



Coupled effects of biochar use and farming practice on physical properties of a salt-affected soil with wheat–maize rotation

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Abstract

Purpose Being carbon-rich and porous, biochar has the potential to improve soil physical properties, so does conventional farming practice. Here, a field trial was conducted to investigate the combined effects of biochar use and farming practice on the physical properties of a salt-affected compact soil for wheat–maize rotation in the Yellow River Delta region.

Materials and methods *Salix fragilis* L. was used as feedstock to produce biochar in the field via aerobic carbonization at an average temperature of 502 °C, terminated by a water mist spray, for use as a soil amendment at 0, 1, 2, and 4 g kg⁻¹ doses (CK, T1, T2, and T3, respectively). Farming practices included rotary tillage/straw returning for wheat sowing, spring irrigation, no-tillage seeding of maize, and autumn irrigation. Both cutting ring and composite samples of the soil were collected at four stages of wheat–maize rotation (22, 238, 321, and 382 d after the benchmark date of land preparation for wheat sowing) for the determination of soil properties by established methods.

Results and discussion Rotary tillage/straw returning reduced soil bulk density (BD) from 1.48 to 1.27 g cm⁻³ (CK) and 1.14 g cm⁻³ (T3) and increased saturated hydraulic conductivity (*K_s*) from 0.05 × 10⁻⁵ to 0.75 × 10⁻⁵ cm s⁻¹ (CK) and 1.25 × 10⁻⁵ cm s⁻¹ (T3). This tillage effect on BD and *K_s* gradually disappeared due to the disturbance from the subsequent farming practice. Biochar use lessened the disturbance. At maize harvest, BD was 1.47 (CK) vs. 1.34 g cm⁻³ (T3), and *K_s* was 0.06 × 10⁻⁵ (CK) vs. 0.28 × 10⁻⁵ cm s⁻¹ (T3); in comparison with CK, T3 increased Na⁺ leaching by 65%, Cl⁻ leaching by 98%, organic carbon content by 40.3%, and water-stable aggregates (0.25–2 mm) by 38%, indicating an improvement in soil properties.

Conclusions Biochar use and rotary tillage improved soil physical properties (BD, *K_s*) and favored soil aeration, water filtration, and salt leaching, which further helped the accumulation of soil organic carbon, the formation of water-stable aggregates, and the amelioration of salt-affected compact soil.

Keywords Bulk density · Saturated hydraulic conductivity · Salt leaching · Organic carbon · Water-stable aggregates · Biochar

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1 Introduction

Soils in the Yellow River Delta region are typically compact (Zhang et al. 2015), with excessive soluble salts and exchangeable Na⁺, resulting in low productivity (Luo et al. 2017). Rotary tillage with straw returning was reported to improve soil structure in this area (Xie et al. 2017). This beneficial effect, however, was short-lived. After irrigation and straw decomposition, the soil gradually became compact again. It remains a challenge to mitigate the compaction of coastal saline soil in the region cost-effectively.

Biochar is a versatile material for environmental and agricultural applications (Wei et al. 2019a, b, c). Its use as a soil

amendment could improve soil porosity, K_s , and water infiltration (Ajayi et al. 2016); alleviate soil compaction (Lehmann and Joseph 2009); reduce salt content (Al-Wabel et al. 2018); increase soil carbon (Xu et al. 2018); and enhance soil aggregation (Saifullah et al. 2018). The effects of biochar attributes, namely the particle size (Sun et al. 2018), pore size (Liu et al. 2017), and dosage, on soil properties were assessed in laboratory studies or field trials for different soils (Khademalrasoul et al. 2014). The large specific surface area and irregular porous structure of biochar (Ibrahim et al. 2016; Liu et al. 2017) reduced soil bulk density (BD) (Blancocanqui 2017), increased soil porosity (Obia et al. 2016), and enhanced saturated hydraulic conductivity of sandy or compact soils (Ouyang et al. 2013), particularly when biochar particle size was less than 1 mm (Sun et al. 2018). Alghamdi (2018) suggested a proper dosage of biochar at 0.5–4% for improving soil physical properties. Omondi et al. (2016) reported a reduction in soil BD by an average of 12% as a result of biochar use. The irregular and fluffy structure of biochar contributed to the reduction in BD (Blancocanqui 2017) and the increase in saturated hydraulic conductivity (Liu et al. 2016). As a source of nutrients, biochar could improve soil microenvironment and enhance its microbial activity (Dong et al. 2016). Further, the secretions of organic compounds from microbes could accelerate the formation of soil aggregates (Burrell et al. 2016). All the above processes and factors could contribute to better soil physical conditions (Pietikäinen et al. 2000; Six et al. 2004; Downie et al. 2009).

