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Effects of Bentonite, Hydrogel and Biochar Amendments on Soil Hydraulic Properties from Saturation to Oven Dryness

Osama MOHAWESH[1,2,*] and Wolfgang DURNER[3]

[1] *Department of Plant Production, Faculty of Agriculture, Mutah University, Karak 61710 (Jordan)*
[2] *Division of Environmental Science and Technology, Graduate School of Agriculture, Kyoto University, Kyoto 6110011 (Japan)*
[3] *Institute of Geoecology, Technical University of Braunschweig, Langer Kamp 19c, Braunschweig 38106 (Germany)*

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ABSTRACT

Effects of hydrogel, bentonite, and biochar as soil amendments on soil hydraulic properties and improving water availability from saturation to oven dryness were investigated. Soils were mixed with hydrogel (0.10%, 0.25%, and 0.50%), bentonite (0.5%, 1.0%, and 2.5%), and biochar (1.0%, 2.5%, and 5.0%) as soil amendments (weight:weight). Three methods (extended multistep outflow (XMSO), evaporation (EVA), and WP4 dewpoint potentiometer) were used to measure soil hydraulic properties from saturation to oven dryness. The cumulative XMSO results were more uniform across all the applied pressure steps for the amended soils. The EVA exhibited a shorter linear decrease during the first evaporation stage and a lower evaporation rate during the second evaporation stage. The WP4 results also exhibited that soil amendments increased the soil water content of the amended soils at low matric potentials. The results of soil water retention curves revealed that the unamended soil retained less water at any matric potential compared to the amended soils. Soil hydraulic conductivity decreased with increasing amount of soil amendments. The saturated hydraulic conductivity was higher for the unamended soil than the soils amended with 2.5% bentonite, 0.50% hydrogel, and 5.0% biochar by 11, 3, and 18 times, respectively. These results suggested that soil amendments improved soil water retentivity, which confirmed the appropriateness of these soil amendments for potential use in sandy soil improvements. However, field experiments and economical perception studies should be considered for further investigation.

Key Words: evaporation, extended multistep outflow, soil amendment, soil matric potential, soil moisture, soil water retentivity, water availability, WP4 dewpoint potentiometer

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INTRODUCTION

Water scarcity and soil degradation can severely endanger food production and rural livelihoods. Appropriate policies are necessary to encourage land-improving investments and better land management to meet food needs sustainably. Sandy soils are the most common agricultural soils globally (Croker *et al.*, 2004). These soils have been recognized as naturally infertile, with limited capacity to retain water and nutrients (Noble *et al.*, 2001). Accordingly, several crop productions require a significant amount of nutrients to sustain plant growth. Adding fertilizers in these amounts to ensure appropriate plant growth can be unfeasible due to the low nutrient- and water-holding capacity. The naturally low cation exchange capacity (CEC) of these soils hinders their capacity to hold added nutrients, which can quickly drain through leaching under farming irrigation management practices. Nutrient addition can be expensive, wasteful, and potentially cause negative environmental impacts, as nutrients can be lost from the soil through leaching into the ground water and overflow into streams and surface water, affecting water quality as well as animal health (Spalding and Exner, 1992; Spalding *et al.*, 2001). Therefore, any attempt to improve soil water- and nutrient-holding capacity can assist in improving conditions for plant growth (Withers *et al.*, 2001; O'Connor and Chinault, 2006). The potential use of soil amendments, such as inorganic amendments hydrogel and bentonite, and organic amendment, such as biochar, to increase soil water- and nutrient-holding capacity has become an important issue over time, especially in regions of reduced water availability and fragile soil ecosystems, such as most of the Middle East region (Mohawesh, 2016).

Hydrogel is synthetic polymers with a large capacity to absorb and store water many times their own

*Corresponding author. E-mail: osama.mohawesh@gmail.com.

weight (Bowman and Evans, 1991; Narjary and Aggarwal, 2014). Addition of hydrogel to soils can increase their water-holding capacity, in addition to nutrient- and plant-available water, offering a great potential for improving soil productivity under water scarcity conditions (Al-Sheikh and Al-Darby, 1996; Hüttermann *et al.*, 1999; Yangyuoru *et al.*, 2006). Hydrogel addition can also improve water storage properties of porous soils by increasing their retention pores, decrease hydraulic conductivity, and reduce evaporation (Choudhary *et al.*, 1995; Al-Omran and Al-Harbi, 1998). Bentonite is a clay smectite mineral, usually montmorillonite. It is used to increase soil exchange properties, water-holding capacity, and plant growth (Noble *et al.*, 2001). It can significantly increase soil CEC because of the surface negative charge, and increase plant-available water as a function of increasing porosity (Soda *et al.*, 2006; Suzuki *et al.*, 2007). Thus, bentonite can enhance retention and nutrient availability, enhancing agricultural productivity and improving fertilizer use efficiency (Croker *et al.*, 2004; Noble *et al.*, 2004). Biochar is produced through the pyrolysis of biomass (Lehmann *et al.*, 2006; Ouyang *et al.*, 2014). It can be produced from a wide range of agricultural wastes, such as olive mill solid waste (Demirbas, 2004) and animal waste (Chan *et al.*, 2008). The application of biochar has many advantages, including boosting soil quality and plant growth performance (Chan *et al.*, 2008; Yuan *et al.*, 2011). Additionally, pyrolyzed biomasses are protected from fast microbial degradation, which might alleviate greenhouse gas emissions (Lehmann *et al.*, 2006).

