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Soil properties and the growth of wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.) in response to reed (*phragmites communis*) biochar use in a salt-affected soil in the Yellow River Delta

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ABSTRACT

Soil salinity and its associated soil compaction and low fertility is a big problem for land management in the arid region or coastal zone. Here, a low-cost and potassium (K)-rich biochar of reed (*phragmites communis*) was demonstrated effective in alleviating the problem in wheat-maize rotation in the Yellow River Delta region. Adding the biochar at 0, 3, 6, and 12 t ha^{-1} to a soil with a 2.8‰ salt content via rotary tillage with straw returning, with or without fertilizers, reduced soil bulk density (BD) and increased saturated hydraulic conductivity (*Ks*). At 12 t ha^{-1} dose and by wheat and maize harvests, respectively, biochar lowered soil BD by 9.1% and 14.5%, increased *Ks* by 82.7% and 91.2%, and reduced sodium adsorption ratio (SAR) by 64.9% and 92.8% in comparison with the control (CK). Further, in comparison with conventional fertilization (CF: 375 kg ha^{-1} for each crop), biochar use (6 and 12 t ha^{-1}), together with 75% of CF, enhanced the nitrogen use efficiency (NUE) by 20.5%–31.4% for wheat and 15.9%–30.9% for maize. It raised the yields of wheat by 11.3%–17.1% and maize by 9.7%–14.8%. By reducing BD, increasing *Ks*, and decreasing SAR, biochar alleviated soil compaction and salt stress and increased NUE and crop yields. This outcome suggests that the conversion of local bio-waste into biochar as a soil amendment is of agronomic and environmental benefits.

1. Introduction

The Yellow River Delta (YRD) is a fragile wetland ecosystem, characterized by high soil salinity and poor soil fertility (Luo et al., 2017). The excessive soluble salts and exchangeable sodium is a crucial constraint to crop growth (Zhang et al., 2015), resulting in low productivity (Wong et al. 2009), low biomass inputs to soil, soil compaction (Luo et al., 2017), poor nutrient retention, and low fertilizer use efficiency (Tedeschi et al., 2011). Besides, bio-waste disposal and over-fertilization are becoming new problems in the YRD (Wu et al., 2016; Shan et al., 2017). The use of straw returning and compost have been reported helpful in remediating salt-affected soil (Xie et al., 2017; Yang et al., 2018). Their side effects, such as nutrient deficiency, seedling growth restriction, and nematode problems (Gu et al., 2015), together with the high cost as a result of high usage and labour shortage (Sastre-Conde et al., 2015), make the large-scale use of compost and straw returning difficult in the YRD. Cost-effective and ecologically beneficial methods and technologies for alleviating soil salinity are much needed (Luo et al., 2017). Converting bio-waste into biochar is a promising means of alleviating the soil problems in the YRD.

Biochar is a carbon-rich material and typically produced by oxygen-limited pyrolysis of bio-waste (e.g., straw, branches, manure) (Lehmann et al., 2006). Biochar use as a soil amendment could improve the fertility and productivity of degraded soils (Alvarez-Campos et al., 2018; Al-Wabel et al., 2018; Yu et al., 2019). More specifically, its use in saline soil increased SOM content, soil fertility, field capacity (FC), and *Ks* (Chaganti et al., 2015), and decreased salt content, electric conductivity (EC), and sodium adsorption ratio (SAR) (Di Lonardo et al., 2017; Ali et al., 2017). These beneficial effects were attributed to the high carbon and nutrient contents (Ajayi et al., 2016), porous structure, large specific surface area (Blanco-Canqui 2017), and abundant functional groups of biochar (Nguyen et al., 2017). For example, biochar addition to saline soil improved soil porosity, FC and *Ks*, and accelerated salt leaching (Burrell et al., 2016; Obia et al., 2016); Sun et al. (2017) reported that biochar use at 5 g kg^{-1} reduced NH_4^+-N and NO_3^--N leaching and NH_3 volatilization, thus helped N retention in a coastal saline soil; Usman

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Table 1
The basic properties of biochar

	Ash content (%)	C	N	H	S	-COOH	Phenolic-OH	Specific surface area (m^2 g^{-1})	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
		(%)				(mol kg^{-1})			(total, mmol kg^{-1})					
Biochar	30.9 ± 3.2	43.5 ± 0.0	0.9 ± 0.0	2.2 ± 0.0	0.1 ± 0.1	1.1 ± 0.0	0.5 ± 0.0	27.5 ± 3.6	516.1 ± 9.9	683.4 ± 38.1	227.7 ± 15.8	356.1 ± 19.8	859.4 ± 47.2	112.9 ± 8.6

et al. (2016) and Zheng et al. (2018) concluded that biochar supplemented soil nutrients (P, K) and provided Ca^{2+} to replace Na^+ in soil, thus facilitating salt removal and nutrient retention (Yu et al., 2019). Despite the numerous reports on the potential agronomic and environmental benefits of biochar use as a soil amendment, field studies on the subject are inadequate in general and short in YRD (Saifullah et al., 2018; Al-Wabel et al., 2018). Most importantly, biochar for agricultural use has been restricted by its high cost (Vochozka et al., 2016; Saifullah et al., 2018).

This study aimed to use inexpensive biochar as a mediator for the interweaved problems of biowaste accumulation, soil salinity and compaction, and low soil productivity in YRD, with a hypothesis that biochar can lessen soil compaction and soil salinity, thus enhancing crop growth. To this end, low-cost biochar, produced in the filed from local bio-waste of reed, was added as a soil amendment with or without chemical fertilizers to a salt-affected soil in the YRD with wheat-maize rotation. Then, the physical and chemical properties of the soil at different crop-growing stages and the chemical compositions of wheat and maize grains were analyzed to assess the effect of biochar on soil properties and crop production. The outcomes from this research would help develop a management protocol of using biochar to remediate salt-affected soils.

