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

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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/hm2) alone (BC100%); application of cow manure (10 t/hm2) alone (CM100%); application of 70% biochar (7 t/hm2) combined with 30% cow manure (3 t/hm2) (BC70%+CM30%); application of 50% biochar (5 t/hm2) combined with 50% cow manure (5 t/hm2) (BC50%+CM50%); and application of 30% biochar (3 t/hm2) combined with 70% cow manure (7 t/hm2) (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$\pm$0.07) $butthelowestvaluesofelectricalconductivity(161.9\pm31.8\mu S/cm), soilorganicmatter(1.88\pm0.27g/k$ kg/hm2) 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.

Full Text

Preamble

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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 remain unclear. To address this knowledge gap, we performed a two-year experiment (2023-2024) in a salinized cotton field in Wensu County, Xinjiang Uygur Autonomous Region, China, with six treatments: control; biochar application alone (10 t/hm^2, BC100%); cow manure application alone (10 t/hm^2, CM100%); 70% biochar (7 t/hm^2) combined with 30% cow manure (3 t/hm^2, BC70%+CM30%); 50% biochar (5 t/hm^2) combined with 50% cow manure (5 t/hm^2, BC50%+CM50%); and 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 treatment effects. Among all treatments, BC50%+CM50% produced the highest soil pH (9.63$±0.07)butthelowestvaluesofelectricalconductivity(161.9±31.8μS/cm),soilorganicmatter(1.88±0.27g/k was also observed under BC50%+CM50% treatment in 2024, which was 1.9 times greater than that under the control. 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 highlights 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 due to its economic importance [?]. As the largest cotton-producing country globally, China produces 1.0×10^{7} t of cotton annually [?]. In China, more than 80% of the cultivated area and over 90% of cotton yield are contributed by Xinjiang Uygur Autonomous Region [?, ?]. However, cotton yield in Xinjiang is subjected to soil salinity stress, as more than 30% of farmland is threatened by soil salinization [?]. With increasing soil salinity stress, cotton is estimated to lose 15%–55% of yield annually [?]. Given that the area of salt-affected soil will increase under future climate change conditions [?], increasing cotton yield in salt-affected soil is vital for maintaining sustainable development of the cotton industry and increasing farmer income.

The adverse effects of soil salinity on cotton yield can be explained through multiple pathways [?, ?]. For example, cotton cannot absorb sufficient water from soil when salt content exceeds its tolerance threshold, leading to reduced growth and development [?, ?]. Moreover, high soil salinity decreases the bioavailability of nitrogen, phosphorus, and potassium—three essential elements for cotton growth and yield formation—via ion competition and reduced enzyme activity [?]. In addition, soil salinity stress negatively affects cotton yield components, such as reducing density by lowering germination rate [?]. Density, in turn, affects boll weight and total boll number through changes in photosynthate allocation [?, ?].

In salt-affected soil, biochar and animal manure application can increase soil nutrients and crop yields via multiple mechanisms [?, ?, ?]. First, biochar is a carbon-rich product associated with labile organic compounds [?], whereas manure contains high macronutrient content [?]. The combined application of biochar and animal manure can increase soil fertility by enhancing nutrient supply [?]. Second, biochar and animal manure decrease soil bulk density and increase soil porosity [?, ?]. High soil porosity facilitates salt leaching and reduces salt stress [?]. Finally, the dark color of biochar alters soil thermal dynamics, positively affecting seed germination [?], suggesting that biochar application could increase crop density. In salt-affected soil, biochar and animal manure application can increase yield for many crops, such as wheat [?], maize [?], and soybean [?]. However, it remains unclear whether biochar and animal manure application improves cotton yield, especially in salt-affected soil. Furthermore, previous studies applied biochar and animal manure either alone or at fixed mixed ratios [?, ?], and their combined effects with varying combination proportions on soil nutrients and cotton yield remain unknown.

