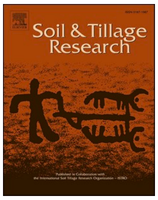
Soil & Tillage Research 235 (2024) 105893

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still



Optimizing biochar application rates for improved soil chemical environments in cotton and sugarbeet fields under trickle irrigation with plastic mulch

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ARTICLE INFO

Keywords:
Saline-alkali land
Soil chemical environment
Biochar
Cotton
Sugarbeet

ABSTRACT

Biochar can potentially change the soil physico-chemical environment significantly, but its impact on the soil chemical environment is poorly understood. To investigate this, a three-year field experiment with drip irrigation under plastic film mulch was conducted from 2018 to 2020 in a saline-alkali cotton and sugarbeet field in Xinjiang, China. The experiment examined the influences of different biochar application rates (BAR) on the distribution and variations of soil Na^+ and K^+ contents, soil nutrient contents (NO_3^--N, NH_4^+-N, soil organic carbon, available phosphorus, and available potassium), soil salt content and accumulation. Four BAR treatments of 0, 10, 50, and 100 t ha^{-1}, namely CK, B10, B50, and B100 were designed in 2018, with adjusted in 2019 and 2020 based on the former 2 year's results, namely CK, B10, B25 (25 t ha^{-1}), B50, and B100 in 2019, and CK, B10, B25, and B30 (30 t ha^{-1}) in 2020. The results indicated that increasing BAR significantly increased Na^+, K^+, and soil nutrient contents in cotton and sugarbeet fields. Soil salinity were the highest in inter-rows, followed by narrow and wide rows, and salt accumulated at 0–60 cm depth the most. Weighted-average planar soil salt storage positively correlated with BAR, with lower soil salt contents for sugarbeet than cotton at the same depth. Based on the effects of different BAR on soil ion concents, soil nutrients, and soil salinity, we recommended 10 t ha^{-1} as an optimal BAR for improving the chemical environment of saline-alkali soil, and sugarbeet as an effective crop for reducing soil salinity. These findings provided valuable technique parameters for biochar application in saline-alkali land.

1. Introduction

Increasing human activities and unpredictable climate change have aggravated the deterioration of ecological environments, particularly soil quality (soil salinization, soil hardening, soil acidification, and soil eutrophication) (Li et al., 2021; Qiao et al., 2022). Soil salinization affects almost 25% of global cultivated land (Wang et al., 2020), with an annual saline-alkali land area expansion of 1.5 million hectares (Hossain et al., 2020). Soil salinization and water scarcity are the two major factors limiting grain production and sustainable agriculture (Li et al., 2023; Saifullah et al., 2018), degrading soil quality, and causing structural changes in terrestrial plants and animals (Hopple et al., 2022). In

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Abbreviations: BAR, biochar application rates; SOC, soil organic carbon.

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https://doi.org/10.1016/j.still.2023.105893
Received 20 June 2023; Received in revised form 3 September 2023; Accepted 8 September 2023

arid and semi-arid regions with low precipitation, shallow water tables, and high evaporation rates, such as in Xinjiang, northwestern China (Liang et al., 2021), soil salinity is a severe issue that decreases water and fertilizer retention capacities and productivity of cultivated soils, threatening sustainable agricultural development (Meena et al., 2019). Therefore, improving the soil quality of salinized farmland is of utmost importance for global food security.

Biochar is a biomass material produced under oxygen-free or oxygen-limited conditions from 300 to 1000 ℃ (Qi et al., 2017). In recent years, biochar has received extensive attention as a means of improving soil quality because: (1) It contains a large carbon fraction that can significantly improve soil fertility and soil bioactivity (Xiao et al., 2020); (2) It is an ideal nutrient source and conversion site , supplying essential nutrients and carbon sources for plants and soil microorganisms; (3) improves soil cation exchange capacity, increases the utilization rate of soil nutrients, promotes nutrient absorption by plants, and improves the retention rate of soil nutrients by adsorption (Ghezzehei et al., 2014); (4) enhances soil microbial and enzymatic activities and improves the soil agglomerate structure and soil activity (Li et al., 2022d; Zhang et al., 2020a); (5) improves crop yield and quality (Jeffery et al., 2015; Liu et al., 2013), increasing farmers' economic incomes. However, despite the promising results of biochar in sustainable agriculture, the high production cost and uncertain regional applicability limit the application of biochar in agrobiology (Li et al., 2022e). Therefore, a reasonable biochar application strategy is needed to improve soil quality in agricultural fields.

The effects of biochar on soil physical and chemical properties and soil microbial environment are closely determined by the BAR. In recent years, studies on the effects on different soil types (sandy, loamy and saline soils, etc.) have shown that different BAR on soil vary widely. With increasing BAR, soil physical properties (water holding capacity, effective water content, bulk density, hydraulic conductivity, etc.), chemical properties (soil ion content and nutrients, etc.) and biological environment (soil microorganisms, enzymes and fungi, etc.) have been generally improved (Fu et al., 2021; Li et al., 2022c; Lu et al., 2019). A five-year field trail from Jin et al. (2019) showed that low BAR (11.4 t ha^{-1}) created high economic benefits, in Jinxian County, Jiangxi Province, China. Zhang et al. (2023a) reported that biochar amendment decreased soil available Cd concentration and Cd toxicity mitigation effect was enhanced with increasing BAR. Vahidi et al. (2022) used biochar produced of barberry and jujube to study the erosion, nutrient, and properties of soil, the results showed that biochar significantly improved the important soil properties, moreover, high BAR (5%, mass ratio) greatly increased cation exchange capacity, organic matter, etc. and more efficient in increasing and retaining soil nutrients. However, excessive BAR have led to the decline of soil quality (Li et al., 2023), especially in the barren saline-alkali land. For example, Liang et al. (2021) showed that a BAR of 100 t ha^{-1} decreased Saline-alkali land hydraulic conductivity and increased bulkiness. It was noteworthy that few studies have reported the effects of different BARs on the soil chemical environment, especially in Xinjiang, China, where saline-alkaline soils are widely distributed.

