



Effect of biochar amendment on water infiltration in a coastal saline soil

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Abstract

Purpose Increasing data have shown that biochar amendment can improve soil fertility and crop production, but there is little knowledge about whether biochar amendment can improve water infiltration in saline soils. We hypothesized that biochar amendment could promote water infiltration in saline soil. The aims of this study were to evaluate the effects of biochar amendment on water infiltration and find the suitable amendment rate and particle size of biochar as a saline soil conditioner.

Materials and methods We measured water infiltration parameters in a coastal saline soil (silty loam) amended with non-sieved biochar at different rates (0.5, 1, 2, 5, and 10%, w/w) or sieved biochar of different particle sizes (≤ 0.25 mm, 0.25–1 mm, and 1–2 mm) at 1 and 10% (w/w).

Results and discussion Compared with the control, amending non-sieved biochar at 10% significantly decreased water infiltration into the saline soil ($P < 0.05$). In contrast, sieved biochar of ≤ 0.25 mm significantly improved water infiltration capacity, irrespective of the amendment rate. Sieved biochar of 1–2 mm was less effective to improve soil porosity and when amended at 10%, it even reduced the water infiltration capacity. The Philip model ($R^2 = 0.983\text{--}0.999$) had a better goodness-of-fit than the Green-Ampt model ($R^2 = 0.506\text{--}0.923$) for simulation of cumulative infiltration.

Conclusions Amending biochar sieved to a small particle size improved water infiltration capacity of the coastal saline soil compared with non-sieved biochar irrespective of the amendment rate. This study contributes toward improving the hydrological property of coastal saline soil and rationally applying biochar in the field.

Keywords Biochar amendment rate · Particle size · Saline soil · Sieved biochar · Water infiltration

1 Introduction

The total area of saline soil in the world is approximately 9.32 million square kilometers, which accounts for ~10% of the total irrigated land (Rengasamy 2006) and is still growing (Aquistat 2016). As an important land resource, the saline soil occurs widely in the Yellow River Delta, Shandong Province,

China. In this delta area, coastal saline soils are facing prominent problems such as easy compaction, poor water and air permeability, and low water and nutrient retention capacity. These problems have severely limited the production potential of salt-resistant crops and become a major factor that restricts the sustainable development of agriculture (Zhou et al. 2017).

Chemical amendments have been commonly used for the improvement of saline soils, such as soluble calcium salts, acid chemicals, and industrial co-products (e.g., phosphogypsum and coal gangue) (Wang et al. 2017). However, these chemical amendments show a short-term effect for soil improvement (Yazdanpanah et al. 2013). Currently, biochar is extensively used as a novel soil amendment in the study of soil improvement. Biochar is a solid material produced from biomass by pyrolysis in anoxic/hypoxic conditions (Glaser et al. 2002). Biochar amendment is conducive to reduce soil density and increase soil porosity, and thus can improve soil structure and facilitate plant root growth (Laird et al. 2010; Githinji 2014; Tammeorg et al. 2014). Moreover, biochar is

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taken from and applied back to agricultural fields. Thus, biochar amendment helps to solve the problem of “taking more and giving less” in traditional agriculture. The majority of calcium, magnesium, potassium, and phosphorous in raw materials are retained in biochar, which, as a soil amendment, can return most nutrients into the soil (Cheng et al. 2008; Masto et al. 2013). Furthermore, the raw materials used for biochar preparation are mainly derived from agricultural wastes (Chan et al. 2008; Hossain et al. 2010; Van Zwieten et al. 2010). Therefore, biochar application provides a new solution to the problems caused by the traditional treatment of agricultural wastes (e.g., straw burning) and thereby contributes to the efficient, environmental-friendly, and sustainable utilization of agricultural wastes.

