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ORIGINAL PAPER

Biochar to Reduce Fertilizer Use and Soil Salinity for Crop Production in the Yellow River Delta

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Abstract

To test the hypothesis that by alleviating the salt stress in salt-affected soil, biochar could maintain crop yields even if fertilizer use is reduced by 25% in the Yellow River Delta (YRD). A field trial was conducted to assess the effect of biochar use alone (3, 6, and 12 t ha^{-1}) and in combination with reduced fertilization (25% reduction) on alleviating salt stress, enhancing nutrient supply, and increasing crop yields in wheat–maize rotation. Porous biochar at 12 t ha^{-1} dose significantly decreased the bulk density of saline soil and increased its saturated hydraulic conductivity (*K*s) and water content at wheat and maize harvest over the control (CK). Being rich in K^+ (493.9 mmol kg^{-1}), the biochar reduced sodium adsorption ratio (SAR) and $Cl^-/\sqrt{SO_4{}^{2-}}$ at wheat harvest by 50% and 73%, respectively, and helped the uptake of K^+ by crops over Na^+, resulting in a higher K/Na ratio of grains in treatments as compared to the control. Similar trends were found when biochar (12 t ha^{-1}) was applied together with 75% of conventional fertilization (CF: 375 kg ha^{-1}). This combined biochar and fertilizers increased soil $NH_4{}^+$-N, Olsen-P, nutrient supply, and crop yields compared to 75% CF. Excessive Na^+ and soil compaction limited crop yields in YRD. Biochar amendment reduced soil bulk density and increased saturated hydraulic conductivity (*K*s). They, in turn, enhanced salt leaching and made salt compositions more favorable to crop growth. Compared with 75% CF, co-application of 6–12 t ha^{-1} biochar and 75% CF increased crop yields.

Keywords Coastal saline soil · Sodium adsorption ratio · Nutrient use efficiency · Fertilizer management · Biochar · Wheat–maize rotation

1 Introduction

A large part of the YRD is associated with shallow groundwater table, salty water, and poor drainage, resulting in soils with variable salinity, high pH and Na^+ content, low organic matter content, and soil compaction. For crop production, local farmers irrigate the soils and apply a high dose of fertilizers (Luo et al. 2017), which is becoming unsustainable due to freshwater shortage and the environmental requirement to reduce nutrient loss to water bodies (Liu and Qi 2011).

Soil organic matter (SOM) is crucial to managing soil salinity and fertility because SOM could increase soil porosity and salt leaching (Liang et al. 2021), help nutrient retention (Rekaby et al. 2020), and enhance soil aggregation (Yang et al. 2018). Straw returning to soil is typical in YRD (Xie et al. 2017) to help SOM accumulation. This practice, however, produces a downside nematode problem (Gu et al. 2015). Thus, an alternative approach is required to deal with the large amount of straw and forestry bio-waste in YRD, for which biochar is a promising option.

Biochar is a porous and carbon-rich material, typically produced from biomass pyrolysis under limited oxygen conditions (Lehmann et al. 2006). Its versatile agronomic and environmental benefits range from increasing soil organic

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carbon content (Chaganti et al. 2015) and soil porosity (Baiamonte et al. 2019) to enhancing nutrient retention (Choudhary et al. 2021), soil fertility (Nguyen et al. 2017), and crop yields (El-Mageed et al. 2021; He et al. 2020; Zhang et al. 2020).

Biochar has the potential for remediating saline soil. As a carbon-rich material with plant nutrients and functional groups (Nguyen et al. 2017; Saifullah et al. 2018), biochar is a multi-functional material capable of improving soil properties (He et al. 2020; Gunarathne et al. 2020). For example, Xiao et al. (2020a), Zhu et al. (2020), and Sun et al. (2017) all reported that the application of a small dosage of biochar (2–10‰) reduced NH_3 volatilization and increased NH_4^+-N and NO_3^--N content in a coastal saline soil via nutrient release and retention. With its porous structure and large specific surface area (Blanco-Canqui 2017), biochar can increase saturated hydraulic conductivity (Ks) (Xiao and Meng 2020) by expanding the leaching channel (Burrell et al. 2016) and then accelerate salt leaching (Obia et al. 2016; Di Lonardo et al. 2017). The release of Ca^{2+} and K^+ from biochar could exchange with Na^+ and adjust the salt compositions of soil solution to create more favorable conditions for crop growth. Zheng et al. (2020) illustrated that biochar supplemented soil nutrients (P, K) and provided Ca^{2+} to replace Na^+ in soil, thus facilitating salt removal and nutrient improvement. He et al. (2020) showed that biochar amendment led to significant improvements in soil physical (i.e., bulk density), chemical (i.e., pH, SOM, N and P metabolism and availability), and biological (i.e., bacterial community structure and diversity) properties. Thus, biochar can be a promising approach to mediate the multiple problems of bio-waste accumulation, soil salinity, low nutrient use efficiency, and poor crop yield in YRD.

Despite the numerous reporting of biochar benefits, it has not been widely used in agriculture in general and in YRD in particular because of two challenges: (1) its high cost and the high dose required (Saifullah et al. 2018); and (2) the beneficial effect of biochar amendment on salt-affected soil has primarily been obtained from laboratory or greenhouse studies instead of field trials (Al-Wabel et al. 2018; Saifullah et al. 2018). Field trial in YRD (Liang et al. 2020) is rare, where climate and soil conditions are complex. Both challenges can be dealt with via an aerobic carbonization process to produce inexpensive biochar for a field trial. Therefore, this study aimed to test the hypothesis that by relieving salt stress in soil, biochar could maintain crop yields in the YRD even if fertilizer use is reduced by 25%. To this end, biochar was first produced in the field from the local bio-waste of bamboo willow (*Salix fragilis* L.) via aerobic carbonization (Xiao et al. 2019). It was then used as a soil amendment in field trials in farmland with a moderate salt content of 2.8‰ in YRD. The effects of biochar amendment alone and its combined use with reduced fertilization on soil salinity, nutrient retention, and crop yield were evaluated. The outputs would help the agricultural applications of biochar in the YRD for the multiple benefits of reducing fertilizer use, ameliorating soil, and converting bio-waste into stable carbon (biochar).