Despite the reported benefits, biochar use as a soil amendment is constrained by high cost (Simon et al. 2011; Shabangu et al. 2014). Even at a 1% dose (ca. 15 tons of biochar/ha) and a low price of \$ 222/ton (Shackley et al. 2011), the cost would be prohibitive to crop production. Besides, limited effort has been made to assess the longevity of biochar effect on soil physical properties via field trials (Saifullah et al. 2018), let alone the combined effect of biochar use and farming operations (e.g., straw return, rotary tillage, irrigation) that have long been in practice (Herath et al. 2013; Alghamdi 2018).

To remove the cost barrier, we used biowaste of *Salix fragilis* L. to produce low-cost biochar (\$24/ton) in the field via aerobic carbonization (Xiao et al. 2019a) by mimicking the natural charring processes of thunder inducing forest fire and rain terminating combustion, as detailed in Section 2.2. The biochar was then used as a soil amendment at small doses (0, 1, 2, and 4 g kg⁻¹) in a field trial to reveal the effect and longevity of biochar and farming operations on the physical properties of a salt-affected soil with wheat–maize rotation. This work differs from other studies in that (1) biochar was produced from local biowaste in the field for use in the same place, thus eliminating transportation and storage cost; and (2) the longevity of biochar effect on soil physical properties was assessed together with the conventional farming operations in

the Yellow River Delta, making the outcome from this research applicable to local soil management.

2 Materials and methods

2.1 Study area

The field trial site of 67.5 m long and 49.0 m wide, located in Xianhe Town, Hekou District, Dongying City (37° 55.30', 118° 48.88'), was farmland with irrigation and drainage system in place. The soils in this region are typically stratified with a sandy loam layer on the top, a sand layer in the middle, and a red earth layer on the bottom, with a compact structure (Zhang et al. 2011). Cotton was planted at the beginning of the land reclamation (in the 1990s), followed by wheat–maize rotation since 2014. This rotation has been accompanied by the return of crop straw to the soil. Wheat (*Triticum aestivum* L.) was sowed in early winter with rotary tillage and maize (*Zea mays* L.) by no-tillage seeding in summer.

2.2 Biochar production and field trial

Biowaste of the local *Salix fragilis* L. was used to produce biochar in the field through an aerobic carbonization process via a coupled fire–water method (Xiao et al. 2019a, 2019b). The carbonization process had the dual features of the combustion on the surface of biomass and the oxygen-limiting pyrolysis inside of the biomass. Briefly, *Salix fragilis* L. branches were ignited at one direction of a brick-constructed trough for aerobic carbonization at an average temperature of 502 °C, followed by a water mist spray to dark red char at 0 min exposure time for the termination of the carbonization and the formation of biochar. Operating parameters that control the properties of biochar in conventional pyrolysis (Al-Wabel et al. 2018), namely the heating rate, pyrolysis temperature, and residence time, were simplified to a single one in aerobic carbonization: exposure time, i.e., the time between a burning char fell to the ground and water spray was applied to terminate the pyrolysis (Xiao et al. 2019b). The properties of biochar were determined by established methods, as described in Section 2.3.

The formed biochar was crushed to less than 1 mm and then mixed with the topsoil (0–20 cm) in the field by rotary tillage (twice). Each plot in the field trial was 10 × 2 m², with 4 replicates. Plots were randomly arranged, with an isolation gap of 0.5 m wide between them. Treatments included control (CK), and 1, 2, and 4 g kg⁻¹ of biochar doses (labeled as T1, T2, T3, respectively).

Table 1 Physical and chemical properties of the salt-affected soil

Horizon	Depth (cm)	Bulk density (g cm ⁻³)	Capillary porosity (%)	Ks (× 10 ⁻⁵ cm s ⁻¹)	pH	EC (mS cm ⁻¹)	Salt content (‰)	Organic carbon (g kg ⁻¹)
Sandy loam	0–15	1.48 ± 0.05	29.5 ± 2.50	0.05 ± 0.00	8.15 ± 0.23	1.32 ± 0.11	2.80 ± 0.13	3.65 ± 0.11

Ks, saturated hydraulic conductivity; EC electrical conductivity

2.3 Soil sample collection and analysis

Soil samples were collected from the topsoil layer (0–15 cm) by the five-point sampling of S route in each plot. Both cutting ring and mixed samples were collected on 25 September 2017 (as benchmark date), at stage 1 (22 days after the benchmark, after the completion of biochar and maize straw mixing with soil via rotary tillage for wheat sowing), at stage 2 (238 days after benchmark, after spring irrigation), at stage 3 (321 days after benchmark, after no-till seeding of maize), and at stage 4 (382 days after benchmark, after autumn irrigation).