To address these knowledge gaps, this study conducted a two-year experiment in a salinized cotton field. Biochar and animal manure were applied alone and in combination at different proportions. By surveying soil salt and nutrients at 0-20 and 20-40 cm depths, 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 soil salt, nutrients, and cotton yield components, which factors are most sensitive to cotton yield? These questions involve soil-crop interactions in salt-affected soil, and the findings can provide scientific guidance for improving crop yield in salinized fields.

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 a warm temperate continental arid climate, with abundant solar and thermal resources but low precipitation. The average annual temperature is 13.3°C and average annual precipitation is 139.0 mm [?]. The soil in the study area suffers from several limiting factors. First, the soil experiences high salt stress, as total salinity contents at 0-20 and 20-40 cm depths are both above 6.00 g/kg (Table 1). Second, soil organic matter, available phosphorus, available potassium, and available nitrogen contents at the study site are below average values reported for farmland in Xinjiang Uygur Autonomous Region [?, ?]. Third, a compacted clay layer existed at 50-70 cm depth because the soil was reclaimed by adding sand to salinized tidal flat soil in 2020 by local farmers.

Table 1 Background values of soil properties

Soil depth	EC (S/cm)	Soil salinity (g/kg)	SOM (g/kg)	AP (mg/kg)	AK (mg/kg)	AN (mg/kg)	BD (g/cm^3)

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 to fields to increase soil fertility and alleviate soil salinity stress and nutrient limitations [?, ?]. Six treatments were applied in this study: control; biochar application alone (10 t/hm^2, BC100%);

cow manure application alone (10 t/hm^2, CM100%); 70% biochar (7 t/hm^2) combined with 30% cow manure (3 t/hm^2, BC70%+CM30%); 50% biochar (5 t/hm^2) combined with 50% cow manure (5 t/hm^2, BC50%+CM50%); and 30% biochar (3 t/hm^2) combined with 70% cow manure (7 t/hm^2, BC30%+CM70%). Cow manure and biochar were surface-applied and incorporated into the soil to 35 cm depth by tillage at the end of April, prior to sowing. Each treatment was replicated four times, with 24 experimental plots total. Each plot measured 11.0 m $\times$ 9.0 m (99.00 m^2).

Biochar was obtained from Xinjiang Henhuijunyang Biotechnology Company in Korla City, Xinjiang Uygur Autonomous Region. The biochar had pH 8.20, organic matter 700.00 g/kg, total nitrogen 8.15 g/kg, total phosphorus 0.60 g/kg, and total potassium 13.00 g/kg. Cow manure was composted and provided by local farmers, with organic matter 446.03 g/kg, total nitrogen 26.04 g/kg, total phosphorus 2.41 g/kg, and total potassium 1.63 g/kg.

To address low soil permeability caused by the compacted clay layer at 50–70 cm depth, we evenly collected five soil cores (5 cm diameter) per plot to extract 0–80 cm soil, thereby breaking the compacted layer and increasing soil permeability. Other management and fertilization practices were consistent with local farmer methods. The cotton variety was ‘Xinluzhong 54’. The planting system consisted of a single plastic film covering three drip irrigation tubes and six planting rows, with a planting density of 225,000 individuals/hm^2. Irrigation water was slightly saline (3.5 g/L salinity), with total irrigation amount of 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 cotton reached the boll opening period, using soil augers 5 cm in diameter [?]. To avoid effects of soil heterogeneity on nutrient availability, we randomly collected five subsamples from each soil layer in each plot, which were mixed into a composite sample. A total of 48 composite samples were included (6 treatments $\times$ 4 replications $\times$ 2 soil layers). Composite samples were air-dried naturally and sieved through a 2-mm mesh in October before analysis. Soil pH and electrical conductivity were measured in a 1:5 soil-water suspension using a pH meter and conductivity meter. Soil organic matter was determined via potassium dichromate oxidation with external heating. Available phosphorus was measured by molybdenum-antimony anti-colorimetric method, available potassium by flame photometry, and available nitrogen by alkaline hydrolysis diffusion method [?].

