



# Effect of wettable and hydrophobic biochar addition on properties of sandy soil

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## Abstract

Sandy soils have high hydraulic conductivity and low retention ability for water and nutrients, resulting in low fertility. As water retention of coarse-textured soil is substantially more sensitive to the amount of organic carbon than fine-textured soils, the amendment of sandy soils with biochar is often used. The objective of this study was to find the effect of water-repellent and wettable biochar addition on the porosity,  $P$ , saturated hydraulic conductivity,  $K_s$ , soil water retention curves, SWRC, plant available water content, AWC, water drop penetration time, WDPT and contact angle, CA of sandy soil. It was observed that biochar addition led to a significant increase in both  $P$  and AWC in all treatments, indicating a positive impact on soil water retention. The water-repellent biochar addition led to the statistically significant decrease in  $K_s$ , caused by the water-repellent biochar particles between the sand grains preventing water movement in the soil. The wettable biochar addition led to a statistically insignificant decrease in  $K_s$ . The addition of very strongly and extremely water-repellent biochar induced slight severity of water repellency ( $40^\circ \leq CA < 90^\circ$ ) and did not induce persistence of water repellency (WDPT < 5 s) in the biochar-soil mixture. After an addition of wettable biochar, the biochar-soil mixtures were wettable. A relation between the  $K_s$  and CA in sandy soil amended with wettable and hydrophobic biochars was found, which is a novelty of our study.

**Keywords** Biochar · Hydro-physical properties · Sandy soil · Soil water repellency

## Introduction

Sandy soils have high hydraulic conductivity and low retention ability for water and nutrients, so they have low fertility. Many plants have problems surviving in them due to the increased frequency and severity of drought, which can be attributed to increased variability in precipitation and enhanced water loss due to warming (Chen et al. 2018; Li et al. 2021). As water retention of coarse-textured soil is substantially more sensitive to the amount of organic carbon compared to fine-textured soils, the amendment of sandy soils with biochar is often used (Liu et al. 2016).

Biochar is frequently added to the soil for various reasons, including carbon sequestration, greenhouse gas mitigation, improved crop production by boosting soil fertility, removing harmful contaminants, and drought mitigation (Bhat et al. 2022). Biochar alters soil hydraulic properties (which include soil water retention and hydraulic conductivity) by changing the physical and chemical characteristics of the soil. Biochar addition can increase porosity,  $P$  (Trifunovic et al. 2018; Alotaibi and Schoenau 2019), and decrease the bulk density, of sandy soil (Chen et al. 2018; Alotaibi and Schoenau 2019; Pu et al. 2019). Verheijen et al. (2019) found biochar to decrease the bulk density of sandy soil even at an application rate of 1% vol. However, Alessandrino et al. (2022) found no significant effects of biochar application on the porosity,  $P$ , of sandy soil.

The addition of biochar to soil can have several positive effects also on biological parameters, particularly in acidic or contaminated soils (Paz-Ferreiro et al. 2016; Yu et al. 2019). Biochar can enhance the activity of enzymes and microbial biomass, as well as increase soil respiration (Sun et al. 2014; Khadem and Raiesi 2017; Beheshti et al. 2018; Ojeda

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et al. 2024). Additionally, biochar amendment can promote mycorrhizal colonization of plant roots, increase the abundance of bacteria and viruses in soil, and improve microbial community stability (Solaiman et al. 2010; Anderson et al. 2011; Lehmann et al. 2011; Sasidharan et al. 2016). Furthermore, biochar can help plants develop systemic resistance against foliar diseases and prevent plant parasitic nematodes in soils (Meller Harel et al. 2012; Mehari et al. 2015; Domene et al. 2021).

Saturated hydraulic conductivity,  $K_s$ , describes the ease with which water can move through saturated porous media. Ajayi et al. (2016), Barnes et al. (2014), and Zhang et al. (2016) found that the  $K_s$  of sandy soil gradually decreased with the increasing ratios of added biochar, which can be attributed either to the water-repellent nature of biochar or to the infilling of large water-conducting pores with biochar. However, Jeffery et al. (2015), Wiersma et al. (2020), and Alessandrino et al. (2022) found no significant effects of biochar application on the  $K_s$  of sandy soil.

Due to its porous structure, biochar can modify the water retention curve of soil. Trifunovic et al. (2018) found that biochar can either decrease (clog) or increase pore spaces in the mixture based on the quantity of fine biochar fraction, which in turn could decrease or increase the hydraulic conductivity of the mixture. Chen et al. (2018) revealed that biochar application increased the water contents of sandy soil at saturation and field capacity, and these characteristic water contents increased with the increase in biochar application rate.

Hlaváčiková et al. (2019) observed a significant increase in the volume of water in macropores (by 1.3% and 2.3% at amendment rates of 3.6 and 7.3% w/w, respectively) and storage pores (by 3.3% at amendment rate of 7.3% w/w) in the silica sand amended with biochar. It should be mentioned that storage pores in the soil greatly contribute to the available water content, whereas macropores and transmission pores enhance soil structure and aeration. Jeffery et al. (2015) found no significant effects of biochar application on soil water retention. They postulated that the strong hydrophobicity of biochar prevented water from infiltrating into the biochar particles, prohibiting an effect on soil water retention. As a result, biochars should be analyzed for hydrophobicity when assessing their potential for improving soil physical properties.

The plant available water content, AWC, is the difference between the field capacity and the permanent wilting point, and its change due to biochar addition depends on the type of biochar feedstock and pyrolysis conditions (Głab et al. 2016; Tomczyk et al. 2020). Abel et al. (2013), Manickam et al. (2015), and Pu et al. (2019) found an increase in AWC in sandy soils. However, Jeffery et al. (2015) and Wiersma et al. (2020) found no significant effects of biochar application

on AWC in sandy soil. Botková et al. (2023) found that the application of 1% w/w of biochar had a significant effect on the AWC of sandy soil, with the effect varying based on the fraction size of the biochar. However, they did not confirm any effect of biochar type on AWC.