2. Materials and methods

2.1. Study area

A field trial was conducted in an area of 67.5 × 49.0 m^2 in a farm in the Shenxiangou basin of Hekou District, Dongying City (37°55.30′ N, 118°48.88′ E). The farm is about 6500 ha in size, with a moderately salt content of 2.0‰–3.0‰. Land reclamation started in the 1990s by planting cotton. Since 2014 the farm has been in wheat-maize rotation, with land management practice of straw returning, base fertilization, and top dressing. The physical and chemical properties of the soil are shown in Table 1. This soil was chosen for a field trial because its moderate salt content is representative of farmland for wheat and maize production in the YRD. Soils with lower salt content (< 2.0‰) usually produce an acceptable yield without remediation, whereas soils with higher salt content (> 3.0‰) are not suitable for wheat and maize production before expensive remediation.

2.2. Biochar, fertilizers, and crop seeds

Bio-waste of reed (*phragmites communis*) was used to produce a low-cost biochar ($ 24/ton) in the field via a fast aerobic carbonization process by fire-water coupled method (Xiao et al., 2019). The process had the dual features: aerobic combustion on the surface of reed and oxygen-limited pyrolysis inside. In brief, a pile of reed was ignited at multiple directions to produce dark red rods (with a measured surface temperature range of 274–282 ℃). Water mist was then sprayed layer by layer on the rods to extinguish combustion and form biochar. Its properties were analyzed by established methods, as detailed in section 2.4.

As shown in Table 1, the biochar had moderate carbon content (43.5%), SSA (27.5 m^2 g^{-1}), carboxyl group (1.1 mol kg^{-1}), and phenolic hydroxyl group (0.5 mol kg^{-1}). The biochar had a much higher water-soluble K^+ (407.1 mmol kg^{-1}) content than the soil (3.3 mmol kg^{-1}) (Table 2), its use as a soil amendment would alter the salt compositions of soil solution by releasing K^+. On the other hand, its water-soluble Na^+ (333.8 mmol kg^{-1}) and Cl^- (330.2 mmol kg^{-1}) suggest that cautions should be exercised to prevent secondary salinity from heavy use of the biochar in the absence of rain or irrigation.

Fertilizers were applied to the soil for each crop, as shown in Table 3. Base fertilization occurred a day before wheat and maize sowing (i.e., October 14th, 2017; June 19th, 2018), and topdressing was done a day before spring and autumn irrigations (March 20th, 2018; August 26th, 2018) with a hydrostatic pressure of 35 cm water each.

Wheat (*Triticum aestivum* L.) seeds of Jimai-22, with a 100-grain weight of 4.70 g, were obtained from the Shandong Academy of Agricultural Sciences. Maize (*Zea mays* L.) seeds of Jishou-303, with a 100-grain weight of 35.93 g, were purchased from Dade Seeds Co. Ltd. of Beijing.

2.3. Plot design, seed sowing, irrigation, and crop harvest

Plots in the field trial were 10 × 2 m^2 with an isolation strip of 2 m long and 0.5 m wide. The biochar was crushed to less than 1 mm, and then added once at 0, 3, 6, and 12 t ha^{-1} (referred to as CK, T1, T2, and T3) to the topsoil (0–20 cm) by rotary tillage before wheat sowing. These doses were much smaller than those reported in the literature (Saifullah et al., 2018; Sun et al., 2019). As shown in Table 4, two levels of fertilization, namely conventional fertilization (CF, being 375 kg ha^{-1} for each crop from a survey of local farmers) and reduced fertilization (being 75% CF), were used in the trial. Also included in the treatment were combinations of biochar use (3, 6, and 12 t ha^{-1}) and 75% CF (referred to as T4, T5, and T6). Treatment of CF without biochar was used as a benchmark for comparison of crop yield. Each treatment had 4 replications, and all plots in the field were randomized. Wheat seeds were sowed on October 15, 2017, at 188 kg ha^{-1} with a furrow spacing of 15 cm, and maize sowed on June 20, 2018, at 25 kg ha^{-1} with a furrow spacing of 35 cm. Pesticides (imidacloprid and carbonfuran) were sprayed on May 10th and July 20th, 2018, as routine practice for wheat and maize production. Wheat was harvested on June 10, 2018, and maize on October 5, 2018.

2.4. Sample collection and analysis

Soil samples were randomly collected from 0–15 cm layer of each plot following the S-shaped pattern in September 2017, June 2018, and October 2018 as the benchmark, wheat harvest, and maize harvest samples, respectively.

Wheat and maize harvests were carried out by whole-plot harvesting, and a thresher (5TF–450) was used to separate the grain from the straw. They were air-dried and weighed, randomly collected and mixed, oven-dried at 85 °C, crushed, and passed a 100-mesh sieve for chemical analyses.

The biochar was analyzed for its ash content by heating at 800 °C for 4 h in a muffle furnace (Lu 1999), elemental compositions by an elemental analyzer (Vario Micro cube, Elementar, Germany), acidic functional groups by the titration method of the International Humic Substances Society (2019), and specific surface area (SSA) by N_2

Table 2
Physical and chemical properties of the soil and biochar

	Bulk density (g cm^{-3})	Capillary porosity (%)	*Ks* ($\times 10^{-5}$ cm s^{-1})	pH	Salt content (‰)	Organic matter (g kg^{-1})	NH_4^+-N	NO_3^--N	Olsen-P	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
							(mg kg^{-1})			(water-soluble, mmol kg^{-1})					
Soil	1.48 ± 0.05	29.5 ± 2.50	0.05 ± 0.00	8.2 ± 0.2	2.8 ± 0.1	6.3 ± 0.2	2.7 ± 0.2	27.1 ± 0.6	0.8 ± 0.0	12.3 ± 0.1	3.3 ± 0.1	8.4 ± 0.0	3.5 ± 0.1	13.3 ± 0.1	2.4 ± 0.1
Biochar	—	—	—	9.1 ± 0.0	—	—	21.6 ± 2.6	0.9 ± 0.1	8.5 ± 0.3	333.8 ± 5.5	407.1 ± 7.5	16.5 ± 0.1	31.3 ± 0.3	330.2 ± 5.9	55.4 ± 1.2

Note: *Ks*, Saturated hydraulic conductivity.