2.4 Measurement of Cotton Yield

At the end of September when cotton reached the boll opening period, cotton yield was measured as follows. First, a 6.70 m^2 subplot was designated within each plot as the yield measurement area. To minimize edge effects, the subplot was positioned at least 2.0 m from plot boundaries. Cotton density was measured in each subplot, and 10 individuals were randomly selected to measure boll number per individual and single boll weight [?, ?]. A total of 240 individuals were selected for cotton yield measurement. Cotton yield was calculated by multiplying density, boll number per individual, and single boll weight [?, ?].

2.5 Statistical Analysis

Two-way analysis of variance (ANOVA) tested main and interaction effects of year and treatment on soil nutrient contents in each soil layer and yield components. When significant main or interaction effects were detected ($P<0.050$), Fisher' s least significant difference (LSD) method was applied for multiple comparisons [?]. Spearman correlation analysis explored relationships between soil nutrients and cotton yield. Because each treatment had only four replications, Spearman correlation analysis was not performed separately for each treatment due to limited sample size. Instead, soil nutrients and cotton yield from all treatments were pooled and analyzed separately by year. Based on Spearman correlation results, a random forest model distinguished the relative importance of soil nutrients to cotton yield. All analyses were performed in R software (v.4.2.1) [?]. Two-way ANOVA and LSD were conducted with the "agricolae" package (v.1.3-5.0), while Spearman correlation and random forest models were performed with the "linkET" package (v.0.0-7.4) and "randomForest" package (v.4.7-1.1), respectively.

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 2023 treatments, BC70%+CM30% and BC50%+CM50% treatments in 2024 increased soil pH but decreased electrical conductivity (Table 2). Soil pH was significantly affected by year × treatment interaction ($P<0.050$). All treatments had no significant effects on soil pH in 2023 ($P>0.050$) but significantly increased soil pH in 2024 ($P<0.050$). Generally, the highest soil pH (9.63$±0.07)*andlowestelectricalconductivity*(161.9±$31.8 S/cm) were both detected under BC50%+CM50% treatment in 2024 (Table 2).

At 20–40 cm depth, soil pH and electrical conductivity were strongly affected only 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, *whileelectricalconductivitydecreasedfrom*560.2(±280.1)*μS/cmin*2023*to*
S/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 (S/cm)				
0–20	CK	8.98$±0.17de	689.7±76.5abcd			BC100±0.13bcde	611.6±135.5bc

Note: CK, BC100%, CM100%, BC70%+CM30%, BC50%+CM50%, and BC30%+CM70% represent control, biochar (10 t/hm^2) alone, cow manure (10 t/hm^2) alone, 70% biochar (7 t/hm^2) + 30% cow manure (3 t/hm^2), 50% biochar (5 t/hm^2) + 50% cow manure (5 t/hm^2), and 30% biochar (3 t/hm^2) + 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.

3.2 Effects of Biochar Combined with Cow Manure on Soil Nutrients

Biochar combined with cow manure had differential effects on soil organic matter, available nitrogen, available phosphorus, and available potassium (Fig. 1 [Figure 1: see original paper]). At 0–20 cm depth, soil organic matter and available potassium were strongly affected by treatment (P<0.050). Among all treatments, CM100% produced the greatest soil organic matter (5.50$±1.14g/kg)in2024(Fig.1a)andhighestavailablepotassium(67.48±5.18mg/kg)in2023(Fig.1d).Thelowestv 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 treatments significantly decreased available nitrogen except CM100% and BC30%+CM70% (Fig. 1b). No treatments significantly affected available phosphorus in 2023, whereas available phosphorus increased 96% under CM100% treatment in 2024 compared with control (Fig. 1c).