2 Materials and Methods

2.1 Study Area

The YRD has a temperate continental monsoon climate, with an average annual precipitation of 591 mm and potential evaporation of 1500 mm (Li et al 2017). The soil in this study is classified as Inceptisols in Soil Taxonomy. It is stratified with a sandy loam layer on the top, a sand layer in the middle, and a red earth layer on the bottom (Xiao and Meng 2020). Soil salinity changes with seasons: in autumn, winter, and spring, salt moves up with capillary water in the soil profile, and it moves down in summer with rainfall. A farmland (ca 6500 ha) in Hekou District, Dongying City, China (37°55.30′N, 118°48.88′E) was chosen for field trials. Soil reclamation started in the 1990s through the cotton plantation to reduce salt content. Since 2014, the farmland has been used for wheat–maize rotation.

2.2 Biochar, Fertilizers, and Seeds

A coupled fire-water technology (Xiao et al. 2019) was used to produce biochar in the field from local bamboo willow (*Salix fragilis* L.) bio-waste. The carbonization process involved the combustion on the surface and oxygen-limiting pyrolysis inside the biomass. Briefly, a pile of bio-waste was ignited at one direction for aerobic carbonization (502 ± 14 ℃), followed by a water-mist spray on the burning dark-red char to terminate the carbonization. The residue was biochar.

Urea-ammonium mixed nitrogen fertilizer (29.96% N) and slow-release fertilizer (28.07% N, 4.84% P) were used as the base and topdressing fertilizers for wheat production. For maize, the base and topdressing fertilizers were ammonium dihydrogen phosphate (21.18% N, 23.45% P) and urea (46.34% N). Seeds of wheat variety Jimai-22, with 100 grains weight of 4.70 g, were provided by the Shandong Academy of Agricultural Sciences whereas seeds of maize variety Jishou-303, with 100 grains weight (35.93 g/100 grains), were obtained from Dade Seeds Co., Ltd. in Beijing.

2.3 Field Trial and Treatments

An area of 67.5 m long and 49.0 m wide with good irrigation and drainage system was used for field trials, and each plot was 10×2 m^2. Between the two plots, a non-experimental area of 5 m^2 (0.5×10 m^2) was maintained to separate the

Table 1 Plot treatments

Treatments	Biochar dose	Treatments	Fertilizer and biochar dose
CK	0 t ha^{-1} biochar	CF	Fertilizers at 375 kg ha^{-1}
T1	3 t ha^{-1} biochar	75% CF	Fertilizers at 281 kg ha^{-1}
T2	6 t ha^{-1} biochar	T4	3 t ha^{-1} biochar + 75% CF
T3	12 t ha^{-1} biochar	T5	6 t ha^{-1} biochar + 75% CF
		T6	12 t ha^{-1} biochar + 75% CF

plots. Biochar was crushed to pass a 1 mm sieve and added once to the topsoil (0–20 cm) by rotary tillage before wheat sowing. The treatments included control (CK), conventional fertilization (CF, being 375 kg fertilizers ha^{-1} from a survey of local farmers), 75% of the CF (75% CF), 3, 6, and 12 t ha^{-1} of biochar use (T1, T2, and T3), and 3, 6, and 12 t ha^{-1} biochar combined with 75% CF (T4, T5, and T6). All treatment plots were randomly arranged, each with 4 replicates, as shown in Table 1. Crushed biochar (< 1 mm) was added while straw was returned to the topsoil (0–20 cm) by rotary tillage (twice) and then furrowed for crop sowing. Wheat was sown (188 kg ha^{-1}) on 15 October 2017, with a furrow spacing of 15 cm, and maize sown (25 kg ha^{-1}) on 20 June 2018, with a furrow spacing of 35 cm and a sow spacing of 25 cm. Base fertilizers were applied to the plots the day before wheat or maize sowing, and the top dressing occurred the day before spring/autumn irrigations (20 March 2018; 26 August 2018). On 10 May and 20 July 2018, pesticides (imidacloprid and carbofuran) were applied to wheat and maize crop, respectively, as routine practice. The wheat crop was harvested on 10 June 2018 and maize on 5 October 2018.

2.4 Sample Collection and Analysis

The soil was randomly sampled from 0 to 15 cm layer of each plot following a S-shaped pattern in September 2017, June 2018, and October 2018 as samples at benchmark, wheat harvest, and maize harvest, respectively. Soil samples were analyzed for organic matter (OM) content, bulk density, saturated hydraulic conductivity (*K*s), and salt content by the wet oxidation method of potassium dichromate and sulfuric acid, cutting ring method, constant head test, and weighing technique (Bao 2000), respectively.

At harvest, plants of wheat and maize were cut at ground level. After that, grains were separated by thresher (5TF–450). Grains and other plant biomass were weighed and mixed, and representative samples were dried in an oven at 85 °C for 24 h. The dried sample is then ground to pass a 100-mesh sieve and analyzed for total Na, K, Ca, and Mg by ICP-MS (Elan DRC II, PerkinElmer) after the digestion of grains by HNO_3-HF-H_2O_2 (Lu 1999) and total N and P by Nessler's reagent and vanadium molybdate methods after digestion by H_2SO_4-H_2O_2 (Lu 1999).

Biochar was determined for its ash content using loss in ignition method (Lu 1999), carbon, nitrogen, hydrogen, and sulfur contents by an elemental analyzer (Vario Micro cube, Elementar, Germany), acidic functional groups by the titration method of the International Humic Substances Society (n.d.), and specific surface area by Brunauer–Emmett–Teller (BET) technique.

Extracts (solutions) of biochar and soil samples were prepared using CO_2-free-deionized water at a 1:5 ratio, shaking at an orbital shaker for 24 h at 160 rpm, and then centrifuging for 15 min at 3500 rpm. After that, the extracts were filtered through a 0.45-μm Whatman filter and then analyzed for pH using pH meter (Five Easy Plus, METTLER TOLEDO), EC by EC meter (DDS–11A), and ion concentrations by chromatography (ICS3000, Dionex) (Bao 2000).