Table 3
The details of fertilizers and their applications

Crop	Methods of application	Fertilizers	N content (%)	P content (%)	Conventional dose kg ha^{-1}	Application dates
Wheat	Base	Urea-ammonium mixed nitrogen fertilizer	29.96	——	187.5	October 14th, 2017
	Topdressing	Slow-release fertilizer	28.07	4.84	187.5	March 20th, 2018
Mazie	Base	Ammonium dihydrogen phosphate	21.18	23.45	187.5	June 19th, 2018
	Topdressing	Urea	46.34	——	187.5	August 26th, 2018

Table 4
Experimental treatments of the plots

Treatments	Detailed information	Treatments	Detailed information
CK	0 ton biochar per ha farmland (0 t ha^{-1})	75% CF	281.25 kg fertilizers per ha farmland (281.25 kg ha^{-1})
T1	3 ton biochar per ha farmland (3 t ha^{-1})	T4	3 t ha^{-1} biochar and 281.25 kg ha^{-1} fertilizers
T2	6 ton biochar per ha farmland (6 t ha^{-1})	T5	6 t ha^{-1} biochar and 281.25 kg ha^{-1} fertilizers
T3	12 ton biochar per ha farmland (12 t ha^{-1})	T6	12 t ha^{-1} biochar and 281.25 kg ha^{-1} fertilizers
CF	375 kg fertilizers per ha farmland (375 kg ha^{-1})	——	——

sorption at 77 K using a Quantachrome Autosorb-iQ analyzer and applying the Brunauer-Emmett-Teller (BET) equation. The biochar was digested by HNO_3-HF-H_2O_2 for the analysis of total ions (K^+, Na^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}) by ion chromatography (ICS3000, Dionex) (Lu 1999).

Soil samples were determined for bulk density by the cutting ring method (Lu 1999), saturated hydraulic conductivity (*Ks*) by constant head test (Shao et al., 2006), salt content by weighing method (Bao 2000), and organic matter content by the wet oxidation method of $K_2Cr_2O_7$-H_2SO_4 (Lu 1999).

Extracts (solutions) of biochar and soil samples were obtained by adding biochar or soil samples to CO_2-free-deionized water at 1:5 ratio, shaking at 160 r min^{-1} for 24 h, centrifuging at 3500 rpm for 15 min, and filtering through 0.45 μm membrane for the measurement of pH by a pH meter (Five Easy Plus, METTLER TOLEDO), electrical conductivity (EC) by a conductivity meter (DDS–11A), and ion concentrations by ion chromatography (ICS3000, Dionex) (Bao 2000). The NH_4^+-N and NO_3^--N of biochar and soil samples were extracted by 1 mol L^{-1} KCl. Olsen-P was extracted by 0.5 mol L^{-1} $NaHCO_3$ at a ratio of 1:5 (w/v, shaking at 160 r min^{-1} for 2 h) and measured with a continuous flow analytical system (AutoAnalyzer III, Seal) (Lu 1999).

The fertilizers were digested by H_2SO_4 and then determined for total N contents by titration with NaOH, and total P was measured by phosphorus molybdic acid quinoline weight method (Lu 1999).

Wheat and maize grain samples were digested by HNO_3-HF-H_2O_2 for the analysis of total Na, K, Ca, and Mg by ICP-MS (Elan DRC II, PerkinElmer) (Lu 1999). The samples were digested by H_2SO_4-H_2O_2 for the determination of total N and P by Nessler's reagent and vanadium molybdate methods (Lu 1999).

2.5. Data processing

Two indexes were used to evaluate the effects of individual (i.e., biochar) and conjunctive (biochar + 75% CF) effects on alleviating soil salinity. Sodium adsorption ratio (SAR) was calculated by Eq. (1) (Lesch and Suarez 2009), and Chloride/$\sqrt{}$sulfate ratio was calculated by Eq. (2) (Wang et al., 2018).

$$SAR = \frac{[Na^+]}{\sqrt{[Ca^{2+} + Mg^{2+}]}} \quad (1)$$

$$Chloride \Big/ \sqrt{Sulfate} = \frac{[Cl^-]}{\sqrt{[SO_4^{2-}]}} \quad (2)$$

where $[Na^+]$, $[Ca^{2+}]$, $[Mg^{2+}]$, $[Cl^-]$ and $[SO_4^{2-}]$ (mmol L^{-1}) are the concentrations of the ions in soil solution.

SAR indicates the relative abundance of Na^+, Ca^{2+}, and Mg^{2+} in soil solution. As Na^+ is more harmful to crops than Mg^{2+} and Ca^{2+}, the smaller the SAR is, the weaker the salt stress would be (Shaygan et al., 2017). In analogy to SAR, the ratio of chloride/$\sqrt{}$sulfate indicates the relative concentration of Cl^- and SO_4^{2-}. As Cl^- is much more toxic to plants than SO_4^{2-}, a smaller ratio would suggest less salt stress.

