Peanut Shell Biochar's Effect on Soil Physicochemical Properties and Salt Concentration in Highly Saline-Sodic Paddy Fields in Northeast China

Xuebin Li, Weikang Che, Junlong Piao, Xiang Li, Feng Jin,* Tianxu Yao, Pingyue Li, Wei Wang, Tan Tan, and Xiwen Shao *

Soil salinization is a major ecological threat to crop growth and production. Biochar addition can alleviate the negative impacts of saline-sodic stress in crops. Here, a two-year field experiment was conducted in a highly saline-sodic paddy field to evaluate the response of soil physico-chemical properties, ionic concentration, and rice yield to biochar applications. The soil was amended with peanut shell biochar as follows: zero biochar (B0), 33.75 t ha^{-1} (B1), 67.5 t ha^{-1} (B2), and 101.25 t ha^{-1} (B3). Biochar significantly reduced soil bulk density (BD), while it markedly increased total porosity (TP) and saturated hydraulic conductivity (K_s). Furthermore, biochar markedly decreased the Na^+ concentration, Na^+/K^+ ratio, Na^+/Ca^{2+} ratio, HCO_3^-, and CO_3^{2-} while it increased the concentrations of K^+, Ca^{2+}, and Mg^{2+}. Biochar significantly decreased the electrical conductivity of soil saturation extract (EC_e). The exchangeable sodium percentage (ESP) of B1, B2, and B3 were 53.6%, 62.3%, and 71.0% lower, respectively, than that of B0, and the corresponding decrease in sodium adsorption ratio (SARe) was 51.2%, 58.1%, and 60.5%. Biochar had no effect on the soil pH but significantly increased the soil cation exchange capacity (CEC). The rice biomass yield, grain yield, and harvest index significantly increased after biochar application.

DOI: 10.15376/biores.17.4.5936-5957

Keywords: Saline-sodic soil; Biochar; Ionic concentration; Physicochemical properties; Rice paddy field; Peanut shell; Rice yield

Contact information: Agronomy College, Jilin Agricultural University, Changchun 130118, China;
Xuebin Li, Weikang Che, and Junlong Piao contributed equally to this work;
** Corresponding authors: jinfeng@jlau.edu.cn, 616530670@qq.com*

INTRODUCTION

The Songnen Plain, located between 42°30' to 51°20'N and 121°40' to 128°30'E, is the largest plain in Northeast China. The western area of this plain occupies a total of 3.42 million hectares of saline-sodic soil, which severely restricts its agricultural development and utilization (Wang *et al.* 2003). Over the years, overgrazing by livestock, population growth, and improper soil management have been the main anthropogenic factors responsible for increased soil salinization in the Songnen Plain (Huang *et al.* 2022). Currently, the Songnen Plain is more explored for agriculture than for livestock herding, but low-quality water and improper irrigation-resource management continue to be main factors in increasing soil salinity, sodicity, and alkalinization in recent years. Sodium carbonate and sodium bicarbonate are the main sodium salts in saline-sodic soil in this region, which have strong alkalinity (Chi and Wang 2010). Osmotic stress, ion toxicity, and high pH stress in saline-sodic soil are the main factors that inhibit crop growth and soil organism activity (Al-Karaki 1997; Chi *et al.* 2012). These negative effects can cause nutritional disorders in plants and a decrease in the soil water potential and can limit the uptake of essential plant nutrients (K, Ca, Mg, and P) and water, with decreases in soil infiltration and hydraulic conductivity as well as root respiration, thus reducing the yield (Wong *et al.* 2010; Chaganti and Crohn 2015). Saline-sodic soils can be reclaimed successfully for plant growth following steps aimed at the removal of excessive amounts of exchangeable Na and soluble salts from the cation exchange sites *via* other cations, such as Ca^{2+}, and then leaching the replaced Na^+ from the soil profile with good-quality water (Chi *et al.* 2012; Huang *et al.* 2022). The application of organic conditioners is another important way to ameliorate the impact of saline-alkali stress on plants, which can both improve the physicochemical properties and enhance soil fertility (Yaduvanshi and Swarup 2005; Vijayasatya *et al.* 2015; Srivastava *et al.* 2016). It is a fact that washing or leaching saline-sodic soils with good-quality (low-salinity) water is the most accepted method for mitigating the problem (Huang *et al.* 2022). However, freshwater is increasingly becoming scarce in arid/semiarid areas afflicted by saline-sodic soils. These soils have high concentrations of montmorillonite clay, which is high in negative charges and adsorb Na^+ very efficiently, leading to clay-particle dispersion into pores, decreasing soil permeability and drainage (Chi *et al*. 2012). Therefore, it is necessary to use tested and proven methods to mitigate soil salinity and sodicity through the lixiviation of salts away from the crop root zone.

Similar to organic matter, a biochar application is effective in reducing salinity stress by limiting Na^+ uptake by plants (Lashari *et al.* 2013; Thomas *et al.* 2013). Recent research shows that the benefit of biochar added to salt-affected soil is related to the stabilization of the soil structure, an improvement in the soil physical properties, an increase in the content of soil organic carbon and nutrients, and an enhancement of the soil cation exchange capacity (CEC) and soil surface area (Esfandbod *et al.* 2017; Liu *et al.* 2020; Yao *et al.* 2021). In addition, a biochar addition can enhance the nutrient levels of salted-affected soils by providing habitats for soil microorganisms and improving their vitality (Saifullah *et al.* 2018). The authors' previous research showed that a biochar addition clearly reduced the Na^+ concentrations in rice plants and decreased the Na^+/K^+ ratio of the rhizosphere soil in a saline-sodic paddy field mainly because of its high Na^+ adsorption potential and K^+ supply capacity (Jin *et al.* 2018; Ran *et al.* 2020; Zhao *et al.* 2020; Li *et al.* 2022). Moreover, biochar applied to saline-sodic soil can promote rice growth through an improvement in the soil nutrient status and an increase in the soil enzyme activity (Yao *et al.* 2021). A laboratory column-leaching experiment and a greenhouse study demonstrated that biochar effectively removed salts from saline-sodic soil, promoted a balanced ratio of Na^+/K^+ in the soil solution, and significantly reduced the electrical conductivity of soil saturation extract (ECe), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR) because of its influence on pore size distribution and Na^+ displacement (Santos *et al.* 2021). Similar results were observed in soybean amended with modified biochar (Mehmood *et al.* 2020). Generally, biochar is considered to be an effective organic ameliorant for saline soils; however, most research has been primarily conducted using small buckets in laboratories or greenhouses, and mainly focused on dry crops or on the aboveground parts of crops (Lashari *et al.* 2013; Drake *et al.* 2016; Mehmood *et al.* 2020; Santos *et al.* 2021). It is not clear how biochar is involved in improving the soil physicochemical characteristics, increasing the ion concentration, and regulating the yield formation of rice in highly saline-sodic paddy fields. Therefore, long-term field experiments on the effect of a biochar application in paddy fields with saline-sodic soil are necessary. The authors hypothesize that peanut shell biochar can improve the soil physicochemical properties by reducing the soil Na^+ concentration, Na^+/K^+ ratio, and Na^+/Ca^{2+} ratio, and offsetting saline-alkali stress, which in turn promotes the yield formation of rice in saline-sodic paddy fields.

In this study, the response of the soil physicochemical properties, ion concentration, and yield formation of rice was evaluated in response to peanut shell biochar additions under highly saline-sodic paddy field conditions. The mechanisms through which peanut shell biochar promoted the yield formation of rice were explored by measuring the soil bulk density (BD), total porosity (TP), saturated hydraulic conductivity (K_s), ionic concentrations, and soil saline-alkali parameters in two planting years. The research findings provide new insight into the amelioration of saline-sodic stress in rice and the improvement of health parameters of saline-sodic paddy soil by biochar applications.

EXPERIMENTAL

Setup of Experiment

Experimental site and soil sampling analysis

A 2-year field experiment was conducted in Sheli, Da'an Country, Jilin Province, Northeast China (45°35′N, 123°50′E). This area has a typical dry-cold monsoon climate, with an average annual air temperature of 4.7 °C, average precipitation of approximately 413.7 mm, and average evaporation of approximately 1696.9 mm. The imbalance between precipitation and evaporation is attributed to a high ground water level in these low-lying areas, in combination with an arid or semi-arid climate. The basic physicochemical characteristics of the soil in this experiment were measured before experiment, and the relevant indexes are shown in Table 1. The soil type at this experimental site is Solonchak (IUSS Working Group 2014).