The effect of biochar on soil water migration has been evaluated by laboratory simulation experiments (Mukherjee et al. 2014; Chaganti and Crohn 2015; Lim et al. 2016). For example, Ibrahim et al. (2017) found that biochar amendment decreased the saturated hydraulic conductivity of a sandy loam soil. Głąb et al. (2016) showed that the effective water content increased in a sandy loam amended with 0.5–4% (w/w) wheat straw-derived biochar. Novak et al. (2016) reported that except for the biochar produced from 100% poultry litter, all other biochars amended significantly increased water infiltration in a Norfolk soil. Moreover, Liu et al. (2016) found that different particle sizes of biochar showed varying effects on the hydraulic conductivity of silica sand, which lacked the basic soil structure. Inconsistent results of biochar effect were reported in the above studies, mainly due to the differences in soil type, biochar amendment rate, and biochar particle size. In addition, biochar could be produced by different types of pyrolysis (slow, fast, and gasification) and obtained by different types of biomass (vegetal and sludges). To the best of our knowledge, only Yue et al. (2016) has investigated water migration in a slightly alkaline soil amended with biochar. It was found that sunflower straw biochar led to much faster salt leaching and thus was considered a potential amendment of saline soils in the Hetao region of China (Yue et al. 2016). Presently, we have little knowledge about the effects of biochar amendment rate and particle size on the hydrodynamic changes of coastal saline soil pedon in the Yellow River Delta.

The aims of this study were to analyze the effects of amending different rates and sizes of biochar on water filtration of a coastal saline soil, and determine the suitable rate and size of biochar as a saline soil conditioner through a one-dimensional vertical infiltration experiment. We hypothesized that biochar amendment would promote water infiltration in saline soil, while the effect might depend on biochar amendment rate and particle size. The results contribute to rational application of biochar in coastal saline soil and returning of agricultural wastes to the field in the Yellow River Delta.

2 Materials and methods

2.1 Experimental materials

The experimental soil was taken from a flat wasteland near the Yellow River Delta ecological experimental station of coastal wetlands (37° 45' 50" N, 118° 59' 24" E), Chinese Academy of Sciences (Dongying, Shandong, China). The Yellow River Delta has significant temperature variations in the four seasons, with the annual average temperature of 11.7–12.6 °C, extreme maximum temperature of 41.9 °C, and extreme minimum temperature of –23.3 °C. The average annual sunshine hour is 2590–2830 h, and the frost-free period is 211 days. The average annual precipitation is 530–630 mm, 70% of which occurs in summer. The average evapotranspiration is 750–2400 mm (Kong et al. 2015). The vegetation in the study area shows a patchy distribution and simple community composition, mainly salt-tolerant plants. The dominant species are *Suaeda salsa*, *Phragmites australis*, *Tamarix chinensis*, and *Imperata cylindrica*. Nearly 50% of soils are saline and alkaline in the Yellow River Delta (Li et al. 2013). After rain or irrigation, it is relatively difficult for water and salt to infiltrate into the soil profile and tends to form surface runoff, which can accelerate the loss of soil nutrients and negatively affect the root growth of plants.

Soil core was collected to a depth of 60 cm based on the depth of plant roots in the study area. Five cores were randomly taken and mixed to form a composite sample. After removal of impurities, the soil was air-dried, ground, and passed through a 2-mm sieve before use. The soil contained 11.6% clay (<0.002 mm), 48.7% silt (0.002–0.02 mm), and 39.6% sand (>0.02 mm). The soil texture was silty loam.

Biochar was prepared from corn straw by pyrolysis at 450 °C for 0.5 h. The pH of the biochar was 6.93, and the electrical conductivity was 0.388 dS/m. The basic physico-chemical properties of the soil and biochar are shown in Table 1.

2.2 Experimental design

The experiment was conducted by one-dimensional vertical infiltration. The container of the soil column was a transparent PVC cylinder, 6 cm in the inner diameter and 340 mm in height. Vaseline was evenly applied to the inner wall of the cylinder to reduce the effect of the inner wall on the infiltration. To simulate the permeability of the soil in the field, we placed a 20-mm layer of quartz sand at the bottom of the cylinder. The material was filled layer by layer and weighed in every 2 cm intervals. The soil was disturbed between layers to prevent the stratification during infiltration. The top of the soil was covered with a filter paper to prevent erosion.