Various effects of applying these amendments to soil were evaluated in most studies, but mainly for a small moisture range (Choudhary *at al.*, 1995; Al-Sheikh and Al-Darby, 1996; Githinji, 2014). Therefore, this study sought to fully explore the effects of hydrogel, bentonite, and biochar as soil amendments on soil hydraulic properties and water availability improvement across the whole moisture range from saturation to oven dryness.

MATERIALS AND METHODS

Soil sampling and soil properties

This study was performed using arable soils from the Lower Saxony region, Braunschweig City, northwestern Germany. Soil samples were collected, air-dried, sieved to pass through 2-mm mesh, and mixed for homogeneity. The initial soil properties were 96% sand, 4% silt and clay, 1 g kg^{-1} carbon, pH 5.9, and 0.65 cmol$_c$ CEC at pH 6. Beyond the unamended soil (control), soils were mixed with three soil amendments in two replicates based on dry weight (weight/weight) as follows: 0.10%, 0.25%, and 0.50% hydrogel (Luquasorb hydrogel, BASF Southeast Company, Germany), 0.5%, 1.0%, and 2.5% bentonite (natural hydrophilic bentonite, Sigma-Aldrich, Germany), and 1.0%, 2.5%, and 5.0% biochar. The biochar was produced from wood chips, pulverized, and sieved to pass through 2-mm mesh. It was obtained from slow pyrolysis at 350 °C (Halle University, Germany) with following properties: 910 g kg^{-1} carbon, 1.9 g kg^{-1} nitrogen, 2.1 g kg^{-1} phosphorous, 0.48 g cm^{-3} bulk density, 2.1 g kg^{-1} potassium, and 1.7% ash, which gave a C/N ratio of 433. The amended soil samples were mixed using a rotating shaker to ensure a homogenized mixture and then carefully packed in metallic cylinders of 500 cm^3 (height, 7.3 cm; internal diameter, 9.3 cm) for measuring soil hydraulic properties using the extended multistep outflow (XMSO) method (Durner and Iden, 2011) and in metallic cylinders of 250 cm^3 (height, 6.31 cm; internal diameter, 7.1 cm) for measuring soil hydraulic properties using the evaporation (EVA) method (Durner and Lipsius, 2005). Each treatment was packed to the same soil bulk density of 1.6 g cm^{-3}. Extra 10 g soil samples were used to measure soil water retention using the WP4 dewpoint potentiometer method (WP4 dewpoint potentiometer, Decagon Devices Inc., USA). In total, there were 60 soil samples, comprising 20 soil samples for each soil hydraulic property measurement method. The packed soil samples were slowly fully saturated, after packing from the bottom, for the XMSO and EVA methods. Then, soil samples were allowed to drain until reaching hydrostatic equilibrium. After this, tensiometers were installed in the soil samples: one tensiometer was installed for the XMSO method at a depth of 3.65 cm, and two tensiometers were used for the EVA method at depths of 1.525 and 4.575 cm of the soil column length. All experiments were performed at 21 ± 1 °C in an air-conditioned room. At the end of each experiment, the soil samples were weighed and oven-dried at 105 °C for 24 h to determine the final volumetric water content. The initial water content was obtained from the final water content and mass balances obtained from the cumulative outflow data during the experiments.

Soil hydraulic properties

Extended multistep outflow method. The XMSO commences as a falling-head infiltration method through saturated infiltration and is sustained as a normal multistep outflow (MSO) through attaching an extension to the soil cylinder, which is fixed to the top of the soil column for water ponding. The upper end of the soil column was closed to avoid evaporation, with a small hole that kept the upper boundary condition in equilibrium with the atmosphere. The soil samples were completely saturated from the bottom by applying a slowly increasing pressure to the water at the lower boundary until a ponding depth of 1.1 cm was reached. The initial condition was specified by a hydrostatic pressure head distribution. To commence the XMSO experiments, the pressure head at the bottom was lowered to 0 cm. This induced a saturated water flow. Subsequently, the upper boundary condition changed from a ponding condition to a no-flux condition, and the filtration process was altered to a draining flow. After that, the soil sample was drained by a stepwise decrease in the pressure head at the bottom boundary condition, from −10 to −50 cm with a −10 cm step-size, for a total duration of three days. The water flux (Q, cm) through the lower boundary and pressure head (h, cm) inside the soil samples were recorded during the experiments. The XMSO-measured data were assessed by inverse modeling using the Richards' equation, solved numerically by the HYDRUS-1D model (Simunek *et al.*, 2008). The hydraulic conductivities of the saturated ceramic plates were determined separately by the constant-head method before mounting the soil samples (Reynolds *et al.*, 2002).