At 20–40 cm depth, 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% treatment in 2024 and 2023, respectively, which were 2.1 and 1.1 times greater than those under control (Fig. 1e and f). 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 2023, all treatments in 2024 significantly decreased the number of cotton bolls (except BC70%+CM30%) but increased single boll weight, density, and cotton yield (except control and BC70%+CM30% treatments) (Fig. 2 [Figure 2: see original paper]). 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$\pm$467.72kg/hm^{2}) was observed under BC50%+CM50% treatment in 2024, which was 1.9 times greater than control (Fig. 2d). Additionally, BC50%+CM50% treatment significantly increased cotton yield, number of cotton bolls, and single boll weight in 2023 (Fig. 2).

3.4 Relationships of Cotton Yield with Soil Nutrients and Yield Components

Spearman correlation analysis revealed that cotton yield was affected by different factors in 2023 and 2024 (Fig. 3 [Figure 3: see original paper]). In 2023, cotton yield was positively associated with yield components (density and number of cotton bolls) and available soil nutrients (available phosphorus and available potassium) at both 0-20 and 20-40 cm depths (Fig. 3a and b). However, cotton yield in 2024 was positively related only to 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 random forest model further revealed that among yield components, the number of cotton bolls was the most important factor regulating cotton yield in both 2023 and 2024, as it produced the largest increase in mean square error when its true value was used instead of random data (Fig. 4 [Figure 4: see original paper]). Among soil nutrients, available phosphorus at 0–20 cm depth was more important than available potassium at 0–20 and 20–40 cm depths for modifying cotton yield in 2023 (Fig. 4a).

4.1 Contrasting Variations of Soil pH and Electrical Conductivity

Previous studies propose that biochar application can increase or have no significant effect on soil pH depending on soil texture, salinization level, or application amount [**?**, **?**], while animal manure decreases soil pH because humic acids in animal manure can buffer alkaline substances [**?**]. This study revealed that BC70%+CM30% and BC50%+CM50% treatments significantly increased soil pH at 0–20 cm depth in 2024 (Table 2), consistent with previous pot and field studies [**?**, **?**]. The highest soil pH under BC50%+CM50% treatment (Table 2) can be explained by two reasons. First, irrigation water used in this study was saline water (3.5 g/L), which can increase soil pH by promoting salt ion accumulation [**?**]. Second, both biochar and cow manure contain large amounts of salt ions such as Ca^{2+} and Mg^{2+}, which lead to relatively high soil pH [**?**, **?**]. High soil pH promotes combination of OH^{-} and cations to form insoluble substances, thereby decreasing electrical conductivity [**?**], which aligns with our findings that BC50%+CM50% treatment had the highest soil pH but lowest electrical conductivity (Table 2).

4.2 Diversified Responses of Soil Nutrients

Many studies suggest that biochar and animal manure applications increase soil nutrient availability in saline soils [?, ?, ?]. This two-year experiment revealed that at 0-20 cm 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), consistent with previous studies [?, ?]. Increased soil organic matter, available phosphorus, and available potassium under CM100% treatment partly resulted from nutrients contained in cow manure [?]. Additionally, cow manure application can lower soil bulk density and increase soil porosity [?], which increases nutrient inputs by promoting microbiome activity and root growth [?]. Unlike earlier research by Meki et al. [?], this study demonstrated that BC50%+CM50% treatment lowered soil organic matter and available potassium contents at 0–20 cm depth in 2024 (Fig. 1a and d). The decrease in soil organic matter and available potassium may have resulted from cotton uptake, as BC50%+CM50% treatment produced the highest cotton yield in 2024 (Fig. 2d). A recent meta-analysis proposed that in arid areas, animal manure addition has no significant effect on nitrogen availability due to limitations in soil enzyme activity [?]. This phenomenon was also observed in our study, as all 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 can be explained by biochar' s ability to increase soil organic matter stability due to its highly porous structure and sorption capacity [?, ?]. Increased soil organic matter positively affects soil inorganic nitrogen via ammonium adsorption and changes in soil biochemical properties [?, ?], which was confirmed in this study (Fig. 2f). In contrast to soil organic matter and available nitrogen, available phosphorus and available potassium at 20–40 cm depth did not significantly vary among treatments each year (Fig. 2g and h), as available potassium is easily dissolved and leached due to low adsorption affinity [?], whereas phosphorus dynamics are limited in alkaline soil owing to low initial content [?].