The positive or negative influences of different biochar application methods and application rates on soil quality have been reported for a long time. However, the duration of biochar application should also be considered by researchers due to its unique structure that determines its lasting efficacy. Shi et al. (2022) investigated the influence of different BAR for soil hydraulic parameters on sloping (3°) cropland in the black soil region of Northeast China for four consecutive years. They showed that multi-year biochar application improved soil structure and reduced soil erosion, recommending 50 t ha^{-1} for at least two consecutive years as optimal. Hu et al. (2021) showed that biochar increased markedly soil nutrients such as SOC and total nitrogen in the soil tillage layer compared to a straw return field for four consecutive years in a wheat–maize rotation system. In a 3-year field experiment, Liang et al. (2021) found that biochar improved the physical characteristics of saline-alkali soil in southern Xinjiang, China, proposing a BAR of 21.9 t ha^{-1} to significantly increase porosity and specific surface area and thus enhance water retention, water infiltration, and cationic exchange capacity. Meanwhile, studies on the short-term influences of biochar application have focused on soil microorganisms, crop growth, and soil hydraulic and physical properties. For example, Li et al. (2022a) showed that biochar increased soil water content, reduced electrical conductivity, and increased total microbial, fungal, and bacterial biomasses in the upper soil layer (0–10 cm) of alpine grassland. Zhang et al. (2020b) investigated the influence of biochar combined with gypsum on saline-alkali soil in soil column experiments, reporting that biochar application significantly increased the saturated water content and field water capacity of saline-alkali soil. The authors recommended combined applications of biochar and gypsum to improve saline-alkali soil. Numerous studies have demonstrated the impact of biochar on soils, providing a scientific basis for sustainable agricultural development and soil quality improvement. Nevertheless, few studies have examined the effects of continuous multi-year biochar application on the chemical environment of saline soils, especially in Xinjiang, where saline-alkali soil is widespread. Thus, it is important to investigate the impact of continuous biochar application on salt and nutrient distributions in saline soils to obtain insights into the effects of biochar on these soils.

Previous studies have generally supported the hypothesis that biochar application reduces soil salinity. For instance, Sanchez et al. (2022) found that the low applications (5% mass ratio) of almond shell biochar (ASB) in soils with different salinity levels significantly reduced the pH and conductivity of saline soils. Cui et al. (2021) demonstrated that biochar application reduced soil salt content and improved microbial enzyme activity in pot experiments. Mehdizadeh et al. (2020) showed that biochar application regulated soil nutrient status, overcoming adverse salinity effects on soils and crops. However, some research has shown that biochar application can actually exacerbate soil salinization (e.g., Zhao et al., 2020). Luo et al. (2016) conducted a short-term (52 d) pot experiment using saline-alkali soil from the coastal area of the Yellow River Delta in China, reporting that excessive biochar (10% mass ratio) significantly increased soil salt content. Lee et al. (2022) conducted field and laboratory soil column experiments in Kashgar Oasis, Xinjiang, China, reporting that biochar application aggravated soil salinization. Josely Fernandes et al. (2019) also found that biochar significantly increased soil salinity, particularly in the surface layer (0–10 cm). Therefore, to further improve the applicability of biochar in agriculture, more detailed and in-depth studies are needed on the effect of biochar on salt migration and distribution in soils.

Biochar has obvious influences on improving soil fertility due to its 1) high ash content (nutrient source) (Hossain et al., 2020), 2) large specific surface area and strong adsorption (nutrient sink) (Gul and Whalen, 2016), and 3) ability to improve soil physico-chemical properties (soil amendments) (Liang et al., 2021). Studies have demonstrated the effectiveness of biochar in improving soil nutrient content. For instance, Zhang et al. (2020c) showed that replacing 40% of conventional potassium fertilizer with 2% (mass ratio) biochar accelerated the conversion of slowly used potassium to available potassium. Khan et al. (2021) demonstrated that biochar increased soil nutrients under drought stress, ensuring crop yield. The pot experiment by Yan et al. (2021b) showed that biochar increased basic soil nutrient contents such as available P, K, and Mg in the root zone. Zhao et al. (2020) showed that a BAR of 20 t ha^{-1} increased the cation exchange capacity, organic matter, and nutrient contents in saline soil layers (0–20 cm at seedling stage and 20–40 cm at harvest stage), and increased the aboveground and underground parts of maize grown in soda saline-alkili soil. Nevertheless, few studies have examined the effects of biochar on soil nutrients in saline-alkali cotton and sugarbeet fields in Xinjiang, with further research needed to explore the influences of different biochar additions on nutrient contents in saline-alkali soil.

Ensuring good soil quality is crucial for food security, as it serves as the foundation for crop growth. In Xinjiang, where saline-alkali soil is widely distributed, biochar application has been shown to increase the economic yield of salt-tolerant crops such as cotton and sugarbeet. However, the response of soil chemical characteristics to the addition of biochar in saline-alkali soil in Xinjiang remains unclear. Therefore, this study investigated changes in salt distribution and nutrients in saline-alkali soil resulting from continuously adding different BAR over several years. We hypothesized that the biochar application would improve the soil chemical environment by changing ion contents, salt distribution and accumulation, NO_3^--N, NH_4^+-N, SOC, available phosphorus, and available potassium. The specific objectives of this research were to: (1) examine the effect of biochar application on the distribution and variation of soil Na^+ and K^+ contents in cotton and sugarbeet fields, (2) assess changes in NO_3^--N, NH_4^+-N, SOC content, available phosphorus, and available potassium in soil, and (3) determine the salt distribution and storage resulting from biochar application in different growing seasons.

2. Materials and methods

2.1. Study area and climate conditions

The cotton and sugarbeet field planting experiments in 2018, 2019, and 2020 were conducted in, Bayingolin Mongolian Autonomous Prefecture (Yuli County; 86°56′58″ E, 40°53′03″ N) of Xinjiang, China. The site has long-term mean sunshine hours of 2941.8 h, maximum potential evaporation of 2472 mm, frost-free period of 180 days, and annual mean temperature of 10.8 ℃ (Liang et al., 2021). Crop growth is often affected by cold weather, gales, and sandstorms in spring.

HOBO U30 weather station (USA) was used to record daily meteorological data during the cotton and sugarbeet growing periods. The 2018, 2019, and 2020 crop growing seasons (April to September) had 22.1, 20.0, and 32.4 mm precipitation, 23.5, 24.1, and 24.1 ℃ average air temperatures, 1.32, 0.81, and 0.91 m s^{-1} mean wind speeds, and 41.7%, 41.5%, and 41.7% mean relative humidities, respectively. Fig. S1 illustrates the variations in daily meteorological variables in the three growing seasons.