Evaporation method. Soil samples were saturated from the bottom and allowed to drain, then sealed at the bottom. Two tensiometers (2.5 and 5.0 cm length) were inserted at depths 1.525 and 4.575 cm in each soil sample (Fig. 1). The tensiometers were inserted in an upward direction to minimize the amount of water draining from the tensiometers into the soil during the experimental stage 2 (Stage 1 is saturated water flux only). The cup diameter was 5 mm, with a height of 6 mm, and a wall thickness of 1.5 mm. The EVA experiment was started by removing the upper cap of the soil samples to expose the upper surfaces of the soil samples to evaporation. Overall mass and pressure heads were recorded every 12 h using the HYPROP system (UMS, Germany). The experiment was continued until the measurement limit of the upper tensiometer had reached a pressure head of about −800 cm. The average water content was derived from individual soil sample weights, then pairing the mean pressure and the water content data to yield the points of retention function. The hydraulic conductivity (K) data were calculated by the Darcy-Buckingham equation, which is given by:

$$K(h) = -\frac{q}{\Delta H} \tag{1}$$

$$q = q_{\text{evap}}/2 \tag{2}$$

$$\Delta H = \Delta h_t/\Delta z + 1 \tag{3}$$

where the flux density (q, cm d^{-1}) was calculated based on the evaporation flux density (q_{evap}) measured from the change in soil sample weight and the hydraulic gradient (ΔH) was calculated from the difference of the two pressure heads (h) in the soil column at each time interval (Δh_t, cm) and the distance between the two tensiometers (Δz, cm).

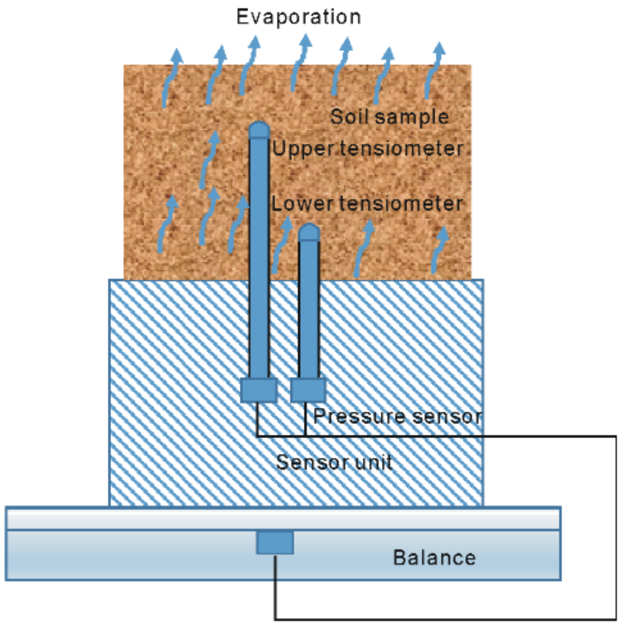

Fig. 1 Fully automated measuring and evaluation system to determine soil hydraulic properties using the evaporation method.

WP4 dewpoint potentiometer method. Water retention of the soil samples in the dry range was determined by a Decagon WP4 dewpoint potentiometer, which uses the chilled-mirror dewpoint method to measure the total matric potential. Sample cups (height, 1 cm; diameter, 4 cm) with a 15-mL capacity were used. We used 10 g soil samples to protect the sensor from contamination. The soil samples were wet to a specific water content, and then their matric potentials were measured at different water contents by allowing the water to evaporate from the soil samples to achieve different soil matric potentials. At each step, the soil samples were opened to the air for 1 to 2 h and closed tightly for 1 d to achieve an equilibrium condition. The matric potential and weight of each soil sample were recorded. Finally, the soil samples were oven-dried to calculate the final water content. Water content at each matric potential was calculated from the final water content and soil sample weight at each matric potential.

Combined soil hydraulic properties of the amended soils

Soil hydraulic property measurements were combined for each amended soil treatment. These combined soil hydraulic properties were used to compare the influence of several soil amendments on soil hydraulic properties from saturation to oven dryness. The whole soil water retention data were combined using the Durner model (Durner, 1994), which is given by:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} \sum_{i=1}^{k} w_i[1 + (\alpha_i h)^{n_i}]^{-m_i}, & h < 0 \\ 1, & h \geq 0 \end{cases} \tag{4}$$

where S_e is the effective saturation, θ is the water content (cm^3 cm^{-3}), θ_s is the saturated water content (cm^3 cm^{-3}), θ_r is the residual water content (cm^3 cm^{-3}), h is the matric potential (cm), α is a fitting parameter (cm^{-1}), n_i and m_i are the fitting parameters (dimensionless) related to the homogeneity of the pore size distribution for sub-curve i, and w_i is the weighting factor for sub-curve i, subject to the constraints $0 < w_i \leq 1$, $\Sigma w_i = 1$.