Inorganic N (NH_4^+-N and NO_3^--N) and Olsen-P of biochar and soil samples were determined with a continuous flow analytical system (AutoAnalyzer III, Seal) (Lu 1999) after extraction with 1 M KCl and 0.5 M $NaHCO_3$, respectively. Total N

Table 2 Properties of biochar used in the field trials

Properties	Values	Properties	Values
Ash content (%)	24.15 ± 1.41	Specific surface area (m^2 g^{-1})	271.68 ± 12.57
C (%)	60.30 ± 0.01	Na^+ (total, mmol kg^{-1})	357.83 ± 5.62
N (%)	0.52 ± 0.01	K^+ (total, mmol kg^{-1})	493.85 ± 27.34
H (%)	1.87 ± 0.01	Ca^{2+} (total, mmol kg^{-1})	4522.75 ± 59.83
S (%)	0.02 ± 0.01	Mg^{2+} (total, mmol kg^{-1})	306.67 ± 25.77
– COOH (mol kg^{-1})	0.98 ± 0.01	Cl^- (total, mmol kg^{-1})	579.04 ± 34.28
Phenolic-OH (mol kg^{-1})	0.59 ± 0.04	SO_4^{2-} (total, mmol kg^{-1})	83.58 ± 9.83

content in biochar was determined by Kjeldahl method, and total P was measured by the phosphorus molybdic acid quinoline weight method (Lu 1999).

2.5 Data Processing

Sodium adsorption ratio (SAR) in Eq. 1 (Lesch and Suarez 2009) indicates the relative contents of Na^+, Ca^{2+}, and Mg^{2+} in soil solution. Since Na^+ is more detrimental to crops than Mg^{2+} and Ca^{2+}, a smaller SAR value indicates lower sodium stress (Shaygan et al. 2017). Similarly, a lower chloride/$\sqrt{}$sulfate ratio in Eq. 2 (Wang et al. 2018) suggests lower salt stress from anions because Cl^- is more stressful to crops than sulfate.

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

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

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

Nitrogen and phosphorus use efficiency (NUE, PUE) in Eq. 3 indicates the nutrient retention in soil and supply to crops.

$$NUE/PUE = \frac{Total\ N/P\ of\ crop\ in\ fertilized\ plot - total\ N/P\ of\ crop\ in\ the\ control\ plot}{Amount\ of\ N/P\ in\ applied\ fertilizers} \tag{3}$$

The potassium to sodium (K/Na) ratio reflects sodium relief and potassium absorption for crops (Chakraborty et al. 2016). As potassium is an essential nutrient and sodium is stressful to crop growth, a smaller K/Na in crops suggests higher stress from Na^+ (Lin et al. 2015).

2.6 Statistical Analysis

Excel 2016, SPSS 21.0, and Origin 8.1 were used for calculation, analysis, and graph drawing. One-way ANOVA (Duncan's test, $p < 0.05$) was used for statistical significance analysis. Path analysis was performed to clarify the causal relationship of variables and analyze their direct or indirect effects and the relative magnitude of their contributions.

3 Results

3.1 Properties of Biochar and Its Effects on Soil Porosity and Salt Stress

With a high carbon content of 60.30%, a large specific surface area of 271.68 m^2 g^{-1}, and abundant functional groups (carboxyl: 0.98 mol kg^{-1}, phenol hydroxyl:

Table 3 Physical and chemical properties of biochar and saline soil and the soluble ions in their extracts

	pH	Salt content	Organic matter	Bulk density	Saturated hydraulic conductivity	NH_4^+-N	NO_3^--N	Olsen-P	Na^+	K^+	Ca^{2+}	Mg^{2+}	Cl^-	SO_4^{2-}
		‰	g kg^{-1}	g cm^{-3}	$\times 10^{-5}$ cm s^{-1}	mg kg^{-1}			water-soluble, mmol kg^{-1}					
Biochar	9.6±0.0	—	—	—	—	0.9±0.0	5.3±0.0	11.6±0.1	120.4±2.8	200.0±17.5	560.6±25.0	30.8±9.0	120.7±4.4	30.3±6.8
Soil	8.2±0.2	2.8±0.1	6.3±0.2	1.5±0.1	0.1±0.0	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

0.59 mol kg^{-1}) (Table 2), the biochar has the potential to increase the carbon content and ion exchange capacity of saline soil. Further, it has the potential to release abundant Ca^{2+} (4522.6 mmol kg^{-1}), which can be exchanged with Na^+ in soil solution. Also, the rich K^+ (493.9 mmol kg^{-1}) of biochar can regulate ion composition in soil solution. On the other hand, the high Na^+ (357.8 mmol kg^{-1}) and Cl^- (579.0 mmol kg^{-1}) contents of the biochar might cause a secondary salt hazard if applied in a large quantity. The saline soil had a high pH value, low organic matter content, and low Olsen-P concentration (Table 3), indicating poor soil fertility. In contrast, the biochar had abundant Olsen-P and K^+, suggesting its potential to supply nutrients to crops.

Application of biochar at 12 t ha^{-1} dose (T3) reduced soil bulk density (BD) by 11%, increased *K*s by 52%, and raised soil water content (SWC) by 17% at wheat harvest in comparison to pristine saline soil (Fig. 1a, b, and c). Similar effects were also observed at maize harvest (Fig. 1d, e, and f). The decrease in BD and increase in *K*s indicate that biochar addition not only increased soil porosity but also expanded leaching channels. The rise in soil water content suggests that porous biochar helped soil water retention. The improved soil physical properties would help salt leaching and dilute salt concentration in soil, thus lessening the osmotic effect of salt in the soil.

The concentrations of Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} in soil solution at wheat and maize harvest times (Table 4) were significantly reduced by a small dose of biochar use (T1–T3). Similarly, co-applications of biochar and reduced fertilizers (T5–T6) also lowered the ion concentrations. As soluble salt concentration reduced, salt stress decreased. Both biochar alone (T1–T3) and biochar in combination with 75% CF (T5–T6) increased K^+ in saline soil (except for biochar plus 75% CF at maize harvest time), suggesting a better nutrient (K) retention.