2.2. Initial soil properties

In 2018, soil samples were collected from six depth intervals (0–20, 20–40, 40–50, 50–60, 60–80, and 80–100 cm) to determine the soil basic properties, before crop sowing. The results of pre-experiment indicated that there were differences in soil types at different depths (above 50 cm is silt clay loam and below that is sandy soil), so the samples taken at intervals of 10 cm from 40 to 60 cm soil layers. The Malvern laser particle size analyzer (Mastersizer 2000) was used to measure soil particle size distribution. After air drying, dry soil samples were passed through a 1 mm sieve. Electrical conductivity was measured by conductivity meter (DDS-307), pH was measured by pH meter. The atomic absorption spectrophotometer (AA7003) and the titration method were used to measure soil cation contents(Na^+, Ca^{2+}, and Mg^{2+}) and anion contents(Cl^-, HCO^{3-}, and SO_4^{2-}) Table S1 details the soil physicochemical properties.

According to the soil classification method (IUSS Working Group WRB, 2006), the soil was classified as silt clay loam at 0–50 cm depths (29.82% sand, 52.29% silt, and 17.89% clay) and sand at 50–100 cm depths (96.74% sand, 1.83% silt, and 1.43% clay). The saline soil severity level was classified as light, because the range of average soil salt content (SS) was 0.1–0.2% at 0–60 cm depth based on the calibrated relationship ($SS=3.4238\ EC_{1:5}+1.0513$, $R^2=0.9511$, 42 samples). The salinity type was classified as chloride sulfate (chloride/sulfate ions range from 20% to 100%) (Li et al., 2022e). The soil pH was around 8.5.

2.3. Field plot experiments

2.3.1. Biochar characteristics and experimental design

Biochar raw material was the fruit bunches of palm empty (Elaeis guineensis Jacq.), which were Sieved to remove impurities and crushed before oven drying at 200 °C to constant weight, slowly cracked at 600 °C to form biochar under anaerobic conditions, and then ground into powder. The provider of biochar was Zhengzhou Yongbang New Energy Equipment Technology Co., Ltd. The biochar parameters were shown in Table 1. Biochar produced from the same batch was used throughout to ensure consistency and reduce errors.

The biochar application depth was 0–30 cm. Before the test, we spread uniformly biochar on each plot and then ploughed it using a rotary tiller to ensure the soil was thoroughly mixed with biochar. Three BAR treatments B10 (10 t ha^{-1}), B50 (50 t ha^{-1}), and B100 (100 t ha^{-1}) and a control treatment CK (0 t ha^{-1}) were tested in 2018. The 2018 test results revealed 10 and 50 t ha^{-1} was a suitable BAR range, which could improve soil hydraulic parameters, crop yield and growth. (Liang et al., 2021; Wang et al., 2022). Therefore, in 2019, we added a biochar treatments B25 (25 t ha^{-1}) to determine the optimal BAR. Interestingly, excessive BAR (50 and 100 t ha^{-1}) were not economical and did not have obvious improvement effects on the soil quality and crop growth. Therefore, in 2020, biochar treatments of CK, B10, B25, and B30 (30 t ha^{-1}) were designed (Table S3).

Each field plot had an area of 6 m × 6 m, with each treatment replicated three times in a random complete block design. A road (1.5 m wide) was set between contiguous fields to prevent water and fertilizer infiltration between them.

2.3.2. Crop field layout

The field layout and planting patterns are illustrated in Fig. 1.

The cotton (cultivate variety was Xinluzhong 66) and sugarbeet (cultivate variety was Detian 7) were sown on April 11, 15, and 15 in 2018, 2019, and 2020, and the sown a density of 30 and 20 seeds m^{-2}, respectively. The harvest dates were September 24, 20 and 20 of the planting year, respectively. The cotton-drip and sugarbeet-drip line arrangement followed the local practice (Fig. 1). The same width plastic film (106 cm) was used for both crops. The seed spacing, along the drip lines, were 10 and 30 cm for cotton and sugarbeet, respectively. For cotton, the row spacing of were wide rows, narrow rows, and no mulch zones were 66 cm, 10 cm, and 30 cm. For sugarbeet, the row spacing was 35 cm. The irrigation method used for both crops was drip irrigation, with a drip emitter spacing of 30 cm and drip discharge was 2.0 L h^{-1}. Cotton and Sugarbeet were harvested on the growth period of cotton were divided into sowing and germination, seedling, flowering, boll-development, and boll-open, and sugarbeet were seeding, rapid growth, swelling stage, and sugar accumulation stages.

2.3.3. Water and fertilization in the study

All treatments applied same irrigation and fertilization scheme in 2018, 2019, and 2020 (June–August; Detailed data are shown in Table S3). In addition, for the purpose of reducing accumulated salts in the depth of upper soil, we applied a winter border irrigation (300 mm, around November), according to the local management model.

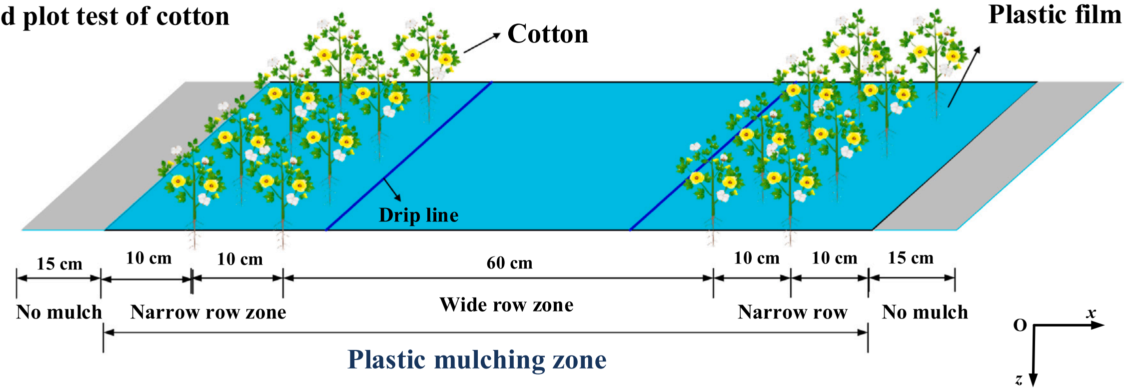
2.4. Soil chemical properties measurements and analysis

