INTRODUCTION

The Yellow River Delta, China, is a large land area covered by sediment derived from the Loess Plateau (Kong et al., 2015). The agricultural productivity of the delta, however, is constrained by salinity because of the flat topography, shallow groundwater table and salty groundwater (Fan, Liu, Tang, & Shu, 2010). Salt movement in soils is influenced by season, soil structure, irrigation and drainage conditions (Fan et al., 2012). In general, from winter to spring, salt (high concentrations of soluble salt and exchangeable sodium) accumulates in topsoil (Zhang, Wang, Liu, Wang, & Zhou, 2015); meanwhile, the inherent low fertility of saline soil is detrimental to plant growth (Luo et al., 2017), especially around Tomb-sweeping Day, a key period for spring sowing (i.e. cotton, spring maize), and the high salt content in the soil further inhibits crop growth. Thus, it urgently requires irrigation to force salt down, and local farmers often use traditional flooding to promote salt leaching (Ye, Bai, Lu, & Q.Q., Zhao, Q.Q. & Wang, J.J., 2014). However, the effect of irrigation cannot produce a long-lasting effect as we expected due to the low infiltration and subsequent salt accumulation (Luo et al., 2017).

Evaluating the effect of biochar on salt leaching and nutrient retention of Yellow River Delta soil

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Abstract

Biochar has the potential to decrease salinity and nutrient loss of saline soil. We investigated the effects of biochar amendment (0–10 g kg⁻¹) on salinity of saline soil (2.8‰ salt) in NaCl leaching and nutrient retention by conducting column leaching experiments. The biochar was produced in situ from Salix fragilis L. via a fire-water coupled process. The soil columns irrigated with 15 cm of water showed that biochar amendment (4 g kg⁻¹) decreased the concentration Na⁺ by 25.55% in the first irrigation and to 60.30% for the second irrigation in sandy loam layer over the corresponding control (CK). Meanwhile, the sodium adsorption ratio (SAR) of soil after the first and second irrigation was 1.62 and 0.54, respectively, which were 15.2% and 49.5% lower than CK. The marked increase in saturated hydraulic conductivity (Kₚ) from 0.15 × 10⁻⁵ cm s⁻¹ for CK to 0.39 × 10⁻⁵ cm s⁻¹, following 4 g kg⁻¹ of biochar addition, was conducive to salt leaching. Besides, biochar use (4 g kg⁻¹) increased NH₄⁺-N and Olsen-P by 63.63% and 62.50% over the CK, but accelerated NO₃⁻-N leaching. Since 15 cm hydrostatic pressure would result in salt accumulation of root zone, we would recommend using 4 g kg⁻¹ of biochar, 30 cm of water to ease the problem of salt leaching from the surface horizon to the subsoil. This study would provide a guidance to remediate the saline soil in the Yellow River Delta by judicious application of biochar and irrigation.

KEYWORDS
biochar, nutrient retention, saturated hydraulic conductivity, sodium adsorption ratio, soil profile
Biochar is a porous and carbon-rich material, typically produced by pyrolysis of biomass in oxygen-limited conditions (Blackwell, Reithmuller, & Collins, 2009; Lehmann, Gaunt, & Rondon, 2006; Wang & Wang, 2019). As a carbon-rich material with a porous porosity, large specific surface area and rich functional groups (Blanco-Canqui, 2017), biochar is a good amendment and the application of biochar in soil improvement and remediation has attracted high attention from researchers (Wang & Wang, 2019; Wang et al., 2020). Some studies have reported that biochar plays a role in enriching humic-like component, promoting the microbial growth and reducing the nitrate-N leaching in the soil (El-Naggar et al., 2020; Uchida, Morizumi, & Shimotsuma, 2019); and others have illustrated that biochar decreases the emissions of CO₂ and CH₄ from agriculture (El-Naggar et al., 2019). An emerging pool of knowledge shows that biochar addition is effective in improving physical, chemical and biological properties of salt-affected soils (He et al., 2020; Saifullah, Naem, Rengel, & Naidu, 2018). The application of biochar in association with irrigation to salt-affected soil is potentially capable of reducing salinity (Baiamonte, Crescimanno, Parrino, & Pasquale, 2019; Saifullah et al., 2018). The good porosity and large specific surface area of biochar can increase soil porosity and infiltration to enhance salt leaching during irrigation (Di Lonardo et al., 2017). Owing to the some contents of K⁺ and Ca²⁺, biochar can also regulate ion composition and abate the negative effect of soil salinity on plant growth by exchanging its Ca²⁺ with Na⁺ in soil solution (Lashari et al., 2015; Zheng et al., 2018). With its rich carbon (Lehmann et al., 2006), some plant nutrients (Ajayi, Holthusen, & Horn, 2016) and abundant oxygen-containing functional groups (Nguyen et al., 2017), biochar is a multi-functional material capable of increasing soil carbon and nutrient contents as well as nutrient retention (He et al., 2020; Usman et al., 2016; Yu et al., 2019). Thus, the effect of biochar on saline soil depends on its multiple properties (Liu, Dugan, Masiello, & Gonnermann, 2017; Saifullah et al., 2018).