At wheat and maize harvest times, SAR, $Cl^-/\sqrt{SO_4^{2-}}$, pH, and EC decreased by small biochar doses (T1–T3) (Table 5). Lower SAR and $Cl^-/\sqrt{SO_4^{2-}}$ ratios implied less stress from Na^+ and Cl^- in saline soil, and the decreased pH and EC suggested lower salt stress. The conjunctive effects of biochar and fertilizer on SAR and $Cl^-/\sqrt{SO_4^{2-}}$ were complex. Overall, 12 t ha^{-1} biochar combined with 75% CF reduced SAR and $Cl^-/\sqrt{SO_4^{2-}}$ at wheat harvest time, but it had no effect at maize harvest. This inconsistency was probably due to the complex dry–wet alternations at maize harvest than at wheat harvest, resulting in the circular upward movement of salty groundwater in the soil profile and the accumulation of salt (dominated by NaCl) in topsoil. However, both the SAR and $Cl^-/\sqrt{SO_4^{2-}}$ of T4–T6 at wheat and maize harvest times were lower than the corresponding CK values, indicating a positive conjunctive effect of biochar and 75% CF on soil solution compositions. In other words, single biochar use or biochar in combination with fertilizer reduced the relative abundance of stressful Na^+ and Cl^-. Consequently, biochar as a soil amendment alleviated soil salinity by lowering salt concentrations and producing more favorable salt compositions.

Biochar use alone at 12 t ha^{-1} dose (T3) increased the K/Na ratio of wheat grain by 25%, and co-applications of biochar and 75% CF (T4–T6) increased the K/Na ratio of

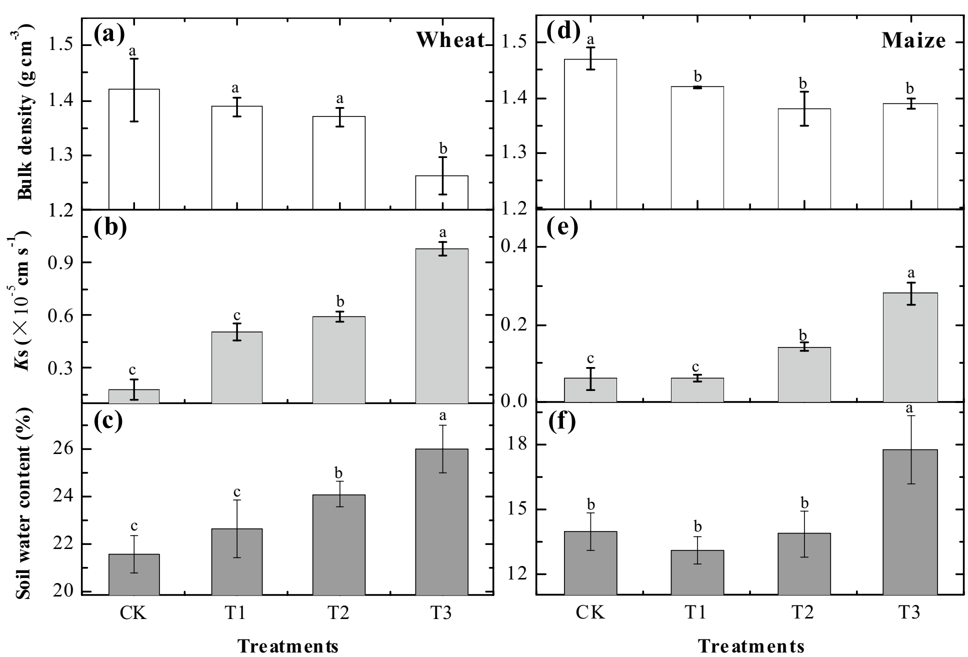

Fig. 1 Bulk density (**a** and **d**), saturated hydraulic conductivity *K*s (**b** and **e**), and soil water content (**c** and **f**) at wheat and maize harvest. *CK*, pristine saline soil; *T1–T3*, biochar-amended soil (at 3, 6, and 12 t ha^{-1}). Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test)

wheat grain by 9, 15, and 17 over the 75% CF, respectively (Fig. 2). Further, the K/Na ratios of wheat grains in T5–T6 were higher than in CF. In other words, biochar alone or together with fertilizers changed Na^+ and K^+ concentrations in soil solution, thus favoring crop uptakes of K^+ over Na^+.

3.2 The Effects of Biochar and Fertilizer on Nutrient Retention and Supply

Biochar amendments (T1–T3) significantly increased NH_4^+-N and Olsen-P contents but decreased NO_3^--N content at wheat harvest time (Table 6). In contrast, biochar did not affect NH4+-N content at maize harvest but increased NO_3^--N and Olsen-P contents. Biochar and fertilizer treatments (T4–T6) increased NH_4^+-N and Olsen-P and reduced NO_3^--N at wheat and maize harvest times.

T4–T6 gradually increased the nutrient use efficiency of wheat compared to 75% CF (Fig. 3). Specifically, NUE in wheat increased by 13, 40, and 42% for T4, T5, and T6 treatments, respectively; PUE increased by 5, 16, and 44%. Notably, T5–T6 significantly improved the NUE, and T6 significantly improved PUE. They were even considerably higher than CF (Fig. 3a and b). The improvement in nutrient use efficiency helped increase wheat yield. Surprisingly, biochar and fertilizer had no effects on the NUE and PUE of maize (Fig. 3c and d). The difference between wheat and maize indicated that the biochar improving nutrient use efficiency might be short-lived.

3.3 The Effects of Biochar and Fertilizer on Crop Yields

As biochar dose increased from 3 to 12 t ha^{-1} (T1–T3), wheat yield increased by 49, 51, and 58%, respectively (Fig. 4). The yield at T4 was even higher than CF (Fig. 4a). This remarkable effect can be mainly attributed to the porous structure (Fig. 5) and the rich P and K contents of biochar (Table 3). With reduced fertilization (T4, T5, and T6), biochar increased wheat yield by 20, 35, and 43% over 75% CF. Notably, the wheat yields of T5 and T6 were 11 and 22% higher than that of the CF (Fig. 4b). Similar results can also be found in maize yields, regardless of biochar alone or together with fertilizers (Fig. 4c and d).

3.4 The Critical Constraints on Crop Yield

The regression and path analysis results indicated that Na^+ concentration in soil solution, EC, and soil bulk density were critical for wheat production (Table 7). For example, the simple correlation coefficient between wheat yield and Na^+ concentration is – 0.988, and the direct path coefficient is – 0.567 (Table 8). Both indexes reflected the adverse effects of Na^+ on crop yield.

