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Effects of a combination of biochar and cow manure on soil nutrients and cotton yield in salinized fields

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Abstract: Biochar and animal manure application can improve crop yields in salt-affected soil. Previous studies have primarily applied biochar and animal manure either alone or at fixed ratios, while their combined effects with varying combination proportions are still unclear. To address this knowledge gap, we performed a 2-a experiment (2023–2024) in a salinized cotton field in Wensu County of Xinjiang Uygur Autonomous Region of China with the following 6 treatments: control; application of biochar (10 t/hm^2) alone (BC100%); application of cow manure (10 t/hm^2) alone (CM100%); application of 70% biochar (7 t/hm^2) combined with 30% cow manure (3 t/hm^2) (BC70%+CM30%); application of 50% biochar (5 t/hm^2) combined with 50% cow manure (5 t/hm^2) (BC50%+CM50%); and application of 30% biochar (3 t/hm^2) combined with 70% cow manure (7 t/hm^2) (BC30%+CM70%). By measuring soil pH, electrical conductivity, soil organic matter, available phosphorus, available potassium, and available nitrogen at 0–20 and 20–40 cm depths, as well as yield components and cotton yield in 2023 and 2024, this study revealed that soil nutrients in the 0–20 cm depth were more sensitive to the treatment. Among all the treatments, BC50%+CM50% treatment had the highest value of soil pH (9.63±0.07) but the lowest values of electrical conductivity (161.9±31.8 μS/cm), soil organic matter (1.88±0.27 g/kg), and available potassium (42.72±8.25 mg/kg) in 2024. Moreover, the highest cotton yield (5336.63±467.72 kg/hm^2) was also observed under BC50%+CM50% treatment in 2024, which was 1.9 times greater than that under the control treatment. In addition, cotton yield in 2023 was jointly determined by yield components (density and number of cotton bolls) and soil nutrients (available phosphorus and available potassium), but in 2024, cotton yield was only positively related to yield components (density, number of cotton bolls, and single boll weight). Overall, this study highlighted that in salt-affected soil, the combination of biochar and cow manure at a 1:1 ratio is recommended for increasing cotton yield and reducing soil salinity stress.

Keywords: biochar; animal manure; yield components; crop yield; soil nutrients; soil salinity stress; salt-affected soil

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1 Introduction

Cotton is one of the most broadly cultivated crops worldwide because of its high importance for economies (Jans et al., 2021). As the largest cotton-planted country in the world, China produces 1.0×10^7 t of cotton annually (FAO, 2022). In China, more than 80% of the cultivated area and

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more than 90% of the cotton yield are contributed by Xinjiang Uygur Autonomous Region (National Bureau of Statistics, 2023a, b). However, cotton yield in Xinjiang has been subjected to stress from soil salinity, as more than 30% of the farmland is threatened by soil salinization (Luo et al., 2001). With increasing soil salinity stress, cotton is estimated to lose 15%–55% of yield annually (Satir and Berberoglu, 2016). Given that the area of salt-affected soil will increase under further climate change conditions (Eswar et al., 2021), increasing cotton yield in salt-affected soil is vital in terms of maintaining sustainable development of the cotton industry and increasing farmer income.

The adverse effects of soil salinity on cotton yield can be explained by a number of pathways (Cabot et al., 2014; Zhang et al., 2023). For example, cotton is unable to absorb enough water from soil when the salt content exceeds its tolerance threshold, leading to a reduction in growth and development (Munns, 2002; Munns et al., 2006). Moreover, high soil salinity decreases the bioavailability of nitrogen, phosphorus and potassium, which are three important and essential elements for cotton growth and yield formation, via ion competition and reduction of enzyme activity (Fageria et al., 2011). In addition, soil salinity stress also has negative effects on cotton yield components, such as reducing density by lowering the germination rate (Sharif et al., 2019). Density, in turn, affects boll weight and the number of total bolls via changes in photosynthate allocation (Zhang et al., 2004; Wang et al., 2011).

In salt-affected soil, the application of biochar and animal manure can increase soil nutrients and crop yields via multiple mechanisms (Biederman and Harpole, 2013; Liu et al., 2023; Su et al., 2024). First, biochar is a carbon-rich product associated with labile organic compounds (Schmidt et al., 2021), whereas manure contains a high content of macronutrients (Garbowski et al., 2023). The combined application of biochar and animal manure can increase soil fertility by increasing the nutrient supply (Hu et al., 2024). Second, biochar and animal manure decrease soil bulk density and increase soil porosity (Liu et al., 2023; Su et al., 2024). The high level of soil porosity in turn facilitates salt leaching and decreases salt stress (Zong et al., 2023). Finally, the dark color of biochar alters the thermal dynamics of soil, leading to a positive effect on seed germination (Genesio et al., 2012), suggesting that the application of biochar could increase crop density. In salt-affected soil, the application of biochar and animal manure can increase yield for many crops, such as wheat (Fouladidorhani et al., 2020), maize (Lashari et al., 2014) and soybean (Zhang et al., 2020). However, it is still unclear whether the application of biochar and animal manure improves cotton yield, especially in salt-affected soil. In addition, biochar and animal manure in previous studies were applied either alone or in a mixed ratio (Ali et al., 2017; Lebrun et al., 2024), and their combined effects with varying combination proportions on soil nutrients and cotton yield are also unknown.

