–500	1%	–	–	–		0.001498	**1.12**	39
		Winter wheat	0–500	2%	–	–	–		0.001753	**1.31**	41
		Winter wheat	0–500	4%	–	–	–		0.001598	**1.2**	49
		Winter wheat	500–1000	0.5%	–	–	–		0.001087	0.81	40
Glab et al. (2016)	Loamy sand	Winter wheat	500–1000	1%	81%	14%	5%	4.26	0.002351	**1.76**	41
		Winter wheat	500–1000	2%	–	–	–		0.002097	**1.57**	46
		Winter wheat	500–1000	4%	–	–	–		0.001319	0.99	51
		Winter wheat	1000–2000	0.5%	–	–	–		0.002513	**1.88**	42
		Winter wheat	1000–2000	1%	–	–	–		0.002038	**1.53**	43
		Winter wheat	1000–2000	2%	–	–	–		0.002201	**1.65**	45
		Winter wheat	1000–2000	4%	–	–	–		0.002073	**1.55**	53
Glab et al. (2016)	Loamy sand	Miscanthus	0–500	0.5%	81%	14%	5%	4.26	0.001359	**1.02**	39
		Miscanthus	0–500	1%	–	–	–		0.001782	**1.33**	40
		Miscanthus	0–500	2%	–	–	–		0.001514	**1.13**	42
		Miscanthus	0–500	4%	–	–	–		0.001409	**1.05**	47
		Miscanthus	500–1000	0.5%	–	–	–		0.001163	0.87	40
		Miscanthus	500–1000	1%	–	–	–		0.001731	**1.3**	42
		Miscanthus	500–1000	2%	–	–	–		0.002019	**1.5**	46
		Miscanthus	500–1000	4%	–	–	–		0.001332	1	50
		Miscanthus	1000–2000	0.5%	–	–	–		0.001547	**1.16**	38.6
Glab et al. (2016)	Loamy sand	Miscanthus	1000–2000	1%	81%	14%	5%	4.26	0.001197	0.9	42.3
		Miscanthus	1000–2000	2%	–	–	–		0.002053	**1.54**	45.1
		Miscanthus	1000–2000	4%	–	–	–		0.000862	0.64	48

Bold letter (1 < biochar conductivity factor) implies that the permeability of soil-biochar mix is either equal or greater than that of bare soil

