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Study of the saturated hydraulic conductivity by falling–head method for different soil types amended with different biochar fraction size

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Saturated hydraulic conductivity is an important soil property related to soil water regime. Generally, loam soil has a convenient moisture regime. However, if this type of soil is gradually drying out, its moisture regime may change for the worse. Our task is therefore to search for methods to increase the hydraulic conductivity of the loamy soils. In contrast, one of the goals of sandy soil management is slowing down flow velocity. In our research, we focused on the effect of biochar particle size on saturated hydraulic conductivity changes in three different soil types. The soils were selected based on their textures – sandy, silt loam and silty clay. Our results confirmed that addition of biochar with particle size <125 μm produced from paper fiber sludge and grain husks significantly ($p<0.05$) reduced saturated hydraulic conductivity in sandy soil by approximately 61% compared to control with sandy soil. Further, the results indicated that biochar with a fraction size >2 mm effectively increased the saturated hydraulic conductivity of silt loam soil by approximately 165% compared to pure silt loam soil. The difference was also statistically significant ($p<0.05$). Biochar amendment to the finest textured soil used in this study (silty clay) also increased the saturated hydraulic conductivity of the soil. The biochar with a fraction size of 125 μm–2 mm and >2 mm significantly ($p<0.05$) increased the saturated hydraulic conductivity by approximately 629% and 1063%, respectively when compared to pure silty clay soil.

KEY WORDS: biochar fraction size, soil type, saturated hydraulic conductivity, falling–head method

Introduction

It is essential to know the hydraulic properties of the soil for better planning and management of water resources. Increasing the velocity, when water enters into the soil is very important for capturing rainfall, soil water retention and overall soil management (Blaco–Canqui, 2017). From this point of view, saturated hydraulic conductivity (*K*) is important soil property in solving problem with the soil water regime. It is also important soil property, especially for modeling water flow and solute transport in soil, irrigation and drainage design, groundwater modeling and other agricultural or engineering processes as well. Some studies state that biochar addition can increase *K* in clay soils and loamy soils (Dan et al., 2015) by increasing the number of connected macropores. Other study (Uzoma et al., 2011) suggests that biochar could effectively suppress water loss in sandy soils. The biochar particle fraction size itself and the particle size of the soil into which the biochar was applied also play an important role (Hardie et al. 2014; Lehmann and Joseph 2015; Esmaeelnejad et al. 2017).

K represents the ease with which water flows through soil when pore spaces are completely filled with water and it reflects the number of pores and their arrangement. It is difficult to characterize it because of its high variability even over short distances, and measurement methods, typically require considerable time and resources. However, accurate estimation of *K* in soil is essential for various hydrological applications (Shwetha and Varija, 2015). *K* depends mainly on soil structure, soil texture, organic matter content and bulk density which can vary in both space and time (Hillel, 1998; Beckwith et al., 2003). Chirico et al. (2007) stated that the relationship between *K* and above-mentioned soil properties is not strong enough to permit accurate estimations of *K*. However, anisotropy of *K* is not routinely determined because practical and validated methods are still lacking (Petersen et al., 2008).

In laboratory conditions, *K* could be affected by the quality of undisturbed soil sample and the content of the preferred water flow pathways in the soil sample. Another factor influencing the measurement could be the number of repetitions of the measurement. Regardless of the determination method of *K* in the field or laboratory, the measured value is representative both for the specific place and time at which the measurement was carried out (Kargas et al., 2021). There are lots of laboratory methods for measuring *K* (e.g. falling–head method, constant–head method) (Antal and Igaz, 2012).

In our study K was measured using the falling–head method (FHM) in laboratory conditions. Three different soil types were chosen based on their texture (sandy, silt loam and silty clay) and amended by biochar with three different fraction sizes (<125 µm, 125 µm–2 mm, >2 mm).

Material and methods

Used soils for the laboratory experiment

Soils with different structure were chosen for this experiment. The grain size analysis was determined based on USDA classification protocol. Measurements of the sandy and silty clay soils were performed using the hydrometer method described, e.g., by Novák and Hlaváčiková (2019). The analysis of the silt loam soil was obtained by Šimanský and Klimaja (2017).
Sandy soil used in this experiment was taken from site of Záhorská nížina (area Plavecký Štvrtok). The soil sample contained 91% of sand, 7.5% of silt and 1.5% of clay.
Sample of silt loam soil was taken from site of Nitrianská pahorkatina (area Dolná Malanta). Its content of sand was 15.2%, silt 59.9% and clay 24.9%.
Silty clay soil was taken from site of Východoslovenská nížina (area Senné) and it consisted of 11.1% of sand, 42.9% of silt and 46% of clay.