As biochar is often amended in the surface soil layer in field conditions (Obia et al. 2017), we applied the corn straw

Table 1 Basic physicochemical properties of the coastal saline soil and corn straw biochar used in this study

Soil property	Coastal saline soil (silty loam)	Corn straw biochar
Bulk density (g cm^{-3})	1.48	–
Porosity (%)	42	–
pH	8.48	6.93
Electrical conductivity (dS m^{-1})	2.28	0.388
Saturated hydraulic conductivity (cm s^{-1})	9.08×10^{-5}	–
Cation exchange capacity (cmol L^{-1})	11.4	18.8
Total organic carbon (mg g^{-1})	4.24	490
Soil particle composition (%)	< 0.002 mm	11.6
	0.002–0.02 mm	48.7
	> 0.02 mm	39.6

biochar to the 0–10 cm depth of the soil column. A biochar-soil mixture was filled into the 0–10 cm layer, and the coastal saline soil was filled into the 10–30 cm layer. We prepared the materials with a fixed bulk density (1.35 g cm^{-3}) based on the actual soil conditions and the maximum volume of high-rate biochar (10%, w/w) that could be filled into the soil column. The experiment was divided into two groups. Experiment one was amended with non-sieved biochar at different rates, 0% (control, CK), 0.5% (C0.5), 1% (C1), 2% (C2), 5% (C5), and 10% (C10). Experiment two was amended with sieved biochar of different particle sizes, ≤ 0.25 mm, 0.25–1 mm, and 1–2 mm, at rates of 1 and 10%. Each treatment had three replicates.

During the experiment, a Mariotte bottle was used to supply water and maintain a constant head (Hewitt 1966). The Mariotte bottle was a transparent PVC cylinder, 6 cm in the inner diameter and 600 mm in height. It had an outlet at the bottom and was connected to the external air through an air intake tube. Before the start of the experiment, the height of the Mariotte bottle was adjusted to make the lower end of the intake tube at approximately 1.5–2.0 cm above the soil surface, thereby maintaining a constant water head of 1.5–2.0 cm. Changes in the wetting front and infiltration amount were recorded every 1 min for the first 10 min, every 2 min for 10–30 min, and then every 3 min until the end of the experiment. Time recording ended and water supply stopped when the wetting front reached the bottom of the soil column (300 mm).

2.3 Data analysis

The change process of the distance and time of wetting front migration fits the power function: $F = at^b$, where F is the wetting front migration distance (mm), t is the time (min), and a and b are empirical constants. The a value indicates the wetting front migration distance within the first unit of time, and the b value indicates the attenuation of wetting front advance process.

Infiltration data were fitted using the Philip model (Philip 1957) and the Green-Ampt model (Green and Ampt 1911). The Philip model is expressed as follows:

$$I(t) = St^{0.5} + At \quad (1)$$

where $I(t)$ is the cumulative infiltration, mm; S is the sorptivity, $\text{mm min}^{-0.5}$; A is the steady infiltration rate, mm min^{-1} ; and t is the infiltration time, min. Sorptivity is defined as the ability of soil to take up or release fluid by relying on capillary force, which is an important indicator for soil water infiltration capacity at an early stage; the higher the S value, the greater the soil water infiltration capacity. Steady infiltration rate refers to the steady infiltration strength or rate of soil and measures soil water infiltration capacity; as the infiltration time increases, the A value plays a major role in determining the soil water infiltration rate.

The Green-Ampt model has been extensively used in the research of soil water movement process. This model has the advantages of simple description and clear physical interpretation. The Green-Ampt model is expressed as follows:

$$i(t) = K_s(1 + H_m/Z_f) \quad (2)$$

where $i(t)$ is the soil infiltration rate (cm min^{-1}); K_s is the saturated hydraulic conductivity (cm min^{-1}); H_m is the average suction of infiltration front (cm); and Z_f is the generalized wetting front depth (cm). The change of $K_s * H_m$ directly reflects the change of soil water diffusivity.

Data were statistically analyzed using SPSS 13.0 Statistics (SPSS Inc., Chicago, IL, USA). The Shapiro-Wilk normality test was conducted before an analysis of variance (ANOVA), and all data followed a normal distribution. For the experiment one, a one-way ANOVA was applied to test the difference of parameters between biochar amendment rates. For the experiment two, mean difference was examined by a two-way ANOVA, followed by a post hoc test (e.g., Duncan or Tukey). If significant interactions were found between biochar particle size and amendment rate ($P < 0.05$), a one-way

ANOVA was applied to test the difference between particle sizes at each biochar amendment rate, separately.

