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Impact of biochar particle size and feedstock type on hydro-physical properties of sandy soil

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Abstract: Biochar, as an organic amendment, could positively change soil properties, especially soil with low organic matter and/or poor structure. Biochar application in sandy soil with low organic matter could be an effective tool for improving hydro-physical parameters of the soil economically and ecologically as well. The effect on bulk density, particle density, porosity, saturated hydraulic conductivity and available water content for plants of two biochar types applied at three different particle sizes in a sandy soil was examined. The results confirmed previous studies, showing decreased bulk density, particle density and saturated hydraulic conductivity and partially increased available water content for plants and porosity. Both biochar type and particle size affected the studied soil hydro-physical parameters. After analysis and comparison of two different types of biochar and three particle sizes, the most effective treatment for sandy soil was proved by the biochar produced from willow with the smallest particle size (<125 μm).

Keywords: Feedstock biochar; Sandy soil; Soil hydro-physical parameters.

INTRODUCTION

Biochar is a product of the thermal decomposition of organic materials in the absence of oxygen and under elevated pressure (pyrolysis) (Zimmerman, 2010). Due to the beneficial effects not only on soil structure but also on the whole range of other soil properties, biochar could find its practical application in agricultural soils as a soil ameliorant because it can improve soil quality and increase crop yields (Juriga et al., 2021; Sohi et al., 2010; Vitková et al., 2017), mainly in sandy soils (Butnan et al., 2015). Biochar has many benefits when applied to soil, such as preventing compaction, increasing permeability, improving water content (Tan et al., 2017), soil water holding capacity, bulk density, porosity (Kammann et al., 2011; Vitková et al., 2019), inner surface area (van Zwieten et al., 2009), and soil structure (Obia et al., 2016).

Due to its porous structure, biochar can modify the fundamental hydro-physical parameters of soil, e.g., pore-size distribution and water flow (Devereux et al., 2012; Hlaváčiková et al., 2019), influencing the water retention curve of soil (Trifunovic et al., 2018), and, consequently, the available soil water content (AWC) for plants (Seyedsadr et al., 2022; Vitková et al., 2022). These features can also depend on the application rate and the particle size of biochar, the type of raw material used and the pyrolysis conditions. Biochar proportion is influenced by feedstock properties and operation parameters (such as temperature, heating rate, particle size, etc.) (Yanik et al., 2013). It is well known that variations in feedstock composition, material flow rate, or in process conditions lead to changes in product properties (Crombie et al., 2013; Zhao et al., 2013). In particular, biochar quality is strongly dependent on the type of pyrolysis unit, scale and degree of control (Buss et al., 2016; Buss, 2016; Hale et al., 2012; Weidemann et al., 2018). Hassan et al. (2020) evaluated the influence of pyrolysis temperature on a wide range of feedstocks to investigate their effects on biochar properties. With increasing high temperature treatment, biochar pH, surface area, pore size, ash content, hydrophobicity and O/C vs. H/C (oxygen/carbon vs. hydrogen/carbon) (ratios that denote stability) increased, whereas, hydrophilicity, yield of biochar, O/C, and H/C decreased. The study by Tan et al. (2017) claims that the main factors controlling the quality of biochar during preparation include biomass materials, reaction retention time and reaction temperature. The reaction temperature is the most important factor. Ndede et al. (2022) concluded that biochar made from woody feedstocks has a higher capacity to retain more water that is readily available for effective plant use. The results of Sun et al. (2014) study showed that feedstock types could influence characteristics of the biochars. These findings indicated that biochars with different properties could be developed by changing production conditions to better satisfy their environmental application. Various biochar size fractions in the soil can influence hydraulic conductivity (Trifunovic et al., 2018), water retention (Duarte et al., 2019; Gluba et al., 2021; Obia et al., 2016), or field capacity and permanent wilting point (Liu et al., 2017; Verheijen et al., 2019). The rate of biochar application in the field ranges typically from 0.5 to 100 Mg/ha (<4%, w/w) (Jeffery et al., 2015; Major et al., 2010; Šurda and Vitková, 2016; Zhao et al., 2016). The research of Liu et al. (2016) showed that the hydraulic conductivity (K) of sand was influenced by biochar particle size. The results of this study

showed that K decreased when biochar particles were finer than sand particles. The decrease of K following the addition of finer biochar particles was likely the result of increased tortuosity and reduced pore throat sizes in the mixture. The decrease of K associated with larger biochar particles was likely caused by the bimodal particle size distribution in the sand–biochar mixture (Liu et al., 2016). Alghamdi et al. (2020) investigated the effect of biochar particle size on water characteristics and soil structure of a sandy loam soil, date palm biochar prepared at a pyrolysis temperature of 450–500 °C was fractioned by dry sieving into four sizes (2–1; 1–0.5; 0.5–0.1; <0.1 mm), mixed in soil pots with a sandy loam soil at an application rate of 4%. Water retention, hydraulic conductivity, and soil structure parameters were measured and results showed that the largest increase in both water content at field capacity and available water content was observed with the smallest biochar particle size due to increased microporosity as a result to the larger internal surfaces and the porous structure of the biochar particles.

Soil hydraulic properties are important indicators for evaluating soil physical quality. They are closely related to the storage and movement of water, air, and nutrients in the soil and the growth and yield of crops (Cullotta et al., 2016).

Usually, sandy soils show high hydraulic conductivity and low retention ability for water and nutrients. Thus, it is necessary to investigate the effect of biochar application on the hydraulic properties of sandy soils. Soil hydraulic properties include soil water retention and hydraulic conductivity. The characteristics of soil water content demonstrating the state and availability of soil water to plants are known as hydrolimits. The hydrolimits can be estimated from the soil water retention curve, and the difference between hydrolimits field capacity and wilting point produced by the water retention curve shows the AWC for plants (Novák and Hlaváčiková, 2019). Many studies have reported that biochar application in sandy soils increased water retention capacity (e.g. Lim et al., 2016) and its porosity (Githinji, 2013) and decreased saturated hydraulic conductivity (Sorrenti and Toselli, 2016), bulk density (Verheijen et al., 2019) and particle density (Githinji, 2013). In the study of Balashov et al. (2021) results have shown that application of biochar resulted in a significant reduction in the bulk density of the sandy soil. The addition of biochar also increased water retention capacity.