Used biochar for the laboratory experiment

Biochar used in this experiment was made from paper fiber sludge mixed grain husks at a 1:1 ratio (according to their weight). The feedstock was processed by pyrolysis at 550°C for 30 minutes in a Pyreg reactor (Pyreg GmbH, Görhe, Germany) and provided by Sonnenerde company (Austria) as a final commercial product. Further detailed information of the biochar parameters is shown in Table 1.

Mixtures of soil and biochar

Mixtures of each soil type (sandy, silt loam and silty clay) with biochar were prepared in laboratory conditions. We applied a biochar with concentration of 1.5% (20 t ha^{-1}) in steel cylinders with a volume of 100 cm^3. Overall, three treatments, representing different particle size fractions (< 125 µm, 125 µm–2 mm and > 2 mm), were prepared. For each treatment 3 replicates of soil and biochar mixtures were prepared. These prepared mixtures were compared with the control treatment (without biochar amendment – each for sandy soil, silt loam soil and silty clay soil), which was prepared in 3 replicates as well. The treatments of the laboratory experiment are presented in Table 2.

Laboratory measurement of saturated hydraulic conductivity

Saturated hydraulic conductivity of the soil (K) was determined by prepared mixtures of each soil type and biochar in steel cylinders for all treatments of the laboratory experiment. Each treatment was made in three replicates, so 36 samples were measured in total (Table 2). We performed 3 measurements of K for each soil sample, which means that we had 9 values (n=9) of K for each treatment for further statistical analysis.
We used falling–head (variable) method (FHM) to measure the amount of water that goes through the soil sample in a fixed time interval. The water level above the soil sample decreases over time (Antal and Igaz, 2012; Igaz et al., 2017, Dulovičová et al., 2022) (Fig. 1). A digital caliper (Emil Lux GmbH & Co. KG) was used to measure the water level drop with accuracy +/- 0.2 mm (Fig. 1). K was calculated according to Eq. 1:

$$K = \frac{L}{t}\ \ln\frac{H_2}{H_1} \qquad [\text{cm s}^{-1}] \qquad (1)$$

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

Statistical analysis

In our study we used Microsoft Excel program for descriptive statistics (Mean, Standard deviation – SD) to describe and summarize the basic features of the given dataset and to create the box plots. The effect of biochar application on the saturated hydraulic conductivity of the soil was evaluated using a one–way analysis of variance (one–way ANOVA). Statistically significant effects at $p<0.05$ were determined by least significant difference (LSD) test. All statistical analyses were performed in Statgraphics Centurion XV.I software (Statpoint Technologies, Inc., Warrenton, VA, USA).

Table 1. The chemical and physical properties of biochar (Kondrlova et al., 2018; Šimanský et al., 2019)

SSA* [m^2 g^{-1}]	Size fraction [mm]	pH [–]	Total C [g kg^{-1}]	Total N [g kg^{-1}]	P [g kg^{-1}]	K [g kg^{-1}]	Ca [g kg^{-1}]
21.7	1–5	8.8	531	14	6.2	15	57

** SSA specific surface area*

Table 2. **Treatments of the laboratory experiment**

Treatment	Replication
sandy soil (control)	3
sand and biochar (<125 µm) mixture	3
sand and biochar (125 µm–2 mm) mixture	3
sand and biochar (>2 mm) mixture	3
silt loam soil (control)	3
silt loam and biochar (<125 µm) mixture	3
silt loam and biochar (125 µm–2 mm) mixture	3
silt loam and biochar (>2 mm) mixture	3
silty clay soil (control)	3
silty clay and biochar (<125 µm) mixture	3
silty clay and biochar (125 µm–2 mm) mixture	3
silty clay and biochar (>2 mm) mixture	3
Total	36