To address these knowledge gaps, this study conducted a 2-a experiment in a salinized cotton field. The biochar and animal manure used in this study were applied alone and in combination with different proportions. By surveying soil salt and nutrients at depths of 0–20 and 20–40 cm as well as yield components in 2023 and 2024, this study aimed to explore three scientific questions. First, how do soil salt and nutrients change when biochar and animal manure are applied alone and mixed in different proportions? Second, are biochar and animal manure applied in different combination proportions superior to those applied alone in terms of cotton yield? Third, among the soil salt, nutrients, and yield components of cotton, which factors are most sensitive to cotton yield? These questions involve soil–crop interactions in salt-affected soil, and the findings of this study can provide scientific guidance for improving crop yield in salinized field.

2 Materials and methods

2.1 Study area

This study was performed in a cotton field (41°09′59″N, 80°40′43″E; 1056.3 m a.s.l.) in Wensu County, Xinjiang Uygur Autonomous Region, China, in 2023 and 2024. The study area is characterized by warm temperate continental and arid climate, with abundant solar and thermal resources but low precipitation. The average annual temperature is 13.3°C and the average annual precipitation is 139.0 mm (Li et al., 2021). The soil in the study area suffers from a series of limiting factors. First, the soil is characterized by high salt stress, as the total salinity contents at 0–20 and 20–40 cm depths are both above 6.00 g/kg (Table 1). Second, the soil organic matter, available phosphorus, available potassium, and available nitrogen contents at the study site are below the average values reported for farmland in Xinjiang Uygur Autonomous Region (Jiang et al., 2004; Ma et al., 2022). Third, there was a compacted clay layer at the depth of 50–70 cm because the soil was reclaimed by adding sands to salinized tidal flat soil in 2020 by local farmers.

Table 1 Background values of the soil properties

Soil depth (cm)	Soil pH	EC (μS/cm)	SOM (g/kg)	AP (mg/kg)	AK (mg/kg)	AN (mg/kg)	BD (g/cm^3)	Soil salinity (g/kg)
0–20	8.60	3451.0	3.42	7.96	70.36	22.21	1.67	6.01
20–40	8.70	2992.0	4.28	4.89	45.00	13.16	1.65	6.90

Note: EC, electrical conductivity; SOM, soil organic matter; AP, available phosphorus; AK, available potassium; AN, available nitrogen; BD, bulk density.

2.2 Experimental design

Cow manure and biochar can be applied in the fields to increase soil fertility and alleviate soil salinity stress and nutrient limitations (Lashari et al., 2014; Gao et al., 2019). The following 6 treatments were applied in this study: control; application of biochar (10 t/hm^2) alone (BC100%); application of cow manure (10 t/hm^2) alone (CM100%); application of 70% biochar (7 t/hm^2) combined with 30% cow manure (3 t/hm^2) (BC70%+CM30%); application of 50% biochar (5 t/hm^2) combined with 50% cow manure (5 t/hm^2) (BC50%+CM50%); and application of 30% biochar (3 t/hm^2) combined with 70% cow manure (7 t/hm^2) (BC30%+CM70%). In this study, cow manure and biochar were surface-applied and then incorporated into the soil at 35 cm depth by tillage at the end of April, which was prior to sowing. Each treatment was replicated 4 times, and a total of 24 experimental plots were included. Each plot measured 11.0 m×9.0 m (99.00 m^2). In this study, biochar was obtained from Xinjiang Henhuijunyang Biotechnology Company in Korla City of Xinjiang Uygur Autonomous Region. The pH and organic matter, total nitrogen, total phosphorus and total potassium contents of biochar were 8.20, 700.00 g/kg, 8.15 g/kg, 0.60 g/kg, and 13.00 g/kg, respectively. Cow manure was composted and provided by local farmers. The contents of organic matter, total nitrogen, total phosphorus and total potassium in cow manure were 446.03, 26.04, 2.41, and 1.63 g/kg, respectively.

To address the low soil permeability caused by the compacted clay layer at 50–70 cm depth, we evenly collected 5 soil cores (5 cm in diameter) per plot to extract 0–80 cm soil, thereby breaking the compacted layer and increasing soil permeability. The other management and fertilization methods used were consistent with those applied by local farmers. The cotton variety used was 'Xinluzhong 54'. The planting mode consisted of a single plastic film covering 3 drip irrigation tubes and 6 planting rows, with a planting density of 225,000 individuals/hm^2. The irrigation water used was slightly saline water, with a salinity of 3.5 g/L. The total irrigation amount was 4570 m^3/hm^2 during the cotton growing season.