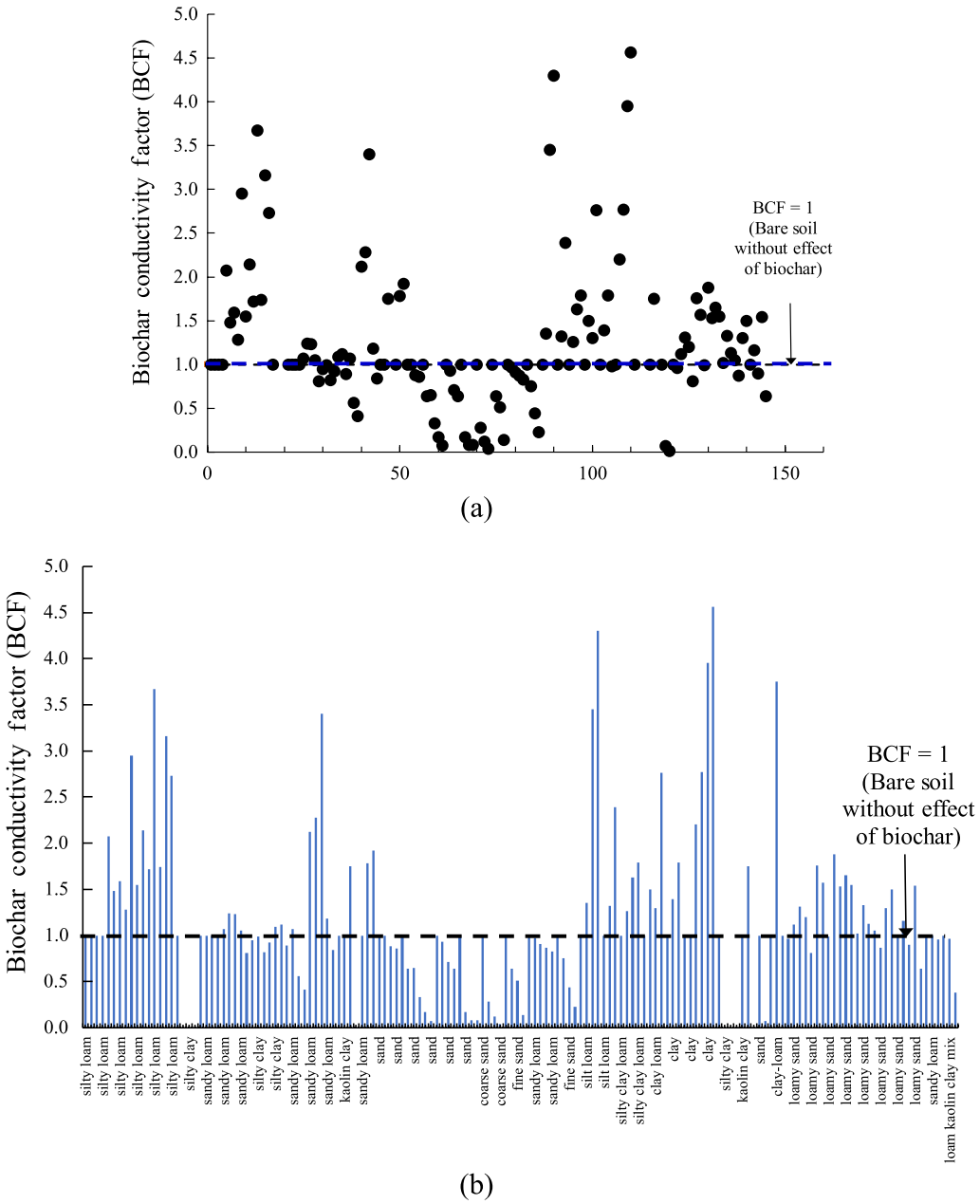


Fig. 3 **a** Biochar conductivity factor (BCF) for 148 studies in literature and **b** its variation with soil type. BCF equal to 1 implies bare soil in this graph for reference. BCF close to 1 implies slight effect of biochar. BCF greater than 1 implies higher conductivity of soil-biochar mix as compared with bare soil

temperature) may affect soil water retention. An increase in pyrolysis temperature leads to disappearance of the functional groups on biochar surface, leaving behind highly stable (i.e., due to aromatic structure of Benzene) and porous carbon structure (i.e., Turbidostratic char). Typical biomass constituting of lignin, cellulose and hemi-cellulose is broken down into biochar up on pyrolysis. Since feedstock type (plant type or animal waste) consists of varying compositions of lignin, cellulose and hemi-cellulose, it is obvious that micro-structure and composition of respective biochars (plant type or animal waste) will also vary significantly. Recently, the effect of pyrolysis temperature on water retention and crack suppression was discussed by Ganesan et al. (2020), who found that biochar produced at relatively high temperatures is likely to retain more