Table 4 Concentrations of ions in soil extracts at wheat and maize harvest times

Treatments	Na^+		K^+		Ca^{2+}		Mg^{2+}		Cl^-		SO_4^{2-}	
	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 ± 0.02c	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
T1	0.67 ± 0.02b	0.08 ± 0.03b	0.32 ± 0.03c	0.06 ± 0.00c	0.51 ± 0.04b	0.16 ± 0.02b	0.20 ± 0.02b	0.06 ± 0.01b	0.32 ± 0.00b	0.04 ± 0.00b	0.10 ± 0.02b	0.01 ± 0.00b
T2	0.58 ± 0.00bc	0.06 ± 0.01b	0.51 ± 0.01a	0.08 ± 0.01b	0.55 ± 0.02b	0.16 ± 0.01b	0.25 ± 0.01b	0.06 ± 0.00b	0.18 ± 0.02c	0.05 ± 0.00b	0.07 ± 0.00b	0.01 ± 0.00b
T3	0.49 ± 0.01c	0.08 ± 0.02b	0.42 ± 0.02b	0.07 ± 0.00b	0.57 ± 0.02b	0.15 ± 0.02b	0.21 ± 0.01b	0.05 ± 0.00b	0.16 ± 0.00c	0.09 ± 0.02b	0.06 ± 0.00b	0.02 ± 0.00b
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
75% CF	0.62 ± 0.02b	0.25 ± 0.01a	0.37 ± 0.01c	0.24 ± 0.01a	0.63 ± 0.02a	0.72 ± 0.05a	0.21 ± 0.00c	0.23 ± 0.01a	0.14 ± 0.00b	0.13 ± 0.03a	0.06 ± 0.01a	0.02 ± 0.00a
T4	0.72 ± 0.01a	0.09 ± 0.05b	0.45 ± 0.01a	0.07 ± 0.01b	0.62 ± 0.00a	0.22 ± 0.03b	0.27 ± 0.01a	0.07 ± 0.02b	0.37 ± 0.02a	0.10 ± 0.05c	0.07 ± 0.00a	0.02 ± 0.00a
T5	0.57 ± 0.01c	0.09 ± 0.03b	0.44 ± 0.00a	0.07 ± 0.03b	0.58 ± 0.00b	0.18 ± 0.01b	0.20 ± 0.01c	0.05 ± 0.01b	0.14 ± 0.01b	0.10 ± 0.00c	0.06 ± 0.00a	0.02 ± 0.00a
T6	0.37 ± 0.01d	0.10 ± 0.02b	0.39 ± 0.01b	0.05 ± 0.02b	0.51 ± 0.01c	0.20 ± 0.02b	0.24 ± 0.01b	0.06 ± 0.01b	0.08 ± 0.01c	0.11 ± 0.01b	0.03 ± 0.01b	0.03 ± 0.01a

[a]*CK*, pristine saline soil; *T1–T3*, biochar-amended soil (at 3, 6, and 12 t ha^{-1}); *CF*, conventional fertilization (375 kg ha^{-1}); 75% *CF*, 75% of conventional fertilization; *T4–T6*, biochar-amended soil (at 3, 6, 12 t ha^{-1}) with 75% CF; [b]Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test)

Table 5 SAR, $Cl^-/\sqrt{SO_4^{2-}}$, pH and EC of saline soil at wheat and maize harvest times

Treatments	SAR		$Cl^-/\sqrt{SO_4^{2-}}$		pH		EC_{25}(mS cm^{-1})	
	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest
CK	1.11 ± 0.05a	3.57 ± 0.03a	2.42 ± 0.44a	6.17 ± 0.09a	7.87 ± 0.01a	8.07 ± 0.03a	0.46 ± 0.04a	0.69 ± 0.01a
T1	0.79 ± 0.04b	0.17 ± 0.05b	1.00 ± 0.09b	0.40 ± 0.06c	7.82 ± 0.07a	7.98 ± 0.03b	0.22 ± 0.00b	0.15 ± 0.02b
T2	0.65 ± 0.00c	0.12 ± 0.02b	0.69 ± 0.07b	0.43 ± 0.03c	7.76 ± 0.09ab	7.94 ± 0.01c	0.27 ± 0.00b	0.15 ± 0.02b
T3	0.55 ± 0.00d	0.18 ± 0.03b	0.65 ± 0.04b	0.69 ± 0.04b	7.64 ± 0.01b	7.91 ± 0.03c	0.27 ± 0.03b	0.04 ± 0.02c
CF	0.98 ± 0.02	0.22 ± 0.00	0.79 ± 0.02	0.65 ± 0.05	7.53 ± 0.13	8.01 ± 0.01	0.29 ± 0.02	0.12 ± 0.01
75% CF	0.68 ± 0.03b	0.26 ± 0.00a	0.58 ± 0.01b	0.58 ± 0.21a	7.65 ± 0.06b	7.93 ± 0.01a	0.26 ± 0.00c	0.14 ± 0.01b
T4	0.76 ± 0.01a	0.17 ± 0.08a	1.45 ± 0.13a	0.73 ± 0.30a	7.71 ± 0.03ab	7.81 ± 0.05b	0.37 ± 0.00a	0.25 ± 0.05a
T5	0.65 ± 0.02b	0.19 ± 0.06a	0.59 ± 0.04b	0.67 ± 0.04a	7.62 ± 0.01b	7.88 ± 0.03a	0.28 ± 0.00b	0.22 ± 0.01a
T6	0.42 ± 0.00c	0.18 ± 0.02a	0.44 ± 0.04b	0.68 ± 0.20a	7.75 ± 0.01a	7.79 ± 0.04b	0.22 ± 0.01d	0.30 ± 0.07a

[a]*CK*, pristine saline soil; *T1–T3*, biochar-amended soil (at 3, 6, and 12 t ha^{-1}); *CF*, conventional fertilization (375 kg ha^{-1}); 75% *CF*, 75% of conventional fertilization; *T4–T6*, biochar-amended soil (at 3, 6, 12 t ha^{-1}) with 75% CF; [b]*SAR*, sodium adsorption ratio; EC_{25} is electrical conductivity at 25 ℃; [c]Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test)