2.3 Soil sampling and analysis

Soil samples from 0–20 and 20–40 cm depths were collected at the end of September, when the cotton reached the boll opening period, via soil augers with the diameter of 5 cm (Li et al., 2024b). To avoid the effects of soil heterogeneity on nutrient availability, we randomly collected 5 subsamples from each soil layer in each plot, after which these subsamples were mixed into a composite sample. A total of 48 composited samples were included in this study (6 treatments×4 replications/treatment×2 soil layers/replication). The composited soil samples were used to measure soil nutrients after they were air-dried naturally and sieved through a 2-mm mesh in October. In this study, soil pH and electrical conductivity were measured in a 1:5 soil-water suspension using a pH meter and a conductivity meter. Soil organic matter content was determined via the potassium dichromate oxidation method with external heating, available phosphorus was measured by molybdenum-antimony anti-colorimetric method, available potassium was determined by the flame photometer method and available nitrogen was measured by the alkaline hydrolysis diffusion method (Bao, 2000).

2.4 Measurement of cotton yield

At the end of September, when the cotton reached the boll opening period, the cotton yield was measured via the following procedures. First, a 6.70 m^2 subplot was designated within each plot as the yield measurement area. To minimize edge effects, we positioned the subplot at least 2.0 m inland from the plot boundaries. Cotton density was subsequently measured in each subplot, and 10 individuals were randomly selected to measure the boll number of each individual as well as the single boll weight (Wang et al., 2011; Li et al., 2024b). A total of 240 individuals were selected to measure cotton yield. The cotton yield was calculated by multiplying the density, boll number of each individual and single boll weight (Wang et al., 2011; Li et al., 2024b).

2.5 Statistical analysis

A two-way analysis of variance (ANOVA) was used to test the main and interaction effects of year and treatment on the soil nutrient contents in each soil layer as well as the yield components. When significant main or interaction effects were detected ($P<0.050$), the Fisher's least significant difference (LSD) method was further applied to conduct multiple comparisons (Tian et al., 2018). Spearman correlation analysis was used to explore the relationships between soil nutrients and cotton yield. Given that each treatment in this study had 4 replications, Spearman correlation analysis was not performed for each treatment because of the limited sample size. Thus, during the Spearman correlation analysis, soil nutrients and cotton yield from all the treatments were pooled together and separately analyzed by year. On the basis of the results of the Spearman correlation analysis, we further used a random forest model to distinguish the relative importance of soil nutrients to cotton yield. All analyses were performed in R software (v.4.2.1) (R Development Core Team, 2012). Specifically, two-way ANOVA and LSD method were conducted with the "agricolae" package in R v.1.3-5.0, whereas Spearman correlation analysis and the random forest model were performed with the "linkET" package in R v.0.0-7.4 and the "randomForest" package in R v.4.7-1.1, respectively.

3 Results

3.1 Effects of biochar combined with cow manure on soil pH and electrical conductivity

At 0–20 cm depth, year had significant but contrasting effects on soil pH and electrical conductivity ($P<0.010$). Compared with the treatments in 2023, the BC70%+CM30% and BC50%+CM50% treatments in 2024 increased soil pH but decreased electrical conductivity (Table 2). In addition, soil pH was significantly affected by the interaction effects of year and treatment ($P<0.050$). For example, all the treatments had no significant effects on soil pH in 2023 ($P>0.050$) but significantly increased soil pH in 2024 ($P<0.050$). In general, the highest value of soil pH (9.63±0.07) and the lowest value of electrical conductivity (161.9±31.8 µS/cm) were both detected under BC50%+CM50% treatment in 2024 (Table 2).

At the depth of 20–40 cm, soil pH and electrical conductivity were only strongly affected by year ($P<0.050$; Table 2). On average, soil pH increased from 9.07 (±0.20) in 2023 to 9.39 (±0.24) in 2024, whereas electrical conductivity decreased from 560.2 (±280.1) µS/cm in 2023 to 319.4 (±159.7) µS/cm in 2024.

Table 2 Effects of biochar combined with cow manure on soil pH and electrical conductivity (EC)

Soil depth (cm)	Treatment	Soil pH		EC (μS/cm)	
		2023	2024	2023	2024
0–20	CK	8.98±0.17^{de}	8.73±0.22^{e}	689.7±76.5^{abcd}	775.0±228.6^{abc}
	BC100%	9.08±0.13^{bcde}	9.39±0.13^{abcd}	611.6±135.5^{bcd}	221.5±52.7^{cd}
	CM100%	8.96±0.17^{de}	9.50±0.10^{ab}	730.0±276.1^{abcd}	260.2±21.5^{bcd}
	BC70%+CM30%	8.70±0.26^{e}	9.39±0.08^{abcd}	1247.1±450.3^{a}	605.3±241.4^{bcd}
	BC50%+CM50%	8.88±0.22^{e}	9.63±0.07^{a}	835.0±248.4^{ab}	161.9±31.8^{d}
	BC30%+CM70%	9.00±0.05^{cde}	9.45±0.15^{abc}	482.9±21.8^{bcd}	344.8±86.6^{bcd}
20–40	CK	9.07±0.17^{bc}	8.97±0.28^{c}	616.6±141.0^{ab}	729.8±186.4^{ab}
	BC100%	9.26±0.13^{abc}	9.44±0.31^{abc}	417.1±92.1^{ab}	349.6±217.8^{b}
	CM100%	9.14±0.19^{abc}	9.63±0.07^{ab}	794.6±438.1^{ab}	250.6±39.6^{b}
	BC70%+CM30%	8.09±0.25^{c}	9.22±0.34^{abc}	1064.1±442.5^{a}	422.5±183.2^{ab}
	BC50%+CM50%	8.81±0.31^{c}	9.35±0.19^{abc}	753.2±285.9^{ab}	445.9±114.8^{ab}
	BC30%+CM70%	9.24±0.07^{abc}	9.72±0.04^{a}	443.3±72.0^{ab}	162.4±29.9^{b}