In this context, the purpose of the present study was to test the effects of feedstock biochar type produced under similar pyrolysis conditions and of the biochar particle size on the available water content for plants, soil porosity, saturated hydraulic conductivity, bulk density and particle density of sandy soil. It is important to investigate the influence of biochar type and particle size on the hydro-physical properties of sandy soil and also to understand their coupled effects on water in soils. We hypothesized that the different types of biochar, as well as the different biochar size fractions, will affect all the investigated soil parameters.

MATERIALS AND METHODS

Preparation of soil and soil-biochar samples

Our experiment took place in laboratory conditions on samples of sandy soil collected from the Plavecký Štvrtok area at Záhorská nížina, Slovakia (N 48°21'58.33"; E 16°59'49.23"), with an altitude 157 m a.s.l. approximately. The grain size analysis of the soil was performed by using the hydrometer method (Novák and Hlaváčiková, 2019) and showed 91% sand, 7.5% silt and 1.5% clay. Accordingly, the soil was classified as sandy based on the USDA classification protocol.

Two different types of biochar were used, produced from different feedstock materials at similar pyrolysis temperatures (520 °C ≈ 550 °C). The raw materials for the biochars were Swedish willow, Tordis variety (salix) and a mixture of fiber sludge and grain husks (mix). Biochar (salix) was formed at a pyrolysis temperature of 520 °C in the UNYPIR reactor, which is part of the AgroBioTech center (Slovak University of Agriculture, Nitra, Slovakia). Biochar (mix) was formed at a pyrolysis temperature of 550 °C in the PYREG reactor (PyregGmbH, Dörthe, Germany) by the Sonnenerde company, Austria. Mix biochar is a commercial product available for sale. Salix biochar is a non-commercial product produced on a small scale because of research. Table 1. shows the basic properties of both types of biochar.

Table 1. Basic properties of two biochar types (C – carbon, H – hydrogen, N – nitrogen).

Biochar	C (%)	H (%)	N (%)	pH (–)	Ash (%)
salix (520 °C)	83.1	2.21	1.19	7.93	7.06
mix (550 °C)	53.1	1.84	1.4	8.8	38.3

Experimental setup

Six treatments and one control of the experimental samples were prepared in laboratory conditions, consisting of sandy soil, two different types of biochar, three different particle sizes of biochars (<125 µm; 125 µm–2 mm; >2 mm) and one application rate (1% by weight ≈ 20 Mg/ha in field conditions). The soil was sieved to a fraction with a particle diameter size ≤2 mm. Both types of biochar were grounded with a hammer mill and sieved to a fraction with 125 µm and 2 mm particle sizes. Soil and soil-biochar mixtures were prepared in steel cylinders with a volume of 100 cm^3. We prepared a control treatment (sandy soil), a mixture of soil and salix with particle size <125 µm, a mixture of soil and salix with a particle size of 125 µm – 2 mm and a mixture of soil and salix with a particle size of >2 mm. The same design was applied to the "mix" biochar mixtures. For each treatment, 3 replicates were prepared. To optimize repetitions for similar experimental conditions, valuable guidance is offered by Fouladidorhani et al. (2023), Comegna et al. (2023), Dokoohaki et al. (2017), Fér et al. (2020), Meng et al. (2021) or Minhal et al. (2020). The choice of three repetitions in these studies balances representative results with logistical constraints caused by equipment capacity. Fewer repetitions are justified in controlled laboratory experiments with prepared samples, where minimal variation and enhanced control over experimental factors reduce variability.

Chemical analysis of two different types of biochar

To extract macronutrients and essential elements from biochar (salix), air-dried samples of 1 g were digested on a hot plate (80 °C) by adding ultrapure concentrated HNO_3 and drops of 30% (v/w) H_2O_2 until the digestion solution became white or colorless, indicating the end of the digestion process. Then, the digest was diluted to 25 ml with deionized water and analyzed for macronutrient and essential element content. Mg, Ca, Fe, Cu, Zn and Ni were determined in an atomic absorption spectrophotometer (Varian-spectra A300 system), while P concentration was determined by a Shimadzu UV-1700 spectrophotometer. A Microprocessor flame photometer (Electronics India Model 1382) was used to determine K and Na. Total nitrogen was determined using the Kjeldahl distillation-titration method (Bremner and Mulvaney, 1982).

The chemical composition of the biochar (mix) was measured by Eurofins (Halsbrücke, Germany). Methods used for the measurement of Cu, Ni, Zi, and Mn are described in DIN 22022 (DIN EN ISO 17294-2). Parameters such as P, Mg, Ca, K, Na, and Fe were measured by DIN 51729-1/-11 (DIN EN ISO 11885). Table 2. shows the chemical parameters analysis of biochars.

Measurement of basic hydro-physical properties of experimental samples

The soil particle density is defined as the weight of a unit volume of the solid soil phase measured by the pycnometric method (Novák and Hlaváčiková, 2019). Using a precisely calibrated pycnometer could determine the volume of water displaced by a specific weight of absolutely dry soil. By using the method was possible to calculate the soil particle density based on the obtained values. It is defined as the weight of a unit volume of the solid soil phase, given by the Equation (1):

$$\rho_s = \frac{m_S}{V_S} \quad (1)$$

where ρ_s – soil particle density (g cm^{-3}), m_s – the weight of dried fine soil/mixture (g), V_s – the volume of water displaced by the soil/mixture (cm^3).

The bulk density of the soil is determined based on the portion of the weight of the dry soil sample or mixture and its known volume (Jury et al., 1991, pp. 61–62). The bulk density of soil was determined on samples taken in steel cylinders with a volume of 100 cm^3. We weighed the soil sample in laboratory conditions and subtracted the weight of the cylinders, thus obtaining the weight of pure soil/mixture. The soil samples were dried at a temperature of 105 °C. The bulk density of dry soil was determined based on Equation (2):

$$\rho_d = \frac{m_S}{V} \quad (2)$$

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

The total porosity of the soil was calculated based on Equation (3), into which the known values of the soil particle density and the bulk density of dry soil enter (Novák and Hlaváčiková, 2019):

$$P = \frac{\rho_S - \rho_d}{\rho_S} . 100 \quad (3)$$

where P – porosity (%), ρ_s – soil particle density (g cm^{-3}), ρ_d – bulk density of the soil (g cm^{-3}).