Soil water repellency (SWR) reduces the affinity of soils to water such that they resist wetting for periods ranging from a few seconds to hours, days or weeks (Doerr et al. 2000). The most significant hydrological impacts of SWR include reduced infiltration and increased overland flow (Holko et al. 2023), spatially localized infiltration and/or percolation, often with fingered flow development (Lichner et al. 2018). Bubicic et al. (2016) stated that biochar produced at high temperatures has the highest water repellency due to aromaticity. In contrast, Kinney et al. (2012), Zornoza et al. (2016), and Li et al. (2021) reported that biochar water repellency decreases with increasing pyrolysis temperature and disappears when the peak pyrolysis temperature reaches a threshold level. The type of feedstock and pretreatment procedures may also affect the degree of biochar water repellency (Kinney et al. 2012; Zornoza et al. 2016).

The persistence and severity of SWR are usually quantified by water drop penetration time, WDPT, and soil-water contact angle, CA, respectively. Steenhuis et al. (2005) demonstrated that a few hydrophobic grains (5.5%) could already prevent water entry into the soil. Kinney et al. (2012) reported that the WDPT of sandy soil increased from < 1 s to 61–870 s after 2–7% biochar application, which is in line with the Steenhuis et al. (2005) findings. Abel et al. (2013) found no significant decrease in WDPT for moderately to strongly water-repellent soil mixed with strongly water-repellent biochar. On the other hand, Wiersma et al. (2020) reported that sandy soil remained wettable after an application of strongly to severely water-repellent biochar.

Liu et al. (2022) found that SWR increased with biochar-application rate. In contrast, the biochar particle size (> 1 mm or < 1 mm) had no significant effect on SWR. However, an increase in CA after biochar application must be taken into account because a slight increase in CA will have a remarkable effect on soil water movement, even if it is < 90° (Wang and Wallach 2021).

The objective of our study was to find the effect of water-repellent and wettable biochars on the  $P$ ,  $K_s$ , AWC, WDPT, and CA of sandy soil. Our primary hypothesis was that the water-repellent biochar should induce water repellency in sandy soil and statistically significant changes in the  $P$ ,  $K_s$ , AWC, WDPT, and CA of sandy soil. Our secondary hypothesis was that wettable biochar addition should not induce significant changes in WDPT and CA but would significantly change the  $P$ ,  $K_s$ , and AWC compared to the Control (= unamended sandy soil).

## Materials and methods

### Experimental setup

During our experiment, we conducted tests on three types of biochar and sandy soil under controlled laboratory conditions. Disturbed samples of sandy soil were collected from the study site near Plavecký Štvrtok in the Záhorská nížina lowland (western Slovakia) (48°21'58.33" N, 16°59'49.23" E, elevation 157 m a. s. l.). The study site is situated in a region with a temperate oceanic climate (Cfb) (Kottek et al. 2006). The mean annual temperature is 9 °C, and the mean annual precipitation is 600 mm, with most rainfall occurring during the summer season. The soil is classified as Arenosol and has a sandy texture (WRB 2015), with 91% sand, 7.5% silt, and 1.5% clay. The pH (H<sub>2</sub>O) of the soil is 6.84, and it contains 0.04% of organic carbon. The low organic carbon content affects the adsorptive properties of soil. However, there is significant potential for improvement by applying organic soil conditioners, which can increase organic matter content and enhance adsorption, nutrient retention, and overall soil fertility and health.

We used three different types of biochar produced from different feedstock materials and at various pyrolysis temperatures. The first and second biochars were produced from the Swedish biomass willow variety (*Salix viminalis x schwerinii* var. Tordis) and formed at 300 °C and 520 °C (hereafter referred to as B300 and B520, respectively) in the UNYPIR reactor in the AgroBioTech centre at the Slovak University of Agriculture, Nitra, Slovakia. The third biochar was produced from a mix of paper fiber sludge and grain husks and formed at 550 °C (hereafter referred to as B550) in the PYREG reactor by the Sonnenerde company, Riedlingsdorf, Austria.

Table 1 provides an overview of the basic properties of three different biochars. The pH (H<sub>2</sub>O) was determined according to ISO 10,523 (2008), and elemental analysis of biochar carbon (C), hydrogen (H) and nitrogen (N) was performed using a CHNSO elemental analyzer (Perkin Elmer, Inc., Waltham, MA, USA), water drop penetration time test (WDPT) was measured based on the methodology described by Doerr (1998) and Tinebra et al. (2019) and contact angle (CA) was determined by reviewing the image recordings taken with the optical goniometer OCA 11 (DataPhysics Instruments GmbH, Filderstadt, Germany).

The first two biochars exhibit hydrophobic characteristics, whereas the third biochar is wettable. The chemical analysis of three biochars, B300, B520, and B550, revealed minor differences in their composition. Biochars B300 and B520 showed higher carbon content compared to B550, which indicates their potential for stable carbon sequestration. In terms of hydrogen content, B300 and B520 had relatively higher percentages than B550. On the other hand, biochar B550 had slightly higher nitrogen content, indicating the potential for better nutrient availability compared to B300 and B520.

The soil was carefully sifted to a fraction with a particle diameter of 2 mm or less. All biochars used in the experiment were ground with a hammer mill and then sifted to obtain a fraction with particle diameters ranging from 125 µm to 2 mm. A 125 µm to 2 mm fraction of biochar was used to prepare the biochar-soil mixtures, and the application rate was 1% w/w. The soil and biochar-soil mixtures were placed in steel cylinders with a volume of 100 cm<sup>3</sup> and a target bulk density of 1.6 g cm<sup>-1</sup> (Control) and 1.57 g cm<sup>-1</sup> (biochar-soil mixtures). Four treatments, including a Control treatment with sandy soil and three biochar-soil mixture treatments (SB300, SB520, and SB550), were prepared in the laboratory, and five replicates were made for each treatment.