3 Results

3.1 Effects of biochar amendment rate on water infiltration in saline soil

Figure 1 shows the dynamic changes of wetting front in the saline soil amended with biochar at different rates. With an increase of biochar amendment rate, the *a* value initially increased and then decreased. Compared with the CK, lower rates of biochar treatment (C0.5, C1, and C2) promoted wetting front migration within the first unit of time (1 min) during the experiment. In contrast, wetting front migration was limited by higher rates of biochar treatment (C5 and C10). When the wetting front reached 300 mm depth (bottom of soil column), the duration of water infiltration was 201 min for the control. As the biochar amendment rate increased from 0.5 to 1, 2, and 5%, the infiltration duration initially increased from 189 to 198 min and then decreased to 180 min, followed by a rebound to 192 min. When 10% biochar was amended, the infiltration duration increased significantly by 8.96% compared with the control ($P < 0.05$).

At the initial stage of water infiltration, the soil mass was dry with a low soil matric potential. In this case, soil water infiltration was less affected by biochar amendment rate. The cumulative infiltration curves were steep, showing a high curve coincidence degree. As the infiltration time increased, the effect of different biochar treatments on the soil water cumulative infiltration was gradually revealed (Fig. 2). At the infiltration time of 170 min, the cumulative infiltration in the soil amended with biochar at different rates ranged from 99 mm (C10) to 117 mm (C2). Statistical analysis revealed slight but not significant increases in the cumulative

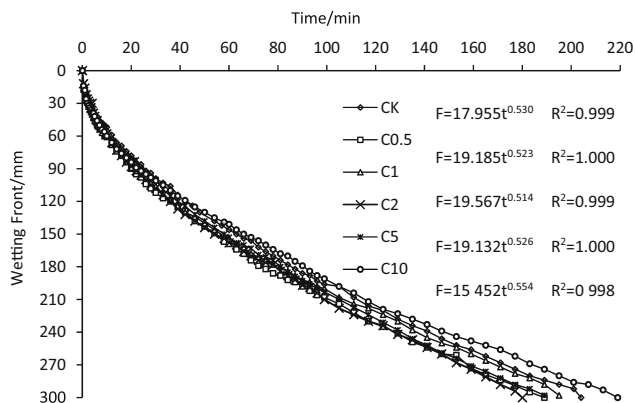


Fig. 1 Dynamic changes of wetting front in the saline soil amended with biochar at different rates (0, CK; 0.5%, C0.5; 1%, C1; 2%, C2; 5%, C5; and 10%, C10)

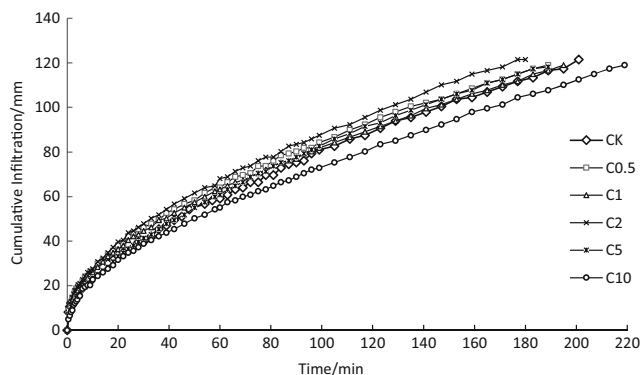


Fig. 2 Effects of different biochar amendment rates (0, CK; 0.5%, C0.5; 1%, C1; 2%, C2; 5%, C5; and 10%, C10) on cumulative infiltration into the saline soil

infiltration of C0.5 to C5 treatments (by 6.6, 5.2, 4.7, and 1.5%, respectively; $P > 0.05$), whereas a significant decline was found in C10 treatment (by 10.05%; $P < 0.05$), as compared with the control (Fig. 3).

3.2 Effects of biochar particle size on water infiltration in saline soil

For different treatments of biochar particle size, soil wetting front and cumulative infiltration changed over time, similar to the trends observed with biochar amended at different rates (data not shown). Figure 4 presents the trends of infiltration duration in the saline soil amended with biochar of different particle sizes. The infiltration time required for the wetting front to reach 300 mm depth significantly differed in the soil amended with biochar at 0, 1, and 10%. When biochar was amended at 1%, the wetting front required 201, 180, 189, and 201 min to reach 300 mm depth for the CK, ≤ 0.25 mm, 0.25–