The saturated hydraulic conductivity of the soil was determined using a falling-head method (Reynolds et al., 2002). The values of the saturated hydraulic conductivity (K_s) of the soil are obtained according to Equation (4):

$$K_S = \frac{L}{t} . ln \frac{H_2}{H_1} \quad (4)$$

where L – soil cylinder height (cm), t –time of water level decrease from height $H_2 – H_1$ (s), H_2 – the initial water level in the extension (cm), H_1 – the height of the water in the extension after the drop.

The soil water retention curves were measured in the pressure plate apparatus (STN EN ISO 11274, 2014) made by Soil Moisture Equipment Corp. (Santa Barbara, CA, USA). All measured samples and mixtures were weighed, fully saturated with water, and moved to the pressure plate apparatus. A total of nine measurement points were used at pressure potentials of 0; 6; 10; 30; 56; 100; 300, 480 and 1500 kPa. Based on measured data, the water retention curve values were fitted using the unimodal van Genuchten model (van Genuchten, 1980). The dependence between soil water content (θ) and matric potential (h) reads as:

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

where θ_r and θ_S are the residual and saturated volumetric water contents, respectively. The parameter $m = 1 – 1/n$, where n is dependent on the pore-size distribution. The matric potential of air entry is described by α. AWC for plants is defined as the difference between the hydrolimits field capacity (FC) and wilting point (WP). These hydrolimits are different for different types of soils. In Slovak conditions, Šútor and Rehák (1999) established that the field capacity hydrolimit for this soil type is at pF = 2. Additionally, Mollinedo et al. (2015) found that in coarse-textured soils, FC is often reached at a lower tension of 0.01 MPa. The hydrolimit wilting point, on the other hand, is typically determined at pF = 4.18. In our study, we determined hydrolimits for each sample from the soil water retention curve and used the average AWC value for each treatment for statistical analysis.

Statistical analysis

Our experiment was a factorial experiment 2 × 3 in three replicates. The proposed data analysis had two factors: one factor was the different biochar types and the second factor was different fraction sizes. One-way ANOVA allows comparisons between treatment means but does not examine the effect that each factor might have on the physical properties. Considering that the initial scope was to test the effect of both biochar type and the size fraction on the hydro-physical properties of sandy soil, applying two-way ANOVA is preferable since it will highlight the effect of each factor and the possible interaction between them. Control was not included in the two-way ANOVA because it did not have two examined factors. Tukey's Honest Significant Difference (HSD) post-hoc test was performed after two-way ANOVA for biochar treatments only (two-way ANOVA HSD post hoc test). The statistical significance of the study was defined at $\alpha < 0.05$. In our experiment, we tested three hypotheses using two-way ANOVA (Table 3).

Consequently, comparisons between the six biochar treatments and the control have been performed by t-test. A t-test is a statistical test used to compare the means of two groups. It was used in hypothesis testing to determine whether any biochar treatment has an effect on the population of control. The null hypothesis (H0) is that the true difference between the control and biochar treatment group means is zero. The alternate hypothesis (Ha) is that the true difference differs from zero.

Table 2. Chemical parameters analysis of two biochar types.

Biochar	P	K	Na	Mg	Ca	Fe	Mn	Cu	Zn	Ni
				(mg kg^{-1})					(g t^{-1})	
salix	3020	8200	405	5512.5	85025	999	191	15	535	63
mix	6200	15000	770	3900	57000	1900	150	25	110	7

Table 3. Null and alternate hypotheses of a conducted experiment for a two-way ANOVA test.

Null hypothesis (H0)	Alternate hypothesis (Ha)
Biochar type has no significant effect on the physical parameter of soil (there is no difference in mean values of soil parameters for any biochar type).	Biochar type has a significant effect on the physical parameter of soil.
Biochar size fraction has not significant effect on physical parameters of soil (there is no difference in mean value of soil parameter for any biochar size fraction).	Biochar size fraction has a significant effect on the physical parameters of soil.
The effect of one factor on soil parameter does not depend on the effect of the other factor (no interaction effect between biochar type and size fraction).	There is an interaction effect between biochar type and size fraction.

The ANOVA-F and t-test are employed to compare group means, but they do not reveal the extent of differences between means or the portion of variance influenced by groups (Mendes and Yigit, 2013). Although low p-values suggest significance, they are influenced by sample size. Increasing the sample size makes it more likely to find a statistically significant effect, no matter how small the effect is in the real world. In contrast, effect sizes are independent of the sample size (Bhandari, 2023). If the effect size of the factor is large, it is possible to detect such an effect in smaller sample numbers, whereas a smaller effect size would require larger sample sizes. Huge sample sizes may detect differences that are quite small and possibly trivial (Grissom et al., 2005). Effect size measures (Partial eta squared (η_p^2) or Cohen's *d*) help accurately evaluate both the statistical significance and practical implications of findings thus helping the researchers to determine whether an observed effect is large enough to be practically important.

The η_p^2 ranges between 0 and 1. It clarifies how much of the variability in the outcome can be attributed to a specific factor. A higher η_p^2 indicates a greater influence of the factor on the dependent variable. Cohen (1988) has provided benchmarks to define small ($\eta_p^2 = 0.01$), medium ($\eta_p^2 = 0.06$), and large ($\eta_p^2 = 0.14$) effects. Although η_p^2 can be compared against the benchmarks, this should only be done as a last resort, and it is preferable to relate the effect size to other effects in the literature (Thompson, 2007).

A larger Cohen's *d* value indicates a more substantial effect size. A commonly used interpretation is to refer to effect sizes as small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$) based on benchmarks suggested by Cohen (1988). However, these values are arbitrary and should not be interpreted rigidly (Thompson, 2007).

In our study, Cohen's *d* was computed for the t-test and η_p^2 for two-way ANOVA through the G*Power software (Faul et al., 2009). The presence of a large effect size in conjunction with a small sample size suggests that the observed effect is both statistically and practically significant. This implies that the limited sample adequately represents the effect of interest. However, caution is advised in interpreting this finding. While a large effect size is promising, it does not address the representativeness of the sample itself.

RESULTS AND DISCUSSION

Particle density

The effect of any of the studied factors (biochar type and biochar size fraction) or their mutual interaction on particle density (ρ_s) was not statistically confirmed in the conditions of our study. The associated effect sizes (η_p^2) values were 0.062, 0.071, and 0.063 (for the first factor, the second factor, and their interaction), indicating a medium effect size. This implies that approximately 6.2%, 7.1%, and 6.3% of the variability in particle density could be attributed to differences in biochar type, fraction size, and their interaction, respectively. The computed effect sizes were relatively small, indicating a small impact in the natural conditions. An HSD post-hoc test did not confirm significant pairwise differences between any biochar treatments (Fig. 1).