The BD, capillary porosity (CP), and filed capacity of the salt-affected soil were determined by the cutting ring method (Lu 1999; Shao et al. 2006), and saturated hydraulic conductivity by constant water head test (Herath et al. 2013). Water-stable aggregates (WSA) (0.25–0.5 mm, 0.5–1 mm, 1–2 mm) were determined by the wet sieve method by an aggregate analyzer (TTF-100, Zhejiang Xiaolong) (Elliott 1986). Composite soil samples were analyzed for salt content by the weighing method (Bao 2000) and organic carbon by wet oxidation using K₂Cr₂O₇-H₂SO₄ (Lu 1999). The pH and electric conductivity (EC) of the biochar and soil were measured in a suspension at a sample: water ratio of 1:5 (w/v) after shaking at 160 r min⁻¹ for 24 h, using a pH meter (Five Easy Plus, METTLER TOLEDO) and a conductivity meter (DDS-11A), respectively. Cations and anions in the soil extracts (soil: water ratio of 1:5 w/v) were measured by ion chromatography (ICS3000, Dionex) (Chaganti et al. 2015). Biochar was analyzed for its ash content by heating in a muffle furnace at 800 °C for 4 h, and for elemental compositions using an elemental analyzer (Vario Micro cube, Elementar, Germany) (Xiao et al. 2019b). The concentration of acidic functional groups in biochar was determined by the titration method (the International Humic Substances Society 2019). The biochar was observed for its morphological features by a

scanning electron microscope (Hitachi S-4800, Japan) and determined for its specific surface area by sorption of N₂ at 77 K, using a Quantachrome Autosorb-iQ analyzer, and applying the Brunauer-Emmett-Teller (BET) equation (Herath et al. 2013; Xiao et al. 2019b).

2.4 Statistical analysis

Excel 2013, SPSS 16.0, and Origin 8.0 were used for calculation, data analysis, and figure drawing. One-way ANOVA was performed for statistical significance analysis (Duncan's test, $p < 0.05$).

3 Results

3.1 Basic properties of soil and biochar

The soil had a high BD, low saturated hydraulic conductivity, alkaline pH, and low organic carbon content (Table 1). They are typical for salt-affected soils in the region.

As shown in Table 2 and Fig. 1, the biochar used in the field trial had an alkaline pH, a moderate ash content, a high carbon content, and a porous structure. With abundant oxygen-containing functional groups (carboxyl and phenolic-hydroxyl) and a large specific surface area (271.68 m² g⁻¹), the biochar would be a suitable adsorbent for cations.

3.2 Soil bulk density

As shown in Fig. 2, with an increase in biochar dosage, BD followed a declining trend at each sampling stage. A dosage of 4 g kg⁻¹ was sufficient to make a significant difference to CK in BD. With the lapse of time, the magnitude of difference in BD among treatments gradually decreased. For example, at 4 g kg⁻¹ dosage, BD decreased by 11.3%, from 1.42 in CK to

Table 2 Physical properties, elemental compositions, surface functional groups, and specific surface area of biochar

pH	EC (mS cm ⁻¹)	Ash (%)	C	N	H	S	-COOH (mol kg ⁻¹)	-OH	SSA (m ² g ⁻¹)
9.62 ± 0.02	4.93 ± 0.05	24.15 ± 1.41	60.30 ± 0.01	0.52 ± 0.01	1.87 ± 0.01	0.02 ± 0.01	0.98 ± 0.01	0.59 ± 0.04	271.68 ± 12.57