The whole soil hydraulic conductivity data were combined using the Mualem-van Genuchten model (van Genuchten, 1980), which is given by:

$$K(S_e) = \begin{cases} K_s S_e^{\lambda}[1 - (1 - S_e^{1/m})^m]^2, & h \leq 0 \\ K_s, & h \geq 0 \end{cases} \tag{5}$$

where λ is a fitting parameter and K_s is the saturated hydraulic conductivity. The fitting algorithm minimized the sum of squares deviations between data points and fitted models. The hydraulic conductivity data were fitted using a log-scale; otherwise, the large K values would have totally governed the fitting result.

RESULTS AND DISCUSSION

The XMSO results showed that the control treatment (sandy soil only) released a small amount of water down to a lower boundary pressure head of -20 cm (Fig. 2). Then, during the low pressure heads (-30 and -40 cm), the accumulated outflow reached 1.9 cm, which indicated that a major part of the pore space drained at this pressure head, corresponding to more than 25% of the overall sample volume. This behavior indicated a very steep soil water retention curve, narrow pore size distribution, and low water- and nutrient-holding capacity. The control treatment was dominated by large pores, and the movement of water through sandy soils is therefore relatively unhindered and fast. This behavior was less noticeable in all amended soils (Fig. 2). Cumulative outflow showed more uniformity across all the applied pressure steps for the amended soils (Fig. 1). The soil amendments modified the total porosity and pore size distribution (PSD), which played important roles in altering the hydraulic properties of the amended soils. Medium pores (mesopores) might also increase at the expense of macropores in the amended soils, compared to control. The amount of water retained in soils at lower matric potentials depends on the capillary effect and PSD (Jury and Horton, 2004).

The EVA method showed that the evaporation rate was nearly constant during the first 12 d of the control treatment, and then decreased (Fig. 3). Evaporation was controlled by the atmospheric conditions at the first stage of evaporation, while water flux decreased as soil sample water content decreased and became a limiting factor through the second stage. Pressure decreased relatively slow during the first stage of evaporation, with a hydraulic gradient close to hydrostatic conditions. Subsequently, the pressure head dropped abruptly and the hydraulic gradient between the two tensiometers increased promptly, which resulted in a strong decline in the hydraulic conductivity with drying of the upper part of the soil sample. Effects of soil amendments on evaporation rate among the different treatments were variable. This behavior reflected the effects of the soil amendments on soil hydraulic properties. The evaporation rate decreased linearly in the control treatment during the first stage; however, the linear decrease was shorter, and the second stage evaporation rate was smaller. During the first stage, the soil evaporation rate decreased with increasing amount of soil amendments. This reflected a decline in soil hydraulic conductivity associated with the addition of these amendments (Fig. 3, Table I). The effect of soil amendments on soil hydraulic properties depended on the soil amendment type. These results showed that bentonite and hydrogel were strong evaporation barriers compared to biochar. This is in agreement with several studies which have shown the addition of the soil amendments, bentonite (Croker *et al.*, 2004; Suzuki *et al.*, 2007), hydrogel (Abedi-Koupai *et al.*, 2008; Koupai *et al.*, 2008; Agaba *et al.*, 2010), and biochar (Novak *et al.*, 2009; Busscher *et al.*, 2010), increased water-holding capacity and decreased soil hydraulic conductivity.

The WP4 results exhibited that soil amendments increased the soil water content at low matric poten-