Note: CK, BC100%, CM100%, BC70%+CM30%, BC50%+CM50%, and BC30%+CM70% represent the control, application of biochar (10 t/hm^2) alone, application of cow manure (10 t/hm^2) alone, application of 70% biochar (7 t/hm^2) combined with 30% cow manure (3 t/hm^2), application of 50% biochar (5 t/hm^2) combined with 50% cow manure (5 t/hm^2) and application of 30% biochar (3 t/hm^2) combined with 70% cow manure (7 t/hm^2), respectively. Mean±SE. Different lowercase letters indicate significant differences in soil pH and EC among treatments and between years at $P<0.050$ level.

3.2 Effects of biochar combined with cow manure on soil nutrients

Biochar combined with cow manure had different effects on soil organic matter, available nitrogen, available phosphorus, and available potassium (Fig. 1). At 0–20 cm depth, soil organic matter and available potassium were strongly affected by treatment ($P<0.050$). Among all the treatments, the CM100% treatment had the greatest soil organic matter (5.50±1.14 g/kg) in 2024 (Fig. 1a) and the highest available potassium (67.48±5.18 mg/kg) in 2023 (Fig. 1d). Moreover, the lowest values of soil organic matter (1.88±0.27 g/kg) and available potassium (42.72±8.25 mg/kg) were detected under BC50%+CM50% treatment in 2024. Available nitrogen was only significantly affected by year ($P<0.001$). Compared with 2023, all the treatments significantly decreased available nitrogen, except for CM100% and BC30%+CM70% treatments (Fig. 1b). All the treatments had no significant effect on available phosphorus in 2023, whereas available phosphorus increased 96% under CM100% treatment in 2024 compared with the control treatment (Fig. 1c).

At the depth of 20–40 cm, soil organic matter and available nitrogen were significantly affected by treatment ($P<0.010$) and year ($P<0.010$), respectively. The highest values of soil organic matter and available nitrogen were found under BC70%+CM30% treatments in 2024 and 2023, respectively, which were 2.1 and 1.1 times greater than those under the control treatment (Fig. 1e and f). In addition, treatment and year had no significant effects on available phosphorus and available potassium ($P>0.050$; Fig. 1g and h).

3.3 Effects of biochar combined with cow manure on yield components and cotton yield

The number of cotton bolls, single boll weight, density and cotton yield were strongly affected by year ($P<0.001$). Compared with those in 2023, all the treatments in 2024 significantly decreased the number of cotton bolls, with the exception of BC70%+CM30% treatment, but increased the single boll weight, density and cotton yield, with the exceptions of control and BC70%+CM30% treatments (Fig. 2). Moreover, the number of cotton bolls, single boll weight and cotton yield were also significantly affected by treatment ($P<0.050$). The highest cotton yield (5336.63±467.72 kg/hm^2) was observed under BC50%+CM50% treatment in 2024, which was 1.9 times greater than that under the control treatment (Fig. 2d). In addition, BC50%+CM50% treatment also significantly increased the cotton yield, number of cotton bolls and single boll weight in 2023 (Fig. 2).