EC, electrical conductivity; SSA, specific surface area

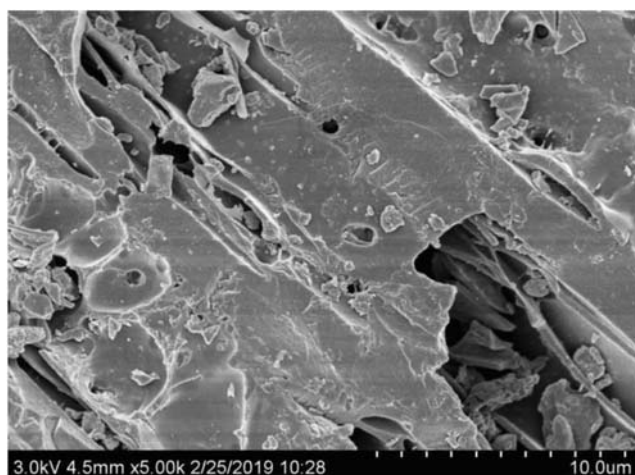


Fig. 1 Scanning electron microscopic image of biochar

1.26 g cm⁻³ in T3 at stage 3, whereas the corresponding decrease at stage 4 was 8.8%. The beneficial effect of biochar in reducing BD, however, disappeared over time with the disturbance from the subsequent farming practice. The BD of T3, for example, changed from 1.14 at stages 1–2 to 1.26 at stage 3 and 1.34 g cm⁻³ at stage 4, accompanied by a decline in standard deviation (0.09, 0.11, 0.09, and 0.01 at stages 1–4, respectively), which indicated the effects of farming practice on BD were gradually stabilized. In comparison with the benchmark BD of 1.48 g cm⁻³, it can be concluded that biochar application reduced BD at all stages during the wheat–maize rotation.

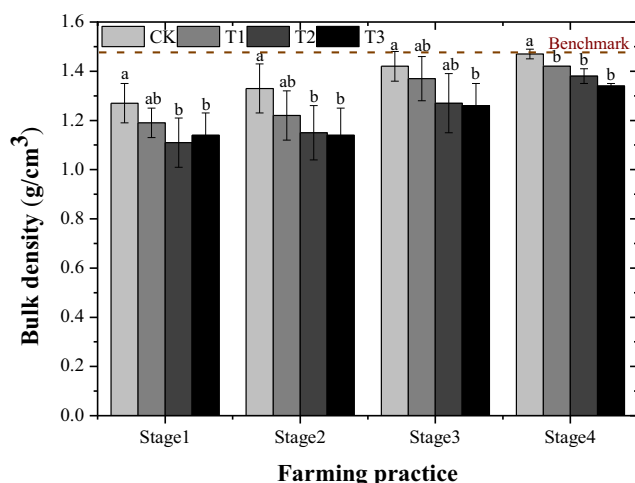


Fig. 2 Effects of biochar use on soil bulk density, as modulated by farming practice. Stage 1, after rotary tillage with straw returning for wheat sowing; Stage 2, after spring irrigation; Stage 3, after no-till seeding of maize; and Stage 4: after autumn irrigation. CK, saline soil without biochar use; T1–T3, biochar-amended saline soil (at the dose of 1, 2, 4 g kg⁻¹). Different lower-case letters at the same stage indicate significant differences between treatments ($p < 0.05$, Duncan's test)

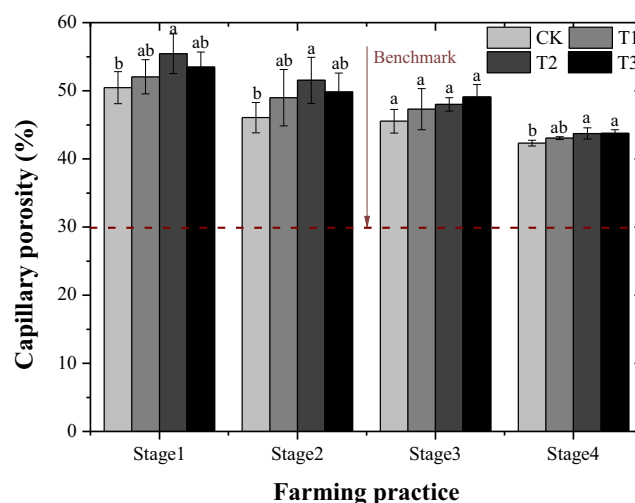


Fig. 3 The effects of biochar use on capillary porosity, as modulated by farming practice. Stages 1–4, CK, and T1–T3 are the same as noted in Fig. 2. Different lower-case letters at the same stage indicate significant differences between treatments ($p < 0.05$, Duncan's test)