Table 1. Physicochemical Properties of the Soil

Soil Properties (0 to 25 cm Soil Layers)	Value
Sand content (%)	23.13 ± 1.11
Silt content (%)	38.14 ± 1.31
Clay content (%)	37.60 ± 2.09
Bulk density (g cm^{-3})	1.61 ± 0.13
ECe (μs m^{-1})	24.08 ± 0.71
pH	10.10 ± 0.24
SARe (mmolc $L^{-1})^{1/2}$	368.11 ± 4.03
ESP (%)	55.11 ± 2.17
Organic matter (%)	0.64 ± 0.04
Total N (g kg^{-1})	0.27 ± 1.11
Alkali-hydrolysable N (mg kg^{-1})	16.30 ± 1.11
Available P (mg kg^{-1})	9.13 ± 0.68
Available K (mg kg^{-1})	107.25 ± 5.68

Notes: EC_e: electrical conductivity of soil saturation extract, SAR: sodium adsorption ratio of soil saturation extract, ESP: exchangeable sodium percentage, N: nitrogen, P: phosphorus, K: potassium

Experimental design

The field trial was performed from April 2017 to October 2018. The experiment was designed as a randomized complete block with three replications, with a total of 12 plots (each 5 m × 6 m). The peanut shell biochar was applied to the saline-sodic paddy field at the following rates: 0 biochar (B0), 33.75 tons per hectare (B1), 67.50 tons per hectare (B2), and 101.25 tons per hectare, based on 0 g, 15 g, 30 g, and 45 g per kilogram of soil in the 0 to 20 cm plow layer. Biochar was only applied in the spring of 2017. The biochar was uniformly spread on the surface of the saline-sodic paddy soil before rice planting and then thoroughly ploughed into the topsoil (0 to 20 cm) using a wooden rake. Each experimental plot was separated by a 60-cm-wide soil ridge. Individual plots were equipped with an independent inlet and drainage valve.

Field management

The rice variety planted in this field study was japonica rice Changbai 9, one of the elite cultivars used in saline-sodic paddy soil in Northeast China. Rice seeds were sown in a greenhouse on 10 April 2017 and 9 April 2018. On May 20, 2017 and May 19, 2018, the rice seedlings were transplanted to the field plots. The transplanting density (per hill) was 30 cm × 16.5 cm, and each hill contained three seedlings. The rice was harvested on September 30, 2017, and October 1, 2018. In the four biochar treatments, the application rates of chemical (NPK) fertilizer were as follows: 250 kg N per hectare, 75 kg P per hectare, and 100 kg K per hectare. Before transplanting, 300 kg $(NH_4)_2SO_4$ per hectare, 150 kg diammonium phosphate per hectare, and 50 kg K_2SO_4 per hectare were incorporated into the 0 to 20 cm topsoil layer. Ten days after transplanting, urea was added at 150 kg ha^{-1} on the water-soil surface to support tillering. At the rice panicle stage (52 days after transplanting), urea (60 kg per hectare) and K_2SO_4 (50 kg per hectare) were applied. Field management was the same as that used in local production fields to minimize yield loss.

Methods

Biochar characterization

The biochar was produced from peanut shells using a vertical kiln, manufactured by Jinhefu Agricultural Development Company, Liaoning Province, China, and the pyrolysis temperature was 350 to 550 °C for 4 h. The peanut shells were obtained from Jinhefu Agricultural Development Company, AnShan city, Liaoning Province, China. The physiochemical properties of the biochar and peanut shells were measured before experiment, and the relevant indexes are presented in Table 2.

Measurements of soil properties

In each plot, three undisturbed soil cores (100 cm^3) at a depth of 20 cm from the plough layer were randomly collected after the rice harvest to measure the soil BD, TP, and K_s. The bulk density was calculated as the ratio of the oven-dry weight (105 °C) and the core volume. The soil specific gravity was measured by the drainage weighing method, and then the soil TP was calculated. A soil saturated hydraulic instrument (TST-55A, Nanjing Soil Instrument Co., Ltd., Nanjing, China) was used to collect undisturbed soil samples. The K_s values of soil samples from all treatments were determined using the constant water head method (Wang *et al.* 2008), and K_s was calculated by measuring the volumes drained (Q, unit) at the same time intervals (t) using Darcy' law,

$$K_S = \frac{Q \times L}{S \times t \times H} \quad (1)$$

where S (cm^2) is the cross-section of the penetration soil column, L (cm) is the thickness of the soil sample, and H (cm) is the height of the constant water head.

Table 2. Basic Properties of Raw Peanut Shell and Biochar

pH and Elemental Component	Peanut Shell	
	Raw Material	Biochar
pH	5.56 ± 0.11	7.94 ± 0.32
CEC (cmol•kg^{-1})	—	78.69 ± 11.32
EC (dS•m^{-1})	—	7.88 ± 0.59
C (mg•g^{-1})	429.19 ± 13.05	540.64 ± 26.58
N (mg•g^{-1})	10.85 ± 0.61	15.93 ± 1.01
S (mg•g^{-1})	2.58 ± 0.05	6.85 ± 0.34
P (mg•g^{-1})	0.29 ± 0.00	0.74 ± 0.03
Mg (mg•g^{-1})	1.46 ± 0.01	0.25 ± 0.00
K (mg•g^{-1})	5.51 ± 0.21	12.53 ± 0.51
Ca (mg•g^{-1})	6.32 ± 0.43	2.01 ± 0.02
Na (mg•g^{-1})	1.79 ± 0.39	1.17 ± 0.21

Notes: CEC: cation exchange capacity, EC: electrical conductivity, C: carbon, N: nitrogen, S: Sulfur, Mg: magnesium, P: phosphorus K: potassium, Ca: calcium, Na: sodium

After the rice harvest, five soil samples (0 to 20 cm depth) from randomly selected sites in each plot were collected using an auger. All samples were air dried and sieved through a 2-mm mesh. The concentrations of Na^+, Ca^{2+}, and Mg^{2+} were measured using 1:5 soil to water extracts. These extracts were prepared by adding 20 mL of distilled water to 4 g soil in a 100-mL bottle. The bottle was sealed with a stopper, agitated for 15 min on a mechanical shaker (100 rpm), allowed to stand for 1 h, and then agitated again for 5 min. A sample was then obtained by filtration. The concentrations of sodium, magnesium, and calcium were detected by inductively couple-plasma spectroscopy (GBC-906AAS, GBC Scientific Equipment Pty Ltd., Melbourne, Australia). The K^+ concentration was quantified using a flame photometer (M410, Sherwood Scientific Ltd., Cambridge, England). The Na^+/K^+ ratio and Na^+/Ca^{2+} ratio were calculated after the determination of Na^+, K^+, and Ca^{2+}.

The pH was measured in a 1:5 suspension of soil to water using a pH meter (Mettler Toledo International Trade Co., Ltd., Shanghai, China). The electrical conductivity (EC) was measured in a 1:5 extract (EC1:5) of soil to water using a conductivity meter (DDS-307, Shanghai Precision Scientific Instrument Co., Ltd., Shanghai, China), and the EC of a saturated paste extract (ECe) was estimated according to Chi and Wang (2010):

$$\mathrm{ECe} = 10.88\ \mathrm{EC1{:}5} \quad (2)$$

The sodium adsorption ratio (SAR) was determined after measuring the Na+, Ca^{2+}, and Mg^{2+} contents in a 1:5 soil to water extract (USDA 1954). According to the method of Chi and Wang (2010), the SAR of a saturated paste extract (SARe) was measured:

$$\text{SAR1:5} = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})\,/\,2}} \quad (3)$$

$$\text{SARe} = 13.19\ \text{SAR1:5} \quad (4)$$

The soil CEC was determined according to Bower saturation (Richards 1954). Soil extractable cations were determined by rinsing soils for 10 min with 1 M ammonium acetate solution buffered at pH 8.5. Exchangeable cations were determined by the difference between the extractable and soluble cations.

The exchangeable sodium percentage (ESP) was determined according to Eq. 5:

$$\text{ESP (\%)} = \frac{Exhangeable\ Na^{+}}{CEC} \times 100 \quad (5)$$

The HCO_3^- and CO_3^{2-} concentrations were determined *via* sulfuric acid titration following Bao (2000) and Richards (1954). The content of chloride ions (Cl^-) in the soil was determined by silver nitrate ($AgNO_3$) titration, and the content of sulfate ions (SO_4^{2-}) was measured *via* the EDTA complexometric method (Richards 1954; Bao 2000).

Measurements of rice yield properties

At the mature stage (132 days after transplantation), 15 rice plants were randomly harvested in each plot. These plants were oven-dried at 105 °C for 30 min and then at 60 °C to a constant weight. The biomass was recorded. The rice plants were selected from 5 m^2 in each experimental plot, and then the rice grain yield was calculated. The harvest index was calculated as the ratio of the rice grain yield to the biomass yield.

Statistical analysis

The data were analyzed using SPSS 18.0 software (IBM Corp., Armonk, NY, USA) based on the trial design. A two-way analysis of variance (ANOVA) and Tukey tests were applied to evaluate the interactive effects between the biochar treatment and year. One-way ANOVA and Tukey tests were employed to analyze the effect of biochar on the relevant test indicators. The mean value was determined with the least significant difference at the $p < 0.05$ level.

RESULTS AND DISCUSSION

Effect of Biochar on Soil Physical Properties

Year and biochar treatment significantly affected the soil physical properties in the saline-sodic paddy soil (Fig. 1).

The average bulk density (BD) was 4.05% lower in 2018 compared with 2017, while the TP and K_s values increased by 4.42% and 6.33%, respectively. Compared with B0, the BD was reduced by 22.29% in B3, by 15.66% in B2, and by 12.65% in B1 (Fig. 1a). The TP and K_s values were significantly increased by the biochar application (Fig. 1b, c). The TP value of B0 was 17.88, 22.41, and 33.40% lower than that of B1, B2, and B3, respectively. The K_s value was ranked as B3 > B2 > B1 > B0, and obvious differences were detected among all treatments.