K/Na ratio in grains (Lin et al., 2015), indicates the ability of a crop to preferably take up K^+ rather than passively absorb toxic Na^+.

Nitrogen and phosphorus use efficiency (NUE, PUE), calculated by Eq. (3), indicates the nutrient retention in soil and nutrient supply for wheat and maize growth (Lu et al., 2019).

NUE or PUE = [(total N or P of the crops in the plot where fertilizers were applied − total N or P of the crops in the plot of control) / the amount of N or P in fertilizers × 100%] (3)

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

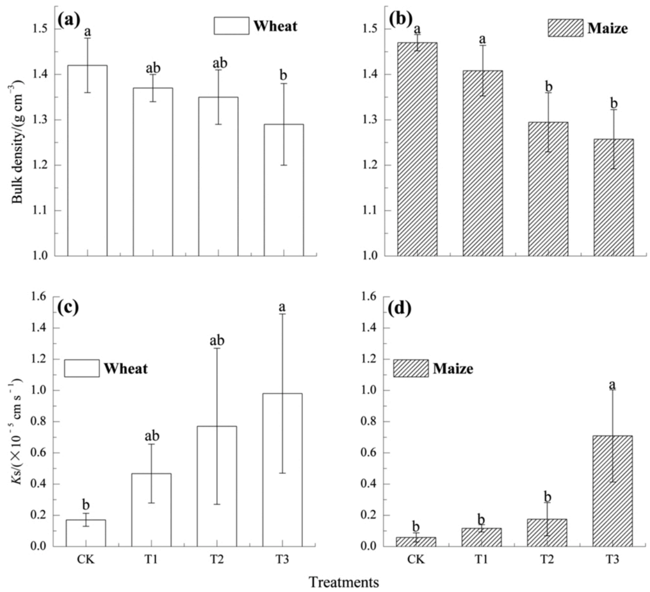

Fig. 1. Bulk density (a, b) and saturated hydraulic conductivity *Ks* (c, d) at harvest times, as affected by the biochar amendment. CK, pristine soil; T1–T3, biochar use at 3, 6, 12 t ha^{-1}. Different lower-case letters indicate significant differences between.

3. Results

3.1. Response of soil physical properties to biochar use

Use of the biochar reduced soil BD by 3.52% (T1), 4.93% (T2), and 9.15% (T3) over the control (CK) at wheat harvest time, but only 12 t ha^{-1} biochar dose (T3) showed a significant difference (Fig. 1a). Likewise, 6 and 12 t ha^{-1} biochar doses significantly reduced soil BD at maize harvest by 12.3 % and 14.5% over the CK, respectively (Fig. 1b). In agreement with BD reduction, biochar application increased *Ks*. However, only the 12 t ha^{-1} biochar dose showed a statistically significant difference (Fig. 1c, d) at wheat and maize harvests from the CK. The decrease in BD and increase in *Ks* by biochar addition indicated the biochar amendment lessened the compaction, which in turn would affect salt and nutrient leaching.

3.2. Response of soil chemical properties to biochar use

As shown in Table 5, the concentrations of Na^{+}, K^{+}, Ca^{2+}, Mg^{2+}, Cl^{-}, and SO_4^{2-} in soil solution were all significantly reduced by biochar treatments (T1–T3) over the CK at wheat and maize harvests. Compared with the 75% CF, the conjunctive effects of biochar and reduced fertilization treatments (T4–T6) on Na^{+}, K^{+}, Ca^{2+}, and Mg^{2+} concentrations followed the same trend as biochar alone at wheat harvest time. Though ion concentrations of T4–T6 at maize harvest were higher than those of 75% CF, they were lower than CK. In other words, biochar alone (3–12 t ha^{-1}) or in combination with 75% CF reduced soluble salt concentrations, thus alleviating salt stress on the crops. Besides, biochar use (12 t

Table 5
Concentrations of ions in soil extracts and soil pH at wheat and maize harvest