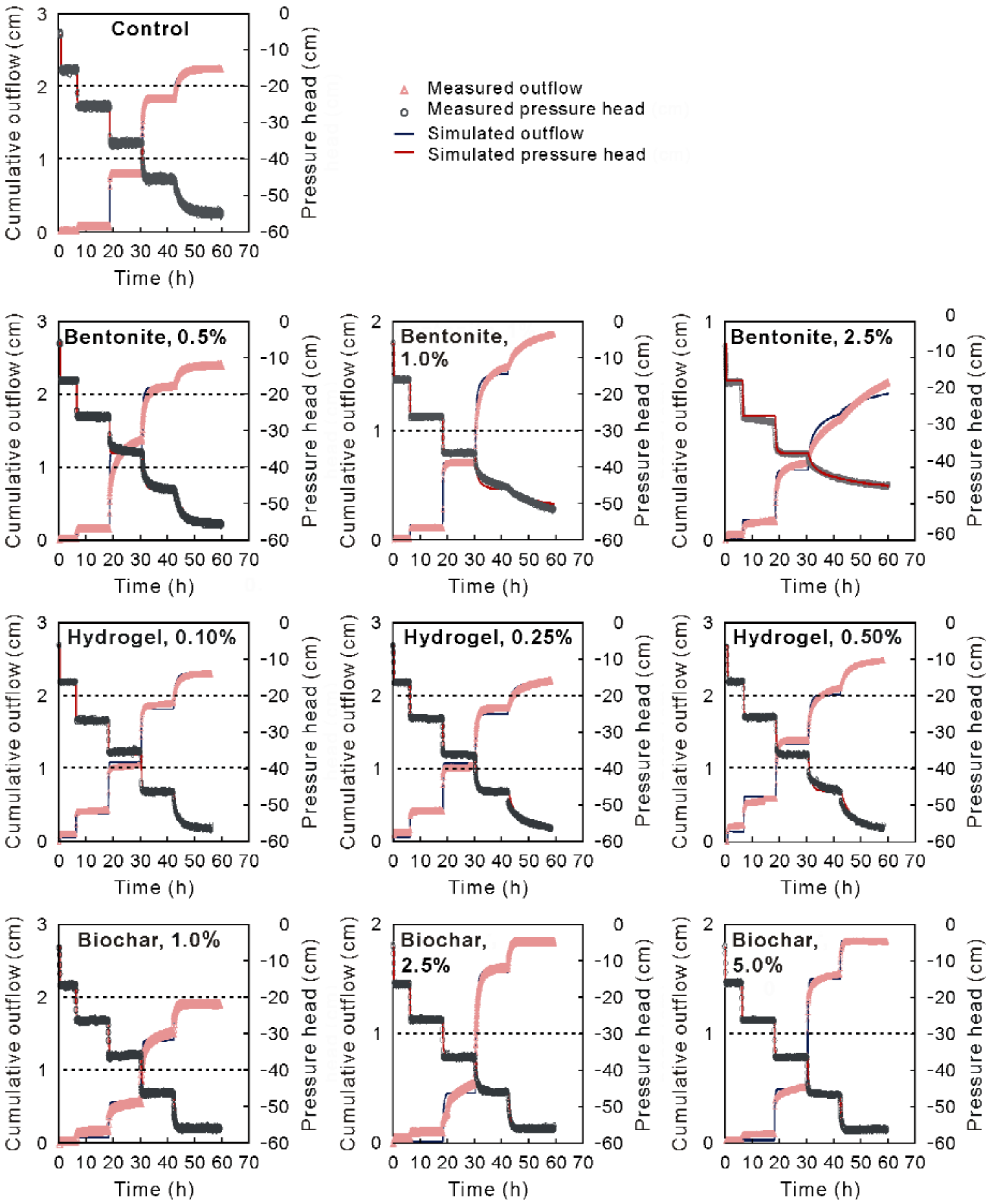

Fig. 2 Simulated and measured results of the extended multistep outflow for the unamended soil (control) and soils amended with bentonite, hydrogel, or biochar at different rates.

tials. These soil amendments may alter pore size distribution (increase meso- and micropores) and increase the surface area, which affected the water retention at low matric potentials (Fig. 4). Soil water retention at low matric potentials predominantly depends on adsorptive forces between the soil solid surface and soil solution; therefore, it is affected by the specific surface area of the soils. It was suggested that the inferred increases in specific areas are due to applied soil amendments (Soda *et al.*, 2006).

Soil water retention, which reflects soil ability to retain water, was increased significantly by mixing soil with bentonite, hydrogel, and biochar. Consequently, saturated water content, permanent wilting point, field

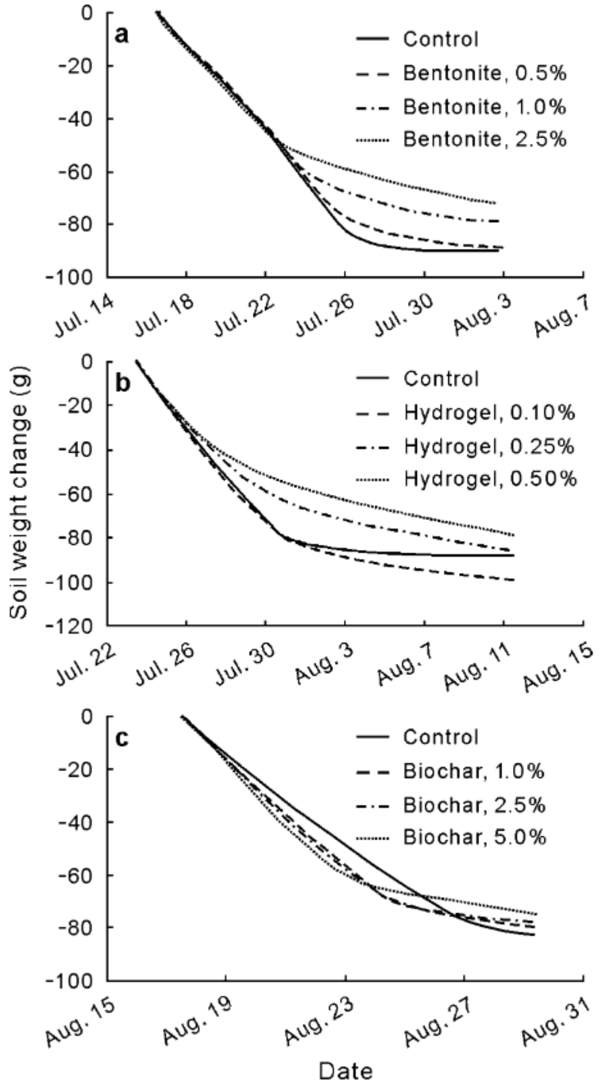

Fig. 3 Experimental course of evaporation (EVA) for the unamended soil (control) and soils amended with bentonite (a), hydrogel (b), or biochar (c) at different rates using the EVA method.