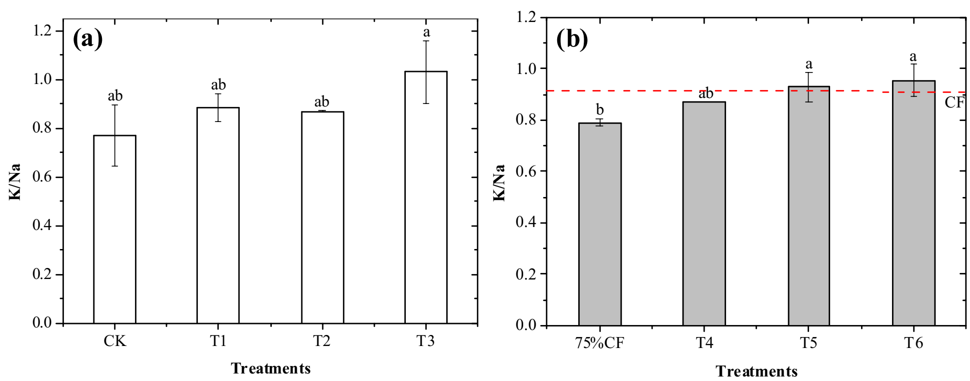

Fig. 2 K/Na ratios of wheat grain affected by biochar (**a**) and co-applications of biochar and fertilizers (**b**). *CK*, pristine saline soil; *T1–T3*, biochar-amended soil (at 3, 6, and 12 t ha^{-1}); *CF*, conventional fertilization (375 kg ha^{-1}); 75% *CF*, 75% of conventional fertilization; and *T4–T6*, biochar-amended soil (at 3, 6, 12 t ha^{-1}) with 75% CF. Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test)

Table 6 NH_4^+-N, NO_3^--N, and Olsen-P of saline soil at harvest times

Treatments	NH_4^+-N		NO_3^--N		Olsen-P	
	Wheat harvest (mg kg^{-1})	Maize harvest	Wheat harvest	Maize harvest	Wheat harvest	Maize harvest
CK	2.69 ± 0.49b	4.18 ± 0.06a	27.11 ± 0.67a	1.21 ± 0.23c	0.59 ± 0.02b	0.52 ± 0.01a
T1	5.57 ± 1.27a	3.33 ± 0.48a	6.17 ± 2.92b	2.70 ± 0.23b	2.12 ± 0.41a	0.83 ± 0.03b
T2	7.06 ± 1.69a	4.19 ± 0.14a	5.56 ± 3.81b	4.29 ± 0.21a	2.52 ± 0.55a	1.07 ± 0.02c
T3	6.81 ± 0.78a	3.85 ± 0.41a	9.82 ± 2.47b	3.80 ± 0.70ab	2.77 ± 0.32a	0.80 ± 0.01b
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
75% CF	4.41 ± 0.57c	2.78 ± 0.21b	28.60 ± 1.33a	17.87 ± 1.62a	1.26 ± 0.06c	1.49 ± 0.03ab
T4	5.69 ± 0.89bc	3.27 ± 0.68b	17.31 ± 1.01b	9.29 ± 1.94b	2.86 ± 0.30ab	1.22 ± 0.14b
T5	6.68 ± 2.45a	3.61 ± 0.05b	16.59 ± 1.67b	9.22 ± 1.46b	3.48 ± 0.52a	1.98 ± 0.22a
T6	6.28 ± 0.33b	5.12 ± 0.46a	17.63 ± 2.02b	7.57 ± 0.76b	3.67 ± 0.34a	2.35 ± 0.32a

[a]*CK*, pristine saline soil; *T1–T3*, biochar-amended soil (at 3, 6, and 12 t ha^{-1}); *CF*, conventional fertilization (375 kg ha^{-1}); 75% *CF*, 75% of conventional fertilization; *T4–T6*, biochar-amended soil (at 3, 6, 12 t ha^{-1}) with 75% CF; [b]Different lower-case letters indicate significant differences between treatments ($p < 0.05$, Duncan's test)

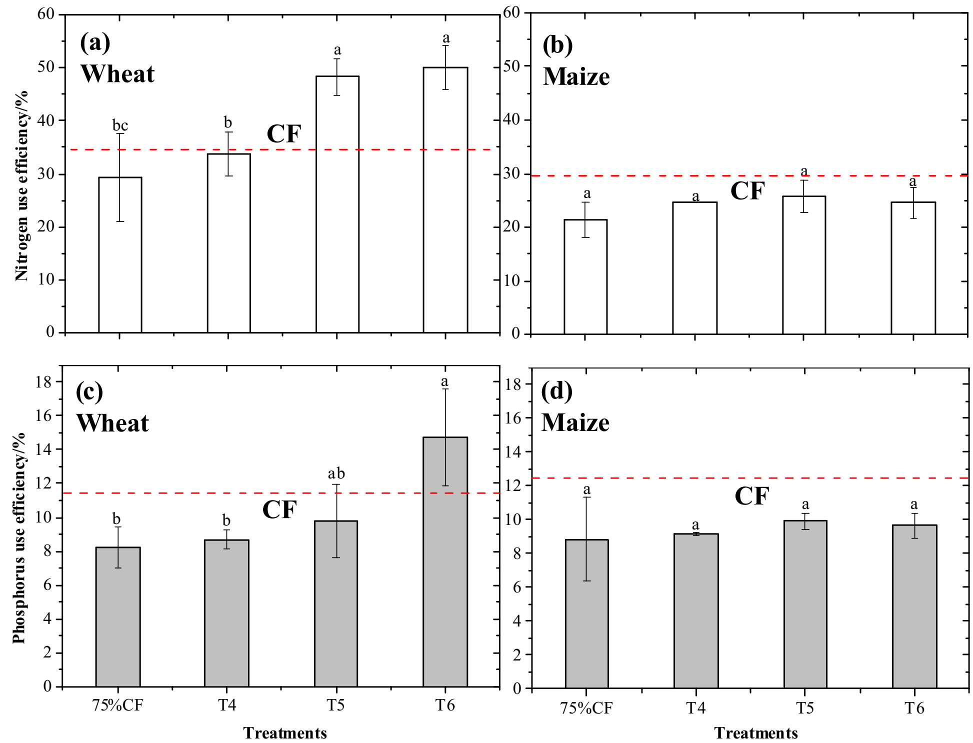

Fig. 3 Nitrogen (**a** and **b**) and phosphorous (**c** and **d**) use efficiency in response to the co-applications of biochar and fertilizers. *CF*, conventional fertilization (375 kg ha^{-1}); 75% *CF*, 75% of conventional fertilization; *T4–T6*, biochar-amended soil (at 3, 6, 12 t ha^{-1}) with 75% CF. Different lower-case letters indicate significant differences between treatments ($p<0.05$, Duncan's test)