### Measurement of hydro-physical parameters

The soil particle density is the weight of the solid soil phase per unit volume, measured by the pycnometric method (Blake and Hartge 1986) and computed as:

$$\rho_s = \frac{m_s}{V_s} \tag{1}$$

where  $\rho_s$ – soil/mixture particle density (g cm<sup>-3</sup>),  $m_s$ – the weight of dried fine soil/mixture (g),  $V_s$ – the volume of water displaced by the soil/mixture (cm<sup>3</sup>).

The bulk density of the soil is the portion of the weight of the soil sample or biocharsoil mixture dried at 105 °C and its volume. The bulk density of dry soil/mixture was determined based on the equation (Jury et al. 1991):

$$\rho_d = \frac{m_s}{V} \tag{2}$$

**Table 1** Characteristics of biochar (C– carbon content, H– hydrogen content, N– nitrogen content, WDPT– water drop penetration time, CA– contact angle)

Biochar	Product of origin	C [%] NR=3	H [%] NR=3	N[%] NR=3	WDPT [s] NR=5	CA [°] NR=5
B300	willow	82.2	2.74	0.86	12609.5 <sup>a</sup>	115.56 <sup>a</sup>
B520	willow	83.1	2.21	1.19	12613.8 <sup>a</sup>	128.30 <sup>b</sup>
B550	fiber sludge and grain husks	53.1	1.84	1.4	1.75 <sup>b</sup>	27.77 <sup>c</sup>

where  $\rho_d$ – bulk density ( $\text{g cm}^{-3}$ ),  $m_s$ – the weight of soil/mixture sample dried at  $105\text{ }^\circ\text{C}$  (g),  $V$ – steel cylinder volume ( $\text{cm}^3$ ).

The total porosity of the soil/mixture was calculated based on the equation (Danielson and Sutherland 1986):

$$p = \frac{\rho_s - \rho_d}{\rho_s} 100 \tag{3}$$

where  $P$ – porosity (%),  $\rho_s$ – soil/mixture particle density ( $\text{g cm}^{-3}$ ),  $\rho_d$ – bulk density of the soil/mixture ( $\text{g cm}^{-3}$ ).

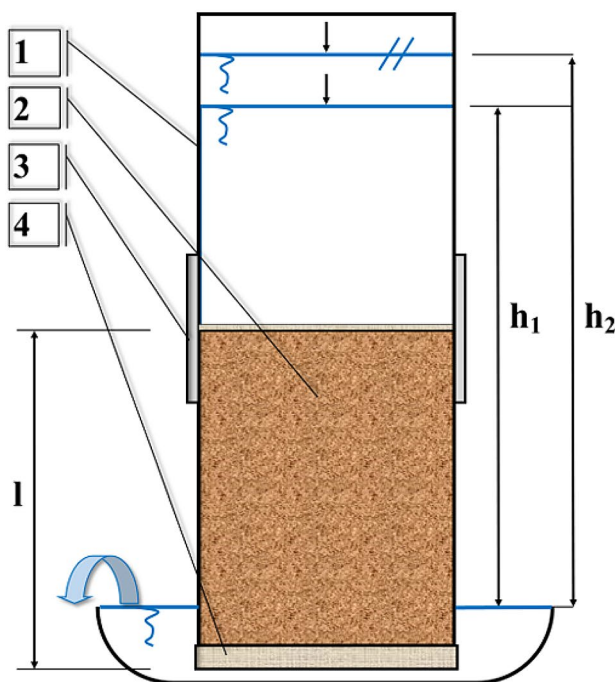
The saturated hydraulic conductivity,  $K_s$ , of the soil/mixture was determined using a falling-head method (modified by Novák and Hlaváčiková 2019) (Fig. 1), and calculated using Eq. 4:

$$K_s = \frac{L}{t} \ln \frac{h_2}{h_1} \tag{4}$$

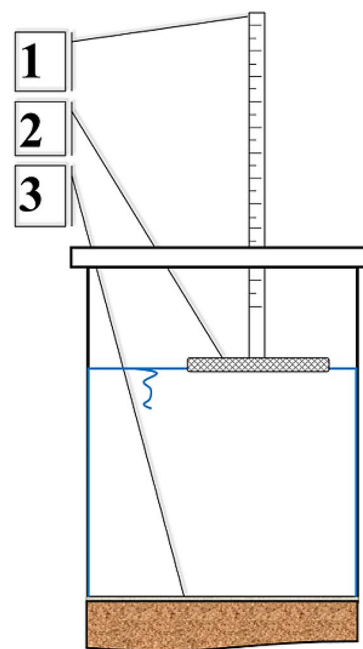
where  $L$ – soil/mixture core height (cm),  $h_2$ – the initial water level (cm),  $h_1$ – the water level at the end of the measurement,  $t$ – time for the water level to decrease from  $h_2$  to  $h_1$  (s).