In practice, current research has two main limitations in biochar application. Firstly, only when the new products have political and economic feasibilities, can it be successfully applied to substitute products and/or remove pollutants (Soltanian et al., 2020). However, biochar prepared from traditional mode has a higher production and application cost under a larger additive dosage (Al-Wabel et al., 2018; Vochozka, Marouskova, Vachal, & Strakova, 2016). Strategies for reducing application costs of biochar and increasing its use efficiency need to be developed (El-Naggar et al., 2019); Secondly, the application of biochar to remediate saline soil in the Yellow River Delta is rarely combined with irrigation (Chaganti, Crohn, & Šimůnek, 2015; Saifullah et al., 2018). In addition, internal and external conditions such as flooding, appropriate water quantity and soil profile must be considered during the remediation (Saifullah et al., 2018).

Here, a low-cost ($24 ton⁻¹) biochar was produced in the field by aerobic carbonization process via fire-water coupled method (Xiao, Yuan, Bi, Wei, & Shen, 2019) for remediating a soil with 2.8‰ salt. The objective of the present investigation is to (a) quantify the effect of biochar amendment on salt leaching and nutrient retention in the soil profile, (b) and find a suitable water quantity for spring irrigation. The purpose of this research is to provide a key to managing salinity for spring seeding through biochar amendment and irrigation in the Yellow River Delta.

### 2. MATERIALS AND METHODS

#### 2.1 Study area

The Yellow River Delta, China, has a temperate continental and monsoon climate with distinct dry and wet seasons (Han et al., 2015; Wei et al., 2020). The region has an average annual rainfall of 590.9 mm, an average annual evaporation of over 1,500 mm and an evaporation to rainfall ratio of 2.54 (Kong et al., 2015). Seasonal droughts and water-logging are conducive to soil salinization (Zhang, Chen, & Liu, 2019). Agriculture in the region is largely determined by soil salt concentration. Cotton often serves as a pioneer plant, followed by a wheat–corn rotation when soil salinity drops below 3.0‰.

#### 2.2 Soil and biochar samples

The soil samples were collected in a field in Xianhe Town, Hekou District, Dongying City (37°55.30′, 118°48.88′). The soil is typically stratified with a sandy loam layer (0–15 cm) sitting on top of a sand layer (15–35 cm) and a red earth layer (35–100 cm), as shown in Figure 1.
From idle in winter to sowing in spring, the soil has undergone a process of salt accumulation. Thus, soil samples depth of 0–15 cm were collected from the same plot in early winter (15 October 2017) and spring (12 March 2018) by the S-shaped sampling method, which were used as baseline and salinization samples, respectively. Further, 12 soil columns were randomly collected in the same plot using 50 cm long stainless steel columns with an inner diameter of 10 cm on 12 March 2018. The columns contain soil from a depth of 0–35 cm including both sandy loam and sand layers (Figure 1), and the basic properties of each layer are shown in Table 1. Composite soil samples were used to explore salt accumulation from winter to spring, and soil columns were used to investigate the effects of biochar on salt leaching and nutrient retention by simulating spring irrigation.

The biochar was derived from local *Salix fragilis* L. and produced in the field via a fire-water coupled process with a measured temperature range (the temperature on the surface of dark red char before spraying water) of 485–527°C, as in the previous study (Xiao, Yuan, et al., 2019). In short, the branches were randomly piled up and ignited from four sides. When the branches burned to dark red char, they were knocked down to the ground, collected it and then sprayed with water-mist to extinguish immediately to form biochar. During carbonization, the temperature will rise rapidly and

**Figure 1** Soil profile characteristics [Colour figure can be viewed at wileyonlinelibrary.com]
the water spray will immediately terminate the carbonization (Xiao, Feng, Yuan, & Wei, 2019). The basic properties of biochar are shown in Table 2.

### 2.3 Desalinization by simulated irrigation

Leaching experiments, simulating spring irrigation, were carried out at a hydrostatic pressure of 15 cm, identical to that often employed in field irrigation (flooding). First, the 0–15 cm soil in the upper part of each column was shovelled out, mixed with biochar (≤1 mm) at a dose of 0, 1, 2, 4 and 10 g kg$^{-1}$, wetted at 60% of field capacity and backfilled to the column; then, the columns were aged for 1 month with enclosed on top of columns. Every treatment was duplicated and labelled as CK, T1, T2, T3 and T4, respectively. The remaining two columns were used for backup and backfill. Before the leaching experiment, the ion concentrations in soil extracts of each layer were determined. During the leaching process, the soil columns were placed on a surface with small holes, allowing the leachate to be collected in a beaker below (Figure S1). 15 cm of deionized water was used to simulate spring irrigation for two consecutive times, and the irrigation time lasted 19 hr and 28 hr. At the end of each irrigation, the volume of leachate was recorded and then filtered through a 0.45-μm membrane for determining the ion concentrations. Meanwhile, soil samples were collected from each layer by using a 12-cm tube with the inside diameter of 0.25 cm to obtain soil extract for determining ion concentrations; in the meantime, each layer of the holes was backfilled. The results were used to calculate ion concentrations in the soil (Appendix S1: Eq. 1) and sodium adsorption ratio (SAR) (Appendix S1: Eq. 2) (Lesch & Suarez, 2009).