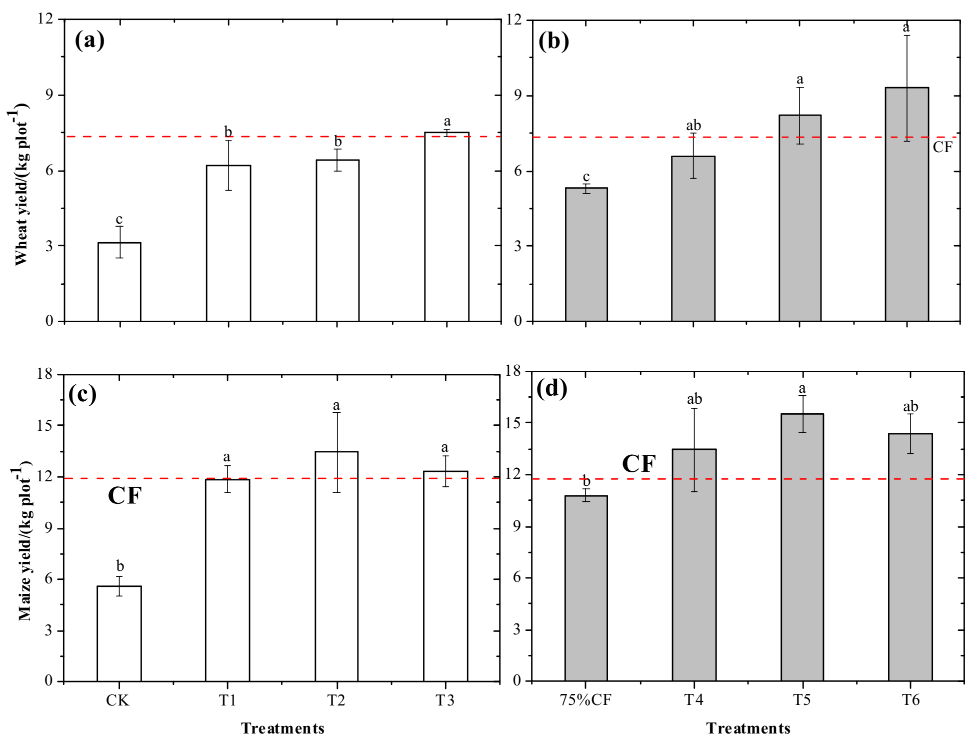

Fig. 4 Wheat (**a** and **b**) and Maize (c and d) yields as affected by biochar alone or co-applications of biochar and fertilizers. *CK*, pristine saline soil; *T1–T3*, biochar-amended soil (at 3, 6, and 12 t ha^{-1}); *CF*, conventional fertilization (375 kg ha^{-1}); 75% *CF*, 75% of conventional fertilization; and *T4–T6*, biochar-amended soil (at 3, 6, 12 t ha^{-1}) with 75% CF. Different lower-case letters indicate significant differences between treatments ($p<0.05$, Duncan's test)

4 Discussion

Biochar amendment (T1–T3) reduced soil salinity, achieved by biochar alleviating soil compact, enhancing salt leaching, and adjusting salt compositions in soil solution. These beneficial effects may be summarized by four biochar-induced processes: (1) The porous biochar (Fig. 5) together with straw returning by rotary tillage reduced soil compact through the creation of a secondary pore system containing macro-pores, as illustrated by Shaygan and Baumgartl

Fig. 5 Scanning electron microscopic image of biochar

Table 7 Model summary of the square

Model	R	R square	Adjusted R square	Std. error of the estimate
1	0.988[a]	0.977	0.973	0.289
2	0.996[b]	0.993	0.990	0.176
3	1.000[c]	0.999	0.998	0.073

[a]Predictors: (Constant), Na^+; [b]Predictors: (Constant), Na^+, bulk density; [c]Predictors: (Constant), Na^+, bulk density, electrical conductivity

(2020), increased soil porosity and *Ks* (Fig. 1), which in turn helped salt leaching on irrigation (Tables 4 and 5); (2) The porous and irregular structure of biochar helped water retention (Fig. 1), thus diluting the concentrations of Na^+, Ca^{2+}, Mg^{2+}, Cl^-, and SO_4^{2-} and reducing the osmotic pressure of soil solution (Burrell et al. 2016); (3) The biochar had abundant Ca^{2+} (4522.75 mmol kg^{-1}) and Mg^{2+} (306.7 mmol kg^{-1}) to exchange with Na^+ in soil solution to reduce Na^+ activity, whereas the released Ca^{2+} and Mg^{2+} could displace Na^+ on soil colloids and help NaCl discharge with irrigation water, as suggested by Usman et al. (2016). Thus, the highly stressful Na^+ and Cl^- were preferably leached out, whereas the less harmful Ca^{2+} and SO_4^{2-} remained in the soil solution; and (4) Due to its abundant K^+ (493.9 mmol kg^{-1}), a small dose of biochar (3–12 t ha^{-1}) could increase K^+ in soil by 11–32%. This extraneous K^+ would change the ion compositions of soil solution, alleviate salt stress, and help crop uptake of K^+ rather than Na^+ (Lashari et al. 2015), as evidenced by the increased K/Na ratio (Fig. 2).