The soil water retention curves were measured with the pressure plate apparatus (Soil Moisture Equipment Corp., Santa Barbara, CA, USA) according to ISO 11,274 (2019). All measured samples of soil and biochar-soil mixtures were weighed, fully saturated with water, and moved to the pressure plate apparatus, which was hermetically sealed using a screw system. Air was supplied to the apparatus through a system of regulating manometers, which allows for setting and maintaining constant air pressure. Water flowed from the samples placed in the pressure plate apparatus at a defined constant air pressure. A total of 9 measurement points were used at pressure potentials of 0, 6, 10, 30, 56, 100, 300, 480, and 1500 kPa. When the water flow from the samples stopped, the air was released from the apparatus, and the samples were removed and weighed. Based on measured data, the water retention curve values were fitted using the unimodal van Genuchten (1980) model as follows:

a)



b)



**Fig. 1** Measurement of saturated hydraulic conductivity through modified falling head method (modified by Novák and Hlaváčiková 2019). (a) Schematic sketch. 1 = connected steel cylinder; 2 = saturated undis-

turbed soil core; 3 = rubber sealing; 4 = cloth sealing. (b) Detail of the water level reading. 1 = scale; 2 = floater; 3 = infiltration paper

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (\alpha |h|)^m]^{-m} \quad (5)$$

where  $\theta$ ,  $\theta_r$ , and  $\theta_s$  are the actual, residual, and saturated volumetric water content, respectively,  $h$  is matric potential,  $m$  and  $n$  are water retention shape parameters, and  $\alpha$  is the parameter describing the matric potential of air entry.

The hydrolimits (soil water content at field capacity and permanent wilting point) for each sample were determined from the soil water retention curve, and the average available water content for plants, AWC, value for each treatment was used for statistical analysis.

The contact angle, CA, is a measure of the severity of SWR. The sessile drop method, used for the CA estimation, involved placing a water drop on the soil sample's surface and analyzing the static contact angle, CA, by reviewing the image recordings taken with the optical goniometer OCA 11 (DataPhysics Instruments GmbH, Filderstadt, Germany). The procedure described by Bachmann et al. (2000) was used to prepare the samples. It involved covering a glass slide with double-sided adhesive tape and pressing soil particles onto the tape for several seconds. The slide was shaken carefully to remove any unglued soil particles, and then a 5- $\mu$ L drop of deionized water was placed on the sample surface using a 0.91 mm syringe needle. After 1 s when mechanical disruption of the surface was complete after drop placement, CA was evaluated by analyzing the shape of the drop (ellipsoid approximation) and fitting tangents on both sides of the drop using dpiMAX version 1.51.90.75 software (DataPhysics Instruments GmbH, Filderstadt, Germany) according to Goebel et al. (2013). CA of each drop was determined as an arithmetic mean of the CA values on the left and right sides. The following classes of the severity of SWR can be distinguished: non-water-repellent (wetable) soil ( $CA < 40^\circ$ ), slightly ( $40^\circ \leq CA < 90^\circ$ ), moderately ( $90^\circ \leq CA < 110^\circ$ ), strongly and very strongly ( $110^\circ \leq CA < 130^\circ$ ), and extremely ( $CA \geq 130^\circ$ ) water repellent soil (Papierowska et al. 2018). CA for each sample was estimated with five replicates.

The water drop penetration time, WDPT, test is a measure of the persistence of SWR. Estimation of WDPT involves placing  $50 \pm 5 \mu$ L of a drop of water from a standard dropper or pipette on the soil/mixture surface and recording the time of its complete penetration (infiltration) into the soil/mixture. An average drop release height of approximately 10 mm above the soil/mixture surface was used to minimize the cratering effect on the soil/mixture surface (Doerr 1998; Tinebra et al. 2019). The following classes of the persistence of SWR were then distinguished: wettable or non-water-repellent soil ( $WDPT < 5$  s), slightly ( $5 \text{ s} \leq WDPT < 60$  s), strongly ( $60 \text{ s} \leq WDPT < 600$  s), severely ( $600 \text{ s} \leq WDPT < 3600$  s), and extremely ( $WDPT \geq 3600$  s) water repellent soil (Bisdorn et al. 1993).

## Statistical analysis

The data was analyzed using the omnibus normality test, which combines skewness and kurtosis tests. If the data passed the omnibus normality test, differences between parameters were evaluated using single-factor ANOVA with Tukey's Honest Significant Difference (HSD) post-hoc test. When the data did not follow a normal distribution, the Kruskal-Wallis test with multiple comparison Kruskal-Wallis Z test was employed. Normality assumption is not necessary for this distribution-free multiple comparison. This is meant for testing the pairs of medians after conducting the Kruskal-Wallis test. The statistical significance of the analysis was defined at  $p < 0.05$ . All statistical analyses were performed using the NCSS statistical software (NCSS 12 Statistical Software 2023).

## Results

The impact of wettable (SB550) and water-repellent (SB300, SB520) biochar addition on sandy soil properties is presented in Table 2; Figs. 2 and 3. A significant increase in sandy soil porosity,  $P$ , was revealed in all biochar treatments compared to Control (Fig. 2a), which confirms our first and second hypotheses. The lowest  $P$  value of biochar-treated soil ( $P = 0.398$ ) was estimated for the water-repellent (SB520) biochar treatment (Table 2).