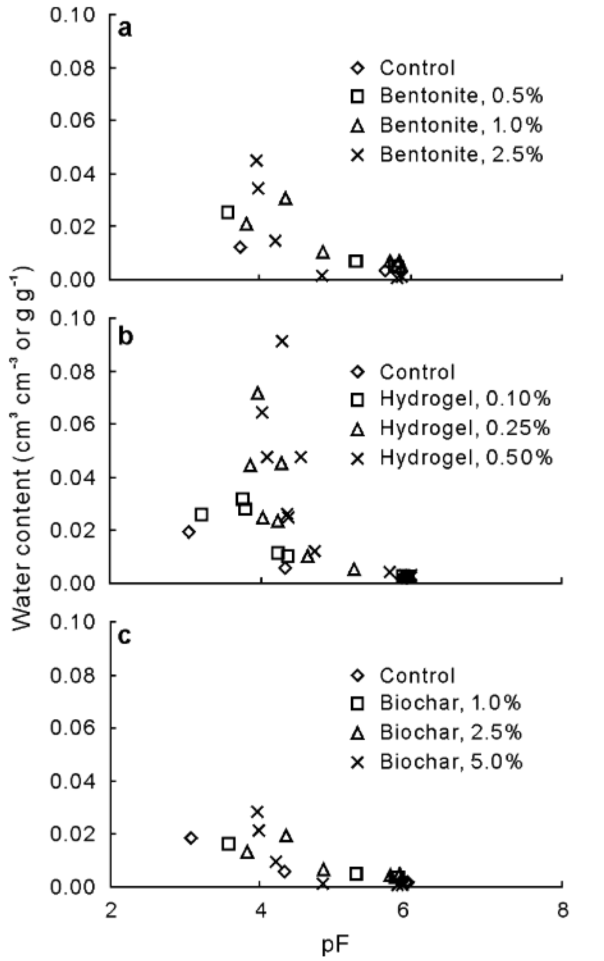

Fig. 4 Soil water contents at different water potentials (pF, dimensionless) for the unamended soil (control) and soils amended with bentonite (a), hydrogel (b), or biochar (c) at different rates using the WP4 dewpoint potentiometer method. It is volumetric water content (cm^3 cm^{-3}) for bentonite-amended soil and weight water content (g g^{-1}) for hydrogel- and biochar-amended soils.

capacity, and available water content were increased with increasing amounts of the soil amendments. The results of soil water retention curves (WRCs) showed that the control treatment retained less water at any matric potential compared to the amended soils (Figs. 5–7). The WRCs demonstrated a significant increase in water retention with increasing rates of bentonite, hydrogel, and biochar. At saturation, the highest water content was 0.669 g g^{-1} for the 0.50% hydrogel treatment (Table I). Bentonite and biochar exhibited medium saturation, with a saturated water content of 0.394 cm^3 cm^{-3} and 0.294 g g^{-1}, respectively. The soil samples of the biochar and hydrogel soil mixtures showed a swelling behavior. Thus, the water content was presented on the basis of weight. The WRC results revealed that hydrogel significantly improved soil water-holding capacity (Narjary *et al.*, 2012).

The direct effects of soil amendments on soil water retention were related to the increases in macro- and medium pores, due to the decreasing soil mixture bulk density and particle packing, respectively (Pietikainen *et al.*, 2000; Narjary *et al.*, 2012). This can be seen from the increase in soil moisture with increasing rate of soil amendments. For all amended soils, soil moisture increased with increasing application rate. The saturated water content increased from 0.358 cm^3 cm^{-3} for the control treatment to 0.388 cm^3 cm^{-3} for the 0.5% bentonite treatment, 0.395 cm^3 cm^{-3} for the 2.5% bentonite treatment, 0.327 g g^{-1} for the 0.10% hydrogel treatment, 0.669 g g^{-1} for the 0.50% hydrogel treatment, 0.237 g g^{-1} for the 1.0% biochar treatment, and 0.245 g g^{-1} for the 5.0% biochar treatment (Table I). The differences observed in water content between

TABLE I

Estimated parameters[a)] obtained from the combined fitting of the measured data for the unamended soil (control) and soils amended with bentonite, hydrogel, or biochar at different rates