Results showed a decrease in average ρ_s in all treatments with biochar compared to sandy soil (Table 5). However, the t-test only confirmed a statistically significant difference between the control and salix (125 µm – 2 mm). Cohen's *d* values indicate varying magnitudes of effect sizes. A Cohen's *d* of 1.83 suggests a large effect (salix (125 µm – 2 mm)), while values of 0.55 and 0.44 indicate moderate effects. Additionally, effect sizes of 0.37 and 0.06 are indicative of small effects. All computed effect sizes (Cohen's *d*) for t-tests comparing control and biochar treatments are listed in Table 5.

The highest decrease (about 1%) was in treatments salix (125 µm – 2 mm) and salix (<125 µm). The decrease in other treatments was less than 0.5%. Lower values of ρ_s in biochar treatments can be attributed to the lower density of biochar compared to soil minerals. Githinji (2013) found similar results in laboratory conditions using loamy sand soil. Usowicz et al. (2016) found that the application of 30 Mg/ha of wood biochar reduced ρ_s by about 14% in field conditions.

Bulk density

We found that bulk density (ρ_d) was significantly affected only by the biochar fraction size factor ($F(2) = 1691$, $p < 0.05/1.9\times10^{-15}$); the interaction between biochar fraction size and type was not significant. The η_p^2 values for the biochar type factor, fraction size factor, and their interaction were 0.221, 0.997, and 0.106, reflecting a large effect size for the first and second factor and a medium effect size for their interaction. An HSD post-hoc test confirmed significant pairwise differences between all biochar size fraction groups (independent of the type of biochar) (Fig. 2).

The value of ρ_d in all biochar treatments decreased significantly compared to sandy soil control (Table 5). All Cohen's *d* values for the t-tests conducted to compare bulk density values between the control and biochar treatments indicate large effect sizes (Table 5).

The highest decrease was in treatments with biochar particle size (>2 mm) (about 6%). Our study confirmed the results by Blanco-Canqui (2017), who found that biochar application reduced bulk density from 3 to 31%, depending on the soil. Chen et al. (2018) and Obia et al. (2016) also found out that bulk density increased with the decrease in biochar particle size in sandy soil. However, Verheijen et al. (2019) observed opposite results, with higher bulk density values at increasing biochar particle size. Comparatively, salix showed a greater decline in bulk density at increasing the particle size.

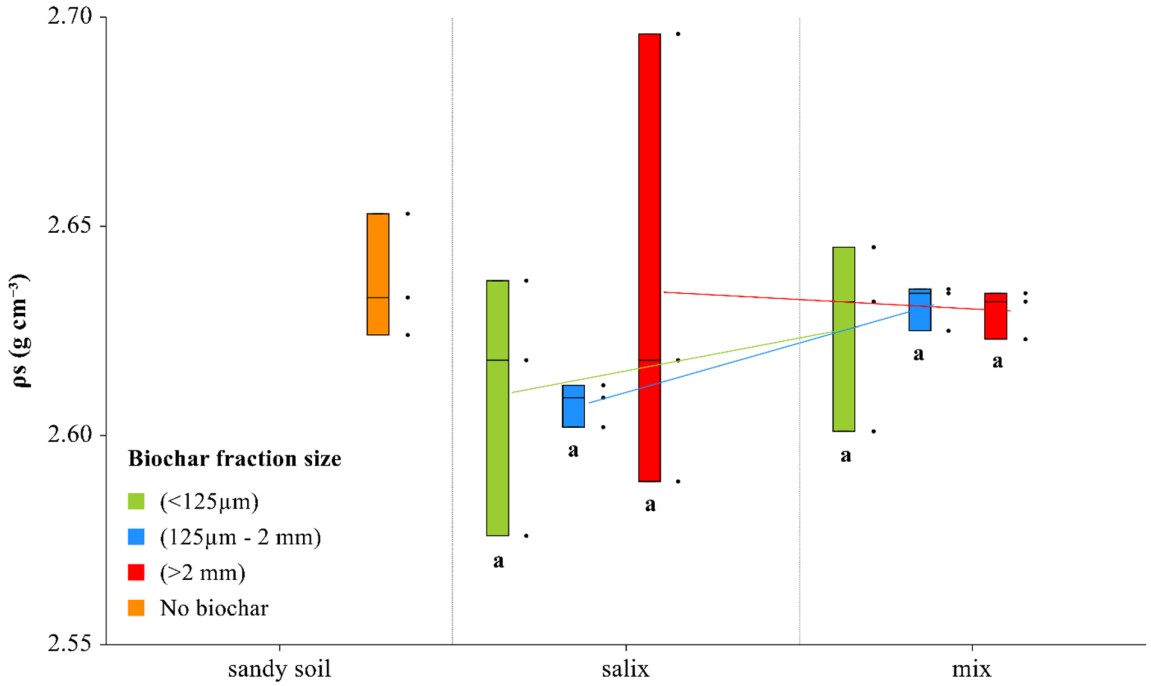


Fig. 1. Measured values of the particle density (ρ_s) for all treatments of the experiment. The whiskers show minima and maxima, and points represent individual measurements. Box plots denoted with the same letters are not significantly different (HSD test) on a significance level $p < 0.05$.