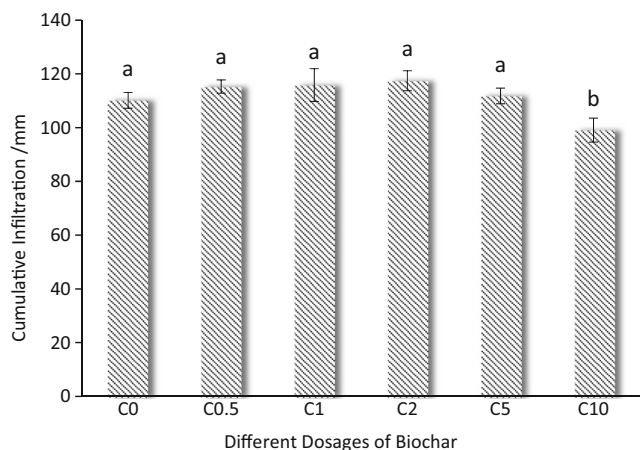


Fig. 3 Cumulative infiltration of water into the saline soil amended with biochar at different dosages (0, CK; 0.5%, C0.5; 1%, C1; 2%, C2; 5%, C5; and 10%, C10). Data recorded at 170 min of infiltration. Different letters above the column indicate significant different at $P < 0.05$

1 mm, and 1–2 mm biochar treatments. Statistical analysis revealed that ≤ 0.25 mm and 0.25–1 mm biochar treatments significantly shortened the duration of infiltration by 10.45 and 5.97%, respectively ($P < 0.05$) compared with the CK. No major differences were found in the water infiltration characteristics of the soil amended with 1–2 mm biochar. When biochar was amended at 10%, the wetting front required 201, 180, 213, and 243 min to reach 300 mm depth for the CK, ≤ 0.25 mm, 0.25–1 mm, and 1–2 mm biochar treatments. Statistical analysis revealed that ≤ 0.25 mm biochar treatment significantly shortened the duration of infiltration by 10.4% ($P < 0.05$), whereas 0.25–1 mm and 1–2 mm biochar treatments significantly prolonged the duration of infiltration by 6 and 23.9%, respectively.

Figure 5 compares cumulative infiltration between different treatments of biochar particle size, which showed the opposite trend to infiltration duration. With biochar amended at 1%, ≤ 0.25 mm and 0.25–1 mm biochar treatments significantly increased the cumulative infiltration at 170 min, while 1–2 mm biochar treatment resulted in no major difference compared with the CK. With biochar amended at 10%, ≤ 0.25 mm biochar treatment significantly increased the cumulative infiltration by 5.5% ($P < 0.05$), while 0.25–1 mm and 1–2 mm biochar treatments significantly reduced the cumulative infiltration by 4.04 and 17.4%, respectively ($P < 0.05$).

3.3 Fitting parameters of the Philip and Green-Ampt models

The coefficient of determination (R^2) for the fit of the Philip model to cumulative infiltration ranged from 0.983 to 0.999. This indicates that the Philip model had a high goodness-of-fit for simulation of water infiltration in the biochar-amended saline soil. Table 2 shows that as the biochar amendment rate increased, the sorptivity (S) of the saline soil first increased (i.e., 0.5, 1, and 2% treatments) and then decreased (i.e., 5 and 10% treatments) compared with the CK. The corresponding steady infiltration rate (A) fluctuated, with the highest value being found for the 5% biochar treatment.

There were no significant interaction effects between biochar particle size and amendment rate on the parameters S and A ($F = 1.626$ and 2.697 , respectively, $P > 0.05$; Table 3). The differences in the model parameters with different biochar particle sizes are shown in Table 4. When biochar of the same particle size was amended, low-rate treatment (1%) resulted in a significantly higher S value than high-rate treatment (10%). When biochar was amended at the same rate, the S value decreased with increasing particle size of biochar. With 1% biochar amendment, the S value was higher for the ≤ 0.25 mm ($9.42 \text{ mm min}^{-0.5}$) and 0.25–1 mm ($9.42 \text{ mm min}^{-0.5}$) biochar treatments, but no significant difference was found