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 [?]. The number of cotton bolls and single boll weight are constrained by density [?]. In this study, yield components varied conversely between 2023 and 2024, as all treatments in 2024 decreased the number of cotton bolls but increased single boll weight and density relative to 2023 (Fig. 2a–c). In 2023, lower density resulted from greater electrical conductivity (Table 2) because high salinity stress can reduce density by lowering germination rate [?]. Under lower-density conditions, a greater number of cotton bolls appears due to increased mainstem nodes and monopodial branches [?]. In 2024, higher density can be explained by lower electrical conductivity (Table 2). Under high-density conditions, relatively high single boll weight compensates for relatively low boll number [?].

It has been widely demonstrated that biochar and animal manure application can increase crop yields [?, ?]. This study also revealed that BC50%+CM50% treatment produced 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 alleviation of soil salinity stress, as biochar application can increase soil porosity and decrease bulk density, thereby promoting salt leaching [?]. Additionally, cow manure application increases soil fertility and promotes cotton growth [?].

4.4 Contributions of Soil Nutrients to Cotton Yield

Previous studies demonstrate that moderate density can increase cotton yield and single boll weight [?, ?] because cotton canopy photosynthetic production is positively related to planting density [?]. This phenomenon was also observed in our study, as cotton yield was positively associated with density and number of cotton bolls in both 2023 and 2024 (Fig. 3a and b). It is widely proposed that cotton yield increases linearly with available phosphorus when content is below the agricultural threshold [?]. Additionally, cotton yield is constrained by available potassium because cotton has high potassium demand [?]. These findings were confirmed in our 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 significantly affected soil nutrient availability and cotton yield. Among all treatments and between 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. These short-term field experiments indicated that in salt-affected soil, biochar and cow manure combined at a 1:1 ratio was the optimal combination for improving cotton yield. Long-term experiments are still needed to explore whether the positive effect of BC50%+CM50% treatment on cotton yield is time-dependent.

Conflict of Interest: The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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References

[?] Ali S, Rizwan M, Qayyum M F, et al. 2017. Biochar soil amendment on alleviation of drought and salt stress in plants: A critical review. *Environmental Science and Pollution Research*, 24(14): 12700–12712.

[?] Baath G S, Shukla M K, Bosland P W, et al. 2020. Water use and yield responses of Chile pepper cultivars irrigated with brackish groundwater and reverse osmosis concentrate. *Horticulturae*, 6(2): 27, doi: 10.3390/horticulturae6020027.

[?] Bai X X, Huang Y W, Ren W, et al. 2019. Responses of soil carbon sequestration to climate-smart agriculture practices: A meta-analysis. *Global Change Biology*, 25(8): 2591–2606.

[?] Bao S D. 2000. *Soil Agrochemical Analysis*. Beijing: China Agriculture Press, 40–120. (in Chinese)

[?] Bednarz C W, Bridges D C, Brown S M. 2000. Analysis of cotton yield stability across population densities. *Agronomy Journal*, 92(1): 128–135.

[?] Biederman L A, Harpole W S. 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. *Global Change Biology Bioenergy*, 5(2): 202–214.

[?] Cabot C, Sibole J V, Barceló J, et al. 2014. Lessons from crop plants struggling with salinity. *Plant Science*, 226(S1): 2–13.

[?] Chan K Y, Zwietn L V, Meszaros I, et al. 2008. Using poultry litter biochars as soil amendments. *Soil Research*, 46(5): 437–444.

[?] Coyle G G, Smith C W. 1997. Combining ability for within-boll yield components in cotton, *Gossypium hirsutum* L. *Crop Science*, 37(4): 1118–1122.