Soil samples were collected every 10–16 days using an auger (5 cm diameter, 15 cm long) of no mulch, narrow and wide row zones at 0–10,

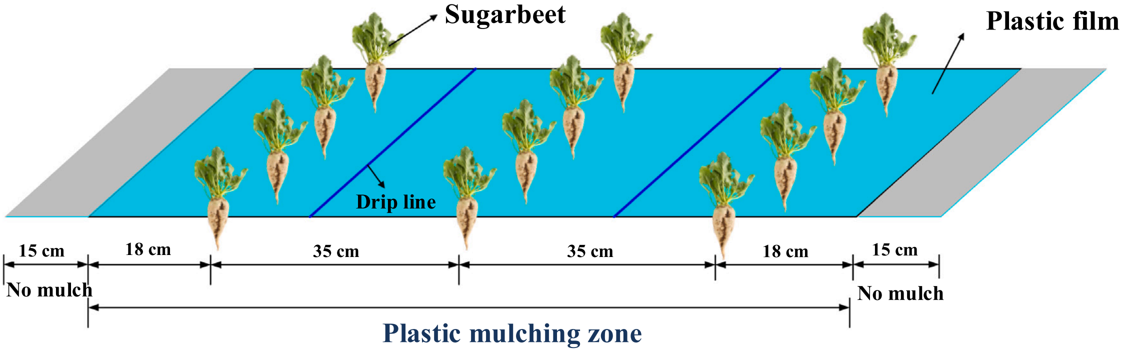
Table 1
Biochar parameters used in the experiment.

specific surface area ($m^2\ g^{-1}$)	bulk density ($g\ cm^{-3}$)	$EC_{1:5}$ (mS cm^{-1})	pH (1: 5 H_2O)	organic carbon content (g kg^{-1})
116.6	0.5	11.02	7.6	472.2

(a) Field plot test of cotton



(b) Field plot test of sugarbeet



(c) Field planted cotton and sugarbeet

Fig. 1. Test site arrangement diagram of cotton and sugarbeet. Fig. 1c shows cotton at the squaring stage and sugarbeet at the sugar accumulation stage.

10–20, 20–30, 30–40, 40–60, 60–80, 80–100 cm soil depths (Fig. 1). The soil samples were air-dried and screened with sieve (2 mm), and used to measure $EC_{1:5}$ and Na^+ and K^+ contents (methods similar to Section 2.2). The contents of soil NO_3^--N and NH_4^+-N were determined using a continuous AutoAnalyzer3 device (AA3, SEAL Company, Germany). Soil available phosphorus content was determined using the sodium bicarbonate/sodium fluoride hydrochloric acid leaching and molybdenum antimony anti-colorimetric method. Soil available potassium content was determined by hot nitric acid solution extraction and flame spectrophotometry. SOC content was determined using the potassium dichromate oxidation-external heating method.

The weighted-average planar soil salt storage (WAPSSS, g kg^{-1} m^{-2}) at the root zone (0–40 cm) was used to reflect the soil salt conditions in the XOZ plane, calculated as:

$$WAPSSS = \frac{\mathrm{H}L_{wz}SS_{ave,wz} + \mathrm{H}L_{nz}SS_{ave,nz} + \mathrm{H}L_{nm}SS_{ave,nm}}{\mathrm{H}(L_{wz} + L_{nz} + L_{nm})} \quad (1)$$

where L_w, L_N, and L_{NM} are 33 (half-width of the wide row), 20 (half-width of the narrow row), and 15 (half-width of the no mulched zones) cm for cotton, and 18, 18, and 18 cm for sugarbeet, respectively, H is 40 cm, and $SS_{ave,wz}$, $SS_{ave,nz}$, and $SS_{ave,nm}$ are average soil salt contents (g kg^{-1}).

2.5. Data analysis

SPSS software (version 26.0) was used for statistical analysis. The difference between biochar application was determined to the one-way analysis of variance (ANOVA). Among the significant differences of each treatments was examined to the least significant differences (LSD) at $p < 0.05$. Origin software (version 2022) was used for drawing figures, and Surfer 15.0 was used to complete the contour maps. Microsoft Visio 2003 was used for drawing the overall framework of this research (Fig. 2).

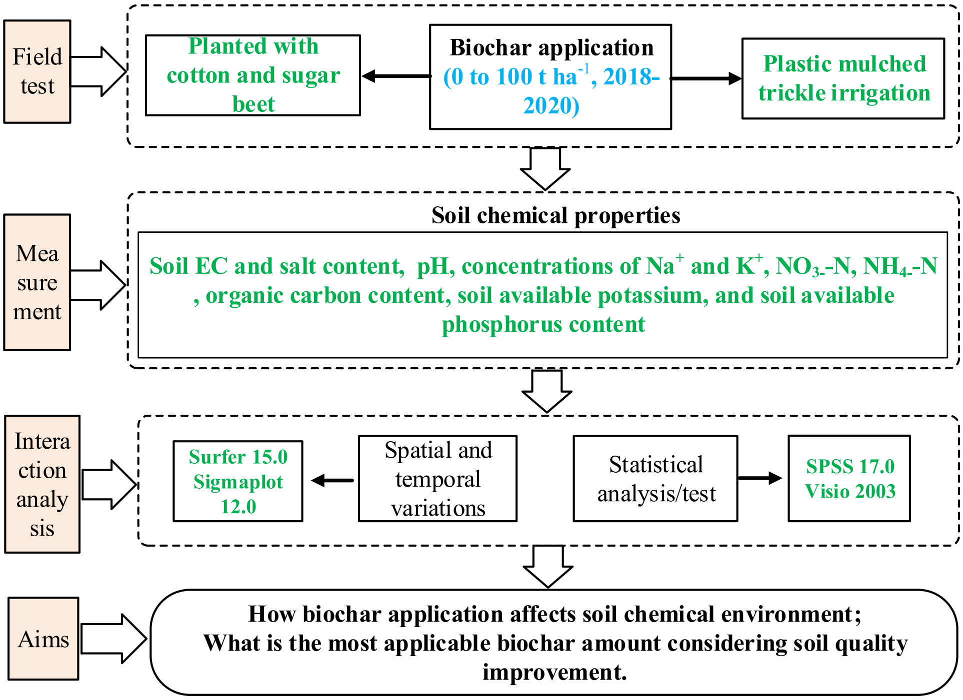


Fig. 2. Overall framework of this research.