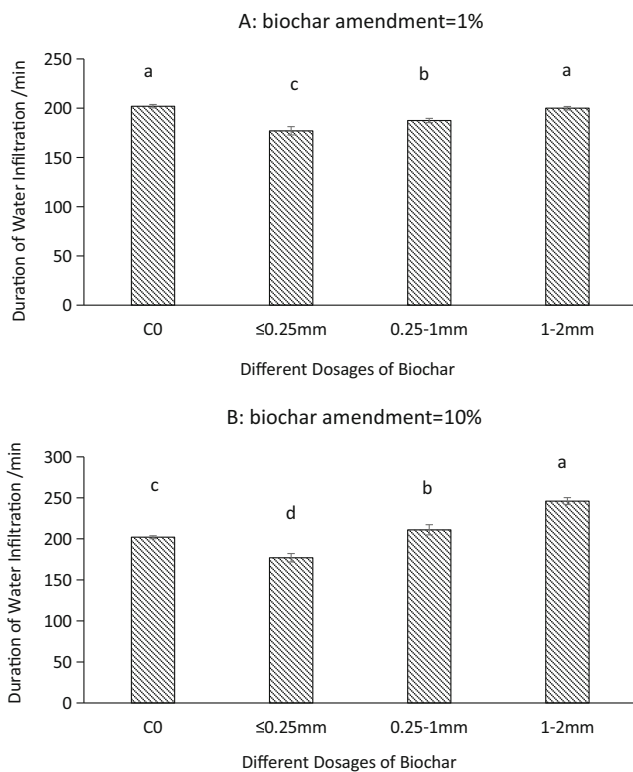


Fig. 4 Changes in the duration of water infiltration into the saline soil amended with biochar of different particle sizes and at the same rates (A, 1%; and B, 10%). Different letters above the column indicate significant different at $P < 0.05$

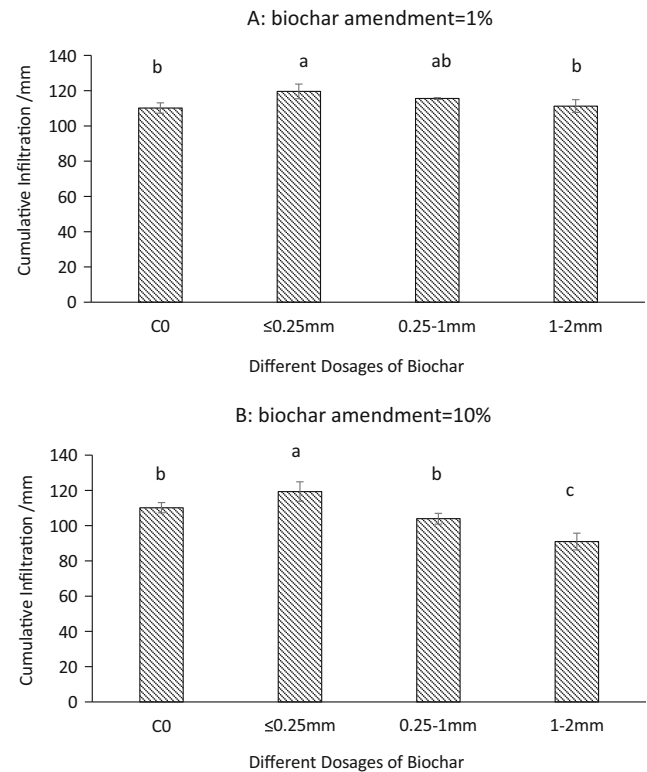


Fig. 5 Cumulative infiltration of water into the saline soil amended with biochar of different particle sizes at the same rates (A, 1%; and B, 10%). Data recorded at 170 min of infiltration. Different letters above the column indicate significant different at $P < 0.05$

Table 2 Parameters of Philip and Green-Ampt infiltration models in experiment 1

Biochar amendment rate (%)	Philip model			Green-Ampt model	
	<i>S</i> (mm min ^{-0.5})	<i>A</i> (mm min ⁻¹)	<i>R</i> ²	<i>K_s*H_m</i>	<i>R</i> ²
0	7.29b	0.36b	0.999	136a	0.657
0.5	8.0a	0.65b	0.999	125.6a	0.664
1	8.26a	0.39b	0.999	146.1a	0.788
2	8.51a	0.55b	0.999	144.5a	0.721
5	7.52ab	0.93a	0.993	132.7a	0.704
10	7.03b	0.54b	0.999	113.6b	0.767

Values with different letters are significantly different at $P < 0.05$ (by one-way ANOVA)

in the 1–2 mm (7.53 mm min^{-0.5}) biochar treatment, as compared with the CK (7.29 mm min^{-0.5}). With 10% biochar amendment, ≤ 0.25 mm biochar treatment resulted in a higher *S* value (8.32 mm min^{-0.5}) than CK, whereas 0.25–1 mm (6.53 mm min^{-0.5}) and 1–2 mm (6.22 mm min^{-0.5}) biochar treatments significantly reduced the *S* value. There were no clear trends in the steady filtration rate (*A*) with the increase of biochar amendment rate or particle size.