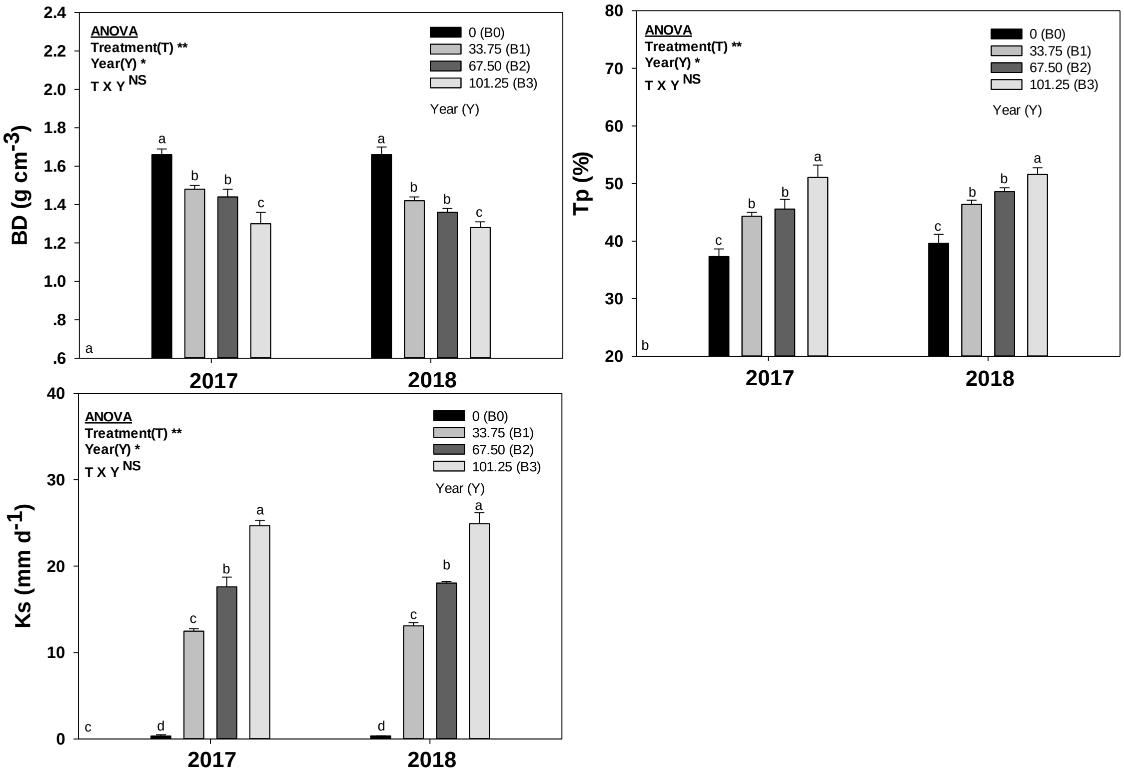

Fig. 1. Main effects of year and biochar treatment on bulk density (BD), total porosity (TP), and saturated hydraulic conductivity (K_s) in saline-sodic paddy soil; Different letters indicate significantly different between biochar application rates ($P < 0.05$); NS, *, and **, Not significant, Significant at $P < 0.05$, and $P < 0.01$ level, respectively

Effects of Biochar on Na^+, K^+, Ca^{2+}, Mg^{2+}, Na^+/K^+ Ratio, and Na^+/Ca^{2+} Ratio

Table 3 shows that the concentrations of Na^+ and K^+ were influenced by year and treatment. The average concentrations of Na^+ and K^+ were 7.51% and 9.07% lower, respectively, in 2018 than in 2017. Compared with B0, there were significant reductions of Na^+ concentrations in B3, B2, and B1, by 30.21%, 25.19%, and 17.73%, respectively, while the K^+ concentrations were 467.58%, 367.19%, and 267.02% higher, respectively. The differences among all treatments reached a significant level. Furthermore, year and biochar treatment exhibited an interactive effect on the Na^+ concentration. The concentrations of Ca^{2+} and Mg^{2+} increased markedly with increasing biochar application rate (Table 3). On average, compared to B0, the treatments of B1, B2, and B3 increased the Ca^{2+} concentration by 43.8% to 84.7% and the Mg^{2+} concentration 17.9% to 42.5%. However, no significant difference was observed between different planting years.

Year and biochar treatment influenced the Na^+/K^+ ratio and Na^+/Ca^{2+} ratio (Table 3). The Na^+/K^+ ratio and Na^+/Ca^{2+} ratio in 2018 was 1.66% and 3.99% lower, respectively, than that in 2017. Compared to B0, the Na^+/K^+ ratio and Na^+/Ca^{2+} ratio decreased by 69.2% and 42.9% under B1, 79.6% and 53.5% under B2, and 85.1% and 62.3% under B3, respectively. In addition, the differences among all biochar treatments reached a significant level, but there was no obvious interactive effect of year and biochar on the Na^+/K^+ ratio and Na^+/Ca^{2+} ratio.

Table 3. Main Effects of Year and Biochar Treatment on Na^+, K^+, Ca^{2+}, Mg^{2+}, Na^+/K^+, and Na^+/Ca^{2+} in Saline-Sodic Paddy Soil

Variable	Na^+ ($mg\bullet kg^{-1}$)	K^+ ($mg\bullet kg^{-1}$)	Ca^{2+} ($mg\bullet kg^{-1}$)	Mg^{2+} ($mg\bullet kg^{-1}$)	Na^+/K^+	Na^+/Ca^{2+}
Year						
2017	5236.21 ± 117.84 a	1890.35 ± 103.29 a	1890.58 ± 143.19 a	210.21 ± 15.17 a	4.23± 0.12 a	3.01 ± 0.18 a
2018	4845.62 ± 235.47 b	1718.81 ± 128.77 b	1815.89 ± 88.7 4 a	200.71 ± 20.35 a	4.16 ± 0.23 b	2.89 ± 0.10 b
Treatment						
0 (B0)	6407.76 ± 374.11 a	629.18 ± 22.23 d	1284.79 ± 243.17 d	170.156 ± 8.92 d	10.19 ± 1.31 a	4.99 ± 0.41 a
33.75 (B1)	5271.57 ± 399.02 b	1680.05 ± 199.77 c	1848.09 ± 109.98 c	200.57 ± 12.19 c	3.14 ± 0.41 b	2.85 ± 0.17 b
67.50 (B2)	4793.48 ± 219.26 c	2310.27 ± 147.58 b	2056.38 ± 99.17 b	227.62 ± 22.23 b	2.08 ± 0.13 c	2.32 ± 0.33 c
101.25 (B3)	4472.08 ± 478.13 d	2941.92 ± 131.14 a	2373.06 ± 133.12 a	242.52 ± 11.17 a	1.52 ± 0.26 d	1.88 ± 0.12 d
ANOVA						
Treat.	**	**	**	**	**	**
Year	**	**	NS	NS	*	*
Treat. × Year	*	NS	NS	NS	NS	NS

Notes: Different letters indicate significant differences between biochar application rates ($P < 0.05$).
NS, *, and **, Not significant, Significant at $P < 0.05$, and $P < 0.01$ level, respectively

Effects of Biochar on HCO_3^-, CO_3^{2-}, Cl^-, and SO_4^{2-}

The concentrations of HCO_3^-, CO_3^{2-}, and SO_4^{2-} were significantly affected by year and biochar treatment, but there was no significant effect on the concentration of Cl^- (Table 4). The concentrations of HCO_3^- and CO_3^{2-} were generally higher in 2017, while the concentration of SO_4^{2-} was significantly lower in 2017. The HCO_3^-, CO_3^{2-}, and SO_4^{2-} concentrations decreased markedly with the addition of biochar. The concentration of HCO_3^- in B1, B2, and B3 was 7.9%, 20.6%, and 31.0% lower, respectively, than that in B0. The CO_3^{2-} concentration of B1 was 30% lower than that of B0, and the corresponding decreases in B2 and B3 were 47.8% and 61.1%, respectively. The corresponding decreases in the SO_4^{2-} concentration were 17.4%, 29.2%, and 32.3%, respectively.