Treatments	Na^{+}		K^{+}		Ca^{2+}		Mg^{2+}		Cl^{-}		SO_4^{2-}		pH	
	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest
	(mmol L^{-1})													
CK	1.29 ± 0.08a	5.40 ± 0.14a	0.35 ± 0.02a	0.58 ± 0.01a	0.99 ± 0.03a	1.41 ± 0.03a	0.35 ± 0.02a	0.90 ± 0.02a	1.65 ± 0.01a	5.87 ± 0.16a	0.49 ± 0.17a	0.90 ± 0.02a	7.87 ± 0.01a	8.07 ± 0.03a
T1	0.07 ± 0.00b	0.23 ± 0.01b	0.04 ± 0.00b	0.30 ± 0.00b	0.01 ± 0.00b	0.70 ± 0.03bc	0.02 ± 0.00b	0.20 ± 0.00b	0.25 ± 0.00c	0.15 ± 0.00b	0.07 ± 0.01b	0.05 ± 0.00b	7.76 ± 0.05ab	7.94 ± 0.03b
T2	0.07 ± 0.00b	0.23 ± 0.01b	0.03 ± 0.00b	0.26 ± 0.00c	0.01 ± 0.00b	0.64 ± 0.01c	0.02 ± 0.00b	0.19 ± 0.01b	0.31 ± 0.00b	0.11 ± 0.00b	0.06 ± 0.00b	0.03 ± 0.00b	7.48 ± 0.20b	8.05 ± 0.01a
T3	0.07 ± 0.01b	0.26 ± 0.00b	0.04 ± 0.00b	0.25 ± 0.00c	0.01 ± 0.00b	0.72 ± 0.01b	0.02 ± 0.00b	0.25 ± 0.00b	0.15 ± 0.00d	0.18 ± 0.01b	0.06 ± 0.00b	0.04 ± 0.00b	7.61 ± 0.14ab	7.94 ± 0.03b
CF	0.88 ± 0.01	0.20 ± 0.00	0.35 ± 0.01	0.23 ± 0.02	0.58 ± 0.04	0.64 ± 0.02	0.23 ± 0.02	0.19 ± 0.01	0.23 ± 0.00	0.14 ± 0.01	0.09 ± 0.00	0.05 ± 0.00	7.53 ± 0.13	8.01 ± 0.01
75% CF	0.62 ± 0.02a	0.25 ± 0.01c	0.37 ± 0.01a	0.24 ± 0.01b	0.63 ± 0.02a	0.72 ± 0.05c	0.21 ± 0.00a	0.23 ± .0.01b	0.14 ± 0.00c	0.13 ± 0.03d	0.06 ± 0.01c	0.02 ± 0.00d	7.65 ± 0.06a	7.93 ± 0.01a
T4	0.07 ± 0.00b	0.50 ± 0.01b	0.03 ± 0.00b	0.20 ± 0.00c	0.01 ± 0.00b	0.84 ± 0.03b	0.02 ± 0.00b	0.23 ± 0.00b	0.36 ± 0.01b	0.82 ± 0.02b	0.15 ± 0.01b	0.14 ± 0.00b	7.58 ± 0.02a	7.84 ± 0.01b
T5	0.07 ± 0.00b	0.27 ± 0.01c	0.04 ± 0.01b	0.32 ± 0.00a	0.02 ± 0.01b	0.63 ± 0.01c	0.02 ± 0.00b	0.18 ± 000c	0.14 ± 0.00c	0.21 ± 0.00c	0.05 ± 0.00c	0.04 ± 0.00c	7.42 ± 0.18a	7.94 ± 0.00a
T6	0.07 ± 0.00b	1.89 ± 0.01a	0.04 ± 0.00b	0.32 ± 0.01a	0.01 ± 0.00b	1.21 ± 0.03a	0.02 ± 0.00b	0.48 ± 0.01a	0.60 ± 0.00a	1.90 ± 0.01a	0.31 ± 0.01a	0.51 ± 0.01a	7.61 ± 0.20a	7.77 ± 0.00c

Note: Treatment symbols were the same as those in Table 4. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test).

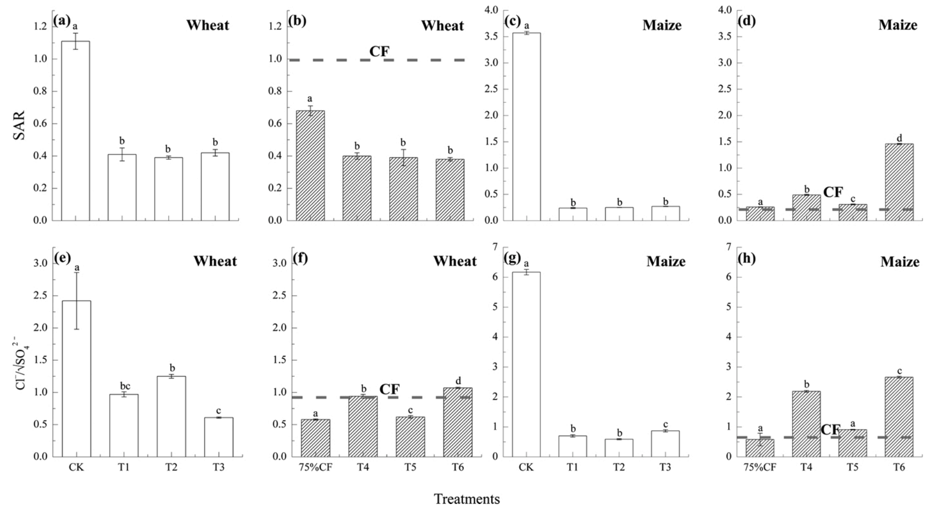

Fig. 2. Sodium adsorption ratio (a–d) and $Cl^-/\sqrt{SO_4^{2-}}$ (e–h) at harvest times. CK and T1–T3 were the same as those in Fig. 1. CF (dotted line) was the conventional fertilization (375 kg ha^{-1}); 75% CF was 75% of the CF. T4–T6 were treatments of biochar at 3, 6, 12 t ha^{-1} together with 75% CF. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test).

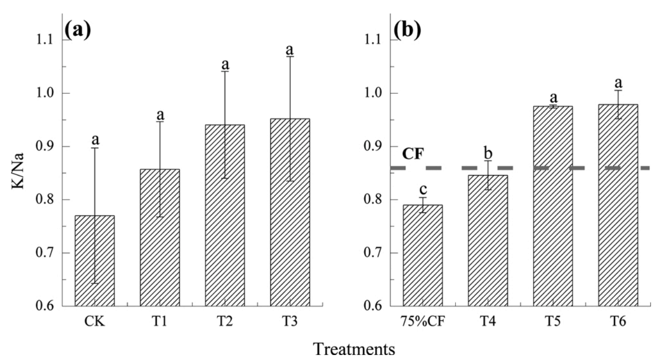

Fig. 3. K/Na ratio in wheat grain as affected by biochar (a) and co-application of biochar and fertilizers (b). The treatments were the same as those in Fig. 2. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test).

ha^{-1}) alone or in combination with 75% CF reduced soil pH at wheat and maize harvest times.

Fig. 2 shows changes in soil solution compositions. Biochar addition at 3–12 t ha^{-1} (T1–T3) significantly decreased SAR by 62.16%–64.86% and $Cl^-/\sqrt{SO_4^{2-}}$ by 48.35%–74.79% over CK at wheat harvest time (Fig. 2a, e). Similar effects on SAR and $Cl^-/\sqrt{SO_4^{2-}}$ were obtained at maize harvest (Fig. 2c, g). Because biochar alone reduced the relative abundance of the highly toxic Na^+ and Cl^-, its use as a soil amendment alleviated soil salinity not only by lowering salt concentrations but also by producing less toxic salt compositions for crops.