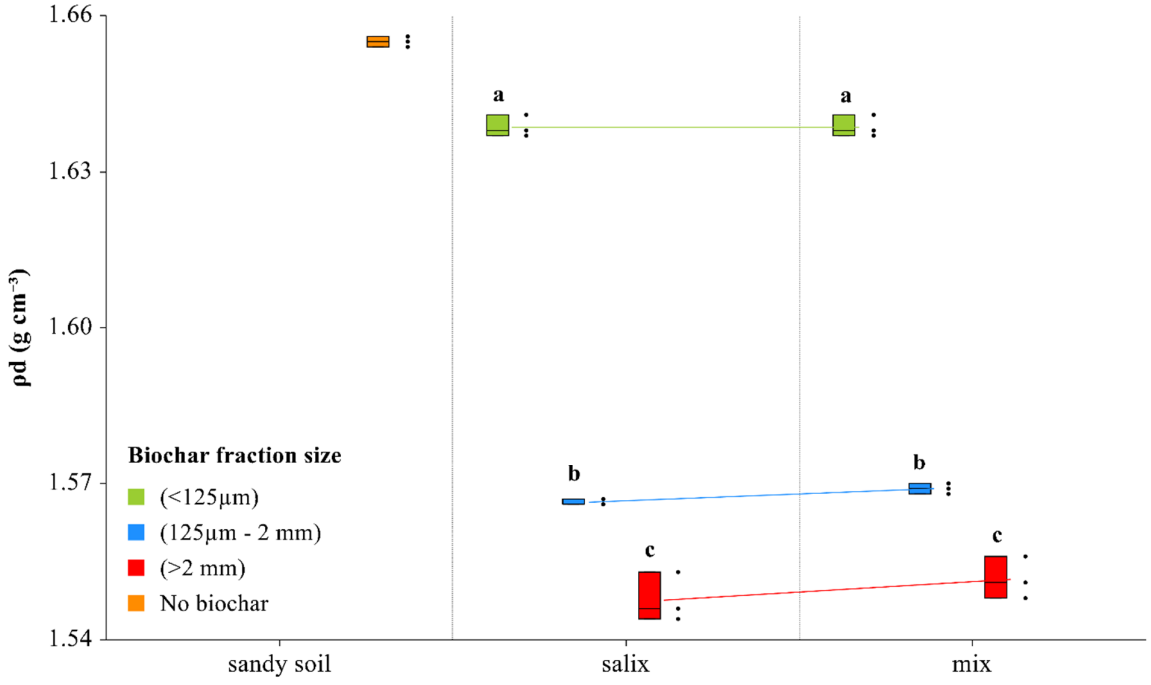


Fig. 2. Measured values of the bulk density (ρ_d) for all experiment treatments. The whiskers show minima and maxima, and points represent individual measurements. Box plots denoted with different letters are significantly different (HSD test) on a significance level $p < 0.05$.

Porosity

Measured values of porosity (P) are related to the effects of bulk density and particle density. In our study, P was significantly affected only by the biochar fraction size factor ($F(2) = 55$, $p < 0.05/ 9\times10^{-7}$); the interaction between biochar fraction size and type was not significant. The η_p^2 values for the biochar type factor, fraction size factor, and their interaction were 0.032, 0.902, and 0.078, reflecting a large effect size only for the fraction size factor. An HSD post-hoc test confirmed significant differences between the smallest size fraction group (salix and mix (<125 µm)) and the other size fractions (salix and mix (<125 µm, 125 µm – 2 mm, >2 mm)) (Fig. 3).

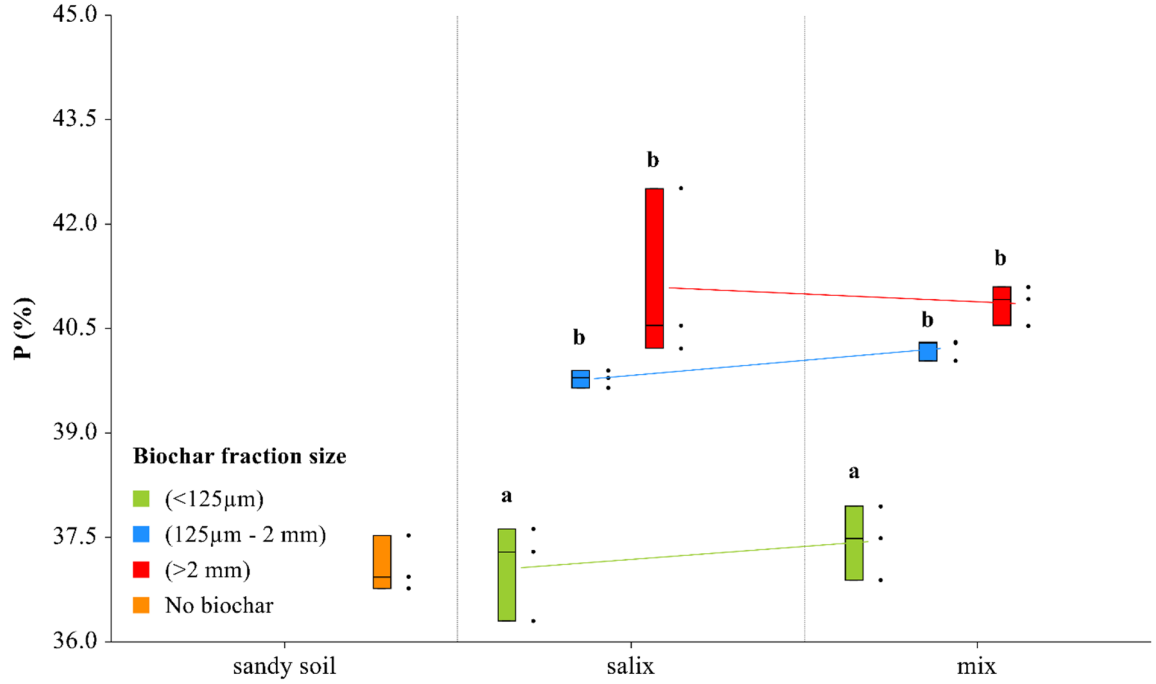


Fig. 3. Measured values of the porosity (*P*) for all experiment treatments. The whiskers show minima and maxima, and points represent individual measurements. Box plots denoted with different (HSD test) letters significantly differ on a significance level $p < 0.05$.