Table 4. Main Effects of Year and Biochar Treatment on HCO_3^-, CO_3^{2-}, Cl^-, and SO_4^{2-} in Saline-sodic Paddy Soil

Variable	HCO_3^- (mg•kg^{-1})	CO_3^{2-} (mg•kg^{-1})	Cl^- (mg•kg^{-1})	SO_4^{2-} (mg•kg^{-1})
Year				
2017	1917.25 ± 107.11 a	106.25 ± 5.81 a	134.94 ± 5.01 a	97.58 ± 4.89 b
2018	1786.79 ± 39.86 b	95.83 ± 9.22 b	129.33 ± 9.17 a	116.16 ± 8.00 a
Treatment				
0 (B0)	2175.67 ± 67.83 a	120.83 ± 13.47 a	136.17 ± 5.33 a	133.11 ± 3.00 a
33.75 (B1)	2002.83 ± 22.79 b	110.83 ± 6.17 b	135.94 ± 4.44 a	109.99 ± 2.08 b
67.50 (B2)	1728.33 ± 69.47 c	97.50 ± 9.01 c	134.29 ± 5.82 a	94.29 ± 1.29 c
101.25 (B3)	1501.25 ± 87.19 d	75.00 ± 12.34 d	131.02 ± 5.19 a	90.09 ± 1.93 c
ANOVA				
Treat.	**	**	NS	**
Year	**	*	NS	**
Treat. x Year	NS	NS	NS	NS

Notes: Different letters indicate significant differences between biochar application rates ($P < 0.05$). NS, *, and **, Not significant, Significant at $P < 0.05$, and $P < 0.01$ level, respectively

Effects of Biochar on Soil Chemical Properties

Year and biochar treatment markedly influenced the soil ECe, CEC, ESP, and SARe, while there was no significant effect on pH (Table 5). The ECe, CEC, ESP, and SARe values were 20.8%, 0.37%, 7.38%, and 20.2% lower, respectively, in 2018 than in 2017. Compared with B0, the soil ECe values of B1, B2, and B3 were 54.2%, 65.2%, and 76.1% lower, respectively.

The biochar application also markedly decreased the soil ESP and SARe values. The soil ESP values of B1, B2, and B3 were 53.6%, 62.3%, and 71.0% lower, respectively, than that of B0. The corresponding decrease in SARe was 51.2%, 58.1%, and 60.5%, respectively. However, the CEC values increased significantly ($P < 0.05$) with increasing biochar application rate. Year and biochar treatment exhibited an obvious interactive effect on the soil ECe value and soil SARe value.

Table 5. Main Effects of Year and Biochar Treatment on pH, ECe, CEC, ESP and SARe in Saline-Sodic Paddy Soil

Variable	pH	EC_e ($ds•m^{-1}$）	CEC ($cmol•kg^{-1}$)	ESP (%)	SARe ($(mmolc•L^{-1})^{1/2}$)
Year					
2017	9.94 ± 0.05 a	13.03 ± 1.06 a	13.44 ± 0.31 a	24.39 ± 0.37 a	213.83 ± 11.22 a
2018	9.95 ± 0.08 a	10.32 ± 0.47 b	13.39 ± 0.43 a	22.59 ± 1.46 b	170.54 ± 14.57 b
Treatment					
0 (B0)	9.89 ± 0.09 a	22.87 ± 1.39 a	11.95 ± 0.33 c	43.77 ± 0.99 a	337.64 ± 11.49 a
33.75 (B1)	9.92 ± 0.04 a	10.48 ± 0.37 b	12.89 ± 0.33 b	20.13 ± 0.68 b	164.62 ± 5.37 b
67.50 (B2)	9.96 ± 0.08 a	7.97 ± 0.34 c	14.01 ± 0.24 b	16.52 ± 1.08 c	141.55 ± 7.96 c
101.25 (B3)	10.01 ± 0.07 a	5.46 ± 0.19 d	14.82 ± 0.60 a	12.68 ± 0.12 d	133.49 ± 8.43 c
ANOVA					
Treat.	NS	**	**	**	**
Year	NS	**	NS	*	**
Treat. × Year	NS	NS	NS	*	*

Notes: Different letters indicate significant differences between biochar application rates ($P < 0.05$).
NS, *, and **, Not significant, Significant at $P < 0.05$, and $P < 0.01$ level, respectively

Effects of Biochar on Rice Yield and Harvest Index

Year and biochar treatment significantly affected the rice yield (Fig. 2). The average biomass and grain yield were 8.7% and 9.7% higher, respectively, in 2018 than in 2017, while there was no significant effect on HI. Compared with B0, the biomass yield (Fig. 2a), grain yield (Fig. 2b), and harvest index (Fig. 2c) increased considerably after the biochar addition in both years, and an obvious difference was observed between B3, B2, and B1 compared with B0, while no marked difference was detected among the biochar treatments. The biomass was ranked as B3 > B2 > B1 > B0; the order of rice grain yield was as follows: B2 > B3 > B1 > B0; and the harvest index was ranked as B2 > B1 > B3 > B0. However, there was no significant interaction between year and treatment on the rice yield.

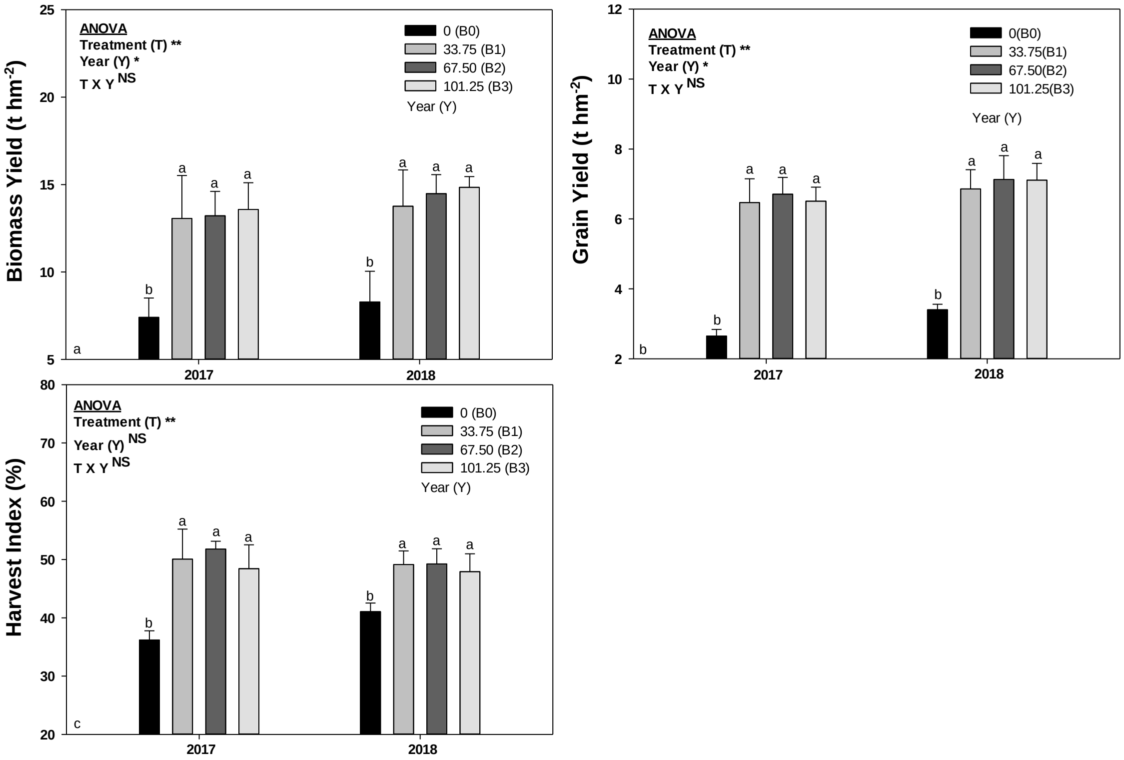

Fig. 2. Main effects of year and biochar treatment on biomass yield, grain yield, and harvest index of rice under saline-sodic paddy field; Different letters indicate significant differences between biochar application rates ($P < 0.05$); NS, *, and **, Not significant, Significant at $P < 0.05$, and $P < 0.01$ level, respectively.

Correlations Among the Rain Yield, Soil Physiochemical Parameters, Na^+/K^+ Ratio, and Na^+/Ca^{2+} Ratio

Correlations among the grain yield, soil physiochemical parameters, $Na^{+/}K^+$ ratio, and Na^+/Ca^{2+} ratio are presented in Table 6. The rice grain yield was positively correlated with the total porosity (TP), saturated hydraulic conductivity (Ks), and CEC ($P < 0.01$), but negatively correlated with the BD, ECe, ESP, SARe, Na^+/K^+ ratio, and Na^+/Ca^{2+} ratio ($P < 0.01$). Moreover, BD was negatively correlated with pH ($p < 0.05$) and CEC ($p < 0.01$), but positively correlated with the ECe, ESP, SARe, Na^+/K^+ ratio, and Na^+/Ca^{2+} ratio ($P < 0.01$). Both TP and Ks were negatively correlated with the EC_e, ESP, SARe, Na^+/K^+ ratio, and Na^+/Ca^{2+} ratio ($P < 0.01$), but positively correlated with CEC ($P < 0.01$).