The R^2 for the fit of the Green-Ampt model ranged from 0.657 to 0.801. The goodness-of-fit of the Green-Ampt model was lower than that of the Philip model. There were significant interaction effects between biochar amendment rate and biochar particle size on $K_s * H_m$ ($F = 6.493$, $P < 0.05$; Table 3). The effect of biochar amendment on soil water infiltration characteristics was mainly reflected in the change of soil water diffusivity ($K_s * H_m$). Correlation analysis revealed that the $K_s * H_m$ was significantly correlated with cumulative infiltration in different treatments ($r = 0.757$; $p < 0.01$). As the biochar amendment rate increased, the $K_s * H_m$ first increased before decreasing; that is, the higher the biochar amendment rate, the lower the soil water diffusivity. When biochar was amended at the same rate (C1 or C10), soil water diffusivity decreased with increasing biochar particle size (Table 5).

4 Discussion

In the present study, we reported the effect of biochar application and its mechanism on water infiltration in a coastal saline soil with regard to different biochar amendment rates and particle sizes. Our purpose was to find the suitable rate and size of biochar for improving the hydrological properties of saline soils and to provide technical support for scientific application of biochar as a saline soil amendment.

We hypothesized that biochar amendment could improve soil aeration and promote water infiltration in the saline soil. However, in the non-sieved biochar treatments, we found that lower rates (0.5–5%) of biochar treatment did not significantly affect the infiltration capacity of soil water compared with the

control. Nonetheless, Abrol et al. (2016) found that 2% biochar significantly increased water infiltration rates by 1.7 times in a non-calcareous loamy sand. The possible reason for the conflict results is that we only applied biochar to the 0–10 surface soil layer, so it did not significantly improve the overall pore structure in the soil column. Our method of mixing biochar and soil in the surface layer is similar to the biochar application method reported by Li et al. (2016); however, Li et al. (2016) found that a biochar amendment rate of 4% significantly promoted wetting front migration. The above study used clay loam soil with a clayey texture and analyzed water infiltration based on the actual bulk density. In the present study, we used a silty loam soil and analyzed water infiltration based on a different bulk density. Thus, the effect of biochar on soil water infiltration was inconsistent between the study of Li et al. (2016) and our study.

Our experimental results obtained from the non-sieved biochar treatments showed that 10% biochar amendment effectively reduced the rate of soil water infiltration and inhibited the downward migration of soil water in the saline soil (Table 2). Others have reported decreases in saturated hydraulic conductivity with increasing rate of biochar amendment to sandy loam textured soils (Brockhoff et al. 2010; Githinji 2014). Castellini et al. (2015) also found that high amendment rate of biochar increased soil water retention, whereas Liu et al. (2016) reported that the hydraulic conductivity of silica

Table 3 Results from a two-way ANOVA testing for the effects of biochar amendment rate, particle size, and their interaction on parameters of Philip and Green-Ampt infiltration models

Soil property	<i>F</i> values, depending on two-way ANOVA		
	Amendment rate (AR)	Particle size (PS)	PS*AR
<i>S</i>	22.961***	11.399**	1.626 N.S.
<i>A</i>	6.355*	5.778*	2.697 N.S.
$K_s * H_m$	39.98***	50.198***	6.493*

N.S. not significant

* $P < 0.05$, ** $P < 0.01$, and *** $P < 0.001$

Table 4 Parameters of Philip infiltration model in experiment 2

Biochar amendment rate (%)	Biochar particle size (mm)	Philip model		
		<i>S</i> (mm min ^{-0.5})	<i>A</i> (mm min ⁻¹)	<i>R</i> ²
Control without biochar		7.29bc	0.36b	0.999
1	≤ 0.25	9.42a	0.11b	0.983
	0.25–1	9.04a	0.6ab	0.999
	1–2	7.53bc	0.65ab	0.992
10	≤ 0.25	8.32ab	0.6ab	0.998
	0.25–1	6.53c	1.03a	0.998
	1–2	6.22c	0.57ab	0.999

Means with different letters are significantly different at *P* < 0.05 by one-way ANOVA

sand amended with 10% biochar decreased by 72% compared with the non-biochar control. We propose that when the non-sieved biochar is amended at high rates (e.g., 10%), more biochar could fill the spaces between soil particles, and thus increase the tortuosity and reduce pore throat size of the mixture (Liu et al. 2016). Additionally, more coarser biochar might be broken down by water flushing into flake-like fragments, some of which have jagged edges (Spokas et al. 2014), eventually clogging soil pores and reducing water infiltration.