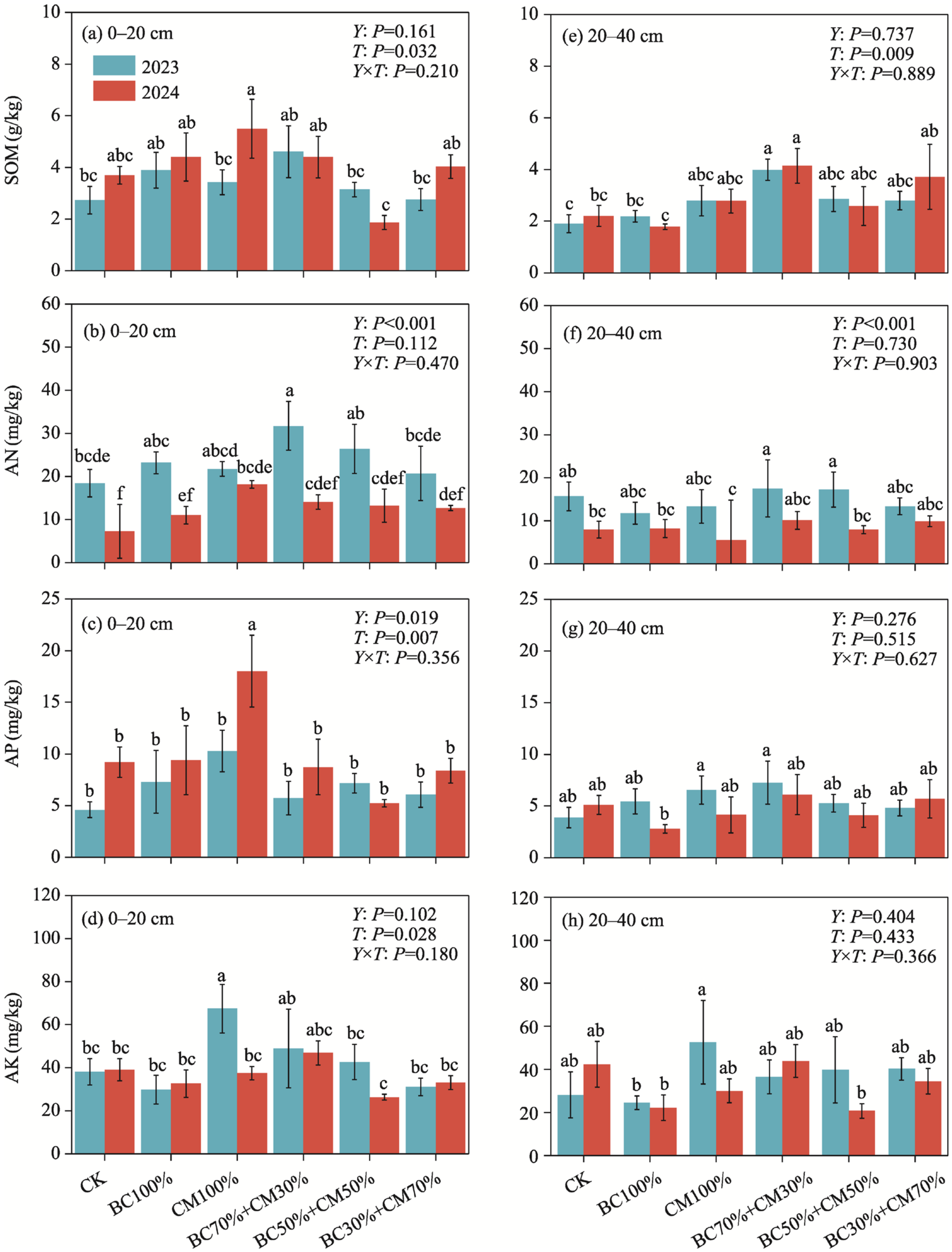

Fig. 1 Variations in soil nutrients in response to biochar combined with cow manure in 0–20 cm (a–d) and 20–40 cm (e–h) soil depths in 2023 and 2024. SOM, soil organic matter; AN, available nitrogen; AP, available phosphorus; AK, available potassium. *Y*, *T*, and *Y*×*T* represent the main effects of year, treatment, and their interaction effects, respectively. CK, BC100%, CM100%, BC70%+CM30%, BC50%+CM50%, and BC30%+CM70% represent the control, application of biochar (10 t/hm^2) alone, application of cow manure (10 t/hm^2) alone, application of 70% biochar (7 t/hm^2) combined with 30% cow manure (3 t/hm^2), application of 50% biochar (5 t/hm^2) combined with 50% cow manure (5 t/hm^2), and application of 30% biochar (3 t/hm^2) combined with 70% cow manure (7 t/hm^2), respectively. Bars are standard errors. Different lowercase letters represent significant differences in soil nutrients among treatments and between years at $P<0.050$ level.