[?] Eden M, Gerke H H, Houot S. 2017. Organic waste recycling in agriculture and related effects on soil water retention and plant available water: A review. *Agronomy for Sustainable Development*, 37(2): 11, doi: 10.1007/s13593-017-0419-9.

[?] Eswar D, Karuppusamy R, Chellamuthu S. 2021. Drivers of soil salinity and their correlation with climate change. *Current Opinion in Environmental Sustainability*, 50(S1): 310–318.

[?] Fageria N K, Gheyi H R, Moreira A. 2011. Nutrient bioavailability in salt affected soils. *Journal of Plant Nutrition*, 34(7): 945–962.

[?] FAO (Food and Agriculture Organization of the United Nations). 2022. Top 10 countries production of cotton seed. [2025-02-13]. http://www.fao.org.

[?] Farrar M B, Wallace H M, Cheng Y X, et al. 2021. Biochar co-applied with organic amendments increased soil-plant potassium and root biomass but not crop yield. *Journal of Soils and Sediments*, 21(2): 784–798.

[?] Fouladidorhani M, Shayannejad M, Shariatmadari H, et al. 2020. Biochar, manure, and super absorbent increased wheat yields and salt redistribution in a saline-sodic soil. *Agronomy Journal*, 112(6): 5193–5205.

[?] Gao S, DeLuca T H, Cleveland C C. 2019. Biochar additions alter phosphorus and nitrogen availability in agricultural ecosystems: A meta-analysis. *Science of the Total Environment*, 654: 463–472.

[?] Garbowski T, Bar-Michalczyk D, Charazinska S, et al. 2023. An overview of natural soil amendments in agriculture. *Soil and Tillage Research*, 225: 105462, doi: 10.1016/j.still.2022.105462.

[?] Genesio L, Miglietta F, Lugato E, et al. 2012. Surface albedo following biochar application in durum wheat. *Environmental Research Letters*, 7(1): 014025, doi: 10.1088/1748-9326/7/1/014025.

[?] Hu W, Zhang Y P, Rong X M, et al. 2024. Biochar and organic fertilizer applications enhance soil functional microbial abundance and agroecosystem multifunctionality. *Biochar*, 6(1): 3, doi: 10.1007/s42773-023-00296-w.

[?] Iqbal B, Khan I, Anwar S, et al. 2024. Biochar and saline soil: Mitigation strategy by incapacitating the ecological threats to agricultural land. *International Journal of Phytoremediation*, 26(8): 1269–1279.

[?] Jans Y, Bloh W V, Schaphoff S, et al. 2021. Global cotton production under climate change–Implications for yield and water consumption. *Hydrology and Earth System Sciences*, 25(4): 2027–2044.

[?] Jiang Y J, Zheng D M, Lu S Q, et al. 2004. Composition features and content of organic matter in cropped soil of Xinjiang. *Soils*, 36(1): 43–45, 60. (in Chinese)

[?] Khadem A, Raiesi F, Besharati H, et al. 2021. The effects of biochar on soil nutrients status, microbial activity and carbon sequestration potential in two calcareous soils. *Biochar*, 3(1): 105–116.

[?] Lashari M S, Ye Y X, Ji H S, et al. 2014. 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. *Journal of the Science of Food and Agriculture*, 95(6): 1321–1327.

[?] Lebrun M, Zahid Z, Bednik M, et al. 2024. Combined biochar and manure addition to an agricultural soil benefits fertility, microbial activity, and mitigates manure-induced CO_2 emissions. *Soil Use and Management*, 40(1): e12997, doi: 10.1111/sum.12997.

[?] Li H B, Liu Y T, Wang W G, et al. 2021. Assessing the impact of meteorological factors on streamflow in Aksu River. *Journal of Irrigation and Drainage*, 40(1): 115–122. (in Chinese)

[?] Li Y J, Zhao W L, Zhu H J, et al. 2024a. Green manure mediated improvement in saline soils in China: A meta-analysis. *Agronomy*, 14(9): 2068, doi: 10.1007/s42773-023-00296-w.