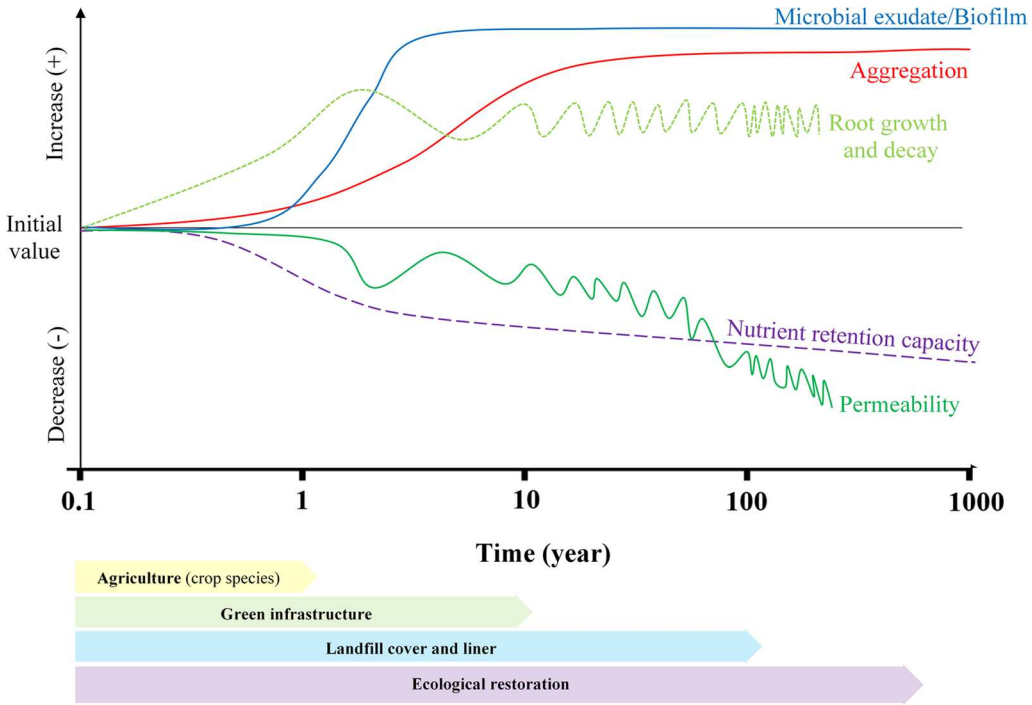


Fig. 4 Typical expected permeability variation with time considering the effects of aggregation, root growth and decay, formation of biofilm and nutrient retention capacity

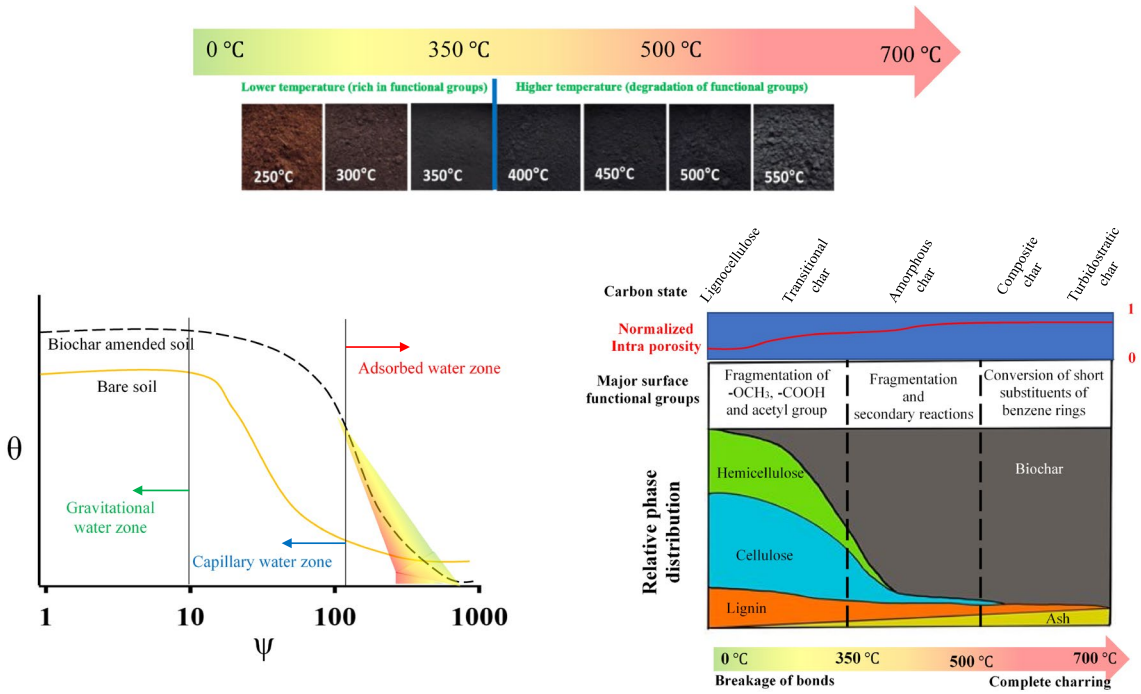


Fig. 5 Change in biochar properties with pyrolysis conditions and consequent effects on water retention

water due to the formation of highly porous structure and thus reduce cracking, and subsequent suppression can further help in reduction in conductivity. However, studies on the effect of pyrolysis conditions (feedstock-type and temperature) on hydraulic conductivity are limited, which needs to be studied in greater detail.