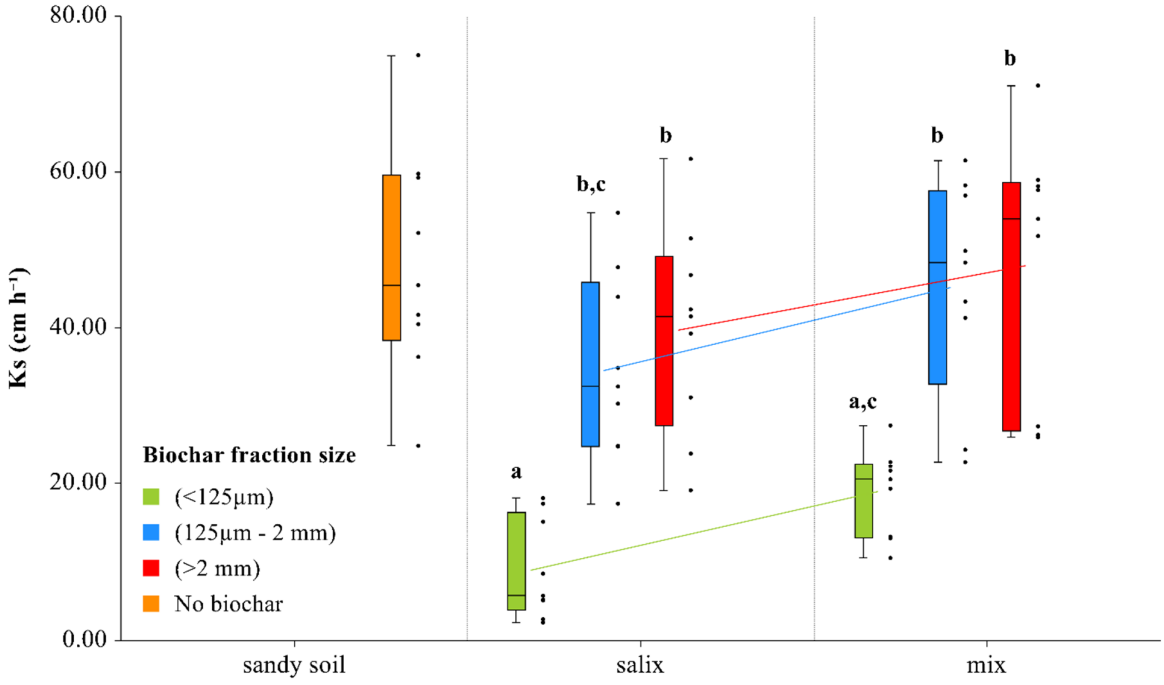


Fig. 4. Measured values of the saturated hydraulic conductivity (K_s) for all treatments of experiment. The whiskers show minima and maxima, and points represent individual measurements. Box plots denoted with different letters are significantly different (HSD test) on a significance level $p < 0.05$.

Results of the t-test have shown statistically significant differences between sandy soil and treatments with a larger biochar particle size (125 µm – 2 mm) and (>2 mm) of both biochar types (Table 5.). Differences between sandy soil and the smallest biochar particle size (<125 µm) were not significant. Computed Cohen's *d* values for the t-tests that compared porosity values between control and biochar treatments indicate a range of effect sizes. Cohen's *d* of 10.79, 9.14, 10.36, and 4.32 signify large effects. Additionally, effect sizes of 0.76 and 0.01 are indicative of small effects (Table 5).

The largest increase, compared to the control, was measured in the salix treatment with biochar particle size (>2 mm) (about 10%). It is in line with the results by Obia et al. (2016). Also Gamage et al. (2016) observed an 18% increase in porosity with 1% amount of biochar in sandy soil. Blanco-Canqui (2017) mentions that the effects of biochar on soil porosity appear to occur regardless of biochar type and soil type, and sandy soils appear to be more responsive to biochar application than soils with high clay content.

Saturated hydraulic conductivity

We found that saturated hydraulic conductivity (K_s) was significantly affected by both biochar type ($F(1) = 8.579$, $p < 0.05/0.005$) and by biochar fraction size ($F(1) = 15.316$, $p < 0.05/1\times10^{-9}$). However, the interaction between the studied factors was not significant. The associated effect sizes (η_p^2) were 0.711, 0.949, and 0.027 (for the biochar type factor, the fraction size factor, and their interaction), indicating a large effect size for the first and second factor and a small effect size for their interaction. Lower K_s values were found for salix biochar compared to mix biochar treatments in all size fractions (Fig. 4.). An HSD post-hoc test revealed significant pairwise differences between the salix treatment (<125 µm) and the other biochar treatments, except mix (<125 µm) and also between mix (<125 µm) and the other biochar treatments except for salix (<125 µm) and salix (125 µm – 2 mm).

The t-test revealed a significant difference in mean values of K_s in both biochar treatments with the smallest fraction size (<125 µm) and sandy soil (Table 5). This fact is in line with Brockhoff et al. (2010), who found that switch grass biochar application in a 5% v/v rate decreased K_s by about 52% in sandy soil. Uzoma et al. (2011) also measured a 54% decrease in K_s in sandy soil with cow manure biochar. In agreement with our measurements, also Chen et al. (2018) observed higher values of K_s in larger biochar particle treatments than in finer ones in sandy soil. Cohen's d values for the t-tests comparing K_s between control and biochar treatments indicate both larger and smaller effect sizes. Notably, Cohen's d values of 3.44 and 2.61 indicate large effects (for the smallest fraction size biochars), while values of 1.01 and 0.60 suggest moderate effects. Additionally, effect sizes of 0.21 and 0.02 signify small effects.

Soil water retention curves and available water content for plants

Mean soil water retention curves (SWRC) for each treatment are shown in Fig. 5. The SWRC shape differences between sandy soil and mixtures of soil and biochar treatments are evident, especially from pF 1.5 and higher. The mean values of fitting parameters of the van Genuchten function (Eq. 5) and mean values of wilting point and saturated water content are listed in Table 4.

SWRC from the control differed from biochar-treated samples (Fig. 5), which was also proved by the significant difference between the n values of the control and all other treatments (Table 4). Table 4 also provides a list of the effect sizes (Cohen's d) derived from the t-tests conducted to compare SWRC parameters in the control and biochar treatments. We found a statistically significant difference in parameter α between the control and all biochar treatments except salix (<125 µm) and salix (125 µm – 2 mm). Saturated water content (θ_S) significantly decreased in treatments with the smallest biochar size fraction compared to the control (Table 4). This is not fully in accordance with the results of our porosity measurements, while the porosity in the smallest biochar size fraction treatments was not different from the control. The θ_S increased significantly only in the salix (>2 mm) and salix (125 µm – 2 mm) treatments, which is in accordance with the porosity measurements. The wilting point values were higher in all biochar treatments compared to the control, but a statistically significant difference was only proved for the treatments salix (>2 mm) and, interestingly, also in the mix (<125 µm) (with similar porosity as control).