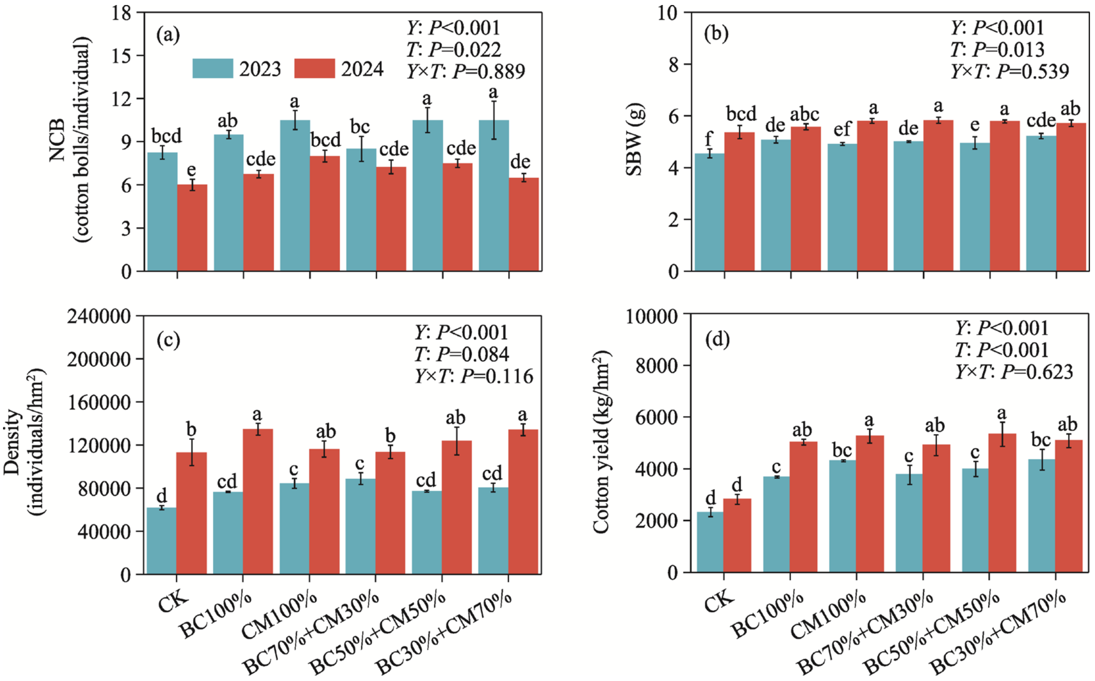

Fig. 2 Variations in yield components and cotton yield under different treatments of biochar combined with cow manure in 2023 and 2024. (a), number of cotton bolls (NCB); (b), single boll weight (SBW); (c), density; (d), cotton yield. Bars are standard errors. Different lowercase letters represent significant differences in yield components and cotton yield among treatments and between years at $P<0.050$ level.

3.4 Relationships of cotton yield with soil nutrients and yield components

The results from the Spearman correlation analysis revealed that cotton yield was affected by different factors in 2023 and 2024 (Fig. 3). For example, cotton yield in 2023 was positively associated with yield components (density and number of cotton bolls) and available soil nutrients (available phosphorus and available potassium) at 0–20 and 20–40 cm depths (Fig. 3a and b). However, cotton yield in 2024 was positively related to only yield components (density, number of cotton bolls and single boll weight) (Fig. 3c and d). These findings demonstrate that cotton yield in 2023 was controlled by both yield components and soil nutrients, whereas in 2024, it was affected only by yield components.

The results from the random forest model further revealed that, among the yield components, the number of cotton bolls was the most important factor in regulating cotton yield both in 2023 and 2024, as it produced the largest increase in the mean square error when its true value was used instead of random data (Fig. 4). Among the soil nutrients, available phosphorus at 0–20 cm depth was more important than available potassium at 0–20 and 20–40 cm depths in terms of modifying cotton yield in 2023 (Fig. 4a).

4 Discussion

4.1 Contrasting variations of soil pH and electrical conductivity

Previous studies have proposed that biochar application can increase or have no significant effect on soil pH, depending on the soil texture, soil salinization level, or application amount (Su et al., 2024; Wang et al., 2024), while animal manure decreases soil pH, as humic acids in animal manure can buffer alkaline substances (Liu et al., 2023). This study revealed that BC70%+CM30% and BC50%+CM50% treatments significantly increased soil pH at 0–20 cm depth in 2024 (Table 2), which is in agreement with previous studies conducted in pots and fields (Liu