3. Results

3.1. *Effects of biochar on soil Na$^+$ and K$^+$ contents*

In 2018–2020, there were significantly ($p < 0.05$) affected on soil Na$^+$ and K$^+$ contents by different BAR in the cotton and sugarbeet fields (depth of 0–100 cm). The Na$^+$ and K$^+$ contents increased proportionally to the BAR (horizontal and vertical directions). Generally, the plastic film mulch zone had lower Na$^+$ and K$^+$ contents than the bare soil zone between the films in the horizontal direction, but in the vertical direction Na$^+$ mainly concentrated at 0–40 cm depth, with higher values at 0–20 cm (Fig. 3), K$^+$ greater differences occurred at different depths. We also found the sugarbeet field had lower Na$^+$ content than the cotton fields for the same treatment in 2019 and 2020, indicating a greater decreasing effect on Na$^+$ of sugarbeet than cotton (Table 2). However, the K$^+$ content showed no difference in the root zone of cotton and sugarbeet at the same BAR (Table 3).

Biochar applied significantly affected Na$^+$ and K$^+$ contents within different soil layers. For sugarbeet field, the biochar treatments significantly increased soil Na$^+$ content from 0 to 40 cm by 30.6–93.0% and 68.4–240.8% and from 0 to 100 cm by 68.4–336.7% and 167.2–240.8% at the seedling and harvest stages, respectively, relative to CK, in 2018 (Fig. 3). Similarly, in 2019, during the seedling and leaf cluster rapid growth stages, the biochar treatments increased soil Na$^+$ content from 0 to 40 cm by 71.8–351.3% and 20.1–125.2%, respectively, relative to CK (Fig. S2).

In 2018, at the same BAR, maximum K$^+$ content occurred at 0–20 cm depth during the seedling stage (Fig. 4) and was inversely proportional to the soil depth, but at 0–40 cm depth, it was proportional to the BAR (i.e., B100 >B50 >B25 >B10). During the harvest period, K$^+$ content was mainly distributed from 0 to 60 cm depth, with the maximum value at 40 cm. No significant differences in K$^+$ content at 60–100 cm soil depth occurred during the whole reproductive period. Similar results for K$^+$ content occurred in 2019. (Fig. S3).

3.2. *Effects of biochar on soil nutrient variations*

3.2.1. *NO$_3^-$-N, NH$_4^+$-N and organic carbon contents*

The different BAR affected soil NO$_3^-$-N contents in the root zone of cotton and sugarbeet in 2018, 2019, and 2020 (Fig. 5 presents the mean values at 0–40 cm depth). Biochar application significantly increased soil NO$_3^-$-N content ($p < 0.05$), proportional to the BAR. At the seedling and harvest stages, the NO$_3^-$-N contents significantly increased in B10, B50, and B100 treatments of 2018 by 64.6–445.2% for cotton and 37.7–878.4% for sugarbeet; B10, B25, B50, and B100 treatments of 2019 by 55.3–857.5% for cotton and 172.9–2460.1% for sugarbeet; B10, B25, and B30 treatments of 2020 by 133.9–1065.2% for cotton and 38.4–567.9% for sugarbeet, relative to CK. For the same treatment, biochar application accumulated more NO$_3^-$-N content in cotton fields than sugarbeet fields, but for the same year, biochar application increased NO$_3^-$-N content more in sugarbeet fields than cotton fields.

The different biochar applications significantly increased soil NH$_4^+$-N contents ($p < 0.05$) in the root zone of cotton and sugarbeet from 2018 to 2020, proportional to the BAR (Fig. 6). In 2018 and 2019, cotton had higher NH$_4^+$-N contents at the seedling stage than harvest stage (67.8–96.3%, 2018; 22.8–96.0%, 2019) while sugarbeet only showed this phenomenon in 2018.

Biochar application significantly affected soil NO$_3^-$-N and NH$_4^+$-N contents. Biochar application significantly increased NO$_3^-$-N content at 0–40 cm depth for all growth stages in both years ($p < 0.05$) in 2018 and 2019 (Fig. 7). However, NO$_3^-$-N content increased more than seedling stage at the harvest stage in 2018 but less at the harvest stage in 2019 and increased with increasing BAR (Fig. 7a). NH$_4^+$-N contents in both years generally increased with increasing BAR but did not show a regular pattern across growth stages like NO$_3^-$-N at 0–40 cm soil depth ($p < 0.05$).

Biochar applications increased SOC contents in the root zone of cotton and sugarbeet (Fig. 8) across planting years, proportional to the BAR, with small differences between the seedling and harvest stages. For cotton, for example, SOC contents increased by 31.9–188.7% of B10, B50, and B100 treatments at the seedling and harvest stages in 2018; by 30.0–197.3% for B10, B25, B50, and B100 treatments in 2019; by 9.7–58.1% for B10, B25, and B30 treatments in 2020, respectively.