Besides alleviating soil salinity, biochar enhanced nutrient retention and supply. With rich functional groups (Table 2), biochar alone or together with fertilizer enhanced NH_4^+-N retention (Table 6). Sun et al. (2017) reported similar results. However, the negatively charged surface of biochar (Kameyama et al. 2012) did not help adsorb NO_3^--N, thus facilitating its leaching (Xiao and Meng 2020). As biochar had higher Olsen-P and K^+ contents than the soil (Table 3), it increased Olsen-P and K supply, as Kim et al. (2016) suggested. Further, biochar use (12 t ha^{-1}) reduced soil pH (Table 5), which could indirectly increase the release of Olsen-P by minimizing the formation of Ca-P crystal phases (Saifullah et al. 2018). Overall, biochar amendment enhanced nutrient retention and improved nutrient use efficiency for wheat (Fig. 3a and c), in agreement with Sun et al. (2020) and Faloye et al. (2019). In comparison, Zhu et al. (2020) reported that salt ions compete with NH_4^+ for adsorption, and biochar use increased NH_3 volatilization and inhibited nitrification in coastal saline soil.

Crop yields (Fig. 4) increased due to biochar reducing salinity and enhancing nutrient supply and nutrient use efficiency (Fig. 3a and b). Co-applications of biochar (6 or 12 t ha^{-1}) and fertilizers (at 75% CF) further raised the crop yields. Xiao et al. (2020a, b) suggested that soil salinity could affect crop growth more than a nutrient deficiency in saline soils. Though limited by its single wheat–maize rotation, this short field trial study proved that Na^+ concentration in soil solution, EC, and soil bulk density were critical for wheat production. In other words, in coastal saline soil, excessive soluble salts (informed by EC), particularly with high Na^+ concentration, and soil compaction (reflected by bulk density) were major obstacles to soil fertility and crop yields. In practice, loosening compact soil to enhance salt leaching is the most effective soil management technique in YRD. This work adds a case to the global effort in halting

Table 8 The breakdown of simple correlation coefficients

Independent variable	Simple correlation coefficients with wheat yield	Direct path coefficients	Indirect path coefficients			
			Na^+	Bulk density	Electrical conductivity	Total
Na^+	−0.988	−0.567	NA	−0.173	−0.247	−0.420
Bulk density	−0.730	−0.271	−0.368	NA	−0.096	−0.464
Electrical conductivity	−0.884	−0.272	−0.515	−0.095	NA	−0.610

NA not applicable

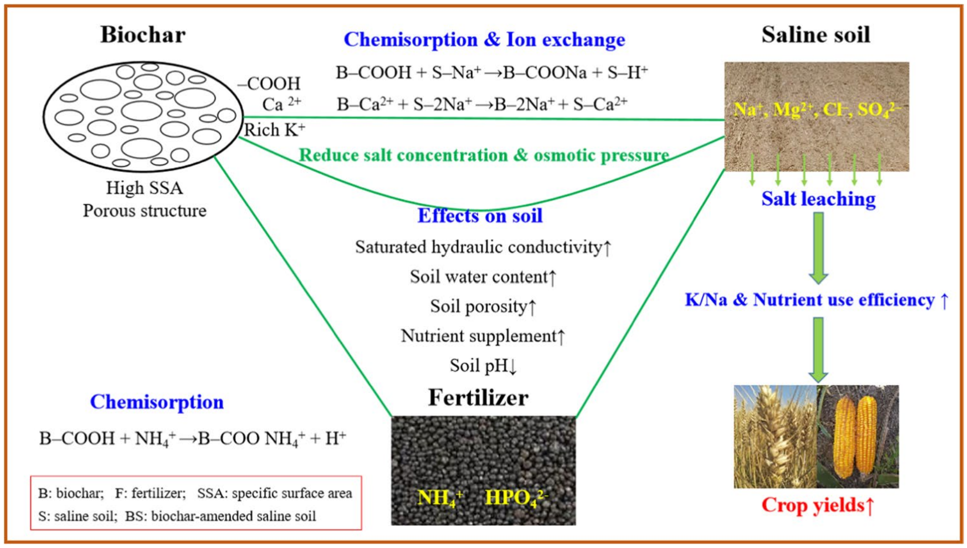

Fig. 6 Processes of biochar improving soil properties and enhancing crop growth

soil salinization and boosting soil productivity, the campaign of World Soil Day 2021 of the UN.

Besides its agronomic benefits, biochar has the potential for offsetting greenhouse gas emissions from the agricultural sector. Because of its stability, biochar effectively breaks the natural carbon cycle of photosynthesis and bio-decomposition. In other words, biomass conversion to biochar prevents a portion of the carbon in plant residue from re-entering the atmosphere. Thus, biochar is a carbon-negative scheme to help meet the carbon neutrality requirement of the Paris Agreement and IPCC. The biochar scheme ($20/ton, Xiao et al. 2019) is less expensive than the engineering techniques developed for carbon capture and storage. It would be particularly applicable to developing countries whose ability to achieve carbon neutrality by the middle of this century is severely restricted by the lack of technologies and finance.

5 Conclusions

Application of biochar (12 t ha^{-1}) alone or together with reduced fertilization lowered soil bulk density and increased saturated hydraulic conductivity and soil water content. These changes in soil physical properties accelerated salts leaching and decreased Na^+, Cl^-, sodium adsorption ratio, and $Cl^-/\sqrt{SO_4^{2-}}$, thus providing more favorable soil solution conditions for crop growth. Biochar use also improved nutrient retention in soil. The combined effects of biochar on alleviating salt stress and enhancing nutrient retention were shown in the higher K/Na ratio in wheat and maize grains, the improved nitrogen and phosphorus use efficiency, and the improved crop yields (Fig. 6). Excessive soluble salts (particularly Na^+) and soil compaction were the major obstacles to crop production. This 1-year field study of wheat–maize rotation proved that co-application of 6–12 t ha^{-1} biochar and 75% conventional fertilization (281.3 kg ha^{-1}) could achieve the goals of increasing crop yields and reducing fertilizer use by 25% in the Yellow River Delta. This work provides an example that could be practiced to convert biomass to biochar for agronomic benefits, particularly in developing countries.

Author Contribution LX and LF performed material preparation, data collection, and analysis. LX and GY wrote the manuscript, and all authors contributed to the revision of the manuscript.

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Data Availability Included in tables and figures, available on request.

Declarations

Conflict of Interest The authors declare no competing interests.

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