3.3 Capillary porosity

In comparison with the benchmark CP before the field trial started, rotary tillage at stage 1 has dramatically increased CP (Fig. 3), which was further enhanced by biochar use. From stages 1 to 4, the CP of each treatment decreased. At T2, for example, CP decreased from 55.4% to 51.5%, 48.0%, and 43.7%. Results demonstrated that farming operations such as tillage and irrigation had a controlling effect on CP, and biochar use at 1–4 g kg⁻¹ further increased it to produce an additive effect. From stages 1 to 4, the variability of each treatment narrowed, suggesting the combined effect of farming practice and biochar use was stabilized. Rotary tillage quickly increased CP of the soil, and biochar application further

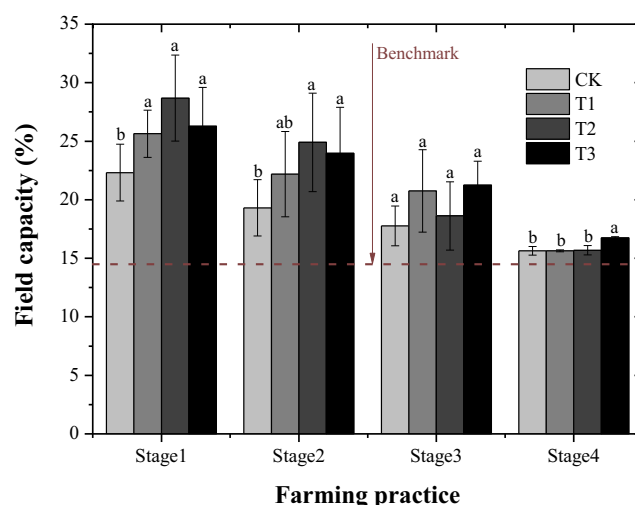


Fig. 4 Effects of biochar use on-field capacity, as modulated by farming practice. Stages 1–4, CK, and T1–T3 are the same as noted in Fig. 2. Different lower-case letters at the same stage indicate significant differences between treatments ($p < 0.05$, Duncan's test)

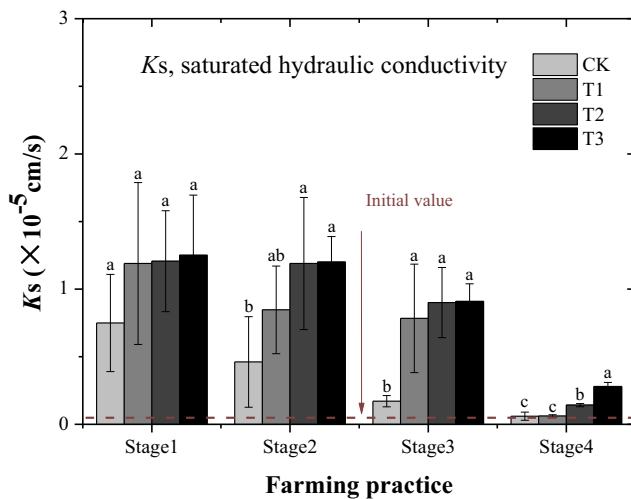


Fig. 5 Effects of biochar use on saturated hydraulic conductivity (K_s), as modulated by farming practice. Stages 1–4, CK, and T1–T3 are the same as noted in Fig. 2. Different lower-case letters at the same stage indicate significant differences between treatments ($p < 0.05$, Duncan's test)

enhanced the effect and helped stabilize it from the disturbance of subsequent irrigation and rainfall.

3.4 Field capacity

In comparison with the benchmark value, rotary tillage before wheat sowing (stage 1) loosed soil and thus increased its field capacity (FC) (Fig. 4). Though not a linear relationship, biochar application further increased FC by 13.0%, 22.2%, and 15.1% at 1, 2, and 4 g kg⁻¹ doses, respectively. Spring irrigation (stage 2) reduced FC in all treatments. This destructive

process was further strengthened by maize sowing and autumn irrigation. By the time of maize harvest, the field capacities were close to the initial value before the field trial started, and only T3 (biochar dose of 4 g kg⁻¹) kept an effect on FC (8.2% higher than CK). Similar to BD and CP, the internal variability of FC for each treatment at stage 4 was smaller than those in stages 1–3, implying the combined effect of farming practice and biochar use became stabilized. Thus, in wheat–maize rotation, biochar use at 4 g kg⁻¹ in combination with rotary tillage/straw returning at the beginning effectively increased FC and maintained this effect to the end of the cropping season.