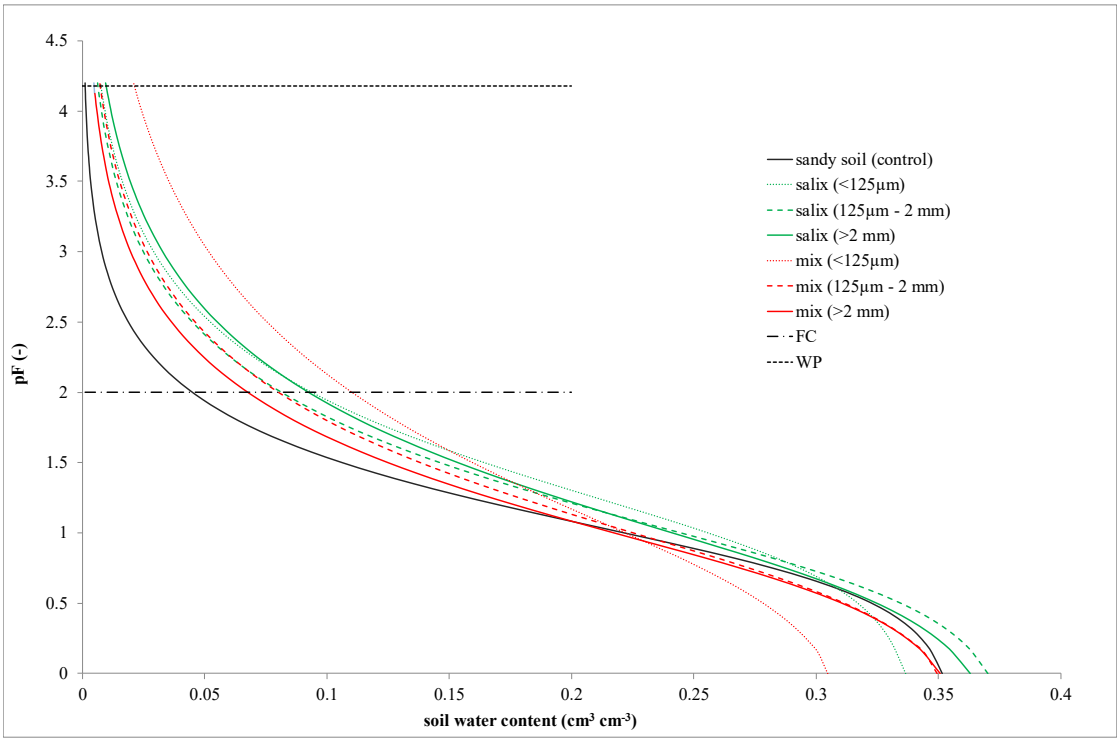


Fig. 5. Soil water retention curves (SWRC) for each experimental treatment.

Table 4. Fitting parameters of the van Genuchten function (α, n) and values of saturated water content and wilting point for experimental treatments. Values are averages over the replicates of the treatments (n), and standard deviations are given between parentheses. Differences between control means and treatment means were evaluated by t-test. Asterisks indicate significant differences between treated samples and control samples ($p < 0.05$) and d denotes Cohen's d for the t-test between control and treated samples.

	α (cm^{-1}) n = 3	n (–) n = 3	θ_{WP} (cm^3 cm^{-3}) n = 3	θ_S (cm^3 cm^{-3}) n = 3
sandy soil/control	0.147 (0.002)	1.77 (0.067)	0.0011 (0.0004)	0.352 (0.006)
salix (<125 µm)	0.123 (0.030) d = 1.12	1.52 (0.068) * d = 3.70	0.0073 (0.0031) d = 1.80	0.337 (0.008) * d = 2.12
salix (125 µm – 2 mm)	0.185 (0.013) d = 1.08	1.53 (0.068) * d = 3.55	0.0061 (0.0032) d = 1.19	0.370 (0.002) * d = 4.02
salix (>2 mm)	0.217 (0.017) * d = 5.78	1.45 (0.022) * d = 6.41	0.0094 (0.0019) * d = 6.04	0.363 (0.005) * d = 1.99
mix (<125 µm)	0.238 (0.026) * d = 4.93	1.33 (0.031) * d = 8.42	0.0208 (0.0045) * d = 6.16	0.305 (0.004) * d = 9.21
mix (125 µm – 2 mm)	0.226 (0.029) * d = 3.84	1.49 (0.026) * d = 5.50	0.0070 (0.0013) d = 1.13	0.349 (0.001) d = 0.69
mix (>2 mm)	0.215 (0.032) * d = 2.99	1.55 (0.073) * d = 3.13	0.0046 (0.0026) d = 1.88	0.351 (0.003) d = 0.21

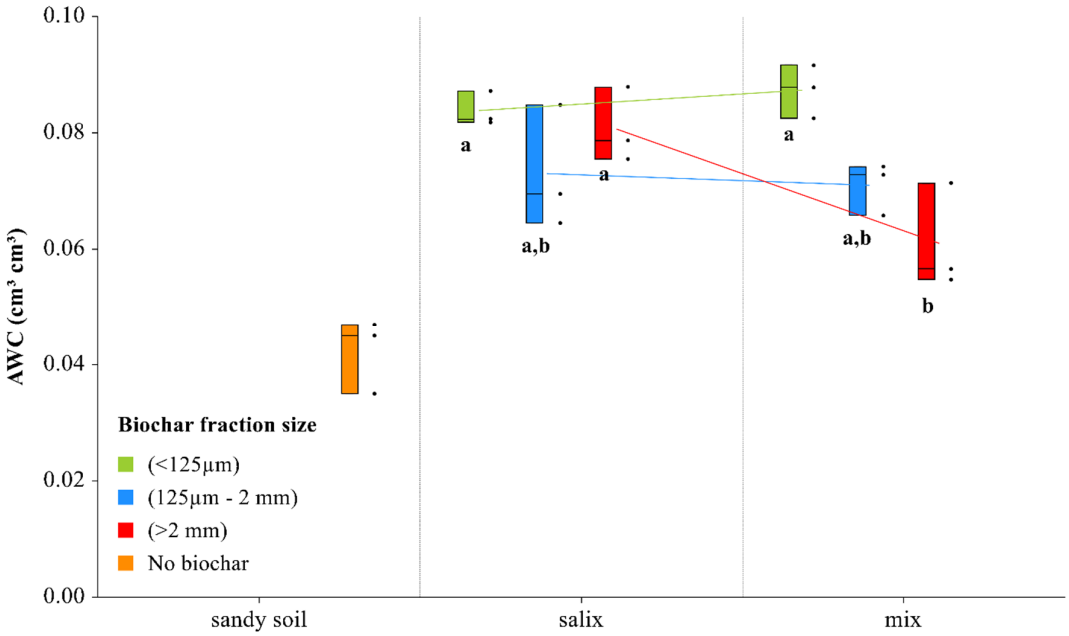


Fig. 6. Measured values of the available water content for plants (AWC) for all experiment treatments. The whiskers show minima and maxima, and points represent individual measurements. Box plots denoted with different letters are significantly different (HSD test) on a significance level $p < 0.05$.