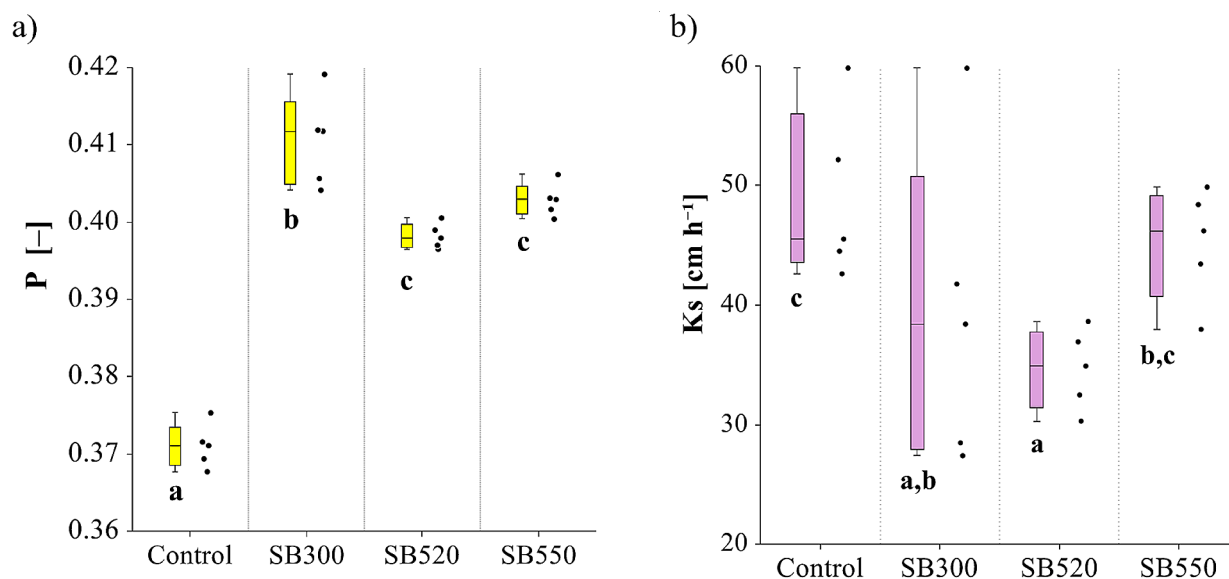
A statistically significant decrease in the  $K_s$  in sandy soil due to the addition of biochar was found for the water-repellent (SB300, SB520) biochar treatments (Fig. 2b), confirming our first hypothesis. In the wettable (SB550) biochar treatment, the mean  $K_s$  decreased compared with the Control, but the statistically significant difference between the Control and SB550 treatment was not confirmed (Fig. 2b), which contradicts our second hypothesis. However, the addition of the water-repellent (SB520) biochar resulted in the lowest mean  $K_s$  value of  $34.65 \text{ cm h}^{-1}$  (Table 2).

Mean soil water retention curves, SWRCs, for each treatment are shown in Fig. 3. The SWRC shape differences between Control and biochar treatments are evident, especially from pF 1 and higher. The mean values of fitting parameters of the van Genuchten model (Eq. 5), soil water content at the permanent wilting point and saturated soil water content are listed in Table 3.

SWRC of the Control treatment differed from wettable and water-repellent biochar-treated samples (Fig. 3), which was proved by the significant difference between the  $n$  values of the Control and all other treatments (Table 3). We found a statistically significant difference in parameter  $\alpha$  between the Control and all biochar treatments and between SB520 with water-repellent biochar and SB550 with

**Table 2** Descriptive statistics of analyzed parameters (namely porosity,  $P$ , (-), saturated hydraulic conductivity,  $K_s$ , ( $\text{cm h}^{-1}$ ), available water content, AWC, (-), contact angle, CA, ( $^\circ$ ), and water drop penetration time, WDPT, (s)), estimated in Control and biochar treatments. (SD = standard deviation, NR = number of replicates)

Treatment	Attribute	Mean	Median	SD	Skewness	Kurtosis	NR
Control	$P$ [-]	0.371	0.371	0.003	0.482	2.236	5
	$K_s$ [ $\text{cm h}^{-1}$ ]	48.93	45.525	7.078	0.751	2.036	5
	AWC [-]	0.042	0.042	0.005	-0.734	2.397	5
	CA [ $^\circ$ ]	15.44	18.400	8.741	-1.406	3.125	5
	WDPT [s]	0	0	0	-	-	5
SB300	$P$ [-]	0.411	0.412	0.006	0.353	1.912	5
	$K_s$ [ $\text{cm h}^{-1}$ ]	39.18	38.408	13.104	0.741	2.271	5
	AWC [-]	0.073	0.071	0.006	1.336	3.070	5
	CA [ $^\circ$ ]	47.79	47.060	3.825	-0.042	1.818	5
	WDPT [s]	0.2	0	0.447	-	-	5
SB520	$P$ [-]	0.398	0.398	0.002	0.453	1.871	5
	$K_s$ [ $\text{cm h}^{-1}$ ]	34.65	34.900	3.347	-0.131	1.647	5
	AWC [-]	0.072	0.071	0.008	0.896	2.684	5
	CA [ $^\circ$ ]	60.06	58.015	7.121	0.845	2.284	5
	WDPT [s]	0.4	0	0.548	-	-	5
SB550	$P$ [-]	0.403	0.403	0.002	0.557	2.317	5
	$K_s$ [ $\text{cm h}^{-1}$ ]	45.180	46.211	4.703	-0.649	2.109	5
	AWC [-]	0.070	0.071	0.004	-0.193	1.451	5
	CA [ $^\circ$ ]	24.01	25.230	6.612	-0.295	1.504	5
	WDPT [s]	0	0	0	-	-	5



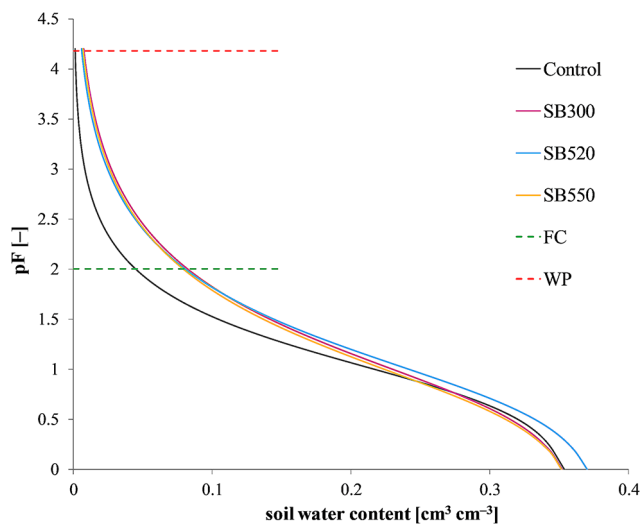
**Fig. 2** Measured values of (a) soil/mixture porosity,  $P$ , and (b) saturated hydraulic conductivity,  $K_s$ , with the points representing individual measurements. The rectangular part of the box plot is defined by two lines representing the 25th percentile and 75th percentile. The distance between the upper (75th percentile) and lower (25th percen-