3.5 Saturated hydraulic conductivity (K_s)

As shown in Fig. 5, biochar application increased K_s , and this trend was maintained during the wheat–maize cropping season. At 2 g kg⁻¹ dose, for example, soil K_s was 33.0%, 61.0%, 78.6%, and 57.1% higher than CK at stages 1 to 4, respectively. The corresponding increases at 4 g kg⁻¹ dose were 40.0%, 61.7%, 81.3%, and 78.6%, respectively. With the increasing disturbance from farming operations at stages 1 to 4, the K_s of the soil gradually decreased from 1.21×10^{-5} to 1.18×10^{-5} , 0.90×10^{-5} , and 0.14×10^{-5} cm s⁻¹ at 2 g kg⁻¹ biochar dose, and from 1.25×10^{-5} to 1.20×10^{-5} , 0.91×10^{-5} , and 0.28×10^{-5} cm s⁻¹ at 4 g kg⁻¹ dose. This decrease was accompanied by reduced variability of K_s among treatments. Rotary tillage before wheat sowing greatly increased K_s , and biochar use enhanced this increase and helped resist the disturbing effect of the subsequent farming operations on K_s .

Fig. 6 Biochar amendment reduced soil salt content at stage 2 (after spring irrigation) and stage 4 (after autumn irrigation). CK and T1–T3 are the same as noted in Fig. 2. Different lower-case letters at the same stage indicate significant differences between treatments ($p < 0.05$, Duncan's test)

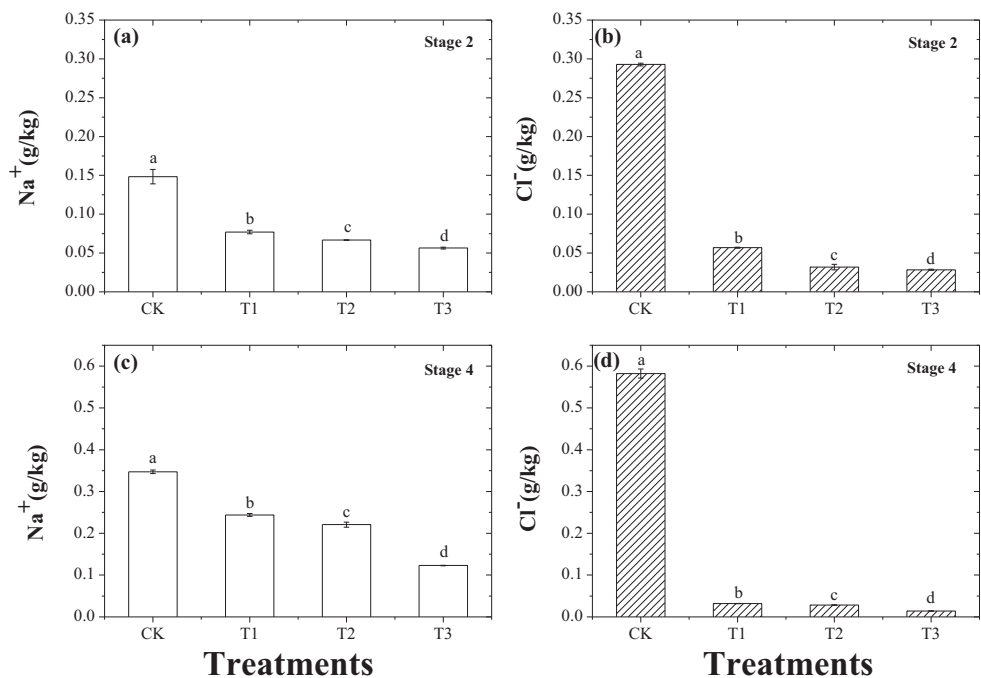


Table 3 Changes in soil organic carbon content during crop rotation

Treatments	Before wheat sowing (benchmark) (g kg ⁻¹)	At maize harvest (stage 4)	Carbon input from biochar use	Carbon increase from the straw return
CK ^a	3.65 ± 0.11	4.87 ± 0.49c ^b	0.00 ± 0.00	1.22 ± 0.38c
T1	3.65 ± 0.11	7.06 ± 0.25ab	0.58 ± 0.01	2.83 ± 0.13a
T2	3.65 ± 0.11	7.37 ± 0.45ab	1.16 ± 0.01	2.56 ± 0.33a
T3	3.65 ± 0.11	8.01 ± 0.27a	2.32 ± 0.02	2.04 ± 0.14ab

^a CK, saline soil without biochar use; and T1–T3, saline soil with biochar amendment (at the dose of 1, 2, 4 g kg⁻¹)

^b Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test)