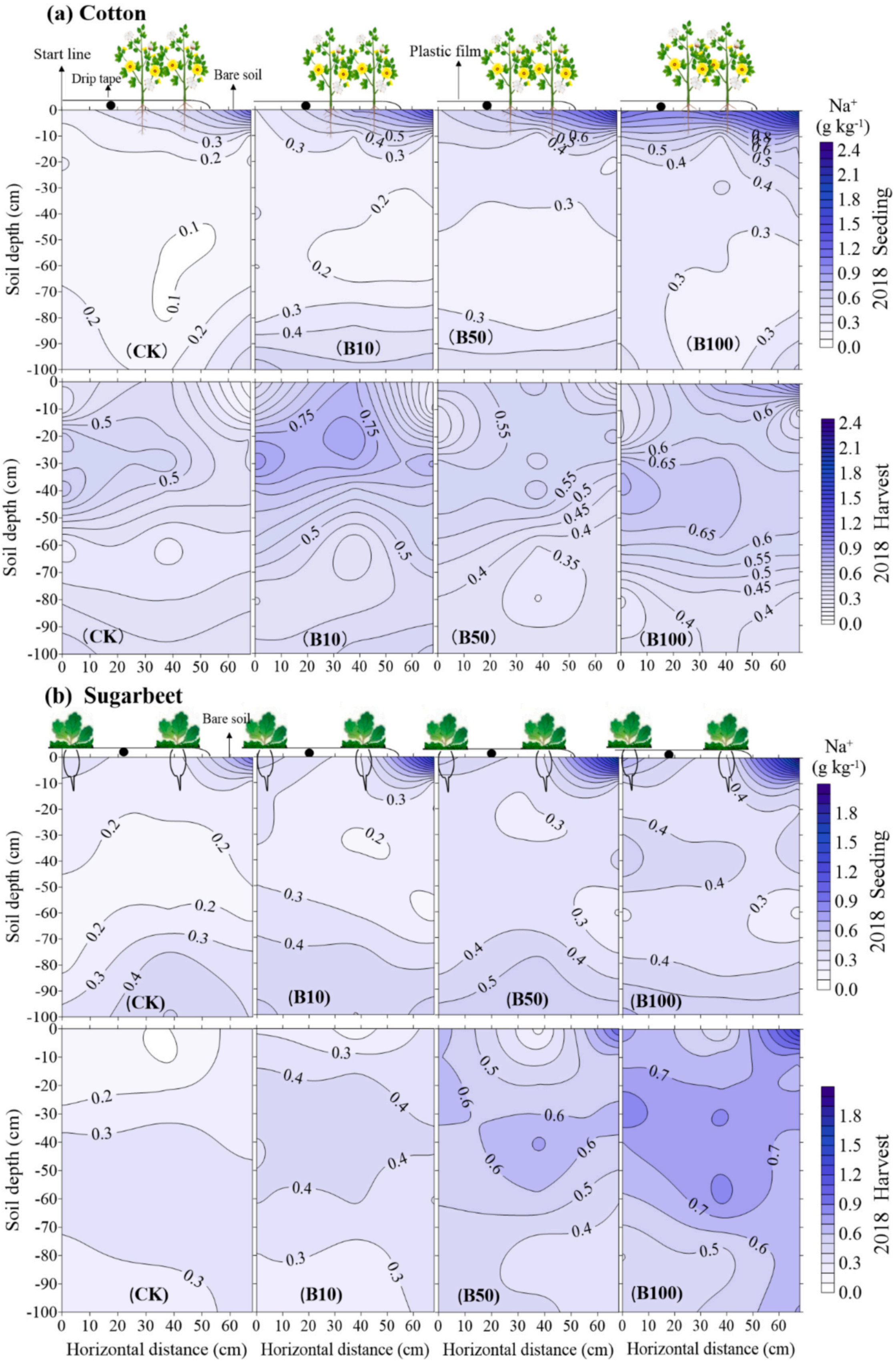


Fig. 3. The Na$^+$ content during seedling and harvest stages of cotton and sugarbeet in 2018.

Table 2
Statistics for Na^+ content (g kg^{-1}) in cotton and sugarbeet fields under different biochar application treatments in 2018 and 2019.

Year	Treatments	Cotton (g kg^{-1})				Sugar–beet (g kg^{-1})			
		Min	Max	Average	Change (%)	Min	Max	Average	Change (%)
2018	CK	0.09	1.21	0.31	–	0.08	0.98	0.28	-
	B10	0.13	1.46	0.41	32.26	0.12	1.64	0.37	32.14
	B50	0.20	1.69	0.48	54.84	0.16	1.82	0.48	71.43
	B100	0.21	2.06	0.59	90.32	0.17	2.06	0.60	114.29
2019	CK	0.01	0.83	0.19	–	0.04	0.89	0.14	-
	B10	0.02	0.88	0.22	15.79	0.10	1.05	0.21	50.00
	B25	0.12	1.16	0.32	68.42	0.10	1.24	0.28	100.00
	B50	0.02	1.45	0.39	105.26	0.10	1.40	0.35	150.00
	B100	0.26	1.66	0.71	273.68	0.21	1.93	0.54	285.71
Average for all treatments and years		0.10	1.34	0.36	–	0.11	1.39	0.34	–

Table 3
Statistics for K^+ content (g kg^{-1}) in cotton and sugarbeet fields under different biochar application treatments in 2018 and 2019.

Year	Treatments	Cotton (g kg^{-1})				Sugar–beet (g kg^{-1})			
		Min	Max	Average	Change (%)	Min	Max	Average	Change (%)
2018	CK	0.09	0.34	0.17	–	0.11	0.29	0.17	–
	B10	0.12	0.54	0.21	23.53	0.12	0.59	0.21	23.53
	B50	0.11	0.70	0.24	41.18	0.11	0.83	0.26	52.94
	B100	0.13	0.90	0.32	88.24	0.12	0.95	0.33	94.12
2019	CK	0.004	0.02	0.01	–	0.01	0.17	0.05	–
	B10	0.002	0.07	0.03	200.00	0.01	0.25	0.05	0.00
	B25	0.02	0.14	0.06	500.00	0.02	0.17	0.06	20.00
	B50	0.02	0.20	0.07	600.00	0.02	0.55	0.08	60.00
	B100	0.04	0.36	0.11	1000.00	0.03	0.67	0.09	80.00
Average for all treatments and years		0.06	0.36	0.14	–	0.06	0.50	0.14	–

Sugarbeet fields increased SOC contents in the root zone than cotton fields in all treatments relative to CK.

3.2.2. Available phosphorus and available potassium

The different biochar applications significantly increased ($p < 0.05$) the available phosphorus content in the root zone of cotton and sugarbeet at 0–40 cm depth in 2018, 2019, and 2020 (Fig. 9). In all three years, the B10 treatment significantly increased the available phosphorus content in the root zone of cotton (104.9%, 22.5%, and 20.8%) and sugarbeet (27.4%, 26.5%, and 18.4%) at the seedling stage and harvest stage (18.4–27.4% for cotton and 23.3–93.8% for sugarbeet) compared to CK. In all years, the cotton root zone had higher available phosphorus content at the seedling stage than the harvest stage, with the opposite pattern for sugarbeet.