Table 6. Correlation Among Grain Yield, Soil Physiochemical Parameters, Na^+/K^+, and Na^+/Ca^{2+}

Parameter	Parameter										
	GY	BD	TP	K_s	pH	EC_e	CEC	ESP	SAR_e	Na^+/K^+	Na^+/Ca^{2+}
GY	—										
BD	-0.901**	—									
TP	0.884**	-0.985**	—								
K_s	0.879**	-0.984**	0.972**	—							
pH	0.651	-0.862*	0.850	0.887	—						
EC_e	-0.964**	0.976**	-0.969**	-0.958**	-0.795*	—					
CEC	0.752**	-0.893**	0.890**	0.941**	0.930*	-0.857**	—				
ESP	-0.965**	0.925**	-0.928**	-0.933**	-0.728*	0.969**	-0.841**	—			
SAR_e	-0.985**	0.941**	-0.929**	-0.912**	-0.725*	0.988**	-0.790**	0.955**	—		
Na^+/K^+	-0.980**	0.935**	-0.917**	-0.938**	-0.730*	0.973**	-0.839**	0.986**	0.970**	—	
Na^+/Ca^{2+}	-0.957**	0.971**	-0.961**	-0.976**	-0.812*	0.987**	-0.896**	0.980**	0.967**	0.986**	—

Notes: *, ** Correlation is significant at the $P < 0.05$ and 0.01 level, respectively

Role of Biochar in Improving BD, TP, and K_s of Highly Saline-sodic Paddy Soil

Excessive amounts of Na^+ lead to slaking, swelling, and dispersion in saline-sodic soil and can cause surface crusting and hard setting of soil; thus, saline-sodic soils exhibit poor physical conditions and infiltration problems (Oster *et al.* 1999). A reduction in plant growth in saline-sodic soil decreases the input of soil organic carbon, leading to a poor soil structure (Wong *et al.* 2010). Qadir *et al.* (2007) reported that the elimination of excessive amounts of sodium ions from the soil profile together with a suitable increase in the soil EC value are crucial for ameliorating the physical characteristics of saline-sodic soil.

Biochar has a high specific surface area and low bulk density due to its abundant pore structure (Brown *et al.* 2006). Many prior studies have indicated that the soil bulk density, total porosity, and water-holding capacity were significantly ameliorated in saline soil (Burrell *et al.* 2016; Obia *et al.* 2016; Liu *et al.* 2020), and the amount of biochar applied to the soil affected the improvement (Vaccari *et al.* 2011; Zhang *et al.* 2012). Similarly, biochar addition to the highly saline-sodic paddy field in this study clearly decreased the bulk density over two years, and the significant reduction in the soil bulk density was directly associated with the quantity of biochar added (Fig. 1). Moreover, the biochar application significantly increased the TP and K_s in both years (Fig. 1). The results of this study suggest that a biochar application, especially at a high application rate, can improve the physical properties of soda saline-alkali soil. Similar results were also obtained by Huang *et al.* (2019), who observed that 20 t/hm^2 biochar addition increased the soil TP, K_s, and winter wheat yield under saline water irrigation. The results can be explained from three perspectives. First, biochar, as a high-surface-area, porous, and surface-charged material, can improve the BD, TP, and K_s of salt-affected soil through a dilution effect and the complex interactions that it establishes with soil particles (Obia *et al.* 2016; Blanco-Canqui 2017; Huang *et al.* 2019). In addition, it is well known that Ca^{2+} is conducive to the leaching of sodium ions from the soil profile, promoting the formation of soil aggregates, reducing the ESP and Na^+ content, and thus significantly increasing the calcium content (Table 3); therefore, biochar application can ameliorate the physical characteristics of salt-affected soils (Clark *et al.* 2007). Third, biochar has a positive effect on the structure of salt-affected soils through soil structure-building processes, such as aggregation, thus promoting the activity of microorganisms in the root zone (Fletcher *et al.* 2014; Kolton *et al.* 2016; Jin *et al.* 2018; Li *et al.* 2022).

Role of Biochar in Balancing in the Ion Content and Improving the Chemical Characteristics of Highly Saline-sodic Paddy Soil

For the reclamation of saline-sodic soils, excess Na^+ must be removed from the colloid's cation exchange sites and then filtered out from the root zone (Rengasamy and Olsson 1991). Previous studies have shown that the application of divalent cations, such as Ca^{2+} and Mg^{2+}, are vital to the reclamation of saline-alkali soil to reduce excess exchangeable sodium, and biochar plays a positive role in this aspect (Chaganti and Crohn 2015; Melas *et al.* 2017; Torabian *et al.* 2018). Laird *et al.* (2010) reported that biochar significantly increased Ca^{2+} levels in Clarion soil. Likewise, in salt-affected upland soil, Phuong *et al.* (2020) and Zheng *et al.* (2018) showed that the availability of Ca^{2+} and Mg^{2+} increased after biochar addition. Consistently, a significant increase in Ca^{2+} and Mg^{2+} concentrations and a decrease in the Na^+/Ca^{2+} ratio (Table 3) in highly saline-sodic paddy field were found in all biochar treatments in both years, suggesting that divalent cations, such as Ca^{2+} and Mg^{2+}, can ameliorate the soil physical properties through a significant reduction in the proportion of sodium ions in the soil exchange complex in the process of saline-sodic paddy soil reclamation. A high Na^+ content can restrict K^+ uptake by crops (Cakmak 2005). Wakeel (2013) discovered that maintaining an optimal potassium content in plant cells is beneficial to plant growth and yield in salt-affected stress soils. An increase in the K^+ content in salted-affected soils due to biochar is a crucial mechanism for promoting crop growth in salt-affected soil (Akhtar *et al.* 2015; Ran *et al.* 2020). In this study, a peanut shell biochar application significantly increased the K^+ concentration and decreased the Na^+/K^+ ratio (Table 3). The results of the current study indicated that biochar reduced the Na^+/K^+ ratio by increasing potassium availability, which is an effective means to ameliorate the soil physical structure (Fig. 1) and increase the rice yield (Fig. 2) in highly saline-sodic paddy soils. A similar result was observed by Huang *et al.* (2018) in sweet corn planted in saline-sodic upland soil. In saline-sodic soil of the western Songnen Plain, sodium ions are usually combined with CO_3^{2-} and HCO_3^-; hence Na_2CO_3 and $NaHCO_3$ are deemed to be the major sodic salt components of this soil. A high quantity of CO_3^{2-} and HCO_3^- emerged due to the hydrolysis of inherent Na_2CO_3 and $NaHCO_3$, which could promote sodium saturation in the soil, accompanied by the enhancement of soil pH (Gupta and Abrol 1990). In this field experiment, a significant decrease in CO_3^{2-}, HCO_3^-, and SO_4^{2-} was revealed in both years, and these reductions were directly related to the biochar application rate (Table 4). Recent research showed that $NaHCO_3$ stress is primarily dependent on the specificities of weak acid ions (HCO_3^-), rather than high pH (Chen *et al.* 2021). This may be one of the important ways for peanut shell biochar to decrease saline-sodic stress in saline-sodic paddy fields.

Abrishamkesh *et al.* (2015) and Liu *et al.* (2020) found that the soil pH was significantly increased after biochar addition to salt-affected soils compared with saline soil without biochar. In contrast, many researchers observed a significant reduction in the pH of salt-affected soils in response to biochar application, and the decrease in soil ESP with biochar was one of the reasons for the reduction in the soil pH value (Wu *et al.* 2014; Lashari *et al.* 2015; Kim *et al.* 2016; Sun *et al.* 2017). Unlike the above conclusions, the authors discovered that planting year and peanut shell biochar treatment (pH = 7.94) had no significant effect on pH (Table 5) although the pH of biochar was alkaline. Sun *et al.* (2016) also revealed that the soil pH remained unchanged after peanut shell biochar (pH = 7.7) was added to salt-affected soil (pH = 8.6). The underlying explanation for the unchanged pH in the highly saline-sodic paddy field may be that (I) biochar application can increase T_p and K_s (Fig. 1), which can help leach Na^+ from the soil profile (Table 3) and decrease ESP (Table 5); (II) H^+ is dissociated from the ion exchange complex *via* K^+, Ca^{2+}, and Mg^{2+} (Table 3) through peanut shell biochar (Wang *et al.* 2015); (III) biochar significantly decreased the concentrations of CO_3^{2-} and HCO_3^- (Table 4), which are main factors resulting in the high pH in saline-sodic soil; and (IV) the improvement of soil physical and chemical properties after biochar application promoted the growth of roots and increased the secretion of organic acids in roots (Li *et al.* 2022). In addition, prior studies also showed that the initial pH of biochar may play a marked role in biochar-induced changes in the pH of salt-affected soils (Liu and Zhang 2012). Sun *et al.* (2016) reported that despite a marked decrease in ESP, the soil pH was unchanged after amendment with maize stalk biochar (pH 8.0) and peanut shell biochar (pH 7.7) in salt-affected soil (pH 8.6). The pH value of the peanut shell biochar used in the current research was 7.94 (Table 2). Therefore, the unchanged pH under biochar applied to the highly saline-sodic paddy field was related to the low pH value of this biochar.

Many studies indicated that biochar decreases soil EC through the improved leaching of soluble salts (Liu and Zhang 2012; Lashari *et al.* 2015; Zhao *et al.* 2020). In a recent study, Zhang *et al.* (2020) indicated that biochar significantly decreased soil EC in saline-sodic soil. Similarly, the EC_e of saline-alkali upland soil was reduced 42% in a two-year field trial compared to non-biochar treatment (Lashari *et al.* 2013). Consistent with these findings, the authors observed that peanut shell biochar application significantly decreased the soil EC_e in the highly saline-sodic paddy field over at least two years and decreased with an increasing rate of biochar application. In addition, year and biochar treatment also exhibited an obvious interactive effect (Table 5). The amelioration of soil porosity and hydraulic conductivity (Fig. 1) after the biochar addition accelerated the leaching of salts and could have caused the reduction in EC_e.