3.6 Salt leaching

Figure 6 shows the contents of Na⁺ and Cl⁻ in soil, converted from their concentrations in soil extract at 1:5 soil: water ratio, at times close to the harvest of wheat and maize. Biochar use reduced the BD (Fig. 2) and increased Ks (Fig. 5), thus facilitating salt leaching out of the topsoil layer during irrigations and rains. Biochar use at 1, 2, to 4 g kg⁻¹ doses favored salt leaching during spring irrigation, resulting in a reduction of Na⁺ at wheat harvest by 48.1%, 55.1%, and 62.0%, and Cl⁻ by 80.6%, 89.1%, and 90.3% respectively; summer rains and autumn irrigation further helped salt leaching, lowering Na⁺ content at maize harvest by 29.8%, 36.4%, and 64.6%, and reducing Cl⁻ content by 94.5%, 95.1%, and 97.6%.

3.7 Soil organic carbon content

Biochar increased soil organic carbon (SOC) content at the maize harvest time (Table 3). As biochar is a stable form of carbon, its addition to the soil at 1, 2, and 4 g kg⁻¹ doses would make a direct contribution to the increase in soil carbon at 0.58, 1.16, and 2.32 g kg⁻¹, respectively. After the deduction of carbon input from biochar, SOC contents of T1, T2, and T3 at maize harvest were 2.20, 2.50, and 3.24 g kg⁻¹ higher than CK (4.87 g kg⁻¹), respectively, suggesting that SOC increase was not due to biochar addition alone. Instead, straw

return and straw decomposition and conversion to SOC were also the causes of carbon increase in saline soil.

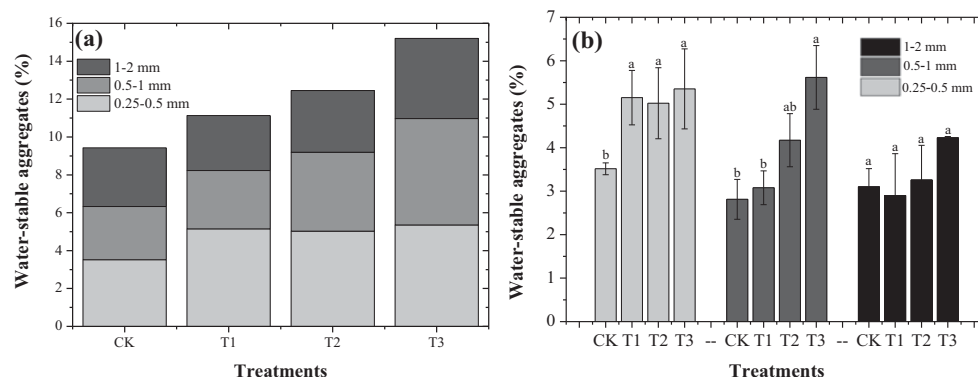
3.8 Water-stable aggregates

Figure 7 shows that the WSA of the soil at the time close to the maize harvest. WSA increased with biochar dose from 9.4% (CK) to 11.1% (T1), 12.5% (T2), and 15.1% (T3). Biochar amendment also altered the size distribution of WSA: the smallest (0.25–0.5 mm) WSA increased at all biochar doses; the medium (0.5–1 mm) WSA only increased significantly at 4 g kg⁻¹ dose; whereas the largest (1–2 mm) WSA was not affected by biochar addition.

4 Discussion

Both soil properties and biochar attributes, including the types (Obia et al. 2016; McBeath et al. 2014), particle size (Sun et al. 2018), shape (Liu et al. 2017), and the dose of biochar (Asai et al. 2009; Mukherjee and Lal 2013), determined the effectiveness of biochar use on altering soil physical properties (Burrell et al. 2016). The measurable effects, however, were often obtained by adding biochar to the soil at a large dosage, which created new problems, such as introducing salt to and causing its accumulation in soils (Saifullah et al. 2018) or becoming unaffordable to crop production (Blackwell et al.

Fig. 7 Biochar amendment improved water-stable aggregates (a, combined; b individual fractions) at stage 4. CK and T1–T3 are the same as noted in Fig. 2. Different lower-case letters at the same fraction indicate significant differences between treatments ($p < 0.05$, Duncan's test)



2009). Alghamdi (2018) suggested that 0.5–4% (about 7.5–60 ton/ha) was an appropriate biochar dosage for improving soil porosity and aggregates. This study demonstrated that biochar at 4 g kg⁻¹ dose, together with rotary tillage/straw returning, alleviated soil compaction, as indicated by a reduction in BD and an increase in CP, saturated hydraulic conductivity, and WSA. Moreover, this biochar effect on alleviating soil compaction was partially maintained during the wheat–maize cropping season. From a practical point of view, the low cost (\$24/ton) of the biochar and its ability to work at a low dosage (4 g kg⁻¹) are two crucial attributes to its potential application for the remediation of salt-affected soils in the Yellow River Delta.