Similarly, biochar application significantly increased ($p < 0.05$) the available potassium content in the root zone of cotton and sugarbeet at 0–40 cm soil depth (Fig. 10), but this increasing effect was more pronounced in the sugarbeet root zone than cotton. For example, the B10 treatment had 31.7%, 31.6%, and 18.8% higher available potassium content in sugarbeet than CK at harvest in 2018, 2019, and 2020, but only 11.3%, 9.7%, and 9.6% higher in cotton. The available potassium content in the root zone of cotton and sugarbeet differed significantly between seedling and harvest stages in 2018, with this difference becoming progressively smaller in 2019 and 2020.

3.3. Effects of biochar on soil salt distributions

3.3.1. Soil salt content variations during the crop growing seasons

From the dynamic soil salinity (0–100 cm) at growth stages for cotton and sugarbeet at different BAR in 2018–2020 (Fig. 11), BAR had great impacts on soil salinity during the entire growing periods of both crops. For the same biochar treatment, soil salinity gradually increased with advancing growth stage, reached peaks during the harvest stage. Cumulative soil salinity occurred at 20–40 cm depth in cotton fields for all treatments and growing seasons, while sugarbeet fields exhibited this phenomenon only in the B100 treatment in 2019. At the same time, sugarbeet had significantly lower soil salt accumulation than cotton.

In Tables 4 and 5 foraverage soil salinity at 0–40 cm depth at the beginning and end of the cotton and sugarbeet growing seasons under different BAR, biochar significantly increased average soil salinity, directly proportional to the BAR ($p < 0.05$). The mulched area had lower soil salinity than bare soil between films in cotton from the seedling to boll-open stage and sugarbeet at the seedling and sugar accumulation stages. Soil salinity significantly increased by 24.0–119.4% for cotton and 32.9–92.4% for sugarbeet in the B10, B50, and B100 treatments in 2018; by 22.4–142.6% for cotton and 24.4–232.7% for sugarbeet for the B10, B25, B50, and B100 in 2019; by 26.7–99.3% for cotton and 14.0–66.4% for sugarbeet in the B10, B25, and B30 treatments in 2020, relative to CK.

3.3.2. Contour map of soil salt contents over three years

The soil salt contents of cotton growth period of 2019 were presented in Fig. 12, Figure Sin 2018 and 2020 of sugarbeet. The different BAR had significantly affected on soil salt distribution in the root zone of cotton and sugarbeet in the horizontal direction (wide row, narrow row, and inter-membrane) and vertical direction (0–100 cm). Overall, soil salt distribution gradually increased from wide rows to narrow row and to inter-row. Soil salt content varied great at 0–60 cm depth layer but little at 60–100 cm depth layer.

For cotton, the CK, B10, and B50 treatments had soil salinity critical values in the upper (0–60 cm) and lower (60–100 cm) soil layers of about 2.0, 2.5, and 2.5 g kg^{-1}, respectively, at the seedling and bud stages, and 2.5, 3.0, and 3.0 g kg^{-1} at other growth stages. The B100 treatment had soil salinity critical values for the upper and lower layers of about 2.5 g kg^{-1} at the seedling, squaring, and flowering stages but about 3.5 g kg^{-1} at the other growth stages. For sugarbeet, salts accumulated mainly at 0–20 cm depth during the seedling, swelling, and sugar accumulation stages and 0–40 cm depth at the leaf rapid growth stage. Notably, sugarbeet had lower soil salinity in the root zone than cotton at the same BAR.