In the sieved biochar treatments, we found that amending biochar of the smallest particle size significantly increased water infiltration capacity of the saline soil compared with the control, regardless of the amendment rate. The improving effect of small biochar particles on water infiltration can be related to the physical properties of the coastal saline soil, which contains a relatively high content (> 60%) of silt and clay particles, with low porosity (42%) and poor permeability (Table 1). In this case, the amendment of small biochar particles (≤ 0.25 mm) improved the connectivity of soil pores and increased the number of effective pores (Atkinson et al. 2010; Novak et al. 2016), thereby facilitating soil water migration. Although 1% non-sieved biochar amendment did not significantly affect water infiltration, we found that ≤ 0.25 mm and 0.25–1 mm biochar treatments at the same rate increased soil water infiltration. The improving effect of small biochar particles on soil pore structure was likely offset by the presence of large biochar particles in the non-sieved biochar treatment. Therefore, amending biochar of uniform particle size (sieved) achieved a better effect than mixed particle size (non-sieved) for improving water infiltration capacity of the coastal saline soil.

However, when the particle size of sieved biochar amended was too large (1–2 mm), its ability to improve soil porosity and promote water infiltration markedly decreased compared with the control, particularly at the amendment rate of 10%. Liu et al. (2016) also found that when biochar particles were slightly coarser (0.853–2.00 mm), biochar amendment caused a 15 ± 2% decrease in the hydraulic conductivity of silica

sand. The large particle size and high amendment rate of biochar might have resulted in more compact packing and increased tortuosity of the soil (Liu et al. 2016), thus reducing the rate of water infiltration.

When biochar was amended at the same rate, the infiltration duration of saline soil was extended, while the cumulative infiltration was reduced with increasing particle size of biochar. Our result is in agreement with that of Ibrahim et al. (2017) who observed an improvement for hydro-properties in coarse-textured soils following biochar amendment, especially with finer particles of biochar. Although biochar of small particle size forms a small number of large pores (Xiao et al. 2016), there might be many effective soil pores promoting the downward movement of soil water.

Based on our above analysis and the existing studies, we conclude that the differences in biochar amendment rate, biochar particle size, bulk density, and soil texture are decisive factors by which biochar affects soil water infiltration in the coastal saline soil. These factors need to be considered with priority in future research for scientific application of biochar and hydrological improvement of coastal saline soil.

Table 5 Parameters of Green-Ampt infiltration model in experiment 2

Biochar amendment rate (%)	Biochar particle size (mm)	Green-Ampt model	
		<i>K_s*H_m</i>	<i>R</i> ²
Control without biochar		136c	0.66
1	≤ 0.25	185.2a	0.78
	0.25–1	161.3b	0.8
	1–2	140.9c	0.79
Control without biochar		136b	0.66
10	≤ 0.25	176a	0.75
	0.25–1	141.8b	0.75
	1–2	113.6c	0.73

For each biochar amendment rate, means with different letters are significantly different at *P* < 0.05 by one-way ANOVA, separately

5 Conclusions

This study provided evidence for revealing the effect of biochar amendment rate and particle size on soil water infiltration in the coastal saline soil from the Yellow River Delta. The results showed that compared with the control, non-sieved biochar amendment at 5% or lower rates did not significantly affect the infiltration capacity of saline soil. A significant negative effect of non-sieved biochar was observed only when the amendment rate reached 10%. Amending small particles of sieved biochar (≤ 0.25 mm) significantly increased cumulative infiltration, whereas a combination of large particle size (1–2 mm) and high amendment rate (10%) significantly reduced cumulative infiltration of the saline soil. The Philip model was superior to the Green-Ampt model for estimation of water infiltration in the biochar-amended saline soil. Irrespective of the amendment rate, amending sieved biochar of small particle size could significantly improve water infiltration and thus contributes to crop growth in the coastal saline soil of the Yellow River Delta. This study provides a scientific reference for biochar application to agricultural production in coastal saline soils and the selection of suitable amendment rate and particle size of biochar.

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