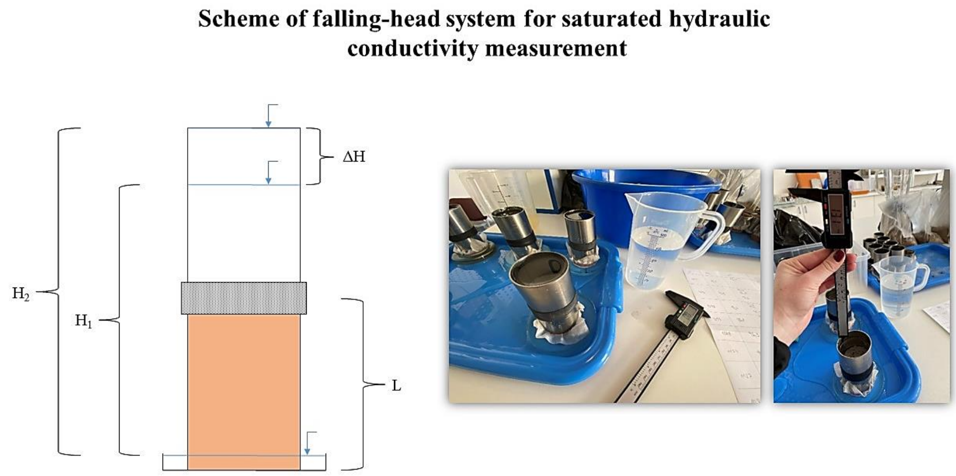

Fig. 1. Scheme of falling–head method for saturated hydraulic conductivity measurement.

Results and discussion

Evaluation of biochar application impact on the soil

The most important observed result of our work was a decrease in *K* after biochar application in sandy soil (Fig. 2) and an increase in *K* after biochar application in silt loam and silty clay soils (Fig. 3 and Fig. 4). According to previous research, biochar is believed to cause slower flow in sandy soils and effectively suppress water loss (Dan et al., 2015). Coarse biochar particles increased intraporosity and fine biochar particles decreased hydraulic conductivity due to reduced macropores. Conversely, in loamy soils, biochar tends to reduce soil bulk density (Toková et al., 2020), increase soil porosity (Vitková et al., 2019), improve soil texture (Sun and Lu, 2014; Walters and White, 2018), and consequently increase *K* (Esmaeelnejad et al., 2017) and soil water content (Vitková et al., 2021). According to previous studies of the effect of biochar on fine textured clay soils, its positive effect is not clearly demonstrable (Castellini et al., 2015). However, from our results, it seems that biochar behaves similarly to loamy soils and thus effectively increases *K* values in clay soils (Fig. 4). Another result observed was a gradual decrease in *K* after application of gradually decreasing the particle size fraction of biochar to sandy soil (Fig. 2), with a statistically significant ($p<0.05$) decrease in *K* observed for the treatment with the smallest size fractions (<125 µm) compared to the control (Table 3). Similar results were also reported by Toková et al. (2022a), where the effect of different biochar sizes (produced from willow tree) on sandy soil was investigated. The authors Lehmann and Stephen (2015) reported that biochar with smaller particles size than the soil particles present in the soil profile can reduce *K* after its application. This statement is consistent with our results as sandy soil contains predominately sandy particles (size fraction in the range of 0.05 to 2 mm) and thus when biochar with a size <125 µm (i.e. 0.125 mm) was applied to soil it could have caused the effect mentioned above. For larger biochar size fractions (125 µm–2 mm and

>2 mm) in combination with sandy soil, this difference was not so obvious (Fig. 2). Further, we observed a gradual increase in *K* after gradually increasing the size fraction of biochar applied to silt loam (Fig. 3), with a statistically significant ($p<0.05$) increase in *K* when the largest particle size fraction (>2 mm) of biochar was used compared to the control (Table 4). Similar results were also reported by Toková et al. (2022b), where the effect of biochar (made from willow tree) applied in different size fractions to clay soil was investigated. Lehmann and Joseph (2015) stated that biochar with larger particles than soil particles could increase *K*. This statement is also consistent with our results, as silt loam soil was used for the experiment and the most obvious *K* enhancement effect was observed for the larger size fractions of used biochar. According to Esmaeelnejad et al. (2017), finer fractions of biochar fill easier the spaces between soil particles. Consequently, the addition of biochar can lead to either clogging (in sandy soil) or enlarging the pores (in silt loam and silty clay). In the case of silty clay soil (Fig. 4), the effect of increasing *K* is more apparent than in the case of silt loam soil. This could be because silty clay soil has a higher representation of the finest clay fraction (<0.002 mm) than silt loam soil.