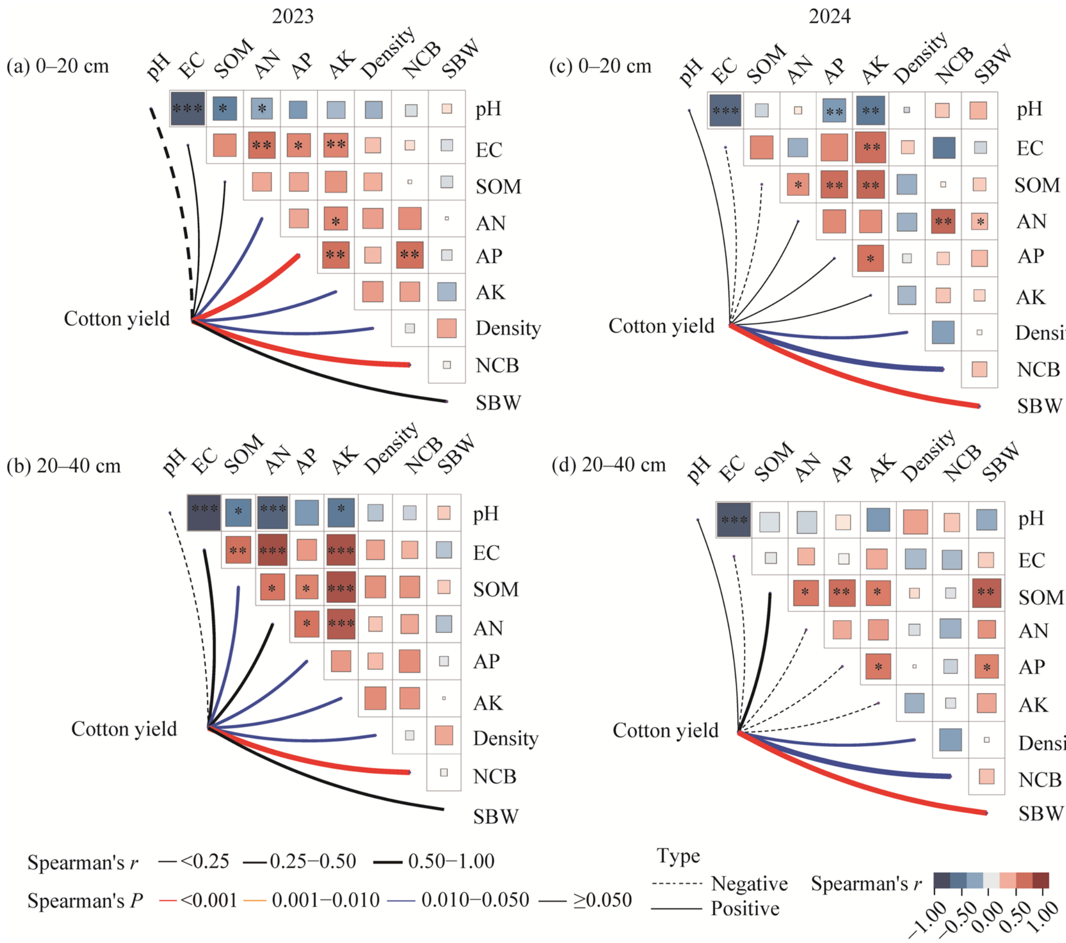

Fig. 3 Spearman correlations of cotton yield with soil pH, electrical conductivity (EC), SOM, AN, AP, AK, density, NCB, and SBW at 0–20 and 20–40 cm soil depths in 2023 (a and b) and 2024 (c and d). The sizes of squares represent absolute values of Spearman correlations among these variables, whereas the blue and red colors in the squares represent negative and positive correlations, respectively. *, **, and *** in the squares indicate that the Spearman correlations are significant at $P<0.050$, $P<0.010$, and $P<0.001$ levels, respectively.

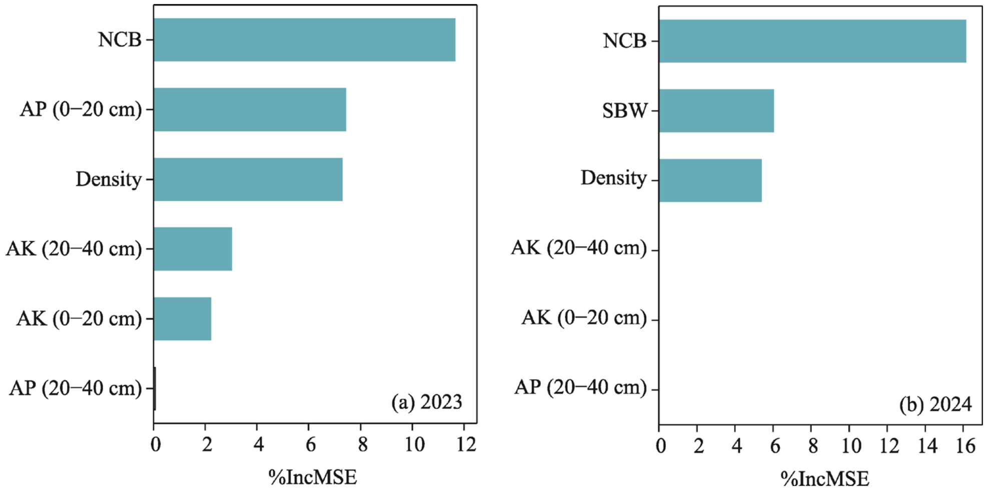

Fig. 4 Relative importances of NCB, density, SBW, AP, and AK at 0–20 and 20–40 cm depths in regulating cotton yield in 2023 (a) and 2024 (b). %IncMSE represents the increase in the mean square error and indicates the importance of an explained variable when its true value is replaced by random data.

et al., 2022; Iqbal et al., 2024). The highest soil pH under BC50%+CM50% treatment (Table 2) can be explained by the following two reasons. First, the irrigation water used in this study was saltwater with a salinity of 3.5 g/L, which can increase the soil pH by increasing the accumulation of salt ions in the soil (Baath et al., 2020). Second, both biochar and cow manure contain large amounts of salt ions such as Ca^{2+} and Mg^{2+}, which in turn lead to a relatively high soil pH level (Chan et al., 2008; Lashari et al., 2014). High soil pH promotes the combination of OH^{-} and cations to form insoluble substances and then decreases electrical conductivity (Sparks et al., 2024), which is also in line with our findings, as BC50%+CM50% treatment had the highest soil pH but the lowest electrical conductivity (Table 2).