In terms of the factors involved in biochar alleviating soil compaction, the high specific surface area (271.68 m² g⁻¹), porous structure (Fig. 1), and irregular shapes of the biochar played a role. Irregular biochar particles would help soil particles to form a porous structure (Liu et al. 2017), thus increasing the FC and hydraulic conductivity (Ouyang et al. 2013; Githinji 2014). Similar views were found in the work of Major et al. (2010) and Baiamonte et al. (2019). Besides, this work proved that biochar not only produced a synergic effect with rotary tillage/straw returning on alleviating soil compaction but also reduced the destructive effect of subsequent farming operations, such as irrigation and maize sowing, on soil structure. In other words, a combination of biochar and straw returning increased the longevity of rotary tillage on loosening soil during the crop rotation season. Furthermore, it is practically important that biochar could be added into the soil without the need for altering existing farming operations (i.e., at no extra cost).

Behind the phenomenon of biochar alleviating soil compaction is probably the role of biochar in promoting soil aggregation. Soil organic matter is an essential cementing material for the formation of soil aggregates (Yuan and Theng 2012; Li et al. 2015). This study found that biochar use increased CP and FC, in agreement with Burrell et al. (2016) and Obia et al. (2016), which in turn would improve the living environment for microbes (Zheng et al. 2017) and enhance their activities (Six et al. 2004), thus accelerating the decomposing of straw and its conversion to soil organic carbon. As shown in Table 3, both organic carbon and its increase were higher in biochar-amended treatments than in control. The observed benefits on soil aggregation from biochar use could be explained by the enhancing effect of organic cementing material produced during straw decomposition on the formation of soil aggregates (Zhao et al. 2014; Khademalrasoul et al. 2014; Xu et al. 2018), which in turn contributes to the improvement in soil structure (Blancocanqui 2017).

Alleviation of soil compaction has extra value in remediating salt-affected soil in the Yellow River Delta region. As BD reduced and CP and saturated hydraulic conductivity increased, soil aeration and water infiltration improved, which in turn helped salt leaching by irrigation and rain

(Fig. 6). Because of the shallow and salty groundwater in the Yellow River Delta, salt content in topsoil fluctuates with seasons. Salt moves up to topsoil in dry spring, moves down during spring irrigation and summer rains, and starts to accumulate in topsoil again in late autumn when the soil becomes dry. At both wheat and maize harvest times, salt contents in treatments with biochar addition were significantly lower than the control. Thus, biochar use not only created a better soil physical environment for crop growth but also reduced salt stress on crops.

The increase in WSA (Fig. 7) gives direct evidence to soil structure improvement and indicates soil fertility enhancement, and the latter was further evidenced by the increase in organic carbon content in biochar treatments (Table 3). Biochar use has dual benefits to the salt-affected soil: improving soil physical properties, and indirect increasing soil organic matter accumulation and enhancing salt leaching out of the topsoil. Thus, the biochar amendment merits further trials in the Yellow River Delta region, in conjunction with the rotary tillage and straw returning, for remediating salt-affected compact soils.

5 Conclusions

In wheat–maize rotation, rotary tillage with straw returning reduced the BD of a salt-affected soil from 1.48 (benchmark) to 1.27 g cm⁻³ and raised its saturated hydraulic conductivity (*K*_s) from 0.05×10^{-5} to 0.75×10^{-5} cm s⁻¹. This alleviation of soil compaction, however, was gradually nullified by the subsequent irrigations. Adding low-cost biochar at 4 g kg⁻¹ dose to the soil produced a synergetic effect with rotary tillage and delayed the nullifying process. Accompanied the changes in BD and *K*_s, salt content in topsoil was reduced, which contributed to the formation of soil organic carbon (SOC) and WSA. In other words, the increased *K*_s accelerated salt leaching out of the topsoil and enhanced the formation of SOC and WSA. This research provides evidence that a small dose (4 g kg⁻¹) of biochar can be used together with rotary tillage/straw returning to lessen soil compaction problem during wheat–maize rotation in the Yellow River Delta region.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Research involving human participants and/or animals This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent Not applicable. This article does not involve any individuals.

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