tile) lines of the box is the interquartile range (IQR). A line inside the box represents the median (50th percentile). The whisker boundary is located at 1.5 times the IQR distance away from the edge of the box. Box plots with different letters are significantly different at a 0.05 significance level

wettable biochar. The permanent wilting point soil water content values ( $\theta_{WP}$ ) were significantly higher in all biochar treatments compared to the Control, while no significant difference between any of the biochar treatments was confirmed. Saturated soil water content ( $\theta_S$ ) was significantly higher in the water-repellent SB520 treatment compared

to the other biochar-treated samples and Control (Table 3). This increase is documented by the shift (towards higher water content values) of the SB520 soil water retention curve for values of pF 1.5 and lower.

A statistically significant increase in sandy soil AWC was revealed in all biochar treatments compared with the Control



**Fig. 3** Soil water retention curves, SWRCs, for each experimental treatment. FC is soil water content at the hydrolimit field capacity, and WP is soil water content at the hydrolimit permanent wilting point

(Fig. 3a), which confirms our first and second hypotheses. AWC increased from a value of  $0.0042 \text{ cm}^3 \text{ cm}^{-3}$  in Control to values around  $0.0070 \text{ cm}^3 \text{ cm}^{-3}$  in all biochar treatments.

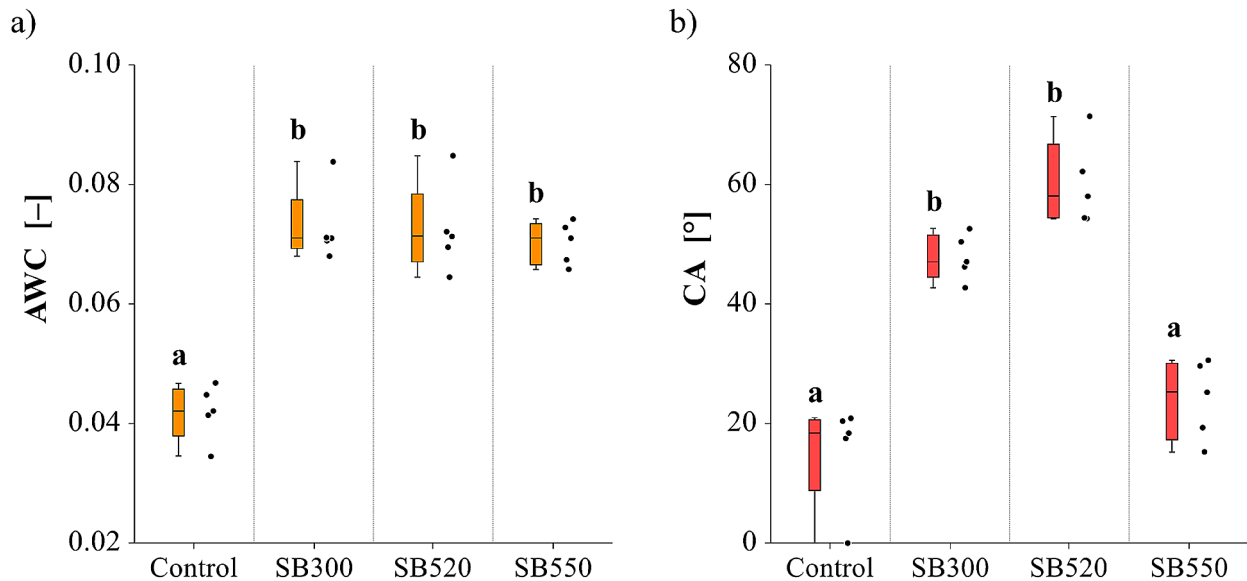
The WDPT values were  $< 5 \text{ s}$  in sandy soil and all biochar-treated samples, indicating wettable soils in terms of the persistence of water repellency. The values greater than  $0 \text{ s}$  were measured only in SB300 and SB520 treatments. As the water-repellent (B300, B520) biochar addition did not result in a statistically significant increase in WDPT, our first hypothesis was not confirmed. On the other hand, our second hypothesis was confirmed because the wettable (B550) biochar addition similarly did not induce statistically significant changes in WDPT.

A statistically significant increase in sandy soil CA was found in the water-repellent (SB300, SB520) biochar treatments compared with the Control (Fig. 4b), which confirms our first hypothesis. A statistically insignificant increase in sandy soil CA due to the biochar addition was found for the wettable (B550) biochar addition (Fig. 3b), which confirms

**Table 3** Values of fitting parameters of the van Genuchten model ( $\alpha$ ,  $n$ ), saturated soil water content and permanent wilting point soil water content for experimental treatments presented as mean values and standard deviations (in parentheses). Single-factor ANOVA with Tukey’s Honest Significant Difference (HSD) post-hoc test evaluated differences between Control means and biochar treatment means

	$n$ [-] NR=5	$\alpha$ [ $\text{l cm}^{-1}$ ] NR=5	$\theta_{\text{WP}}$ [ $\text{cm}^3 \text{ cm}^{-3}$ ] NR=5	$\theta_s$ [ $\text{cm}^3 \text{ cm}^{-3}$ ] NR=5
Control	1.76 (0.053) <sup>b</sup>	0.157 (0.015) <sup>a</sup>	0.0011 (0.0003) <sup>a</sup>	0.354 (0.005) <sup>a</sup>
SB300	1.49 (0.036) <sup>a</sup>	0.211 (0.015) <sup>b, c</sup>	0.0073 (0.0021) <sup>b</sup>	0.352 (0.008) <sup>a</sup>
SB520	1.52 (0.049) <sup>a</sup>	0.193 (0.014) <sup>b</sup>	0.0061 (0.0023) <sup>b</sup>	0.370 (0.001) <sup>b</sup>
SB550	1.49 (0.020) <sup>a</sup>	0.229 (0.020) <sup>c</sup>	0.0069 (0.0010) <sup>b</sup>	0.352 (0.005) <sup>a</sup>