In analogy to SAR, the ratio of chloride/√sulphate was used to indicate the relative concentrations of Cl$^{-}$ and SO$_4^{2-}$ (Appendix S1: Eq. 3), as chloride is toxic to plants, while sulphate is less harmful (Wang, Xiao, Bi, Wei, & Yuan, 2018).

Leaching rate (LR) (calculated by Appendix S1: Eq. 4) was used to illustrate the effect of salt leaching following biochar addition to saline soil at sandy loam layer and sand layer.

After irrigations, soils samples were collected from sandy loam layer to determine bulk density, saturated hydraulic conductivity ($K_s$) and nutrient contents (i.e. NH$_4^+$-N, NO$_3^-$-N, Olsen-P) by established methods as described in section of sample analysis.

### 2.4 Sample analysis

Soil samples were collected from each soil column for measurement at different irrigation stages. Bulk density and porosity were determined by cutting ring method (Lu, 1999), and

| pH | EC (dS m$^{-1}$) | Ash (%) | C (mol kg$^{-1}$) | N (mol kg$^{-1}$) | H (mol kg$^{-1}$) | S (mol kg$^{-1}$) | −COOH (mol kg$^{-1}$) | −OH (mol kg$^{-1}$) | SSA (m$^2$ g$^{-1}$) |
|----|----------------|---------|-----------------|-----------------|-----------------|-----------------|---------------------|-------------------|-------------------|
| 9.62 ± 0.02 | 4.93 ± 0.05 | 2.15 ± 0.005 | 24.15 ± 1.41 | 60.30 ± 0.01 | 0.52 ± 0.01 | 1.87 ± 0.01 | 0.02 ± 0.01 | 0.59 ± 0.04 | 262.20 |

**Abbreviations:** EC, electrical conductivity; SSA, specific surface area.
**TABLE 3** Cations and anions of biochar and saline soil

| Sample                  | Fractions                        | Na⁺ (mmol kg⁻¹) | K⁺ (mmol kg⁻¹) | Ca²⁺ (mmol kg⁻¹) | Mg²⁺ (mmol kg⁻¹) | Cl⁻ (mmol kg⁻¹) | SO₄²⁻ (mmol kg⁻¹) |
|-------------------------|---------------------------------|----------------|----------------|-----------------|----------------|----------------|------------------|
| Biochar                 | Water soluble                   | 120.41 ± 2.77  | 200.03 ± 17.47 | 560.64 ± 25.04  | 30.82 ± 8.98   | 120.73 ± 4.42  | 30.26 ± 6.78     |
|                         | Total                            | 357.83 ± 5.62  | 493.85 ± 27.34 | 4,522.75 ± 59.83| 306.67 ± 25.77 | 579.04 ± 34.28 | 83.58 ± 9.83     |
| Saline soil (0–15 cm)   | Baseline in early winter         | 12.33 ± 0.12   | 3.26 ± 0.05    | 8.43 ± 0.01     | 3.47 ± 0.05    | 13.33 ± 0.06   | 2.42 ± 0.06      |
|                         | Late spring salinization         | 38.04 ± 0.71   | 4.14 ± 0.10    | 13.74 ± 0.16    | 7.91 ± 0.02    | 34.76 ± 0.20   | 7.70 ± 0.15      |

*Note: Value, mean ± standard deviations (M ± SD).*

**FIGURE 2** Na⁺ and Cl⁻ in sandy loam layer after first and second irrigation. CK–T4 the same as Table 4. The red lines represent the value of ions in saline soil on baseline. Value, mean ± standard errors of the mean (M ± SEM) [Colour figure can be viewed at wileyonlinelibrary.com]

Ks was determined by constant water head test (Shao, Wang, & Huang, 2006). The salt content of soil was determined by weighing (Bao, 2000), and soil organic matter was determined by wet oxidation using K₂Cr₂O₇-H₂SO₄ (Lu, 1999). The pH, electric conductivity (EC) and cations and anions of the biochar and saline soil were measured for a suspension in deionized water at a ratio of 1:5 (w/v) after shaking at 160 r min⁻¹ for 24 hr, using a pH meter (Five Easy Plus, METTLER TOLEDO), a conductivity meter (DDS–11A) and an ion chromatography (ICS3000, Dionex), respectively (Lu, 1999). The NH₄⁺-N, NO₃⁻-N extracts of biochar and soil samples were extracted by 1 mol L⁻¹ KCl, and Olsen-P was extracted by 0.5 mol L⁻¹ NaHCO₃ at a ratio of 1:5 (w/v, shaking at 160 r min⁻¹ for 2 hr) and measured with a continuous flow analytical system (AutoAnalyzer III, Seal) (Lu, 1999). The concentrations of total Na⁺, K⁺, Ca²⁺, Mg²⁺, Cl⁻ and SO₄²⁻ of biochar were obtained by digestion in HNO₃-HF-H₂O₂ and analysis by ion chromatography (ICS3000, Dionex) (Lu, 1999). The sample of the soil columns of the same treatment was considered as duplicates.