Treatment	α_1	n_1	θ_r[b)]	θ_s[b)]	α_2	n_2	w_2	K_s	λ
	cm^{-1}		— $cm^3\ cm^{-3}$ or $g\ g^{-1}$ —		cm^{-1}			$cm\ h^{-1}$	
Control	0.008	1.494	0.00	0.358	0.024	7.086	0.853	48.60	2.214
Bentonite									
0.5%	0.057	1.331	0.00	0.388	0.025	6.637	0.716	30.80	1.806
1.0%	0.026	4.137	0.00	0.386	0.002	1.364	0.191	30.30	2.154
2.5%	0.038	3.808	0.08	0.395	6.800	0.218	1.00	4.30	2.687
Hydrogel									
0.10%	0.098	1.246	0.00	0.327	0.025	6.246	0.746	21.88	0.973
0.25%	0.032	1.281	0.00	0.454	0.025	5.606	0.553	21.04	3.564
0.50%	0.030	3.995	0.00	0.669	0.007	1.342	0.352	16.61	3.542
Biochar									
1.0%	0.015	1.459	0.00	0.237	0.025	7.160	0.758	1.90	0.684
2.5%	0.028	1.387	0.00	0.247	0.024	7.331	0.626	1.10	0.145
5.0%	0.023	5.600	0.00	0.295	0.009	1.444	0.448	2.60	0.825

[a)] α_1 and α_2 are the fitting parameters for the sub-curves 1 and 2, respectively; n_1 and n_2 are the parameters related to the homogeneity of the pore size distribution for the sub-curves 1 and 2, respectively; θ_r is the residual water content; θ_s is the saturated water content; w_2 is the weighting factor for the sub-curve 2; K_s is the saturated hydraulic conductivity; λ is a fitting parameter.
[b)] In $cm^3\ cm^{-3}$ for bentonite-amended soil and $g\ g^{-1}$ for hydrogel- and biochar-amended soils.

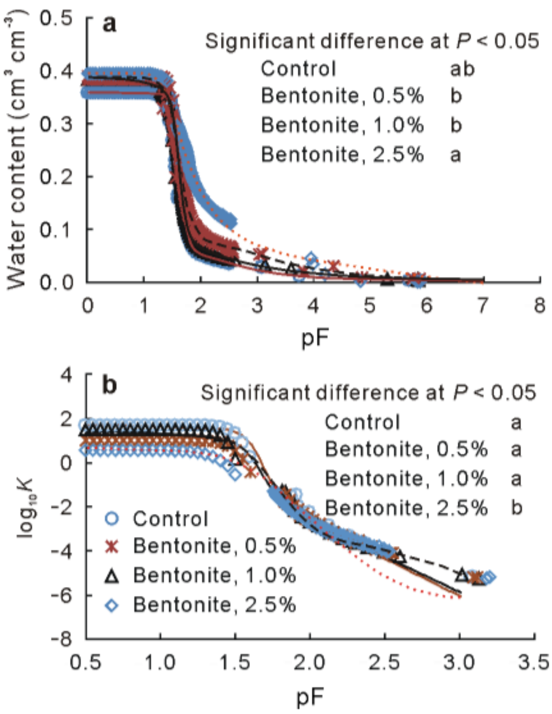

Fig. 5 Soil water retention curves (a) and soil hydraulic conductivity (K) (b) at different water potentials (pF, dimensionless) using the combined methods (extended multistep outflow, evaporation, and WP4 dewpoint potentiometer) for the unamended soil (control) and soils amended with bentonite at different rates.

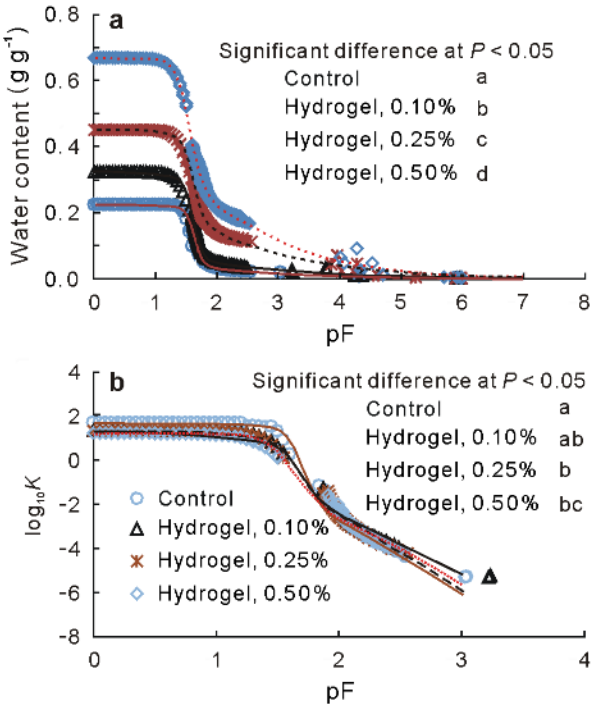

Fig. 6 Soil water retention curves (a) and soil hydraulic conductivity (K) (b) at different water potentials (pF, dimensionless) using the combined methods (extended multistep outflow, evaporation, and WP4 dewpoint potentiometer) for the unamended soil (control) and soils amended with hydrogel at different rates.

the amended treatments and the control treatment appear to be mostly due to altering the porosity of the amended soil and soil amendment retentivity and absorptivity properties, allowing more water to be physically retained (Yates *et al.*, 1992; Narjary *et al.*, 2012). This can be perceived from the decrease in the weighting factor for sub-curve 2 (w_2) with soil amendments, which indicated alterations in the PSD and tortuosity of the amended soils (Narjary *et al.*, 2012; Lim *et al.*, 2016) (Table I).