The CEC is one of the important properties of soil that impacts the uptake of mineral nutrients, such as Ca^{2+}, Mg^{2+}, K^+, Na^+, and NH_4^+, and soil fertility. Zhang *et al.* (2017a) found that soil CEC significantly increased after biochar application. Likewise, EI-Naggar *et al.* (2018) showed that CEC increased 906% after rice straw biochar was applied to sandy soil. In this study, the soil CEC values of saline-alkali soil increased markedly ($P < 0.05$) with an increased rate of peanut shell biochar applied during both years (Table 5). The underlying mechanism for the CEC increase under a saline-alkali paddy field condition is the presence of strong carboxylic and phenolic functional groups with negative charges on the surface of biochar particles (Tian *et al.* 2017; Palansooriya *et al.* 2019). The authors' results indicated that under saline-alkali paddy field conditions, peanut shell biochar can increase the absorption of K^+, Ca^{2+}, and Mg^{2+} (Table 3), decrease soil ESP (Table 5), retain more nutrients, and reduce nutrient leaching (Yao *et al.* 2021) through increasing the soil CEC value. Similar results were observed by Mehdizadeh *et al.* (2020), who applied biochar (2% of total pot mass) to salt-affected soil, which increased the CEC 8.2% in a pot experiment in a greenhouse.

The ESP is one of the most important indicators for salt-affected soil and needs to be reduced for crop growth. The initial ESP of soil in this study was 24.1% (Table 1), which is known to inhibit rice growth. Many studies have shown the beneficial effect of biochar on decreasing ESP in salt-affected soil (Chaganti and Crohn 2015; Drake *et al.* 2016; Kim *et al.* 2016; Sun *et al.* 2017). However, these studies were mostly conducted in short-term laboratory incubations or greenhouses. Here, biochar applied to saline-alkali paddy soil clearly reduced the ESP over two years (Table 5), especially at higher application levels. A decrease in ESP due to the peanut shell biochar addition may be attributed to the following two aspects. First, biochar may decrease ESP by providing exchangeable Ca^{2+}, K^+, and Mg^{2+} to replace Na^+ on the soil colloids; and second, by decreasing the Na^+/K^+ ratio and Na^+/Ca^{2+} ratio (Table 3) and increasing the CEC (Table 5). Biochar application significantly decreased BD and increased T_p and K_s (Fig. 1), which may facilitate Na^+ leaching from the soil profile, and then reduce ESP (Kim *et al.* 2016).

Because soil SARe depends on the relative proportions of Na^+, Ca^{2+}, and Mg^{2+} in soil solution and the contents of Na^+, Ca^{2+}, and Mg^{2+} may vary with biochar type, the usage level and types of biochar are the two most important factors controlling the impact of biochar on SAR in salt-affected soils (Luo *et al.* 2017; Zheng *et al.* 2018; Mehdizadeh *et al.* 2020). In this two-year field experiment, the SAR_e significantly decreased after peanut shell biochar application and decreased with the biochar application rate (Table 5). The reason for the reduction in SAR_e might be that peanut shell biochar significantly improved the soil physical properties (Fig. 1), increased the utilization of positive ions, such as Ca^{2+}, K^+, and Mg^{2+}, and decreased soil Na^+ from the exchange point of soil colloids (Table 3).

Role of Biochar in Improving the Rice Yield in the Highly Saline-sodic Paddy Field

Crop growth and yield in saline-sodic soils are inhibited due to (i) the presence of toxic of excessive Na^+ (Al-Karaki 1997), (ii) reduced availability of water to crops caused by high osmotic pressure of the soil solution (Naidu and Rengasamy 1993), (iii) restrained absorption of indispensable nutrients (K, Ca, P, *etc.*) caused by a high concentration of Na^+ (Chaganti and Crohn 2015), (iv) limited root growth caused by poor physical characteristics (Sumner 1993), and (v) low levels of soil fertility and soil microbial activity (Wong *et al.* 2010). Laboratory and field studies have shown that biochar applications can modify the soil physicochemical properties (Wong *et al.* 2010; Kim *et al.* 2016; Zhang *et al.* 2020), improve the soil nutrient status (Thomas *et al.* 2013; Yao *et al.* 2021), optimize the morphology and physiological characteristics of roots, and thus increase crop yields (Akhtar *et al.* 2015; Drake *et al.* 2016; Sun *et al.* 2017; Zhao *et al.* 2020). Additionally, some studies have shown that the effect of biochar on crop growth is primarily related to the biochar type, biochar application level, and soil texture (Zhang *et al.* 2017b; Santos *et al.* 2021). In this 2-year field experiment, the grain and biological yield of rice were significantly promoted with biochar under saline-sodic field conditions. The treatment with biochar applied at 67.50 t ha^{-1} had the most positive effect on yield performance in the authors' field experiment (Fig. 2). However, there were no significant differences among 33.75, 67.50, and 101.25 t ha^{-1} biochar in terms of grain yield. The mechanism for the yield increase after the biochar application can be attributed to the following four aspects. First, peanut shell biochar significantly improved BD, TP, and K_s (Fig. 1), which can benefit root growth (Drake *et al.* 2016; Sun *et al.* 2017; Zhao *et al.* 2020; Li *et al.* 2022). In addition, the peanut shell biochar applied to the highly saline-sodic paddy field can reduce saline-sodic stress through significant decreases in EC_e, ESP, SAR_e, CO_3^{2-}, and HCO_3^- (Tables 4 and 5). Furthermore, the authors' prior study showed that peanut shell biochar effectively enhanced the availability of soil total nitrogen, available phosphorus, available potassium, soil organic matter (Yao *et al.* 2021) and soil CEC (Table 5), thus facilitating nutrient absorption and promoting rice growth. Finally, peanut shell biochar decreased the soil Na^+, Na^+/K^+ ratio, and Na^+/Ca^{2+} ratio (Table 3) by transient Na^+ binding due to its high adsorption capacity and by releasing mineral nutrients into the soil solution (Chaganti and Crohn 2015; Huang *et al.* 2019; Mehdizadeh *et al.* 2020). A similar result was also found by Zhao *et al.* (2020), who added corn straw biochar to saline-sodic upland soils, which significantly increased corn yield 50% under the 20 t ha^{-1} biochar application level. Peanut shell biochar greatly increased the harvest index (HI) in the current study (Fig. 2), which led to an increase in the conversion rate of photosynthetic C source to rice grain. This may be another reason for the increase in grain yield after peanut shell biochar was applied to the highly saline-sodic paddy field. The average biomass and grain yield in second rice growing season (in 2018) were higher than that in first rice growing season (in 2017), and there was no significant interaction between year and treatment on the rice yield. This may be due to the long-term effects of biochar on soils (Saifullah *et al.* 2018).

CONCLUSIONS

1. Through a two-year field experiment, it was found that peanut shell biochar had beneficial effects on soil bulk density (BD), total porosity (TP), and saturated hydraulic conductivity (K_s) compared to B0, which greatly benefits root growth.

2. Peanut shell biochar applications significantly reduced the soil Na^+, Na^+/K^+ ratio, Na^+/Ca^{2+} ratio, HCO_3^-, CO_3^{2-}, electrical conductivity of soil saturation extract (EC_e), exchangeable sodium percentage (ESP), and sodium adsorption ratio (SAR_e), and markedly increased the soil cation exchange capacity (CEC), primarily by transient Na^+ binding due to its high adsorption capacity and by releasing mineral nutrients (such as K^+, Ca^{2+}, and Mg^{2+}) into the soil solution.
3. Planting year and peanut shell biochar treatment had no significant effect on pH in the highly saline-sodic paddy field for both years.
4. Peanut shell biochar application significantly increased the rice biomass yield, grain yield, and harvest index, but there was no significant difference among the biochar addition levels (33.75, 67.50, and 101.25 t ha^{-1}). This clearly showed the potential of peanut shell biochar to promote rice productivity in highly saline-sodic paddy soils, and the most economical application level of biochar was 33.75 t ha^{-1}.

ACKNOWLEDGEMENTS

This study was funded by the National Natural Science Foundation of China (No.32071951) and Jilin Province Education Department Planning Project (No. JJKH20200340KJ).

REFERENCES CITED

Abrishamkesh, S., Gorji, M., Asadi, H., Bagheri-Marand, G. H., and Pourbabaee, A. A. (2015). "Effects of rice husk biochar application on the properties of alkaline soil and lentil growth," *Plant Soil Environ.* 11(61), 475-482. DOI: 10.17221/117/2015-PSE

Akhtar, S. S., Andersen, M. N., and Liu, F. (2015). "Residual effects of biochar on improving growth, physiology and yield of wheat under salt stress," *Agric. Water Manag.* 158, 61-68. DOI: 10.1016/j.agwat.2015.04.010

Al-Karaki, G. N. (1997). "Barley response to salt stress at varied levels of phosphorus," *J. Plant Nutr.* 20(11), 1635-1643. DOI: 10.1080/01904169709365362

Bao, S. D. (2000). *Soil Analysis for Agronomy*, 3rd Edition, China Agriculture Press, Beijing, China.