### 2.5 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 followed by Duncan’s test (p < .05).
3 | RESULTS

3.1 | Salt accumulation

Biochar contained some water-soluble salts, but its Ca and Mg were largely insoluble, indicating that the biochar has a good potential to exchange Na⁺ in soil solution with its Ca²⁺ or Mg²⁺ (Table 3). As the soil dries out when season went from winter to spring, salt content was also increased in sandy loam layer. For example, the concentration of Na⁺ increased from 12.33 to 38.04 mmol kg⁻¹; similarly, the concentration of Cl⁻ increased from 13.33 to 34.76 mmol kg⁻¹ (Table 3). Other ions, including K⁺, Ca²⁺, Mg²⁺ and SO₄²⁻, also increased synchronously with Na⁺ and Cl⁻ (Table 3), indicating the accumulation of salt in the soil was far more serious during the seasonal transition. Also, this indirectly highlighted the urgency and necessity of spring irrigation, which was essential to force salt leaching from the topsoil (Table 3).

3.2 | The effect of biochar on desalinization

The quantity of Na⁺ and Cl⁻ remaining in the upper layer of soil column after simulated irrigations is shown in Figure 2. Increasing the biochar dose from 0 to 4 g kg⁻¹ during the first irrigation led to a reduction of Na⁺ by 19.05%, 22.05% and 25.55%, and Cl⁻ by 42.18%, 47.24% and 49.47%. The second irrigation caused an even greater reduction, in the case of Na⁺ by 42.64%, 52.04% and 60.30%, and for Cl⁻ by 80.65%, 90.32% and 94.57%. Indeed, Na⁺ and Cl⁻ concentrations in soil extract were lower than those in the baseline, indicating that salt content had been reduced. The higher dose of 10 g kg⁻¹ biochar enhanced Na⁺ leaching during irrigations, but Cl⁻ leaching was less than those at 1–4 g kg⁻¹ dose. Taking cost and effect into account, 1–4 g kg⁻¹ biochar doses would be effective choices for salinity control.

Besides enhancing salt leaching, biochar amendment can alter salt compositions (Figure 3). An increase in biochar dose led to a gradual decrease of both SAR and Cl⁻/√SO₄²⁻. In other words, the highly toxic Na⁺ and Cl⁻ are preferentially leached out, while the less harmful Ca²⁺, Mg²⁺ and SO₄²⁻ ions are retained. Thus, biochar amendment can alleviate salinity not only by reducing salt concentrations, but also through producing more favourable salt compositions. Again, the second simulated irrigation had a more profound effect on the ratios than the first irrigation. When the biochar dose increased from 1, 2 to 4 g kg⁻¹, SAR decreased by 6.80%, 10.47% and 15.18%, while Cl⁻/√SO₄²⁻ fell by 32.18%, 35.63% and 37.07% after the first irrigation. After the second irrigation, SAR was reduced by 28.97%, 37.38% and 49.53%, and Cl⁻/√SO₄²⁻ by 61.02%, 74.58% and 83.05%. The changes in SAR and Cl⁻/√SO₄²⁻ also suggest that biochar doses of 1–4 g kg⁻¹ are optimal for application to salt-affected soil.
The downward movement of salt from the sandy loam layer (0–15 cm) to the sand layer (15–35 cm) further indicates that biochar amendment can relieve salinity. Table 4 shows that raising the biochar dose from 0 to 4 g kg\(^{-1}\) caused the leaching rate of Na\(^+\), Mg\(^{2+}\), Ca\(^{2+}\), Cl\(^-\) and SO\(_4\)\(^{2-}\) in the sandy loam layer (0–15 cm) to increase during the first simulated irrigation. In contrast, the leaching rate of K\(^+\) decreased from 39.25% (CK) to 29.21% (T3), indicating that K\(^+\) was effectively retained in the soil layer. The K\(^+\) ions, released from biochar (493.85 mmol kg\(^{-1}\)), can also replenish K\(^+\) in soil. It is worth noting that the leaching rates of Na\(^+\), K\(^+\), Mg\(^{2+}\), Ca\(^{2+}\), Cl\(^-\) and SO\(_4\)\(^{2-}\) in the sand layer (15–35 cm) were negative when measured after the first irrigation. This observation is indicative of a downward movement of ions from the sandy loam layer to the sand layer where salinity would develop. Furthermore, biochar amendment promoted NaCl leaching during the second simulated irrigation. Thus, the leaching rate of Na\(^+\) increased from 57.65% for the control (CK) to 71.62% for T1, 73.67% for T2 and 78.26% for T3, while the corresponding value for Cl\(^-\) increased from 47.99% to 81.88%, 90.76% and 94.99%, respectively. The positive leaching rates of Na\(^+\), Mg\(^{2+}\) and Cl\(^-\) recorded for the sand layer indicates that the second irrigation sufficiently lowers the concentration of soluble ions as to reduce salinity. The negative value measured for the rate of K\(^+\) leaching suggests that K\(^+\) (transported from the upper sandy loam layer) does not leach out. The retention of K\(^+\) would benefit crop growth.