4 Conclusions

Our study demonstrated that the hydraulic conductivity of biochar amended soil remained lower than that of bare soil throughout the entire suction range (including at 1500 kPa), and the impact of biochar was more pronounced on the unsaturated hydraulic conductivity of sandy soil. The efficiency of biochar at 5% and 10% amendment ratio was found to be similar. Based on the critical review for analyzing ambiguities, it can be concluded that there are five possible mechanisms through which biochar may influence hydraulic conductivity. These include (1) pore filling, (2) cracking, (3) aggregation, (4) root growth and decay and (5) bio-film formation. Extent of these mechanisms may vary with soil and biochar properties during testing. Hence, it is recommended to systematically characterize soil and biochar parameters (pore size distribution, density, void ratio) individually. Biochar production process (i.e., pyrolysis temperature, feedstock type) should be optimized for maximizing the effect on hydraulic conductivity according to the requirements in agriculture and geo-environmental engineering infrastructure. Clay in agricultural field requires higher hydraulic conductivity to avoid waterlogging condition and enhance crop yield, whereas, geo-environmental engineering infrastructure (i.e., landfill cover, slopes) prefers the opposite of it. It is imperative that a transdisciplinary approach need to be considered involving agriculture, geo-environmental engineering, energy and production engineering to put joint efforts in research related to optimization of production process and promote commercial utilization of biochar for large-scale application.

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Author contributions
The first author drafted the manuscript based on idea jointly discussed with the second author. The third author provided feedback from geotechnical engineering point of view while the fourth author (AKS) provided technical guidelines from biochar characterization point of view. The fifth author helped to revise manuscript based on technical advice. The graphs and figures were corrected by the second and fifth authors. All authors read and approved the final manuscript.

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Availability of data and materials
Data is available upon reasonable request.

Declarations

Competing interests
Authors would like to declare that there are no competing interests.

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References

Ajayi AE, Horn R (2016) Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. Soil Tillage Res 164:34–44. https://doi.org/10.1016/j.still.2016.01.011

Asai H, Samson BK, Stephan HM, Songyikhangsuthor K, Homma K, Kiyono Y, Horie T (2009) Biochar amendment techniques for upland rice production in Northern Laos: 1. Soil physical properties, leaf SPAD and grain yield. Field Crops Res 111(1–2):81–84

Barnes RT, Gallagher ME, Masiello CA, Liu Z, Dugan B (2014) Biochar-induced changes in soil hydraulic conductivity and dissolved nutrient fluxes constrained by laboratory experiments. PLoS ONE 9(9):e108340. https://doi.org/10.1371/journal.pone.0108340

Blanco-Canqui H (2017) Biochar and soil physical properties. Soil Sci Soc Am J 81(4):687–711. https://doi.org/10.2136/sssaj2017.01.0017

Bohara H, Dodla S, Wang JJ, Darapuneni M, Acharya BS, Magdi S, Pavuluri K (2019) Influence of poultry litter and biochar on soil water dynamics and nutrient leaching from a very fine sandy loam soil. Soil Tillage Res 189:44–51. https://doi.org/10.1016/j.still.2019.01.001

Bordoloi S, Hussain R, Garg A, Sreedeep S, Zhou WH (2017) Infiltration characteristics of natural fiber reinforced soil. Transp Geotech 12:37–44. https://doi.org/10.1016/j.trgeo.2017.08.007

Bordoloi S, Garg A, Sreedeep S, Lin P, Mei G (2018) Investigation of cracking and water availability of soil-biochar composite synthesized from invasive weed water hyacinth. Biores Technol 263:665–677. https://doi.org/10.1016/j.biortech.2018.05.011

Bordoloi S, Gopal P, Boddu R, Wang Q, Cheng YF, Garg A, Sreedeep S (2019a) Soil-biochar-water interactions: role of biochar from *Eichhornia crassipes* in influencing crack propagation and suction in unsaturated soils. J Clean Prod 210:847–859. https://doi.org/10.1016/j.jclepro.2018.11.051

Bordoloi S, Yamsani SK, Garg A, Sekharan S (2019b) Critical assessment of infiltration measurements for soils with varying fine content using a mini disk infiltrometer. J Test Eval 47(2):868–888. https://doi.org/10.1520/jte20170328

Brockhoff SR, Christians NE, Killorn RJ, Horton R, Davis DD (2010) Physical and mineral-nutrition properties of sand-based turfgrass root zones amended with biochar. Agron J 102(6):1627–1631. https://doi.org/10.2134/agronj2010.0188

Brooks RH, Corey AT (1964). Hydraulic properties of porous media. Hydrology papers (Colorado State University); Paper no. 3

Burdine NT, Gournay LS, Reichertz PP (1950) Pore size distribution of petroleum reservoir rocks. J Petrol Technol 2(7):195–204. https://doi.org/10.2118/950195-g