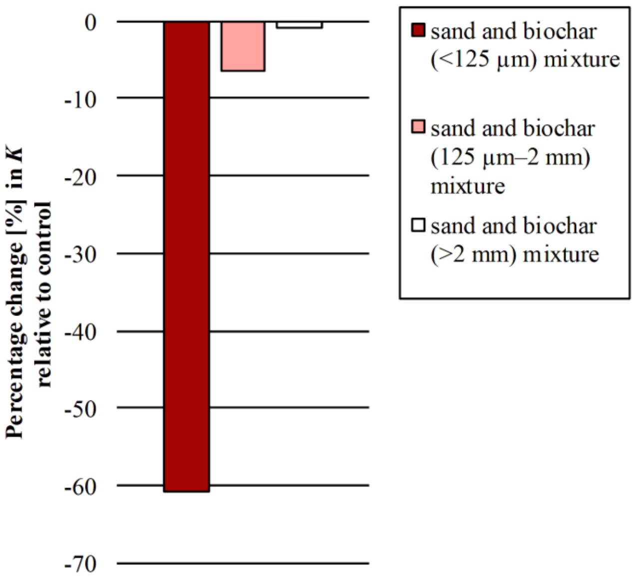

Fig. 2. Graphical representation of the influence of biochar on saturated hydraulic conductivity (K) of the sandy soil expressed as a percentage change relative to control.

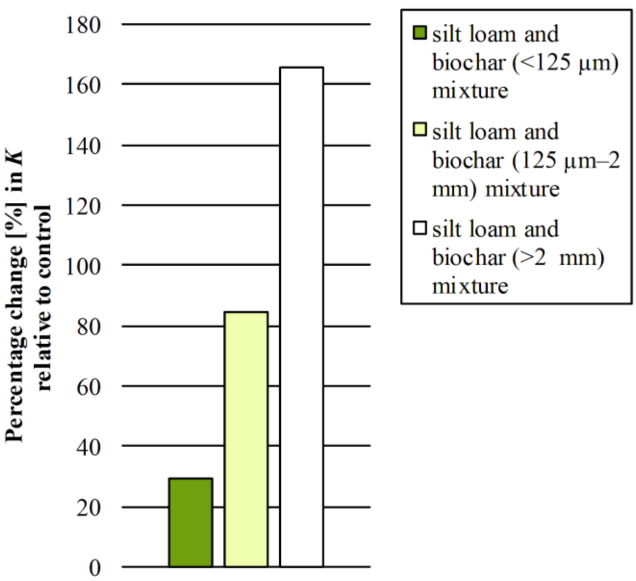

Fig. 3. Graphical representation of the influence of biochar on saturated hydraulic conductivity (K) of the silt loam soil expressed as a percentage change relative to control.

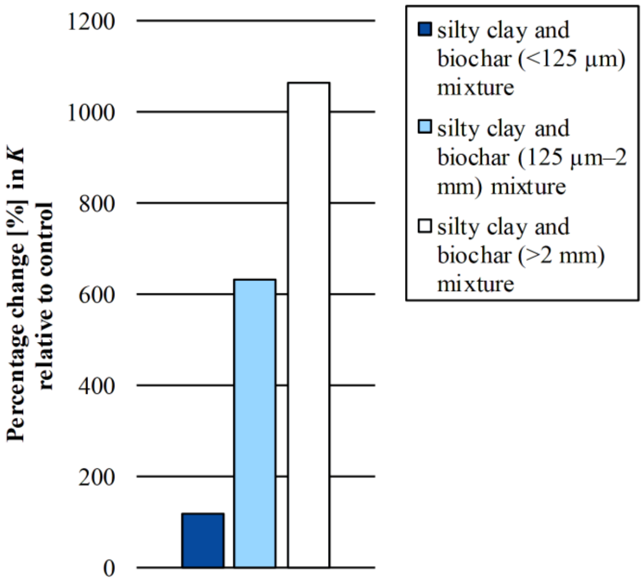

Fig. 4. Graphical representation of the influence of biochar on saturated hydraulic conductivity (K) of the silty clay soil expressed as a percentage change relative to control.