[?] Li Z T, Hu J, Chen Y Q, et al. 2024b. Agronomic threshold of soil available phosphorus and the appropriate rate of phosphate fertilizer for drip-irrigated cotton fields in Xinjiang based on a 5-year field experiment. *Journal of Plant Nutrition and Fertilizers*, 30(11): 2063–2071. (in Chinese)

[?] Liu S B, Razavi B S, Su X, et al. 2017. Spatio-temporal patterns of enzyme activities after manure application reflect mechanisms of niche differentiation between plants and microorganisms. *Soil Biology and Biochemistry*, 112: 100–109.

[?] Liu S B, Wang J Y, Pu S Y, et al. 2020. Impact of manure on soil biochemical properties: A global synthesis. *Science of the Total Environment*, 745: 141003, doi: 10.1016/j.scitotenv.2020.141003.

[?] Liu M, Linna C, Ma S M, et al. 2022. Biochar combined with organic and inorganic fertilizers promoted the rapeseed nutrient uptake and improved the purple soil quality. *Frontiers in Nutrition*, 9: 997151, doi: 10.3389/fnut.2022.997151.

[?] Liu G H, Mai W X, Tian C Y. 2023. Effects of organic fertilizer application on the improvement of saline soils: A meta-analysis. *Journal of Agricultural Resources and Environment*, 40(1): 86–96. (in Chinese)

[?] Luo T B, Ren W, Xie C H. 2001. Necessity and feasibility of biotic improving the saline and alkaline land in Xinjiang. *Arid Zone Research*, 18(1): 46–48. (in Chinese)

[?] Luo C Y, Yang J J, Chen W, et al. 2020. Effect of biochar on soil properties on the Loess Plateau: Results from field experiments. *Geoderma*, 369: 114323, doi: 10.1016/j.geoderma.2020.114323.

[?] Lv Z W, Sun H R, Zhang J P, et al. 2024. Study on soil available potassium rich-lack index and recommended potassium application rate of cotton soil in three cotton planting regions of China. *Soil and Fertilizer Sciences in China*, 30(4): 119–127. (in Chinese)

[?] Ma W D, Chen Y H, Wang F, et al. 2022. Study on the supply of nitrogen, phosphorus and potassium nutrients of arable land in Xinjiang. *Xinjiang Agricultural Sciences*, 59(6): 1401–1408. (in Chinese)

[?] Meki K, Liu Q, Wu S, et al. 2022. Plant- and microbe-assisted biochar amendment technology for petroleum hydrocarbon remediation in saline-sodic soils: A review. *Pedosphere*, 32(1): 211–221.

[?] Munns R. 2002. Comparative physiology of salt and water stress. *Plant, Cell and Environment*, 25(2): 239–250.

[?] Munns R, James R A, Lauchli A. 2006. Approaches to increasing the salt tolerance of wheat and other cereals. *Journal of Experimental Botany*, 57(5): 1025–1043.

[?] National Bureau of Statistics. 2023a. Cotton sowing area. [2025-02-13]. https://www.stats.gov.cn/. (in Chinese)

[?] National Bureau of Statistics. 2023b. Cotton yield per unit area. [2025-02-13]. https://www.stats.gov.cn/. (in Chinese)

[?] Palansooriya K N, Ok Y S, Awad Y M, et al. 2019. Impacts of biochar application on upland agriculture: A review. *Journal of Environmental Management*, 234: 52–64.

[?] R Development Core Team. 2012. R: A language and environment for statistical computing. [2025-02-17]. https://www.r-project.org.

[?] Satir O, Berberoglu S. 2016. Crop yield prediction under soil salinity using satellite derived vegetation indices. *Field Crops Research*, 192: 134–143.