### 3.3 The effect of biochar on nutrient retention

Application of biochar to the saline soil conducted an increase in NH\(_4\)\(^+\)-N and Olsen-P content, but a decrease in...
Increasing the biochar dose from 0 to 4 mg kg\(^{-1}\), the NH\(_4^+\)-N content increased from 0.48 to 1.32 mg kg\(^{-1}\), and the Olsen-P content increased from 0.22 to 0.56 mg kg\(^{-1}\); rather, the NO\(_3^-\)-N content decreased from 7.95 to 2.29 mg kg\(^{-1}\). Besides, the higher dose of 10 g kg\(^{-1}\) biochar in NH\(_4^+\)-N and Olsen-P retention was less than those at 1–4 g kg\(^{-1}\) dose. In consideration of the cost and effect, 2–4 g kg\(^{-1}\) biochar would be an effective choice for NH\(_4^+\)-N and Olsen-P retention during irrigation.

### 3.4 The effect of biochar on bulk density and saturated hydraulic conductivity

Increasing the biochar dose from 0, 2, 4 to 10 g kg\(^{-1}\), soil bulk density decreased from 1.42 to 1.40, 1.36 and 1.30 g cm\(^{-3}\). When the biochar dosage increased to 4 g kg\(^{-1}\), the soil bulk density was significantly less than the CK (Figure 4), and when the biochar dosage increased to 10 g kg\(^{-1}\), the soil bulk density was further reduced; the corresponding saturated hydraulic conductivity increased from 0.15 \(\times 10^{-5}\) (CK) to 0.22 \(\times 10^{-5}\) (T2), 0.39 \(\times 10^{-5}\) (T3) and 0.91 \(\times 10^{-5}\) cm s\(^{-1}\) (T4), and soil Ks increased significantly except for the addition of 1 g kg\(^{-1}\) biochar treatment (T1) (Figure 4). In particular, 4 g kg\(^{-1}\) biochar use showed a significant difference in decreasing bulk density and increasing Ks, which would contribute to salt leaching, and this observation accords with the enhanced leaching of Na\(^+\), Mg\(^{2+}\), Ca\(^{2+}\), Cl\(^-\) and SO\(_4^{2-}\) (Table 4).

### 4 DISCUSSION

The excessive soluble salts and exchangeable sodium caused an increasing of osmotic pressure in soil solutions and physiological drought in plants (Zhang et al., 2015, 2019). As sodium ions (Na\(^+\)) dominated the soil salinity, the soil became compacted, with high bulk density and poor porosity, being
unfavourable for salt leaching, root penetrating and plant growth (Lashari et al., 2015). The salt leaching effect may be explained in terms of four biochar-induced processes: (1), the addition of biochar (4 g kg−1) reduced the soil bulk density and increased the Ks (Figure 4). The enhanced water permeability of soil facilitates salt leaching (Table 4) via preferred pathways, and similar results can be found in Wu, Xu, and Shao (2014) and Yue, Guo, Lin, Li, and Zhao (2016). The reduction in soil bulk density (Figure 4) can also increase salt leaching through creation of secondary pore system including macro-pores as mentioned in Shaygan and Baumgartl (2020); (2), the rich K⁺ of biochar (Table 3) can reduce SAR and Cl⁻/SO₄²⁻ by reducing salt relative concentrations and producing more favourable salt compositions on concentrations of soluble salts, to alleviate salinity. This is in agreement with the work of Lashari et al. (2013); Lin et al., (2015); (3), the Ca²⁺ released from biochar (Table 3) can exchange with Na⁺ on soil particles, facilitating Na⁺ leaching with irrigation and the retention of Ca²⁺ (Chaganti et al., 2015; Lashari et al., 2015); and (4), the functional groups on the surface of biochar (Table 2), notably its high content of carboxyl (0.98 mol kg−1) and phenolic-OH (0.59 mol kg−1) groups, have strong affinity, and can form complexes with Na⁺ and Mg²⁺, thus leaching them through irrigation (Wang et al., 2018).

The key role of irrigation should be attracted serious attention. After the first leaching, the leaching rates of the ions (Na⁺, Mg²⁺, Ca²⁺, Cl⁻ and SO₄²⁻) in the sandy loam layer were positive, but the leaching rates of the sand layer were negative. This showed that the amount of rinsing water in the first leaching process was not enough to completely leach all ions (Table 4), which may be due to the soil at this time was unsaturated. The exchange time of ions between the biochar and the salt-affected soil in the first leaching process is relatively short, so it is too late to dissolve fully. However, in the second simulated irrigation, the soil particles were fully wetted, leading to enhanced ion exchange and ion movement with water; and the K⁺ in biochar was also fully dissolved and accumulated in the sand layer with irrigation water (the secondary leaching rate of the sand layer was positive, Table 4), which was conducive to the retention of potassium in the cultivated layer.