Table 3. Effect of biochar application on saturated hydraulic conductivity (*K*) of the sandy soil (means ± standard deviations)

Treatment	Mean [cm h^{-1}]	SD
sandy soil (control)	48.363^{b}	14.920
sand and biochar (<125 µm) mixture	18.958^{a}	5.581
sand and biochar (125 µm–2 mm) mixture	45.238^{b}	13.965
sand and biochar (>2 mm) mixture	47.940^{b}	16.893

Different letters (a, b) indicate that treatment means are significantly different at p<0.05 according to least significant difference test (one-way ANOVA).

Table 4. Effect of biochar application on saturated hydraulic conductivity (*K*) of the silt loam soil (means ± standard deviations)

Treatment	Mean [cm h^{-1}]	SD
silt loam soil (control)	0.966^{a}	0.558
silt loam and biochar (<125 µm) mixture	1.247^{a}	0.690
silt loam and biochar (125 µm–2 mm) mixture	1.779^{ab}	0.685
silt loam and biochar (>2 mm) mixture	2.563^{b}	0.893

Different letters (a, b) indicate that treatment means are significantly different at p<0.05 according to least significant difference test (one-way ANOVA).

Table 5. Effect of biochar application on saturated hydraulic conductivity (*K*) of the clay soil (means ± standard deviations)

Treatment	Mean [cm h^{-1}]	SD
silty clay soil (control)	0.083^{a}	0.045
silty clay and biochar (<125 µm) mixture	0.182^{a}	0.115
silty clay and biochar (125 µm–2 mm) mixture	0.605^{b}	0.142
silty clay and biochar (>2 mm) mixture	0.966^{c}	0.292

Different letters (a, b, c) indicate that treatment means are significantly different at p<0.05 according to least significant difference test (one-way ANOVA).

Evaluation of the falling–head method used for K measurements

The results showed that FHM is sensitive enough to record high differences in *K* measurements between sandy, silt loam and silty clay soil (Pedescoll et al., 2011) (with or without biochar amendment). Mean values ranged from 18.958 to 48.363 cm h^{-1}, from 0.966 to 2.563 cm h^{-1} and from 0.083 to 0.966 cm h^{-1} for sandy, silt loam and silty clay soil, respectively (Table 3, Table 4 and Table 5). Therefore, FHM appears to be a suitable technique for the evaluation of *K*. However, other authors (Antal and Igaz, 2012) stated that the FHM principle is more suitable to be used for finer soils (loams, clays). For coarser sandy soils, the constant-head method (CHM) measurement principle is recommended. The authors go on to give a cut-off value for "low" saturated soil hydraulic conductivity of 100 cm d^{-1} (i.e. 4.167 cm h^{-1}) and therefore a cut-off value for the use of one or other laboratory K measurement method. Our results showed that FHM exhibits a large standard deviation (SD) between measured values (n=9) within a single treatment in sandy soil (Table 3). In general, the largest SD was recorded in sandy soil (control) (14.920) and with biochar application with fraction >2 mm (16.893) (Table 3). Thus, the greater SD recorded in above mentioned cases was to be expected with the method used. The method used appears to be suitable for use on loamy and clayey soils (Table 4 and Table 5). On these soils, a high standard deviation between the measured values was not observed.

Conclusion

It can be concluded that the saturated hydraulic conductivity of the soil varied depending on the soil type and particle size fraction of the used biochar. Our results showed that biochar with the smallest particle size fraction (<125 μm) (mean value 18.958 cm h^{-1}) in sandy soil effectively retarded flow velocity compared to the control (mean value 48.363 cm h^{-1}). In clay soils, the use of biochar with the largest fraction size (>2 mm) (mean value 2.563 cm h^{-1}) effectively increases the rate of saturated hydraulic conductivity compared to the control (mean value 0.966 cm h^{-1}). As in clay soils, the use of biochar with larger fraction sizes (<125 μm–2 mm and >2 mm) effectively increased saturated hydraulic conductivity velocity (mean value 0.605 cm h^{-1} and 0.966 cm h^{-1}, respectively) compared to the control (mean value 0.083 cm h^{-1}). In all cases, this difference was also demonstrated by statistical analysis (one-way ANOVA). Further investigations are recommended to better understand the influence of biochar particle size on hydraulic conductivity in sandy, silty and clay soils. Our results provide recommendations for farmers that biochar particle size influences the soil hydrological regime. Farmers can choose a biochar fraction that will positively affect a specific soil type.

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