Blanco-Canqui, H. (2017). "Biochar and soil physical properties," *Soil Sci. Soc. Am. J.* 81, 687-711. DOI: 10.2136/sssaj2017.01.0017

Brown, R. A., Kercher, A. K., Nguyen, T. H., Nagle, D. C., and Ball, W. P. (2006). "Production and characterization of synthetic wood chars for use as surrogates for natural sorbents," *Org. Geochem.* 37(3), 321-333. DOI: 10.1016/j.orggeochem.2005.10.008

Burrell, L. D., Zehetner, F., Rampazzo, N., Wimmer, B., and Soja, G. (2016). "Long-term effects of biochar on soil physical properties," *Geoderma* 282, 96-102. DOI: 10.1016/j.geoderma.2016.07.019

Cakmak, I. (2005). "The role of potassium in alleviating detrimental effects of abiotic stresses in plants," *J. Plant Nutr. Soil Sci.* 168, 521-530. DOI: 10.1002/jpln.200420485

Chaganti, V. N., and Crohn, D. M. (2015). "Evaluating the relative contribution of physiochemical and biological factors in ameliorating a saline-sodic soil amended with composts and biochar and leached with reclaimed water," *Geoderma* 259, 45-55. DOI: 10.1016/j.geoderma.2015.05.005

Chen, J. P., Li, X. X., Ye, X. X., Guo, P., Hu, Z. B., Qi, G. N., Cui, F. Q., and Liu, S. K. (2021). "An S-ribonuclease binding protein EBS1 and brassinolide signaling are specifically required for *Arabidopsis* tolerance to bicarbonate," *J. Exp Bot.* 72(4), 1449-1459. DOI: 10.1093/jxb/eraa524

Chi, C. M., and Wang, Z. C. (2010). "Characterizing salt-affected soils of Songnen Plain using saturated paste and 1:5 soil-to-water extraction methods," *Arid Land Research and Management* 24(1), 1-11. DOI: 10.1080/15324980903439362

Chi, C. M., Zhao, C. W., Sun, X. J., and Wang, Z. C. (2012). "Reclamation of saline sodic soil properties and improvement of rice (*Oriza sativa* L.) growth and yield using desulfurized gypsum in the west of Songnen Plain, northeast China," *Geoderma* 187-188, 24-30. DOI: 10.1016/j.geoderma.2012.04.005

Clark, G. J., Dodgshun, N., Sale, P.W., and Tang, C. (2007). "Changes in chemical and biological properties of a sodic clay subsoil with addition of organic amendments," *Soil Biol. Biochem.* 39(11), 2806-2817. DOI: 10.1016/j.soilbio.2007.06.003

Drake, J. A., Cavagnaro, T. R., Cunningham, S. C., Jackson, W. R., and Patti, A. F. (2016). "Does biochar improve establishment of tree seedlings in saline sodic soils?," *Land Degrad. Dev.* 27(1), 52-59. DOI: 10.1002/ldr.2374

Esfandbod, M., Phillips, I. R., Miller, B., Rashti, M. R., Lan, Z. M., Srivastava, P., Singh, B., and Chen, C. R. (2017). "Aged acidic biochar increases nitrogen retention and decreases ammonia volatilization in alkaline bauxite residue sand," *Ecological Engineering* 98, 157-165. DOI: 10.1016/j.ecoleng.2016.10.077

Fletcher, A. J., Smith, M. A., Heinemeyer, A., Lord, R., Ennis, C. J., Hodgson, E. M., and Farrar, K. (2014). "Production factors controlling the physical characteristics of biochar derived from phytoremediation willow for agricultural applications," *Bioenergy Res.* 7, 371-380. DOI: 10.1007/s12155-013-9380-x

Gupta, R. K., and Abrol, I. P. (1990). "Salt-affected soils: Their reclamation and management for crop production," in: *Advances in Soil Science*, R. Lal, and B. A. Stewart (eds.), Springer, New York, NY, USA, pp. 223-288.

Huang, L. H., Liu, Y., Ferreira, J. F. S., Wang, M. M., Na, J., Huang, J. X., and Liang, Z. W. (2022). "Long-term combined effects of tillage and rice cultivation with phosphogypsum or farmyard manure on the concentration of salts, minerals, and heavy metals of saline-sodic paddy fields in Northeast China," *Soil and Tillage Research* 215, article ID 105222. DOI: 10.1016/j.still.2021.105222

Huang, M. Y., Zhang, Z. Y., Zhai, Y. M., Lu, P. R., and Zhu, C. L. (2019). "Effect of straw biochar on soil properties and wheat production under saline water irrigation," *Agronomy* 9, article no. 457. DOI: 10.3390/agronomy9080457

IUSS Working Group WRB (2014). *World Reference Base for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps* [World Soil Resources Reports No. 106], FAO, Rome, Italy.

Jin, F., Ran, C., Anwari, Q., Geng, Y. Q., Guo, L. Y., Li, J. B., Han, D., Zhang, X. Q., Liu, X., and Shao, X. W. (2018). "Effects of biochar on sodium ion accumulation, yield and quality of rice in saline-sodic soil of the west of Songnen plain, northeast China," *Plant, Soil and Environment* 64(12), 612-618. DOI: 10.17221/359/2018-PSE

Kim, H. S., Kim, K. R., Yang, J. E., Ok, Y. S., Owens, G., Nehls, T., Wessolek, G., and Kim, K. H. (2016). "Effect of biochar on reclaimed tidal land soil properties and maize (*Zea mays* L.) response," *Chemosphere* 142, 153-159. DOI: 10.1016/j.chemosphere.2015.06.041

Kolton, M., Graber, E. R., Tsehansky, L., Elad, Y., and Cytryn, E. (2016). "Biochar-stimulated plant performance is strongly linked to microbial diversity and metabolic potential in the rhizosphere," *New Phytol.* 213, 1393-1404. DOI: 10.1111/nph.14253

Laird, D. A., Fleming, P., Davis, D. D., Horton, R., Wang, B., and Karlen, D. L. (2010). "Impact of biochar amendments on the quality of a typical Midwestern agricultural soil," *Geoderma* 158(3-4), 443-449. DOI: 10.1016/j.geoderma.2010.05.013

Lashari, M. S., Liu, Y., Li, L., Pan, W., Fu, J., Pan, G., Zheng, J., Zheng, J., Zhang, X., and Yu, X. (2013). "Effects of amendment of biochar-manure compost in conjunction with pyroligneous solution on soil quality and wheat yield of a salt-stressed cropland from Central China great plain," *Field Crops Res.* 144, 113-118. DOI: 10.1016/j.fcr.2012.11.015

Lashari, M. S., Ye, Y., Ji, H., Li, L., Kibue, G.W., Lu, H., Zheng, J., and Pan, G. (2015). "Biochar–manure compost in conjunction with pyroligneous solution alleviated salt stress and improved leaf bioactivity of maize in a saline soil from central China: A 2-year field experiment," *J. Sci. Food Agric.* 95(6), 1321-1327. DOI: 10.1002/jsfa.6825

Li, X., Yao, T. X., Huang, X. X., Li, X. B., Li, P. Y., Du, S., Wang, W., Miao, S. H., Wang, D., Jin, F., *et al.* (2022). "Biochar increases rice yield by improving root morphological and root physiological functions in heavily saline-sodic paddy soil of northeast China," *BioResources* 17(1), 1421-1456. DOI: 10.15376/biores.17.1.1241-1256

Liu, D. F., Feng, Z. Y., Zhu, H. D., Yu, L. H., Yang, K. J., Yu, S., Zhang, Y. F., and Guo, W. (2020). "Effects of corn straw biochar application on soybean growth and alkaline soil properties," *BioResources* 15(1), 1463-1481. DOI: 10.15376/biores.15.1.1463-1481

Liu, X. H., and Zhang, X. C. (2012). "Effect of biochar on pH of alkaline soils in the loess plateau: Results from incubation experiments," *Int. J. Agric. Biol.* 14(5), 745-750. DOI: 10.1021/jf3034804

Luo, X., Liu, G., Xia, Y., Chen, L., Jiang, Z., Zheng, H., and Wang, Z. (2017). "Use of biochar-compost to improve properties and productivity of the degraded coastal soil in the Yellow River Delta, China," *J. Soils Sediments* 17, 780-789. DOI: 10.1007/s11368-016-1361-1

Mehdizadeh, L., Moghaddam, M., and Lakzian, A. (2020). "Amelioration of soil properties, growth and leaf mineral elements of summer savory under salt stress and biochar application in alkaline soil," *Scientia Horticulturae* 267, article ID 109319. DOI: 10.1016/j.scienta.2020.109319

Mehmood, S., Ahmed, W., Ikram, M., Imtiaz, M., Mahmood, S., Tu, S. X., and Chen, D. Y. (2020). "Chitosan modified biochar increases soybean (*Glycine max* L.) resistance to salt-stress by augmenting root morphology, antioxidant defense mechanisms and the expression of stress-responsive genes," *Plants* 9(9), article no. 1173. DOI: 10.3390/plants9091173

Naidu, R., and Rengasamy, P. (1993). "Ion interactions and constraints to plant nutrition in Australian sodic soils," *Soil Res.* 31, 801-819. DOI: 10.1071/sr9930801

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G., and Børresen, T. (2016). "*In situ* effects of biochar on aggregation, water retention and porosity in light-textured tropical soils," *Soil and Tillage Research* 155, 35-44. DOI: 10.1016/j.still.2015.08.002

Oster, J. D., Shainberg, I., and Abrol, I. P. (1999). "Reclamation of salt affected soils," in: *Agricultural Drainage*, R. W. Skaggs, and J. van Schilfgaarde (Eds.), ASA–CSSA–SSSA, Madison, WI, USA. pp, 659-691.