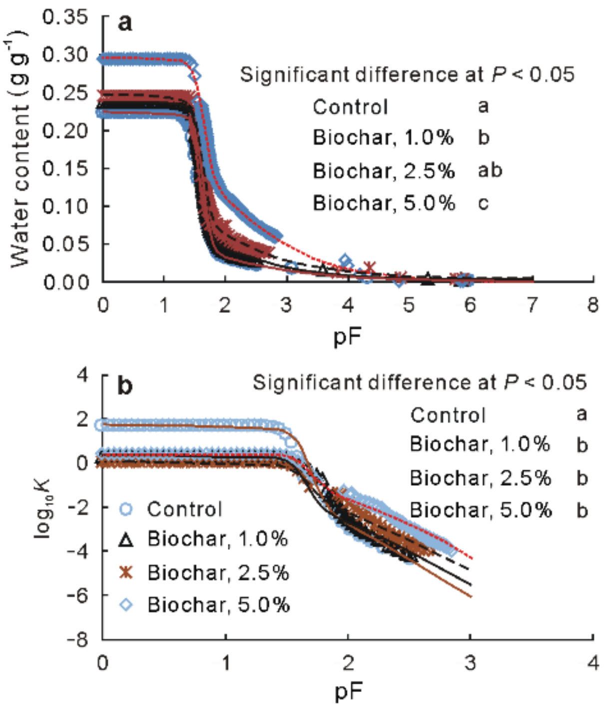

Fig. 7 Soil water retention curves (a) and soil hydraulic conductivity (K) (b) at different water potentials (pF, dimensionless) using the combined methods (extended multistep outflow, evaporation, and WP4 dewpoint potentiometer) for the unamended soil (control) and soils amended with biochar at different rates.

Soil hydraulic conductivity decreased significantly with increasing soil amendments (Figs. 5–7). It was higher in the control treatment than the treatments with bentonite, hydrogel, and biochar across the wet range. The K_s for the control treatment was higher than the soils amended with 2.5% bentonite, 0.50% hydrogel, and 5.0% biochar by 11, 3, and 18 times, respectively. Soil amendments increased soil tortuosity, which can result in significantly lower K_s values (Sun *et al.*, 2013, 2015). Nevertheless, hydraulic conductivity is more affected by PSD (Tuli *et al.*, 2005). This decrease in soil mixture hydraulic conductivity can be beneficial in sandy soils, as it might result in greater growth and yields due to the reduced water and nutrient downward movement. It would also result in additional contact of plant roots with water and nutrients for a longer duration compared to the control treatment. These results are in agreement with previous studies, which also showed that soil hydraulic conductivity in sandy soils decreased with soil amendments (Abedi-Koupai *et al.*, 2008; Ibrahim-Saeedi and Sepaskhah, 2013; Lim *et al.*, 2016). Hydrogel and biochar decreased the soil mixture bulk density, which can be associated with the increase of macroporosity in the soil. Therefore, soil amendment additions affect soil hydraulic properties by increasing soil tortuosity and particle packing, which might affect the PSD (Kameyama *et al.*, 2012; Novak *et al.*, 2012). The saturated and near-saturated hydraulic conductivity decreased significantly with increasing amendment amount. Our results are in agreement with Lim *et al.* (2016), who showed that biochar additions reduced hydraulic conductivity significantly when they were added to coarse and fine sand, and Ibrahim-Saeedi and Sepaskhah (2013), who also showed that light soil hydraulic conductivity decreased with the addition of bentonite.

CONCLUSIONS

Soil amendments bentonite, hydrogel, and biochar significantly increased water content and improved water retention in the soil. The cumulative XMSO results showed more uniformity across all the applied pressure steps for the amended soils, which suggested that PSD was altered by soil amendments. Evaporation exhibited a shorter linear decrease during the first stage, and evaporation rate was lower during the second stage. The WP4 results exhibited that soil amendments increased soil water content at lower matric potentials. The WRC results revealed that the control treatment retained less water at any matric potential compared to the amended soils. The K_s was higher for the control treatment than the amended soils. These results suggested that the soil amendments significantly improved soil water retentivity, which confirmed the suitability of these soil amendments for potential use in sandy soil improvements. The wide use of biochar and bentonite can be enhanced due to their higher availability and low cost compared to hydrogel. However, field experiments and cost-effective assessments should be considered for further investigation.

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