Different letters indicate significant differences between samples ( $p < 0.05$ ). NR = number of replicates



**Fig. 4** Measured values and box plots of (a) available water content for plants, AWC, and (b) contact angle, CA, with the points representing individual measurements. The rectangular part of the box plot is defined by two lines representing the 25th percentile and 75th percentile. The distance between the upper (75th percentile) and lower

(25th percentile) lines of the box is the interquartile range (IQR). A line inside the box represents the median (50th percentile). The whisker boundary is located at 1.5 times the IQR distance away from the edge of the box. Box plots with different letters are significantly different at a 0.05 significance level

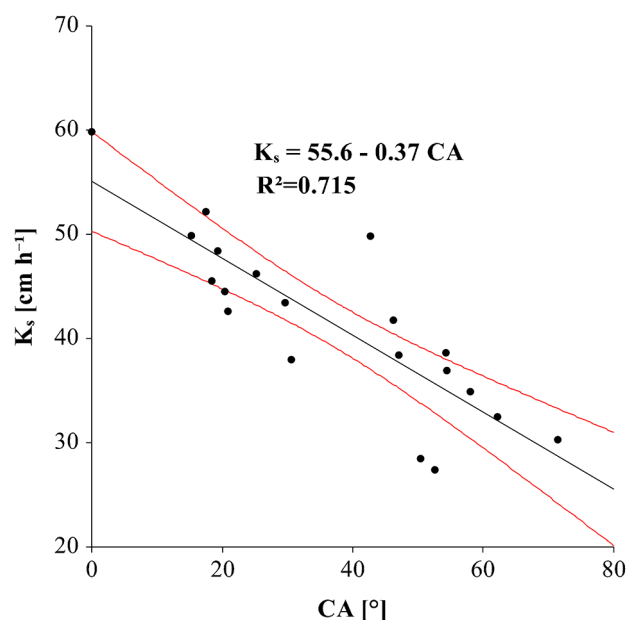
our second hypothesis. The greatest mean CA value of 60.06° was observed for the water-repellent (B520) biochar addition, which resulted in the smallest mean  $K_s$  value for the SB520 treatment (Table 2).

The relationship between  $K_s$  and CA was investigated using a dataset of twenty observations, as presented in Fig. 5. We were able to establish a regression equation that accurately represents this relationship. The coefficient of determination, calculated as 0.7148, indicates a strong dependence between  $K_s$  and CA. This relationship has not been reported in the literature that examines the effects of biochar on the characteristics of sandy soils, which makes it a novel finding of our study.

A powerful positive correlation was also identified between AWC and  $P$  ( $r=0.926$ ), emphasizing the direct relationship between plant-available water and pore space. A strong negative correlation was observed between  $K_s$  and AWC ( $r = -0.783$ ), and a moderate negative correlation was observed between  $K_s$  and  $P$  ( $r = -0.658$ ), respectively.

## Discussion

The results obtained in our study indicated that biochar application influenced the hydro-physical properties of sandy soil. We observed a significant increase in sandy soil porosity due to adding biochar in all treatments. The increase in  $P$  after the addition of biochar to sandy soil was



**Fig. 5** The relation between the saturated hydraulic conductivity,  $K_s$ , and contact angle, CA, in sandy soil amended with wettable and hydrophobic biochars. The black line displays the regression line, and the red lines represent the confidence limits (the upper and lower boundaries of a confidence interval of the mean at a specific value of X)

found by Głąb et al. (2016), who observed that small particles of biochar reduced the volume of soil pores with a diameter below 0.5  $\mu\text{m}$ , but increased the volume of larger pores with a diameter range of 0.5–500  $\mu\text{m}$ . While the increased porosity would usually lead to higher saturated hydraulic conductivity, the water-repellent nature of the biochar might obstruct water movement within these pores. Liu et al. (2016) also observed an increase in  $P$  after biochar addition to sandy soil and found that this increase depended on biochar concentration/rate.

We found a significant decrease in  $K_s$  in sandy soil amended with hydrophobic biochar compared to Control. In contrast, wettable biochar (SB550 treatment) did not induce significant changes in  $K_s$  in sandy soil compared to the Control. Liu et al. (2016) found that  $K_s$  decreased by  $72 \pm 3\%$  as biochar content increased from 0 to 10% w/w. Brockhoff et al. (2010) found that  $K_s$  in sandy soil decreased by 52% after the 5% v/v biochar application. On the contrary, Jeffery et al. (2015) found no significant effects of moderately hydrophobic biochar application on  $K_s$  in field experiments. The decrease in  $K_s$  may be explained by the hydrophobicity, which may affect flow at the pore scale, or pore clogging by finer biochar particles (Liu et al. 2016).

The biochar application in our experiment improved the water retention properties of sandy soil compared with the Control. The previous studies have produced conflicting results, with some finding a positive effect (Chen et al. 2018; Verheijen et al. 2019) and some finding no effect of biochar application on the shape of the SWRC of sandy soils (Jeffery et al. 2015). Abel et al. (2013) observed increased retention in the range between pF 2.5 and 4.2. We found that the differences between the SWRC of biochar treatments and Control appeared not only within a high matric potential range but also in a low range from pF 2 to 1, which is consistent with the results of Głąb et al. (2016). The obtained results of the SWRC measurements do not fully follow the measurements of porosity, as the shift of the SB520 retention curve for low pF values was not detected by a higher  $P$  value in SB520 (Fig. 2). The significant increase in  $\theta_s$  and water retention below pF 1 after application of most hydrophobic biochar was not documented in previous studies. Conversely, the increase in  $\theta_{WP}$  value observed in our experiment after adding biochar to sandy soil was already confirmed by Abel et al. (2013).