4.2 Diversified responses of soil nutrients

Many studies have suggested that biochar and animal manure applications increase soil nutrient availability in saline soils (Liu et al., 2020; Schmidt et al., 2021; Li et al., 2024a). The 2-a experiment in this study revealed that at 0–20 cm soil depth, the greatest values of soil organic matter, available phosphorus, and available potassium were observed under CM100% treatment in 2023 and 2024 (Fig. 1a, c, and d), which is in agreement with previous studies (Shakoor et al., 2021; Lebrun et al., 2024). The increased soil organic matter, available phosphorus, and available potassium under CM100% treatment partly contributed to the nutrients contained in cow manure (Liu et al., 2020). In addition, the application of cow manure can lower the soil bulk density and increase the soil porosity (Eden et al., 2017), which in turn increases nutrient inputs in the soil by promoting microbiome activity and root growth (Liu et al., 2017). Unlike early research conducted by Meki et al. (2022), this study demonstrated that BC50%+CM50% treatment lowered soil organic matter and available potassium contents at 0–20 cm soil depth in 2024 (Fig. 1a and d). The decrease in soil organic matter and available potassium may have resulted from cotton acquisition, as BC50%+CM50% treatment had the highest cotton yield in 2024 (Fig. 2d). A recent meta-analysis proposed that in arid areas, the addition of animal manure has no significant effect on nitrogen availability due to limitations in soil enzyme activity (Liu et al., 2022). This phenomenon was also observed in this study, as all the treatments had no apparent effect on available nitrogen in either 2023 or 2024 (Fig. 1c).

In this study, BC70%+CM30% treatment also increased soil organic matter and available nitrogen contents at 20–40 cm depth in 2024 (Fig. 2e and f). This could be explained by the fact that biochar can increase the stability of soil organic matter due to its highly porous structure and sorption capacity (Weng et al., 2017; Bai et al., 2019). The increased soil organic matter in turn has a positive effect on soil inorganic nitrogen via the adsorption of ammonium nitrogen and changes in soil biochemical properties (Gao et al., 2019; Luo et al., 2020), which was also confirmed in this study (Fig. 2f). In contrast with soil organic matter and available nitrogen, available phosphorus and available potassium at 20–40 cm depth did not significantly vary among all the treatments each year (Fig. 2g and h), as available potassium is easily dissolved and leached due to its low adsorption affinity (Farrar et al., 2021), whereas phosphorus dynamics are limited in alkaline soil owing to its low initial content (Khadem et al., 2021).

4.3 Variations of yield components and cotton yield

Cotton yield is simultaneously affected by the number of cotton bolls, single boll weight, and density (Coyle and Smith, 1997). The number of cotton bolls and single boll weight, in turn, are constrained by density (Bednarz et al., 2000). In this study, the yield components varied conversely in 2023 and 2024, as all the treatments in 2024 decreased the number of cotton bolls but increased the single boll weight and density relative to those in 2023 (Fig. 2a–c). In 2023, the lower density was caused by greater electrical conductivity (Table 2) because high salinity stress can reduce the density by lowering the germination rate (Sharif et al., 2019). Under lower-density conditions, a greater number of cotton bolls appears due to an increase in the number of mainstem nodes and monopodial branches (Bednarz et al., 2000). In 2024, the higher density can be explained by the lower electrical conductivity (Table 2). Under high-density conditions, a relatively high single boll weight compensates for a relatively low number of cotton bolls (Bednarz et al., 2000).

It has been widely demonstrated that biochar and animal manure application can increase crop yields (Lashari et al., 2014; Palansooriya et al., 2019). This study also revealed that BC50%+CM50% treatment had the highest cotton yield in 2024 (Fig. 2d), suggesting that in salt-affected soil, biochar and cow manure combined at a 1:1 ratio has the greatest potential to increase cotton yield. The increased yield under BC50%+CM50% treatment can be partly explained by the alleviation of soil salinity stress because the application of biochar can increase soil porosity and decrease bulk density, which in turn promotes salt leaching (Wu et al., 2023). In addition, the application of cow manure increases soil fertility and promotes cotton growth (Wei et al., 2022).

4.4 Contributions of soil nutrients to cotton yield

Previous studies have demonstrated that moderate density can increase cotton yield and single boll weight (Wang et al., 2011; Zhou et al., 2017) because the photosynthetic product of the cotton canopy is positively related to planting density (Zhang et al., 2004). This phenomenon was also observed in this study, as cotton yield was positively associated with the density and number of cotton bolls both in 2023 and in 2024 (Fig. 3a and b). It is widely proposed that cotton yield linearly increases with available phosphorus when its content is below the agricultural threshold (Li et al., 2024b). In addition, cotton yield is constrained by available potassium because cotton has a high demand for potassium (Lv et al., 2024). These findings were also confirmed in this study, as cotton yield was positively associated with available phosphorus and available potassium at 0–20 and 20–40 cm depths in 2023 (Fig. 3a and b), indicating that in salt-affected soil, cotton yield is concurrently constrained by yield components and soil nutrients.

5 Conclusions

This study clearly revealed that in salt-affected soil, the combination of biochar and cow manure had significant effects on soil nutrient availability and cotton yield. Among all the treatments and between the years, BC50%+CM50% treatment had the greatest effect on modifying soil nutrient availability and increasing cotton yield in 2024. Compared with 2023, BC50%+CM50% treatment in 2024 significantly increased soil pH and cotton yield but decreased electrical conductivity, soil organic matter, and available potassium. The short-term field experiments indicated that in salt-affected soil, biochar and cow manure combined at a 1:1 ratio was the best combination in terms of improving cotton yield. A long-term experiment is still needed to explore whether the positive effect of BC50%+CM50% treatment on cotton yield is time-dependent.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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