In this study, we found that biochar use had good effects on NH₄⁺-N and Olsen-P retention, but accelerated NO₃⁻-N leaching during irrigation (Figure 5). The results are in agreement with the study of Kameyama, Miyamoto, Shiono, and Shinogi (2012) and Al-wabel et al. (2018). With its abundant functional groups (–COOH: 1.1 mol kg⁻¹, phenolic-OH: 0.5 mol kg⁻¹) (Table 2), biochar use can increase NH₄⁺-N retention (Al-wabel et al., 2018; Sun, Lu, Chu, Shao, & Shi, 2017). In contrast, in saline soil (pH > 8), the carboxyl groups would be negatively charged, which was unfavourable to the retention of NO₃⁻-N and accelerated its leaching (Kameyama et al., 2012). Therefore, nitrate-fertilizer should be avoided during biochar together with spring irrigation to remediate saline soil.

By promoting salt leaching during simulated irrigation, biochar amendment at a dose of 4 g kg⁻¹ can alleviate salinity in salt-affected soils. The amount of water has a profound effect on the movement and distribution of salt in soil profile. In general, as the roots of crops (i.e. cotton, spring maize) are distributed over a 0–35 cm depth, the application of insufficient irrigation water would run the risk of moving salt from the surface horizon to subsoil where salinity would develop. Routine flooding with a 15 hydrostatic pressure needs to be corrected, and we would therefore recommend irrigating the soil at a hydrostatic pressure of 30 cm during spring ploughing.

To make up for the lack of this study, our subsequent research will focus on (a) collecting real undisturbed soil columns with biochar applied to carry out experiments; (b) using actual brackish water in the field for leaching experiments; and (c) incorporating soil water potential and model simulation into experimental analysis process.

5 | CONCLUSIONS

Biochar amendment (4 g kg⁻¹) coupled with simulated irrigation can enhance salt leaching in salt-affected soil by increasing saturated hydraulic conductivity; meanwhile, the most toxic salt species (Na⁺ and Cl⁻) are preferably leached out, while non-toxic cations (Ca²⁺, K⁺) and anions (SO₄²⁻) are retained. Biochar use (4 g kg⁻¹) can improve NH₄⁺-N and Olsen-P retention, but accelerate NO₃⁻-N leaching, so nitrate-fertilizer should be avoided during biochar together with spring irrigation. Moreover, the first irrigation (simulated traditional flooding with 15 cm of hydrostatic pressure) facilitates downward movement of salt from the upper horizon to the subsoil (root zone); therefore, the salt-affected soil should be irrigated in spring at ≥ 30 cm of hydrostatic pressure to prevent salt downward accumulation in subsoil. The results of this research would indicate that salt-affected soil in the Yellow River delta, and similar soils located in the same climatic conditions, can be remediated for spring seeding through the judicious application of biochar along with irrigation.

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DATA AVAILABILITY STATEMENT

Authors declare that the data associated with the paper is available and there are no conflict of interest exists in the submission of this manuscript.
REFERENCES

Ajayi, A. E., Holthuizen, D. & Horn, R. (2016). Changes in microstructural behavior and hydraulic functions of biochar amended soils. *Soil and Tillage Research*, 155, 166–175.

Al-Wabel, M. I., Hussain, Q., Usman, A. R. A., Ahmad, M., Abduljabbar, A., Sallam, A. S. & Ok, Y. S. (2018). Impact of biochar properties on soil conditions and agricultural sustainability: A review. *Land Degradation and Development*, 29, 2124–2161.

Baiamonte, G., Crescimanno, G., Parrino, F. & Pasquale, C. D. (2019). Effect of biochar on the physical and structural properties of a desert sandy soil. *Catena*, 175, 294–303.

Bao, S. D. (2000). *Soil agro-chemical analysis*. 3rd edn. pp. 30–34, 187. Beijing: China Agriculture Press (in Chinese).

Blackwell, P., Reithmuller, G. & Collins, M. (2009). Biochar application to soil. In J. Lehmann & S. Joseph (eds), *Biochar for Environmental Management: Science and Technology* (pp. 207–226). London: Earthscan.

Blanco-Canqui, H. (2017). Biochar and soil physical properties. *Soil Science Society of America Journal*, 81, 687–711.

Chaganti, V. N., Crohn, D. M. & Simůnek, J. (2015). Leaching and reclamation of a biochar and compost amended saline-sodic soil with moderate SAR reclaimed water. *Agricultural Water Management*, 158, 255–265.

Di Lonardo, S., Baronti, S., Vaccari, F. P., Albanese, L., Battista, P., Miglietta, F. & Bacci, L. (2017). Biochar–based nursery substrates: The effect of peat substitution on reduced salinity. *Urban Forestry and Urban Greening*, 23, 27–34.

El-Naggar, A., Lee, M. H., Hur, J., Lee, Y. H., Igalavithana, A. D., Shaheen, S. M., … Ok, Y. S. (2020). Biochar-induced metal immobilization and soil biogeochemical process: An integrated mechanistic approach. *Science of the Total Environment*, 698, 134112.