We observed a significant increase in AWC for all biochar treatments compared to the Control, similar to the increase observed for porosity. The addition of biochar resulted in significant modifications in the SWRCs. This improvement was marked by an increase in water retention capacity from pF 1, which implies a higher proportion of pores filled with water within the hydrolimits of field capacity and wilting point (indicating an increase in AWC). Our results agree



with Abel et al. (2013), who found that the increase in AWC in sandy soils after the addition of biochar primarily occurs in the drier range of the AWC (from  $-30$  to  $-1500$  kPa). Głąb et al. (2016) observed that biochar application significantly increased AWC in sandy soil, primarily when the finest fraction was used. On the contrary, Jeffery et al. (2015) reported no significant effects of biochar application on the available water content for plants of sandy soil in the conditions of field experiments.

The application of biochar exhibiting very strong severity and extreme persistence of water repellency at a 1% w/w rate resulted in biochar-soil mixtures that were slightly water-repellent ( $40^\circ \leq CA < 90^\circ$ ) according to Papierowska et al. (2018) classification but wettable (WDPT  $< 5$  s) according to Bisdom et al. (1993) classification. Wiersma et al. (2020) also observed that about 2% w/w application rate of strongly and severely repellent biochars did not affect the persistence of SWR of sandy soil. However, Kinney et al. (2012) reported that the 7% biochar application changed the wettable sandy soil to a severely repellent one, which coincides with the Steenhuis et al. (2005) findings that 5.5% hydrophobic particles can prevent water from entering the soil.

The wettable biochar (B550) application rate of 1% w/w resulted in wettable biochar-soil mixtures, according to Bisdom et al. (1993) and Papierowska et al. (2018) classifications. No changes in water repellency could be expected in this case.

The differences in wettability observed between wood-based biochars (B300 and B520) and sludge-based biochar (B550) (resulting in different CA and WDPT of biochar-soil mixtures) can be explained by variations in feedstock composition and pyrolysis conditions. Wood-based feedstocks typically include lignocellulosic materials with low moisture content but high calorific value and bulk density (Jafri et al. 2018). Studies have shown that high lignin content in wood-based biochars B300 and B520 can promote carbonization, resulting in an increase in biochar carbon content and ash content, associated with increased hydrophobicity (Sohi et al. 2010; Wang et al. 2015). On the other hand, sludge-based feedstocks contain organic matter with high moisture and ash content, lower calorific value, and low bulk density (Tomczyk et al. 2020). Different moisture content levels in biomass can lead to the production of biochars with varying physicochemical properties (Tripathi et al. 2016). Antal and Grønli (2003) and Kinney et al. (2012) found that biochar produced below  $500^\circ\text{C}$  retains organic functional groups from the feedstock, typically water-repellent. However, when pyrolysis temperatures exceed  $500^\circ\text{C}$ , the organic groups linked to hydrophobicity are volatilized, resulting in the production of more hydrophilic biochar. Our study used three different biochars produced at pyrolysis

temperatures of  $300^\circ\text{C}$ ,  $520^\circ\text{C}$ , and  $550^\circ\text{C}$ , respectively. The second biochar, produced at  $520^\circ\text{C}$ , did not show any water repellency loss yet, but there was still an increase in water repellency compared to the first biochar. The third biochar showed a decrease in water repellency due to higher pyrolysis temperature and different chemical compositions of feedstock.

We observed a strong negative correlation between  $K_s$  and  $P$  across treatments. Our results agree with those of Liu et al. (2016), who observed a similar negative correlation between  $K_s$  and  $P$ . Biochar may create additional pores or increase the size of existing pores in the sandy soil, but the increase in porosity does not necessarily provide flow paths for water and thus does not positively affect  $K_s$ .

## Conclusions

The present study reveals that the application of biochar alters the hydro-physical properties of sandy soil. A significant increase in sandy soil porosity and plant available water content due to the biochar addition was observed in all treatments, highlighting a positive effect of biochar addition on soil water retention. A strong positive correlation between AWC and  $P$  across treatments supported this finding.

An increase in porosity after biochar addition did not necessarily lead to increased saturated hydraulic conductivity. The addition of water-repellent biochar led to a statistically significant decrease in sandy soil  $K_s$ , caused by the water-repellent particles of biochar located between the sand grains preventing water movement in the soil. The wettable biochar addition led to a statistically insignificant decrease in sandy soil  $K_s$ .

It was also revealed that the addition of very strongly and extremely water repellent biochar induced slight severity of water repellency ( $40^\circ \leq CA < 90^\circ$ ) and did not induce persistence of water repellency (WDPT  $< 5$  s) in the biochar-soil mixture. After adding wettable biochar, the biochar-soil mixtures were wettable, aligning with expectations.

We found the relationship between the saturated hydraulic conductivity,  $K_s$ , and contact angle, CA, in sandy soil amended with wettable and hydrophobic biochars, which is a novelty of our study, as it has not been previously reported. A slight increase in CA could have a remarkable effect on soil water movement, even if it is  $< 90^\circ$  (Wang and Wallach 2021). As CA is more sensitive to changes in subcritical water repellency than WDPT (Šurda et al. 2023), the severity of biochar soil water repellency should be determined when assessing its potential for improving soil hydro-physical properties.

Our findings provide insights for ongoing soil research and could help establish sustainable soil management

practices in agricultural and environmental domains. Exploring biochar treatments that enhance porosity without significantly affecting water movement might be necessary to remediate the soil. Surface modification of biochar or its mixture with wetting agents could suffer for this purpose.

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**Data availability** No new data were created.

## Declarations

**Conflict of interest** The authors declare no conflict of interest.

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