[?] Schmidt H P, Kammann C, Hagemann N, et al. 2021. Biochar in agriculture–A systematic review of 26 global meta-analyses. *Global Change Biology Bioenergy*, 13(11): 1708–1730.

[?] Shakoor A, Shakoor S, Rehman A, et al. 2021. Effect of animal manure, crop type, climate zone, and soil attributes on greenhouse gas emissions from agricultural soils—A global meta-analysis. *Journal of Cleaner Production*, 278: 124019, doi: 10.1016/j.jclepro.2020.124019.

[?] Sharif I, Aleem S, Farooq J, et al. 2019. Salinity stress in cotton: Effects, mechanism of tolerance and its management strategies. *Physiology and Molecular Biology of Plants*, 25(4): 807–820.

[?] Sparks D L, Singh B, Siebecker M G. 2024. *Environmental Soil Chemistry* (3rd ed). San Diego: Academic Press, 411–432.

[?] Su Z J, Liu X Z, Wang Z J, et al. 2024. Biochar effects on salt-affected soil properties and plant productivity: A global meta-analysis. *Journal of Environmental Management*, 366: 121653, doi: 10.1016/j.jenvman.2024.121653.

[?] Tian X F, Li C L, Zhang M, et al. 2018. Biochar derived from corn straw affected availability and distribution of soil nutrients and cotton yield. *PLoS*

ONE, 13(1): e0189924, doi: 10.1371/journal.pone.0189924.

[?] Wang Z C, Li C D, Zhang Y J, et al. 2011. Effects of different densities on main population quality of cotton. *Cotton Science*, 23(3): 284-288. (in Chinese)

[?] Wang X, Ding J L, Han L J, et al. 2024. Biochar addition reduces salinity in salt-affected soils with no impact on soil pH: A meta-analysis. *Geoderma*, 443: 116845, doi: 10.1016/j.geoderma.2024.116845.

[?] Wei L L, Chen S, Cui J Y, et al. 2022. A meta-analysis of arable soil phosphorus pools response to manure application as influenced by manure types, soil properties, and climate. *Journal of Environmental Management*, 313: 115006, doi: 10.1016/j.jenvman.2022.115006.

[?] Weng Z, Van Zwieten L, Singh B P, et al. 2017. Biochar built soil carbon over a decade by stabilizing rhizodeposits. *Nature Climate Change*, 7(5): 371-376.

[?] Wu Y F, Wang X D, Zhang L, et al. 2023. The critical role of biochar to mitigate the adverse impacts of drought and salinity stress in plants. *Frontiers in Plant Science*, 14: 1163451, doi: 10.3389/fpls.2023.1163451.

[?] Zhang W F, Wang Z L, Yu S L, et al. 2004. Effects of planting density on canopy photosynthesis, canopy structure and yield formation of high-yield cotton in Xinjiang, China. *Acta Phytoecologica Sinica*, 28(2): 164-171. (in Chinese)

[?] Zhang Y J, Ding J Q, Wang H, et al. 2020. Biochar addition alleviate the negative effects of drought and salinity stress on soybean productivity and water use efficiency. *BMC Plant Biology*, 20(1): 288, doi: 10.1186/s12870-020-02493-2.

[?] Zhang D M, Zhang Y J, Sun L, et al. 2023. Mitigating salinity stress and improving cotton productivity with agronomic practices. *Agronomy*, 13(10): 2486, doi: 10.3390/agronomy13102486.

[?] Zhou Y P, Tian H Y, Du H Y, et al. 2017. Influence of different planting densities on growth, boll setting, yield and quality of cotton. *Crops*, 33(4): 84-88. (in Chinese)

[?] Zong Y T, Liu Y J, Li Y Q, et al. 2023. Changes in salinity, aggregates and physicomechanical quality induced by biochar application to coastal soil. *Archives of Agronomy and Soil Science*, 69(13): 2721-2738.

Note: Figure translations are in progress. See original paper for figures.