The conjunctive effect of biochar and fertilizer use (T4–T6) on SAR and $Cl^-/\sqrt{SO_4^{2-}}$ were complex. SAR was reduced at wheat harvest (Fig. 2b) but increased at maize harvest (Fig. 2d) over 75% CF. This inconsistency was probably due to the more complex dry-wet alternations during the maize growth than the wheat season, resulting in the circular upward movement of salty groundwater in the soil profile and salt accumulation (dominated by NaCl) in topsoil. The biochar would preferably adsorb divalent cations (e.g., Ca^{2+}) from fertilizers and groundwater than Na^+, thus increasing the relative abundance of Na^+ in soil solution and producing a higher SAR value. SO_4^{2-} tends to combine with Ca^{2+} of soil particles and biochar to form a less soluble compound, indirectly increasing $Cl^-/\sqrt{SO_4^{2-}}$ (Fig. 2h). Nevertheless, both SAR and $Cl^-/\sqrt{SO_4^{2-}}$ of T4–T6 treatments at wheat and maize harvest times were lower than CK values, suggesting a conjunctive effect of biochar and 75% CF on producing a less toxic soil solution for crop growth.

3.3. Crop uptake of Na and K in response to biochar use

The wheat season is drier than maize season in the YRD, and wheat is more vulnerable to salt stress. As shown in Fig. 3a, with the increase of biochar dose from 0 to 3, 6, and 12 t ha^{-1}, the K/Na ratio increased from 0.77 to 0.86, 0.94, and 0.95, though their differences were not statistically significant due to the large variations among replicates. Co-applications of biochar (3, 6, and 12 t ha^{-1}) and 75% CF (T4–T6) significantly increased the K/Na ratio over 75% CF. Mainly, T5 and T6 had higher K/Na ratios than CF (Fig. 3b). The K-rich biochar enhanced

Table 6
NH_4^+-N, NO_3^--N, Olsen-P and organic matter of the soil at crop harvests

Treatments	NH_4^+–N		NO_3^-–N		Olsen-P		Organic matter	
	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest
	(mg kg^{-1})						(g kg^{-1})	
CK	2.69 ± 0.49b	4.18 ± 0.06a	27.11 ± 0.67a	1.21 ± 0.23c	0.59 ± 0.02c	0.52 ± 0.01b	6.18 ± 0.17c	6.87 ± 0.29b
T1	3.59 ± 0.05a	2.17 ± 0.09c	17.56 ± 0.97b	1.07 ± 0.08c	2.04 ± 0.17b	0.73 ± 0.06b	7.43 ± 0.14bc	8.00 ± 0.69ab
T2	4.20 ± 0.24a	2.96 ± 0.33b	13.87 ± 0.10c	4.10 ± 0.41b	1.99 ± 0.07b	0.72 ± 0.12b	8.29 ± 0.91b	7.29 ± 0.03b
T3	3.59 ± 0.05a	3.94 ± 0.04a	8.95 ± 0.55d	5.87 ± 0.25a	2.31 ± 0.04a	3.29 ± 0.13a	10.26 ± 0.28a	9.04 ± 0.36a
CF	4.88 ± 0.78	3.32 ± 0.24	34.42 ± 6.72	15.91 ± 5.47	3.10 ± 0.81	2.35 ± 0.34	7.28 ± 0.04	8.82 ± 0.09
75% CF	4.41 ± 0.57ab	2.78 ± 0.21a	28.60 ± 1.33a	17.87 ± 1.62b	1.26 ± 0.06c	1.49 ± 0.03a	6.93 ± 0.56b	7.73 ± 0.50b
T4	3.03 ± 0.71ab	1.35 ± 0.07a	26.05 ± 20.85a	5.54 ± 1.50d	0.59 ± 0.15d	0.57 ± 0.01a	7.48 ± 0.54ab	6.91 ± 0.35b
T5	4.83 ± 0.72ab	2.16 ± 1.26a	28.71 ± 5.64a	10.58 ± 0.75c	2.28 ± 0.40b	0.77 ± 0.30a	9.14 ± 0.61a	7.59 ± 0.02b
T6	7.85 ± 2.80a	3.07 ± 0.01a	15.41 ± 9.48a	23.04 ± 0.98a	4.09 ± 0.53a	1.97 ± 1.15a	8.79 ± 0.73a	9.22 ± 0.04a

Note: Treatment symbols were the same as those in Table 4. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test).