Busscher WJ, Novak JM, Evans DE, Watts DW, Niandou MAS, Ahmedna M (2010) Influence of pecan biochar on physical properties of a Norfolk loamy sand. Soil Sci 175(1):10–14. https://doi.org/10.1097/SS.0b013e3181cb7f46

Cobos, D.R., Chambers, C., 2010. Calibrating ECH2O soil moisture sensors, Application Note. Decagon Devices, Pullman, WA.
Das O, Sarmah AK (2015) The love–hate relationship of pyrolysis biochar and water: a perspective. Sci Total Environ 512:682–685
Das BM (2019) Advanced soil mechanics. CRC Press, Boca Raton, pp 170–175
Edeh IG, Mašek O, Buss W (2020) A meta-analysis on biochar's effects on soil water properties–New insights and future research challenges. Sci Total Environ 714:136857
Faybishenko BA (1995) Hydraulic behavior of quasi-saturated soils in the presence of entrapped air: laboratory experiments. Water Resour Res 31(10):2421–2435
Gadi VK, Bordoloi S, Garg A, Sahoo L, Berretta C, Sekharan S (2017a) Effect of shoot parameters on cracking in vegetated soil. Environmental Geotechnics 5(2):123–130. https://doi.org/10.1680/jenge.17.00013
Gadi VK, Tang YR, Das A, Monga C, Garg A, Berretta C, Sahoo L (2017b) Spatial and temporal variation of hydraulic conductivity and vegetation growth in green infrastructures using infiltrometer and visual technique. CATENA 155:20–29. https://doi.org/10.1016/j.catena.2017.02.024
Gámiz B, Velarde P, Spokas KA, Hermosín MC, Cox L (2017) Biochar soil additions affect herbicide fate: importance of application timing and feedstock species. J Agric Food Chem 65(15):3109–3117. https://doi.org/10.1021/acs.jafc.7b00458.s001
Gan L, Garg A, Wang H, Mei G, Liu J (2021) Influence of biochar amendment on stormwater management in green roofs: experiment with numerical investigation. Acta Geophysica 69:2417–2426. https://doi.org/10.1007/s11600-021-00685-4
Ganesan SP, Bordoloi S, Ni J, Sizmur T, Garg A, Sekharan S (2020) Exploring implication of variation in biochar production on geotechnical properties of soil. Biomass Convers Biorefinery. https://doi.org/10.1007/s13399-020-00847-2
Garg A, Huang H, Kushvaha V, Madhushri P, Kamchoom V, Wani I, Koshy N, Zhu HH (2020) Mechanism of biochar soil pore-gas-water interaction: gas properties of biochar-amended sandy soil at different degrees of compaction using KNN modeling. Acta Geophys 68(1):207–217. https://doi.org/10.1007/s11600-019-00387-y
Githinji L (2014) Effect of biochar application rate on soil physical and hydraulic properties of a sandy loam. Arch Agron Soil Sci 60(4):457–470. https://doi.org/10.1080/03650340.2013.821698
Głąb T, Palmowska J, Zaleski T, Gondek K (2016) Effect of biochar application on soil hydrological properties and physical quality of sandy soil. Geoderma 281:11–20. https://doi.org/10.1016/j.geoderma.2016.06.028
Gopal P, Bordoloi S, Ratnam R, Lin P, Cai W, Buragohain P, Garg A, Sreedeep S (2019) Investigation of infiltration rate for soil-biochar composites of water hyacinth. Acta Geophys 67(1):231–246. https://doi.org/10.1007/s11600-018-0237-8
Hillel D (1998) Environmental soil physics. Academic Press, San Diego, p 771
Huang S, Barbour SL, Fredlund DG (1998) Development and verification of a coefficient of permeability function for a deformable unsaturated soil. Can Geotech J 35(3):411–425. https://doi.org/10.1139/t98-010
Huang S (1994) Evaluation and laboratory measurement of the coefficient of permeability in deformable, unsaturated soils. Doctoral dissertation, University of Saskatchewan
Ibrahim H, Al-wabel M, Usman A, Al-omran A (2013) Effect of Conocarpus biochar application on the hydraulic properties of a sandy loam soil. Soil Sci 178(4):165–173. https://doi.org/10.1097/SS.0b013e3182979ea
Jačka L, Trakal L, Ouředníček P, Pohořelý M, Šípek V (2018) Biochar presence in soil significantly decreased saturated hydraulic conductivity due to swelling. Soil and Tillage Research 184:181–185. https://doi.org/10.1016/j.still.2018.07.018
Jien SH, Wang CS (2013) Effects of biochar on soil properties and erosion potential in a highly weathered soil. CATENA 110:225–233. https://doi.org/10.1016/j.catena.2013.06.021
Kameyama K, Miyamoto T, Shiono T (2014) Influence of biochar incorporation on TDR-based soil water content measurements. Eur J Soil Sci 65(1):105–112. https://doi.org/10.1111/ejss.12083
Kozeny J (1927) Uber kapillare leitung der wasser in boden. Royal Academy of Science, Vienna. Proc Class I 136:271–306