Available water content for plants (AWC) was significantly affected only by biochar fraction size ($F(1) = 8.46$, $p < 0.05/0.005$). The effect of biochar type on AWC was not confirmed, though the interaction between studied factors was significant ($F(2) = 4.65$, $p < 0.05/0.03$). The η_p^2 values for the biochar type factor, fraction size factor, and their interaction were 0.226, 0.585, and 0.437, reflecting a large effect size for both factors and also their interaction. Concerning the comparison of individual biochar treatments with each other (HSD test), we found a significant difference only between the treatment mix (> 2 mm) and the salix (<125 µm), salix (>2 mm) and mix (<125 µm) treatments (Fig. 6).

We found a statistically significant difference (t-test) in AWC for plants in all biochar treatments compared to sandy soil (Table 5). Consistently large effect sizes are indicated by Cohen's d values, computed for the t-tests comparing available water content values for plants between the control and biochar treatments. For instance, values of 7.79, 7.39, and 5.98 indicate very large effects, while values of 4.76 and 3.59 represent large effects.

The highest increase in AWC was measured in the treatment mix (<125 µm) (108%) and the smallest increase in the treatment mix (>2 mm) (45%). Gluba et al. (2021) observed similar results with 0.95% dose of biochar in sandy soil. Edeh and Mašek (2021) found out opposite results, as decreasing the biochar particle size produced by softwood pellet resulted in decreased AWC values in sandy loam soil. Obia et al. (2016) measured the highest increase of AWC with middle biochar particle size (0.5–1 mm) in sandy soil. Gamage et al. (2016) observed an increase in field capacity content of about 50% for sandy soils with 1% biochar amendment.

Table 5. Effect of different types of biochar application on hydro-physical parameters of sandy soil. Values are averages over the replicates of the treatments (n), and standard deviations are given between parentheses. Values of biochar treatments not sharing the same letter as the control in each column are statistically different from the control at $\alpha < 0.05$. Differences between control means and treatment means were evaluated by t-test. Asterisks indicate significant differences between treated samples and control samples (* = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$) and *d* denotes Cohen's *d* for the t-test between control and treated samples.

Treatment	ρ_s (g cm^{-3}) n = 3	ρ_d (g cm^{-3}) n = 3	P (%) n = 3	AWC (cm^3 cm^{-3}) n = 3	K_s (cm h^{-1}) n = 9
sandy soil/ control	2.637 (0.02)	1.659 (1x10^{-3})	37.08 (0.4)	0.042 (7x10^{-3})	48.36 (14.92)
salix (<125µm)	2.610 (0.03) *d* = 1.05	1.642 (2x10^{-3}) *** *d* = 10.75	37.07 (0.69) *d* = 0.01	0.084 (3x10^{-3}) * *d* = 7.79	8.89 (6.28) ** *d* = 3.44
salix (125µm – 2 mm)	2.608 (0.01) * *d* = 1.83	1.570 (4x10^{-4}) *** *d* = 116.86	39.78 (0.12) ** *d* = 9.14	0.073 (1.1x10^{-2}) * *d* = 3.59	34.59 (12.13) *d* = 1.01
salix (>2 mm)	2.634 (0.06) *d* = 0.06	1.551 (5x10^{-3}) *** *d* = 29.95	41.09 (1.25) ** *d* = 4.32	0.081 (6x10^{-3}) * *d* = 5.98	39.71 (13.4) *d* = 0.60
mix (<125µm)	2.626 (0.02) *d* = 0.55	1.643 (2x10^{-3}) *** *d* = 10.11	37.44 (0.53) *d* = 0.76	0.087 (5x10^{-3}) * *d* = 7.39	18.96 (5.58) ** *d* = 2.61
mix (125µm – 2 mm)	2.631 (0.01) *d* = 0.37	1.573 (8x10^{-4}) *** *d* = 94.97	40.21 (0.15) ** *d* = 10.36	0.071 (5x10^{-3}) * *d* = 4.76	45.24 (13.96) *d* = 0.21
mix (>2 mm)	2.630 (0.01) *d* = 0.44	1.555 (4x10^{-3}) *** *d* = 35.67	40.85 (0.29) ** *d* = 10.79	0.061 (9x10^{-3}) * *d* = 2.35	47.94 (16.89) *d* = 0.02

CONCLUSIONS

There is always more than one factor that alters the hydro-physical properties of soil after biochar amendment. We have focused on the type of biochar feedstock and its particle size in this study. Biochar does not readily decompose, so we studied if its modification is significant before its application into the soil. Our hypotheses were confirmed, and the results corresponded to other studies about the positive impact of biochar application on the hydro-physical parameters of sandy soil. Statistically significant were changes in bulk density, and shape parameters of SWRC and AWC for plants; changes in particle density were not statistically significant. Changes in porosity were significant for larger particle sizes (125 µm – 2 mm) and (>2 mm) of both biochar types. In contrast, saturated hydraulic conductivity showed significant changes for the smallest fraction size of less than 125 µm. In sandy soil, it is most important to slow down the infiltration into the deeper parts of the soil profile and retain the soil water and, thus also, nutrients in the root zone. Based on our results, the impact of biochar feedstock type produced by similar pyrolysis temperature is not a determining factor affecting the hydro-physical properties of sandy soil. The higher effect was determined by the particle size of biochar. The smallest biochar particle sizes (<125 µm) are the most suitable option for sandy soil. Due to the fact this type of soil contains a small number of pores holding water and the addition of the smallest particle size of biochar modified the soil structure by filling the free volume between the coarse sand particles in the soil matrix. The results were similar for both studied types of biochar, but salix (<125 µm) was more effective in improving the hydro-physical parameters of sandy soil. We expected higher differences between treatments, but the results corresponded to a 1% biochar rate. Our following study will concentrate on higher rates of biochar. The application of biochar into sandy soil has great benefits and our results suggest that biochar particle sizes can be used to achieve its specific parameters. The addition of biochar into the soil can increase or decrease some parameters, and any potential improvement of water delivery to plants is dependent on soil texture, biochar rate, and biochar properties. Biochar might be a useful tool in the management of sandy soils to reduce the stress of plants in critical periods of water restriction.

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