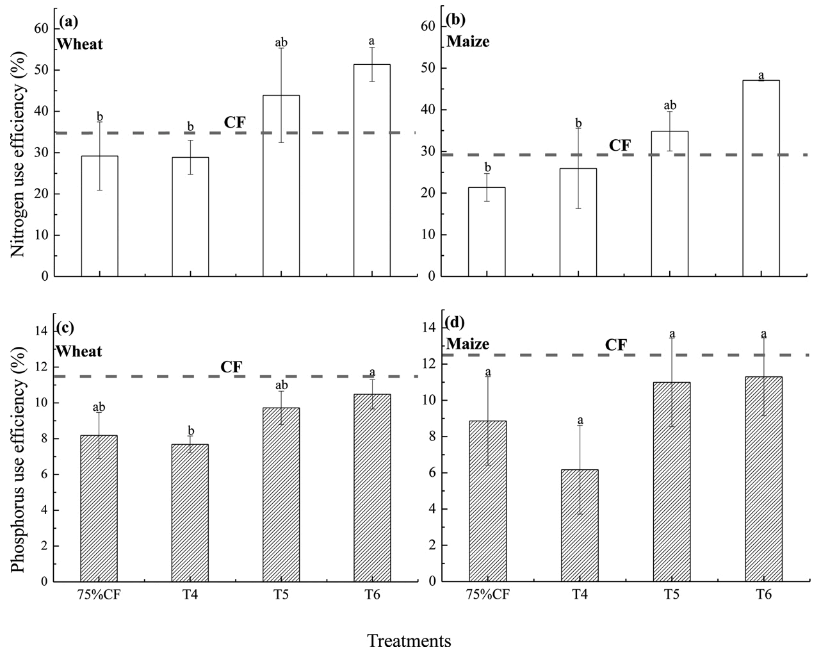

Fig. 4. Nitrogen (a, b) and phosphorus (c, d) use efficiency in response to the co-applications of biochar and fertilizers. Treatments were the same as those in Fig. 2. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test).

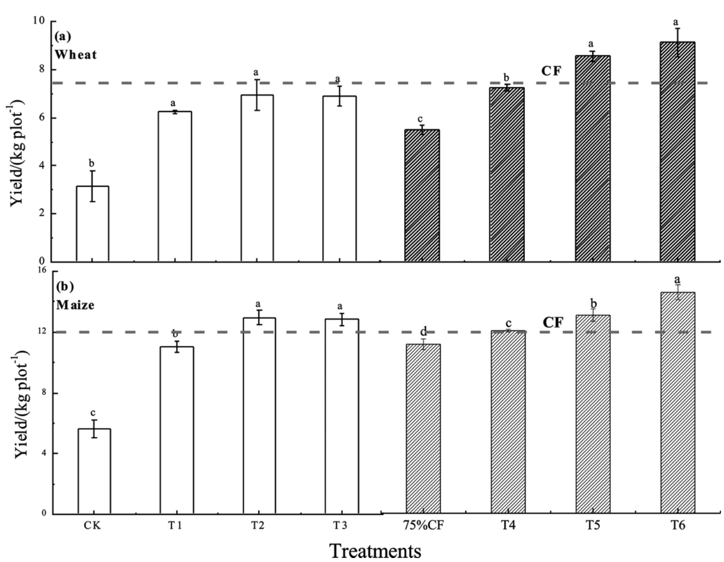

Fig. 5. Wheat (a) and maize (b) yields as affected by biochar alone or the co-applications of biochar and fertilizers. Treatments were the same as those in Fig. 2. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test).

K^+ uptake by wheat, probably due to the changes in soil solution composition.

3.4. Nutrient use efficiency in response to biochar use

Biochar use alone (T1–T3) and in combination with fertilizers (T4–T6) affected soil nutrient and soil organic matter (SOM) contents at wheat and maize harvest times (Table 6). NH_4^+-N, Olsen-P, and SOM contents generally increased, whereas NO_3^--N content sharply decreased with biochar use (T1–T3) over CK at wheat harvest time. In contrast, at maize harvest time, neither T1–T3 nor T4–T6 had a positive effect on NH_4^+-N, whereas T3 or T6 markedly increased NO_3^--N, Olsen-P, and SOM contents over CK or 75% CF.

T4–T6 treatments gradually increased the NUE with biochar doses (Fig. 4a, b). Notably, T5–T6 improved wheat NUE by 33.5–39.4% and maize NUE by 38.71% and 54.61% over 75% CF. Further, T5–T6 had higher NUE values than that of conventional fertilization (CF). PUE was slightly improved for wheat, but insignificant for maize. For both crops, PUE of biochar treatments was lower than CF.

3.5. Crop yields in response to biochar use

Biochar use alone (T1–T3) or in combination with 75% CF (T4–T6) significantly increased crop yields over CK or 75% CF (Fig. 5). T1–T3 increased wheat yield by 49.60%–54.68% and maize yield by 49.23%–56.68%. Indeed, at 6 and 12 t ha^{-1} doses, biochar alone resulted in wheat and maize yields similar to CF, and biochar and 75% CF produced yields higher than CF. In other words, reducing fertilizer use by 25% would not affect crop yields of the year if biochar was added at 6 or 12 t ha^{-1}.

4. Discussion

4.1. Biochar alleviates soil compaction and salt stress

Adding biochar (3, 6, and 12 t ha^{-1}) along with straw returning via rotary tillage to the salt-affected soil reduced its bulk density (BD) and increased its saturated hydraulic conductivity (*Ks*) (Fig. 1), which in turn helped remove soluble salts (Table 5) in soil upon rain and irrigation and reduce osmotic pressure of soil solution (Zörb et al., 2019). The large specific surface area (27.5 m^2 g^{-1}) and irregular shapes of the biochar could be crucial to the alleviation of soil compaction. Irregular and fluffy biochar particles would help soil particles form a porous structure, thus enhancing salt removal via irrigation (Liu et al., 2017; Baiamonte et al. 2019). The creation of a secondary pore system, such as macro-pores, might also play a role in salt leaching (Shaygan and Baumgartl, 2020). Further, the biochar had abundant K^+ (683.4 mmol kg^{-1}), Ca^{2+} (227.7 mmol kg^{-1}), Mg^{2+} (356.1 mmol kg^{-1}), and SO_4^{2-} (112.9 mmol kg^{-1}), release of which would adjust salt compositions in the soil solution to more favorable conditions for crop growth.