El-Naggar, A., Lee, S. S., Rinklebe, J., Farooq, M., Song, H., Sarmah, A. K., … Ok, Y. S. (2019). Biochar application to low fertility soils: A review of current status, and future prospects. *Geoderma*, 337, 536–554. https://doi.org/10.1016/j.geoderma.2018.09.034

Fan, X. M., Liu, G. H., Tang, Z. P. & Shu, L. C. (2010). Analysis on main contributors influencing soil salinization of Yellow River Delta. *Journal of Soil and Water Conservation*, 24, 139–144.

Fan, X., Pedroli, B., Liu, G., Liu, Q., Liu, H. & Shu, L. (2012). Soil salinity development in the Yellow River Delta in relation to groundwater dynamics. *Land Degradation and Development*, 23, 175–189.

Han, G. X., Chu, X. J., Xing, Q. H., Li, D. J., Yu, J. B., Luo, Y. Q., … Rafique, R. (2015). Effects of episodic flooding on the net ecosystem CO2 exchange of a supratidal wetland in the yellow river delta. *Journal of Geophysical Research: Biogeosciences*, 120, 1506–1520.

He, K., He, G., Wang, C. P., Zhang, H. P., Xu, Y., Wang, S. M., … Hu, R. B. (2020). Biochar amendment ameliorates soil properties and promotes Miscanthus growth in a coastal saline-alkali soil. *Applied Soil Ecology*, 155, 103674.

Kameyama, K., Miyamoto, T., Shiono, T. & Shinogi, Y. (2012). Influence of sugarcane bagasse derived biochar application on nitrate leaching in calcareous dark red soil. *Journal of Environmental Quality*, 41, 1131–1137.

Kavitha, B., Reddy, P. V. L., Kim, B., Lee, S. S., Pandey, S. K. & Kim, K. H. (2018). Benefits and limitations of biochar amendment in agricultural soils: A review. *Journal of Environmental Management*, 227, 146–154.

Kong, D. X., Miao, C. Y., Brothwick, A. G. L., Duan, Q. Y., Liu, H., Sun, Q. H., … Gong, W. (2015). Evolution of the Yellow River Delta and its relationship with runoff and sediment load from 1983 to 2011. *Journal of Hydrology*, 520, 157–167.

Lashari, M. S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., … Yu, X. (2013). Effects of amendment of biochar–manure compost in conjunction with pyrolysis and nitrification solution on soil quality and wheat yield of a salt-stressed cropped field from Central China Great Plain. *Field Crops Research*, 144, 113–118. https://doi.org/10.1016/j.fcr.2012.11.015

Lashari, M. S., Ye, Y., Ji, H., Li, L., Kubec, G. W., Lu, H., … Pan, G. (2015). Biochar–manure compost in conjunction with pyrolysis and nitrification solution alleviated and improved leaf bioactivity of maize in a saline soil from central China: A 2–year field experiment. *Journal of the Science of Food and Agriculture*, 95, 1321–1327.

Lehmann, J., Gaunt, J. & Rondon, M. (2006). Biochar sequestration in terrestrial ecosystems—a review. *Mitigation and Adaptation Strategies for Global Change*, 11, 395–419.

Lesch, S. M. & Suarez, D. L. (2009). Technical note: A short note on calculating the adjusted SAR index. *American Society of Agricultural and Biological Engineers*, 52, 493–496.

Lin, X. W., Xie, Z. B., Zheng, J. Y., Liu, Q., Bei, Q. C. & Zhu, J. G. (2015). Effects of biochar application on greenhouse gas emissions, carbon sequestration and crop growth in coastal saline soil. *European Journal of Soil Science*, 66, 329–338.

Liu, Z. L., Dugan, B., Masielo, C. A. & Gomermann, H. M. (2017). Biochar particle size, shape, and porosity act together to influence soil water properties. *PloS One*, 12, e0179079.

Lu, R. K. (1999). *Analytical methods for soil and agricultural chemistry*. pp. 107–108, 156–160, 180–182, 269–271. Beijing: China Agricultural Science and Technology Press (in Chinese).

Luo, X. X., Liu, G. C., Xia, Y., Chen, L., Jiang, Z. X., Zheng, H. & Wang, Z. Y. (2017). Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China. *Journal of Soils and Sediments*, 17, 780–789.

Nguyen, T. T. N., Xu, C. Y., Tahmasbian, I., Che, R. X., Xu, Z. H., Zhou, X. H., … Bai, S. H. (2017). Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. *Geoderma*, 288, 79–96. https://doi.org/10.1016/j.geoderma.2016.11.004

Saifullah, D. S., Naeem, A., Rengel, Z. & Naidu, R. (2018). Biochar application for the remediation of salt-affected soils: Challenges and opportunities. *Science of the Total Environment*, 625, 320–335.

Shao, M. A., Wang, Q. J. & Huang, M. B. (2006). *Soil physics*. Beijing: Higher Education Press.

Shayan, M. & Baumgartl, T. (2020). Simulation of the effect of climate variability on reclamation success of brine-affected soil in semi-arid environments. *Sustainability*, 12, 371–394.