Palansooriya, K. N., Wong, J. T. F., Hashimoto, Y., Huang, L., Rinklebe, J., Chang, S. X., Bolan, N., Wang, H., and Ok, Y. S. (2019). "Response of microbial communities to biochar-amended soils: A critical review," *Biochar* 1, 3-22. DOI: 10.1007/s42773-019-00009-2

Phuong, N. T. K., Khoi, C. M., Ritz, K., Linh, T. B., Minh, D. D., Duc, T. A., and Toyota, K. (2020). "Influence of rice husk biochar and compost amendments on salt contents and hydraulic properties of soil and rice yield in salt-affected fields," *Agronomy* 10(8), article no. 1101. DOI: 10.3390/agronomy10081101

Ran, C., Gulaqa, A., Zhu, J., Wang, X. W., Zhang, S. Q., Geng, Y. Q., Guo, L. Y., Jin, F., and Shao, X. W. (2020). "Benefits of biochar for improving ion contents, cell membrane permeability, leaf water status and yield of rice under saline–sodic paddy field condition," *J. Plant Growth Regul.* 39, 370-377. DOI: 10.1007/s 00344-019 -09988-9

Rengasamy, P., and Olsson, K. A. (1991). "Sodicity and soil structure," *Soil Res*. 29(6), 935-952. DOI: 10.1071/SR9910935

Richards, L. A. (1954). *Diagnosis and Improvement of Saline and Alkali Soils*, USDA Handbook No. 60, Washington, D.C., USA.

Saifullah, Dahlawi, S., Naeem, A., Rengel, Z., and Naidu, R. (2018). "Biochar application for the remediation of salt-affected soils: challenges and opportunities," *Sci. Total Environ.* 625, 320-335. DOI: 10.1016/j.scitotenv.2017.12.257

Santos, W. M., Gonzaga, M. I. S., Silva, J. A., Almeida, A. Q., Santos, J. C. J., Gonzaga, T. A. S., Lima, I. S., and Araújo, E. M. (2021). "Effectiveness of different biochars in remediating a salt-affected Luvisol in Northeast Brazil," *Biochar* 3(2), 149-159. DOI: 10.1007/s42773-020-00084-w

Srivastava, P. K., Gupta, M., Singh, N., and Tewari, S. K. (2016). "Amelioration of sodic soil for wheat cultivation using bioaugmented organic soil amendment," *Land Degrad. Dev.* 27(4), 1245-1254. DOI: 10.1002/ldr.2292

Sumner, M. E. (1993). "Sodic soils: New perspectives," *Aust. J. Soil Res.* 31(6), 683-750. DOI: 10.1071/sr9930683

Sun, C. X., Chen, X., Cao, M. M., Li, M. Q., and Zhang, Y. L. (2017). "Growth and metabolic responses of maize roots to straw biochar application at different rates," *Plant Soil* 416, 487-502. DOI: 10.1007/s11104-017-3229-6

Sun, J., He, F., Shao, H., Zhang, Z., and Xu, G. (2016). "Effects of biochar application on Suaeda salsa growth and saline soil properties," *Environ Earth Sci.* 75, article no. 630 (2016). DOI: 10.1007/s12665-016-5440-9

Thomas, S. C., Frye, S., Gale, N., Garmon, M., Launchbury, R., Machado, N., Melamed, S., Murray, J., Petrof, A., and Winsborough, C. (2013). "Biochar mitigates negative effects of salt additions on two herbaceous plant species," *J. Environ Manage.* 129, 62-68. DOI: 10.1016/j.jenvman.2013.05.057

Tian, S., Tan, Z., Kasiuliene, A., and Ai, P. (2017). "Transformation mechanism of nutrient elements in the process of biochar preparation for returning biochar to soil," *Chin. J. Chem. Eng.* 25(4), 477-486. DOI: 10.1016/j.cjche.2016.09.009

Vaccari, F. P., Baronti, S., Lugato, E., Genesio, L., Castaldi, S., Fornasier, F., and Miglietta, F. (2011). "Biochar as a strategy to sequester carbon and increase yield in durum wheat," *Eur. J. Agron.* 34(4), 231-238. DOI: 10.1016/j.eja.2011.01.006

Wakeel, A. (2013). "Potassium–sodium interactions in soil and plant under saline-sodic conditions," *J. Plant Nutr. Soil Sci.* 176(3), 344-354. DOI: 10.1002/jpln.201200417

Wang, Z. C., Li, Q. S., Li, X. J., Song, C. C., and Zhang, G. J. (2003). "Sustainable agriculture development in saline alkali soil area of Songnen Plain, northeast China," *Chinese Geographical Science* 13(2), 171-174. DOI: 10.1007/s11769-003-0012-9

Wang, L., Wang, Q., Wei, S., Shao, M. A., and Li, Y. (2008). "Soil desiccation for Loess soils on natural and regrown areas," *For. Ecol. Manage.* 255(7), 2467-2477. DOI: 10.1016/j.foreco.2008.01.006

Wang, S., Gao, B., Li, Y., Mosa, A., Zimmerman, A. R., Ma, L. Q., Harris, W. G., and Migliaccio, K. W. (2015). "Manganese oxide-modified biochars: Preparation, characterization, and sorption of arsenate and lead," *Bioresource Technol.* 181, 13-17. DOI: 10.1016/j.biortech.2015.01.044

Wong, V. N. L., Greene, R. S. B., Dalal, R. C., and Murphy, B. W. (2010). "Soil carbon dynamics in saline and sodic soils: A review," *Soil Use Manage.* 26(1), 2-11. DOI: 10.1111/j.1475-2743.2009.00251.x

Wu, Y., Xu, G., and Shao, H. B. (2014). "Furfural and its biochar improve the general properties of a saline soil," *Solid Earth* 5(2), 665-671. DOI: 10.5194/se-5-665-2014

Yaduvanshi, N. P. S., and Swarup, A. (2005). "Effect of continuous use of sodic irrigation water with and without gypsum, farmyard manure, pressmud and fertilizer on soil properties and yields of rice and wheat in a long-term experiment," *Nutr. Cycl Agroecosyst.* 73(2-3), 111-118. DOI: 10.1007/s10705-005-3361-1

Yao, T. X., Zhang, W. T., Gulaqa, A., Cui, Y. F., Zhou, Y. M., Weng, W. A., Wang, X., and Jin, F. (2021). "Effects of peanut shell biochar on soil nutrients, soil enzyme activity, and rice yield in heavily saline-sodic paddy field," *J. Soil Sci. Plant Nutr.* 21, 655-664. DOI: 10.1007/s42729-020-00390-z

Zhang, A. F., Liu, Y. M., Pan, G. X., Hussain, Q., Li, L. Q., Zheng, J. W., and Zhang, X. H. (2012). "Effect of biochar amendment on maize yield and greenhouse gas emissions from a soil organic carbon poor calcareous loamy soil from Central China Plain," *Plant Soil* 351(1-2), 263-275. DOI: 10.1007/s11104-011-0957-x

Zhang, C., Lin, Y., Tian, X., Xu, Q., Chen, Z., and Lin, W. (2017a). "Tobacco bacterial wilt suppression with biochar soil addition associates to improved soil physiochemical properties and increased rhizosphere bacteria abundance," *Appl. Soil Ecol.* 112, 90-96. DOI: 10.1016/j.apsoil.2016.12.005

Zhang, G., Guo, X., Zhu, Y., Han, Z., He, Q., and Zhang, F. (2017b). "Effect of biochar on the presence of nutrients and ryegrass growth in the soil from an abandoned indigenous coking site: The potential role of biochar in the revegetation of contaminated site," *Sci. Total Environ.* 601-602, 469-477. DOI: 10.1016/j.scitotenv.2017.05.218

Zhang, Y., Yang, J. S., Yao, R. J., Wang, X. P., and Xie, W. P. (2020). "Short-term effects of biochar and gypsum on soil hydraulic properties and sodicity in a saline-alkali soil," *Pedosphere* 30(5), 694-702. DOI: 10.1016/S1002-0160(18)60051-7

Zhao, W., Zhou, Q., Tian, Z. Z., Cui, Y. T., Liang, Y., and Wang, H. Y. (2020). "Apply biochar to ameliorate soda saline-alkali land, improve soil function and increase corn nutrient availability in the Songnen Plain," *Sci. Total Environ.* 722, article ID 137428. DOI: 10.1016/j.scitotenv.2020.137428

Zheng, H., Wang, X., Chen, L., Wang, Z., Xia, Y., Zhang, Y., Wang, H., Luo, X., and Xing, B. (2018). "Enhanced growth of halophyte plants in biochar-amended coastal soil: Roles of nutrient availability and rhizosphere microbial modulation," *Plant Cell Environ.* 41(3), 517-532. DOI: 10.1111/pce.12944

Article submitted: May 6, 2022; Peer review completed: August 21, 2022; Revised version received: August 22, 2022; Accepted: August 23, 2022; Published: September 2, 2022.
DOI: 10.15376/biores.17.4.5936-5957