Kumar H, Ganesan SP, Bordoloi S, Sreedeep S, Lin P, Mei G, Garg A, Sarmah AK (2019) Erodibility assessment of compacted biochar amended soil for geo-environmental applications. Sci Total Environ 672:698–707. https://doi.org/10.1016/j.scitotenv.2019.03.417
Kutílek M, Nielsen DR (1994) Soil hydrology. Catena Verlag, Cremlingen - Destedt, Germany, p. 370
Laird DA, Fleming P, Davis DD, Horton R, Wang B, Karlen DL (2010) Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158(3–4):443–449. https://doi.org/10.1016/j.geoderma.2010.05.013
Laliberte, G.E., Corey, A.T., Brooks, R.H., 1966. Properties of unsaturated porous media. Hydrology papers (Colorado State University); no. 17.
Li JH, Zhang LM, Wang Y, Fredlund DG (2009) Permeability tensor and representative elementary volume of saturated cracked soil. Can Geotech J 46(8):928–942. https://doi.org/10.1139/t09-037
Lim TJ, Spokas KA, Feyereisen G, Novak JM (2016) Predicting the impact of biochar additions on soil hydraulic properties. Chemosphere 142:136–144. https://doi.org/10.1016/j.chemosphere.2015.06.069
Liu Z, Dugan B, Masiello CA, Barnes RT, Gallagher ME, Gonnermann H (2016) Impacts of biochar concentration and particle size on hydraulic conductivity and DOC leaching of biochar–sand mixtures. J Hydrol 533:461–472. https://doi.org/10.1016/j.jhydrol.2015.12.007
Mei G, Kumar H, Huang H, Cai W, Reddy NG, Chen P, Garg A, Ganeshan SP (2020) Desiccation cracks mitigation using biomass derived carbon produced from aquatic species in South China Sea. Waste Biomass Valorization. https://doi.org/10.1007/s12649-020-01057-7
Meyer S, Glaser B, Quicker P (2011) Technical, economical, and climate-related aspects of biochar production technologies: a literature review. Environ Sci Technol 45(22):9473–9483. https://doi.org/10.1021/es201792c
Mualem Y (1978) Hydraulic conductivity of unsaturated porous media: generalized macroscopic approach. Water Resour Res 14(2):325–334. https://doi.org/10.1029/wr014i002p00325
Mualem, Y., 1986. Hydraulic conductivity of unsaturated soils: prediction and formulas. Methods of Soil Analysis: Part 1 Physical and Mineralogical Methods, 5, 799–823. https://doi.org/10.2136/sssabookser5.1.2ed.c31
Ng CWW, Wong HN, Tse YM, Pappin JW, Sun HW, Millis SW, Leung AK (2011) A field study of stress-dependent soil–water characteristic curves and permeability of a saprolitic slope in Hong Kong. Geotechnique 61(6):511–521
Ni JJ, Bordoloi S, Shao W, Garg A, Xu G, Sarmah AK (2020) Two-year evaluation of hydraulic properties of biochar-amended vegetated soil for application in landfill cover system. Sci Total Environ 712:136486. https://doi.org/10.1016/j.scitotenv.2019.136486
Novak J, Sigua G, Watts D, Cantrell K, Shumaker P, Szogi A, Johnson MG, Spokas K (2016) Biochars impact on water infiltration and water quality through a compacted subsoil layer. Chemosphere 142:160–167. https://doi.org/10.1016/j.chemosphere.2015.06.038
Ouyang L, Wang F, Tang J, Yu L, Zhang R (2013) Effects of biochar amendment on soil aggregates and hydraulic properties. J Soil Sci Plant Nutr 13(4):991–1002. https://doi.org/10.4067/s0718-95162013005000078
Prober SM, Stol J, Piper M, Gupta V, Cunningham SA (2014) Enhancing soil biophysical condition for climate-resilient restoration in mesic woodlands. Ecol Eng 71:246–255. https://doi.org/10.1016/j.ecoleng.2014.07.019
Reddy KR, Yaghoubi P, Yukselen-Aksoy Y (2015) Effects of biochar amendment on geotechnical properties of landfill cover soil. Waste Manage Res 33(6):524–532. https://doi.org/10.1177/0734242x15580192
Rogovska N, Laird DA, Rathke SJ, Karlen DL (2014) Biochar impact on midwestern mollisols and maize nutrient availability. Geoderma 230:340–347. https://doi.org/10.1016/j.geoderma.2014.04.009
Saha A, Sekharan S, Manna U (2020) Evaluation of capacitance sensor for suction measurement in silty clay loam. Geotech Geol Eng 38:4319–4331. https://doi.org/10.1007/s10706-020-01297-3
Sillers WS, Fredlund DG (2001) Statistical assessment of soil-water characteristic curve models for geotechnical engineering. Can Geotech J 38(6):1297–1313. https://doi.org/10.1139/t01-066
Soil Survey Staff. 2004. Soil survey laboratory methods manual, Soil Survey Investigations Report No. 42, U.S. Department of Agriculture, Natural Resources Conservation Service, National Soil Survey Center
Starr JL, Paltineanu IC (2002) Methods for measurement of soil water content: capacitance devices. Methods of soil analysis: Part, 4.
Sun WJ, Li MY, Zhang WJ, Tan YZ (2020) Saturated permeability behavior of biochar-amended clay. J Soils Sediments. https://doi.org/10.1007/s11368-020-02720-1