The possible mechanisms by which biochar altered soil solution compositions could be summarized as (a) biochar released K^+, Ca^{2+}, and Mg^{2+} to exchange with Na^+ in soil solution thereby reducing Na^+ activity and toxicity (Lin et al., 2015; Zheng et al., 2018); and (b) the released K^+, Ca^{2+}, and Mg^{2+} to soil solution displaced Na^+ on the soil particles and helped Na^+ leaching with irrigation (Usman et al., 2016). The decrease in SAR and $Cl^-/\sqrt{SO_4^{2-}}$ at wheat and maize harvest times (Fig. 2) provides evidence of the mechanisms. Co-applications of biochar with fertilizers, however, complicated the changes in SAR and $Cl^-/\sqrt{SO_4^{2-}}$ for the 2nd mechanism.

Reduced Na^+ (Table 5) and SAR (Fig. 2) from biochar use lowered soil pH (Table 5). This phenomenon was also reported by Chaganti et al. (2015) and Shaygan et al. (2017). Further, the enhanced decomposition of straw by biochar would produce organic acids and reduce soil pH (Xiao et al., 2020).

The changes in osmotic pressure, salt compositions, and pH altogether helped crop absorb K^+ and expel Na^+ (Lashari et al., 2015; Kim et al., 2016), resulting in an increased K/Na ratio of grains (Fig. 3). This ratio indicates the relief of salt stress (Lin et al., 2015; Ali et al., 2017). Among the treatments, T5–T6 increased the ratio the most, suggesting their most significant impact on alleviating Na^+ toxicity.

4.2. Effects of biochar use on nutrient retention and supply

With abundant carboxyl and phenolic-OH groups (Table 1), the biochar would enhance the retention of NH_4^+-N in soil (Zheng et al., 2010; Al-Wabel et al., 2018). In contrast, at the pH of the soil (8.2), the carboxyl groups would be negatively charged, which was unfavorable to the retention of NO_3^--N (Kameyama et al., 2012) at wheat harvest (Table 6). As biochar aged to the maize harvest time, NO_3^--N retention in soil increased with biochar dose, which may be explained by the higher contents of an organic coating (Hagemann et al., 2017), oxidized functional groups, and anion exchange capacity of aged biochar than a fresh one (Mia et al., 2017).

T1–T3 increased Olsen-P because the biochar had a much higher Olsen-P content than the soil (Lashari et al., 2013). Besides reducing soil pH (Table 5), T3 could contribute to the release of available P by reducing the formation of Ca-P crystal phases (Saifullah et al., 2018).

Soils in the YRD are generally rich in potassium (Dong et al., 2006), resulting in high K^+ content in local reed and its derived biochar. Thus, the biochar can provide K^+ to the soil and enhance K^+ uptake by crops. Similar views were reported by Akhtar et al. (2015) and Lin et al. (2015).

Biochar use increased soil organic matter content (Table 6) via the indirect effect of biochar accelerating straw decomposition as a result of enhanced porosity and aeration in biochar-amended saline soil, as suggested by Xiao et al. (2020). T4–T6 treatments increased NUE, which was the combined result of nutrient inputs from biochar (Table 2), the enhanced nutrient retention by the functional groups of biochar (Table 6), and the increased SOM content (Table 6). SOM would enhance microbial activities and increase nutrient supply when crops need (Arif et al., 2017; Al-Wabel et al., 2018; Li et al., 2019).

4.3. Effects of biochar and fertilizer use on crop yields

Crop yields increased in the order of CK < 75% CF < CF (Fig. 5) explains the importance of fertilization in crop production. In contrast, crop yields of biochar treatment alone (T1–T3) were above that of 75% CF and close to CF, suggesting that soil physical conditions could be more important than nutrient supply and retention to crop growth in one wheat-maize rotation (Fig. 5).

T5–T6 treatments further enhanced crop yields by alleviating salt stress (Fig. 3a, b) and improving NUE (Fig. 4a, b). This beneficial effect of biochar on crop yield may be attributed to 1) the reduced salt stress (the increase in K/Na) as a result of improved soil physical conditions and enhanced salt leaching, as discussed above; 2) the increased SOM content and nutrient (N, P) availability; and 3) the provision of K nutrient from the biochar to crop growth (Lin et al., 2015). The results from this field trial indicate that alleviating soil compaction to enhance salt leaching is fundamental to crop production in saline soil in the YRD, and biochar is a useful soil amendment to achieve the objective.

Due to external factors beyond control, the field trial only lasted a year. It would be great if the observed multiple benefits of biochar improving soil physical properties, enhancing salt leaching, increasing nutrient use efficiency, and raising crop yields could be examined for multiple years in the YRD.

5. Conclusions

Inexpensive biochar produced in the field from local reed was trialed to remediate a compact soil with 2.8‰ salt. A single addition of biochar at 3, 6, and 12 t ha^{-1} doses (T1–T3) to a saline soil with straw returning by rotary tillage before wheat sowing alleviated soil compaction (i.e., soil BD decreased, and *Ks* increased) and produced a more favorable soil solution composition (SAR) for wheat and maize growth. The reduced contents of soluble salts (particularly the harmful Na^+ and Cl^-) in soil solution helped alleviate salt stress, thus benefiting crop growth. Biochar also helped SOM accumulation and nutrient retention. Application of 6 and 12 t ha^{-1} biochar (T5–T6) in the field trial can achieve the goals of reducing the use of fertilizers (urea-ammonium mixed nitrogen fertilizer and slow-release fertilizer for wheat, and ammonium dihydrogen phosphate and urea for maize) by 25% and still improving crop yields in wheat-maize rotation.

CRediT authorship contribution statement

Liang Xiao: Investigation, Data curation, Writing - original draft. **Guodong Yuan:** Writing - review & editing. **Lirong Feng:** Formal analysis. **Dongxue Bi:** Supervision. **Jing Wei:** Validation.

Declaration of Competing Interest

Authors declare that no conflict of interest exists in the submission of this manuscript.

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