Soltanian, S., Aghbashlo, M., Almasi, F., Hosseinzadeh-Bandbafha, H., Nizami, A. S., Ok, Y. S., … Tabatabaei, M. (2020). A critical review of the effects of pretreatment methods on the exergetic aspects of lignocellulosic biofuels. *Energy Conversion and Management*, 212, 112792.

Sun, H. J., Lu, H. Y., Chu, L., Shao, H. B. & Shi, W. M. (2017). Biochar applied with appropriate rates can reduce N leaching, keep N retention and not increase NH3 volatilization in a coastal saline soil. *Science of the Total Environment*, 575, 820–825. https://doi.org/10.1016/j.scitotenv.2016.09.137

Uchida, Y., Morizumi, M. & Shimotsuwa, M. (2019). Effects of rice husk biochar and soil moisture on the accumulation of organic and
inorganic nitrogen and nitrous oxide emissions during the decomposition of hairy vetch (Vicia villosa) mulch. *Soil Science and Plant Nutrition*, 65, 1623139.

Usman, A. R., Al-Wabel, M. I., Abdulaziz, A. H., Mahmoud, W. A., El-Naggar, A. H., Ahmad, M., … (2016). Conocarpus biochar induces changes in soil nutrient availability and tomato growth under saline irrigation. *Pedosphere*, 26, 27–38.

Vochozka, M., Marouskova, A., Vachal, J. & Strakova, J. (2016). Biochar pricing hampers biochar farming. *Clean Technologies and Environment*, 18, 1225–1231.

Wang, J. L. & Wang, S. Z. (2019). Preparation, modification and environmental application of biochar: A review. *Journal of Cleaner Production*, 227, 1002–1022.

Wang, J., Xiao, L., Bi, D. X., Wei, J. & Yuan, G. D. (2018). Processes of leonardite altering cation and anion composition of soil solution in salt-affected soil in the Yellow River Delta. *Acta Pedologica Sinica*, 55, 1367–1376. (in Chinese with English abstract).

Wang, L., Chen, L., Tsang, D. C. W., Guo, B. L., Yang, J., Shen, Z. T., … Poon, C. S. (2020). Biochar as green additives in cement-based composites with carbon dioxide curing. *Journal of Cleaner Production*, 258, 120678.

Wei, S. Y., Han, G. X., Jia, X., Song, W. M., Chu, X. J., He, W. J., … Wu, H. T. (2020). Tidal effects on ecosystem CO₂ exchange at multiple timescales in a salt marsh in the yellow river delta. *Estuarine, Coastal and Shelf Science*, 228, 106727.

Wu, Y., Xu, G. & Shao, H. B. (2014). Furfural and its biochar improve the general properties of a saline soil. *Solid Earth*, 5, 665–671.

Xiao, L., Feng, L. R., Yuan, G. D. & Wei, J. (2019). Low-cost field production of biochars and their properties. *Environmental Geochemistry and Health*, 42(6), 1569–1578. https://doi.org/10.1007/s10653-019-00458-5

Xiao, L., Yuan, G. D., Bi, D. X., Wei, J. & Shen, G. H. (2019). Equipment and technology of field preparation of biochars from agricultural and forest residues under aerobic conditions with water-fire coupled method. *Transactions of the Chinese Society of Agricultural Engineering*, 35, 239–244. (in Chinese with English abstract).

Ye, X. F., Bai, J. H., Lu, Q. Q., Zhao, Q. Q. & Wang, J. J. (2014). Spatial and seasonal distributions of soil phosphorus in a typical seasonal flooding wetland of the Yellow River Delta, China. *Environmental Earth Sciences*, 71, 4811–4820.

Yu, H. W., Zou, W. X., Chen, J. J., Chen, H., Yu, Z. B., Huang, J., … Gao, B. (2019). Biochar amendment improves crop production in problem soils: A review. *Journal of Environmental Management*, 232, 8–21.

Yue, Y., Guo, W. N., Lin, Q. M., Li, G. T. & Zhao, X. R. (2016). Improving salt leaching in a simulated saline soil column by three biochars derived from rice straw (*Oryza sativa* L.), sunflower straw (*Helianthus annuus*), and cow manure. *Journal of Soil and Water Conservation*, 71, 467–475. https://doi.org/10.2489/jswc.71.6.467

Zhang, T. J., Chen, Y. J. & Liu, J. Z. (2019). Characteristics of soil salinization in coastal wetlands based on canonical correspondence analysis. *Acta Ecologica Sinica*, 39, 3322–3332. (in Chinese with English abstract).

Zhang, T., Wang, T., Liu, K. S., Wang, L. X. & Zhou, Y. (2015). Effects of different amendments for the reclamation of coastal saline soil on soil nutrient dynamics and electrical conductivity responses. *Agricultural Water Management*, 159, 115–122.

Zheng, H., Wang, X., Chen, L., Wang, Z., Xia, Y., Zhang, Y., … Xing, B. (2018). Enhanced growth of halophyte plants in biochar-amended coastal soil: Roles of nutrient availability and rhizosphere microbial modulation. *Plant, Cell and Environment*, 41, 517–532.

**SUPPORTING INFORMATION**

Additional supporting information may be found online in the Supporting Information section.

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