Thorbjørn A, Moldrup P, Blendstrup H, Komatsu T, Rolston DE (2008) A gas diffusivity model based on air-, solid-, and water-phase resistance in variably saturated soil. Vadose Zone J 7(4):1276–1286. https://doi.org/10.2136/vzj2008.0023

Tian D, Qu Z, Gou M, Li B, Lv Y (2015) Experimental study of influence of biochar on different texture soil hydraulic characteristic parameters and moisture holding properties. Polish J Environ Stud 24(3):1435–1442. https://doi.org/10.11606/t.11.2019.tde-03092019-151945

Uzoma KC, Inoue M, Andry H, Zahoor A, Nishihara E (2011) Influence of biochar application on sandy soil hydraulic properties and nutrient retention. J Food Agric Environ 9(3/4):1137–1143

Wang D, Li C, Parikh SJ, Scow KM (2019) Impact of biochar on water retention of two agricultural soils–A multi-scale analysis. Geoderma 340:185–191. https://doi.org/10.1016/j.geoderma.2019.01.012

Wani I, Sharma A, Kushvaha V, Madhushri P, Peng L (2020) Effect of pH, volatile content, and pyrolysis conditions on surface area and O/C and H/C ratios of biochar: towards understanding performance of biochar using simplified approach. J Hazard Toxic Radioactive Waste 24(4):04020048. https://doi.org/10.1061/(asce)hz.2153-5515.0000545

Wong JTF, Chen Z, Wong AYY, Ng CWW, Wong MH (2018) Effects of biochar on hydraulic conductivity of compacted kaolin clay. Environ Pollut 234:468–472. https://doi.org/10.1016/j.envpol.2017.11.079

Wyllie MRJ, Gardner GHF (1958) The generalized Kozeny-Carman equation. Part 2. A novel approach to problems of fluid flow. World Oil 146(5):210–228

Xiao Q, Zhu LX, Shen YF, Li SQ (2016) Sensitivity of soil water retention and availability to biochar addition in rainfed semi-arid farmland during a three-year field experiment. Field Crop Res 196:284–293. https://doi.org/10.1016/j.fcr.2016.07.014

Yaghoubi, P., 2011. Development of biochar-amended landfill cover for landfill gas mitigation. Doctoral dissertation, University of Illinois.

Zhang J, Chen Q, You C (2016) Biochar effect on water evaporation and hydraulic conductivity in sandy soil. Pedosphere 26(2):265–272. https://doi.org/10.1016/S1002-0160(15)60041-8

Zhang Y, Gu K, Tang C, Shen Z, Narala GR, Shi B (2020) Effects of biochar on the compression and swelling characteristics of clayey soils. Int J Geosynthet Ground Eng 6:1–8. https://doi.org/10.1007/s40891-020-00206-1