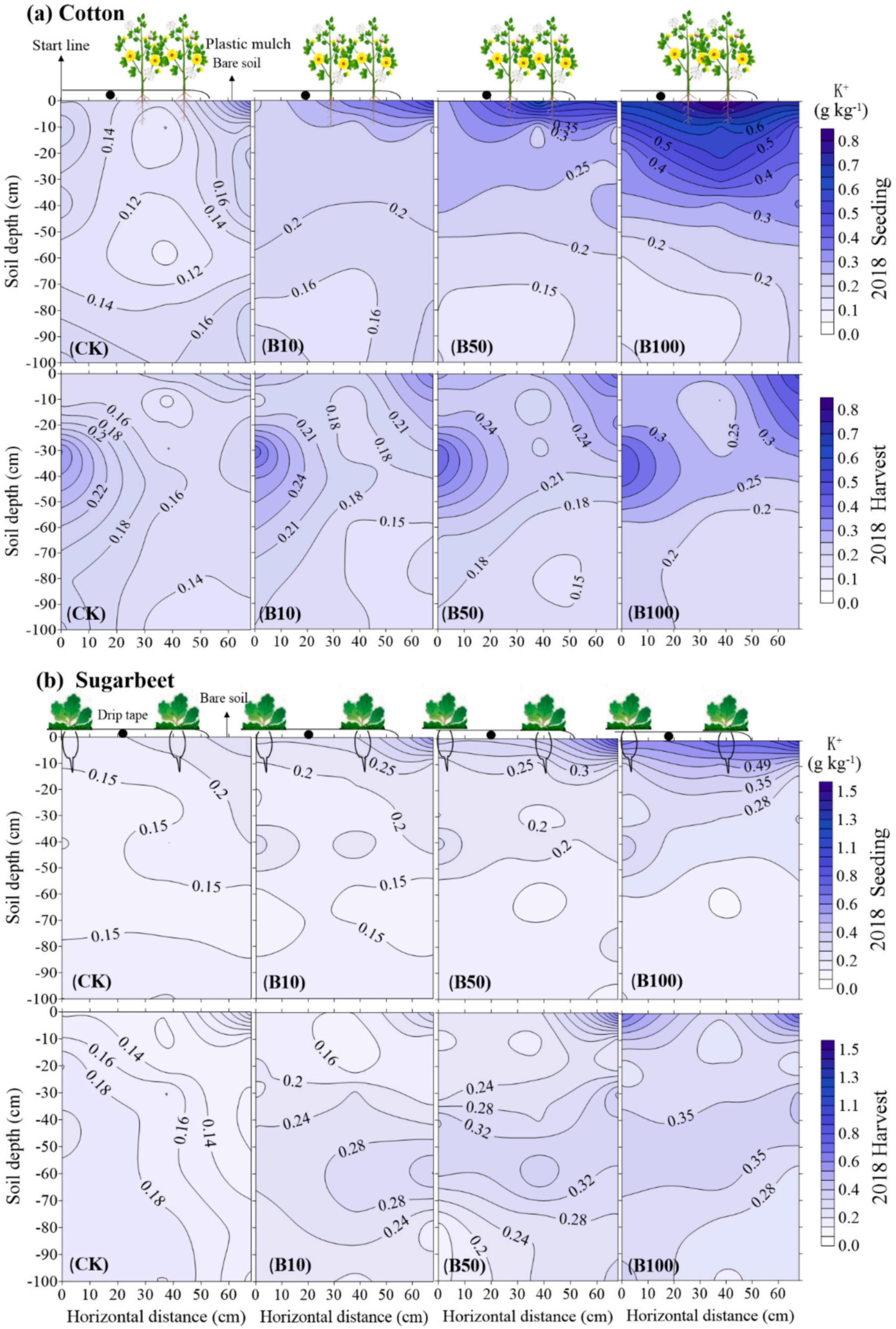


Fig. 4. The K^+ content during seedling and harvest stages of cotton and sugarbeet in 2018.

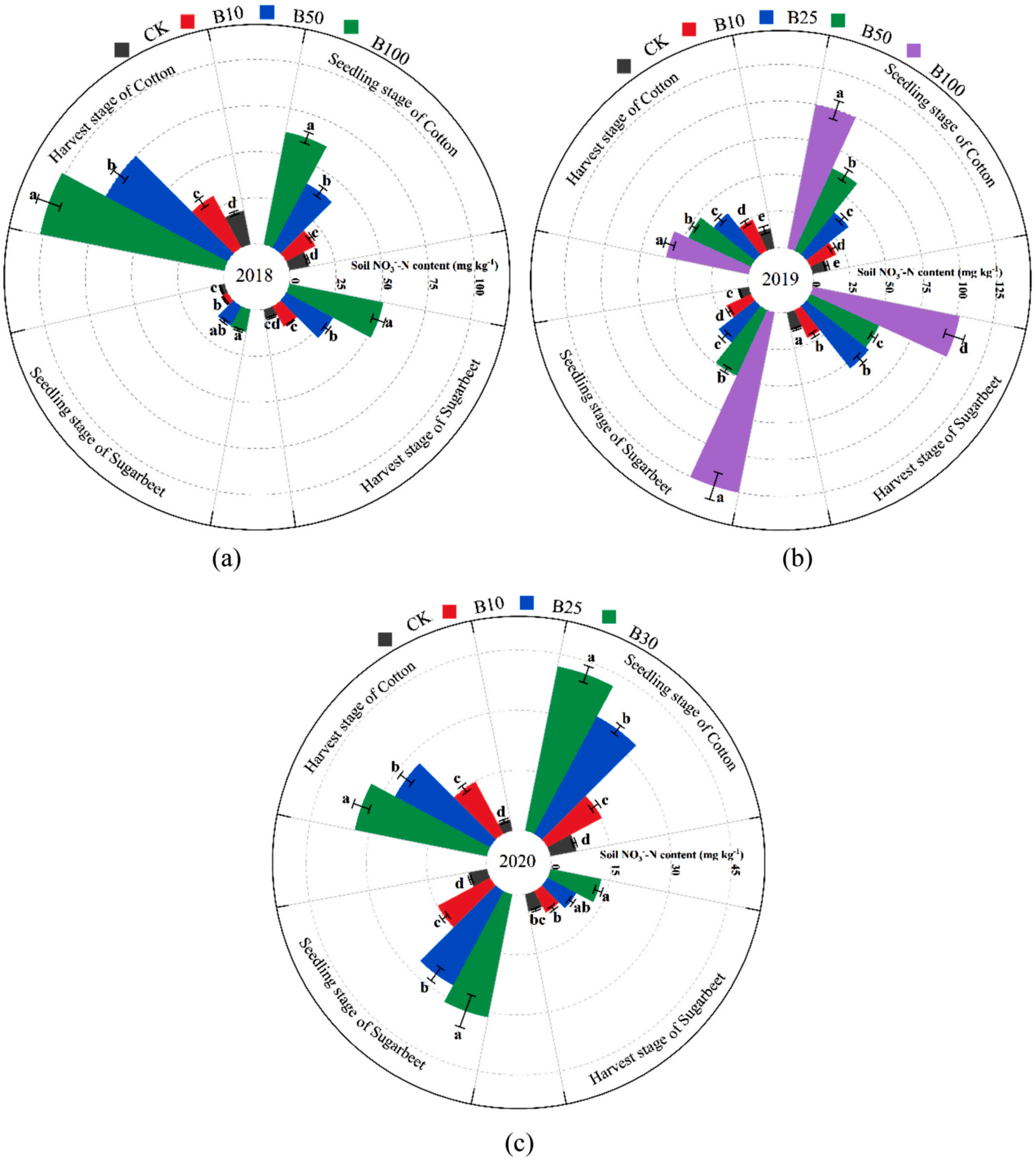


Fig. 5. Comparison of soil NO$_3^-$-N (mg kg^{-1}) for different biochar application treatments during seedling and harvest stages of cotton and sugarbeet in 2018 (a), 2019 (b), and 2020 (c).

3.3.3. WAPSSS variations during seedling and harvest stages of two crops

Fig. 13 illustrates WAPSSS dynamics in the root zone of cotton and sugarbeet at different growth stages in 2018, 2019, and 2020. Biochar application significantly affected WAPSSS at different soil depths in cotton and sugarbeet fields and positively correlated with the amount of biochar applied ($p < 0.05$). Overall, WAPSSS followed the order: B100 >B50 >B30 >B25 >B10 >CK. With the advancing growing period, WAPSSS gradually increased in the 0–10 cm and 0–40 cm soil layers but was relatively stable at 0–100 cm depth. Under the same conditions, cotton fields had 1 g kg^{-1} m^{-2} (on average) higher WAPSSS than sugarbeet fields at 0–40 cm depth.

Biochar application had a greater impact on WAPSSS in the same soil layer (2018 results presented here as each year had similar rates of increase). In 2018, the B10, B50, and B100 treatments significantly increased WAPSSS in 0–10 cm soil layer by 29.6%, 75.3%, and 214.9% for cotton and 36.5%, 80.2%, and 156.4% for sugarbeet; the 0–40 cm

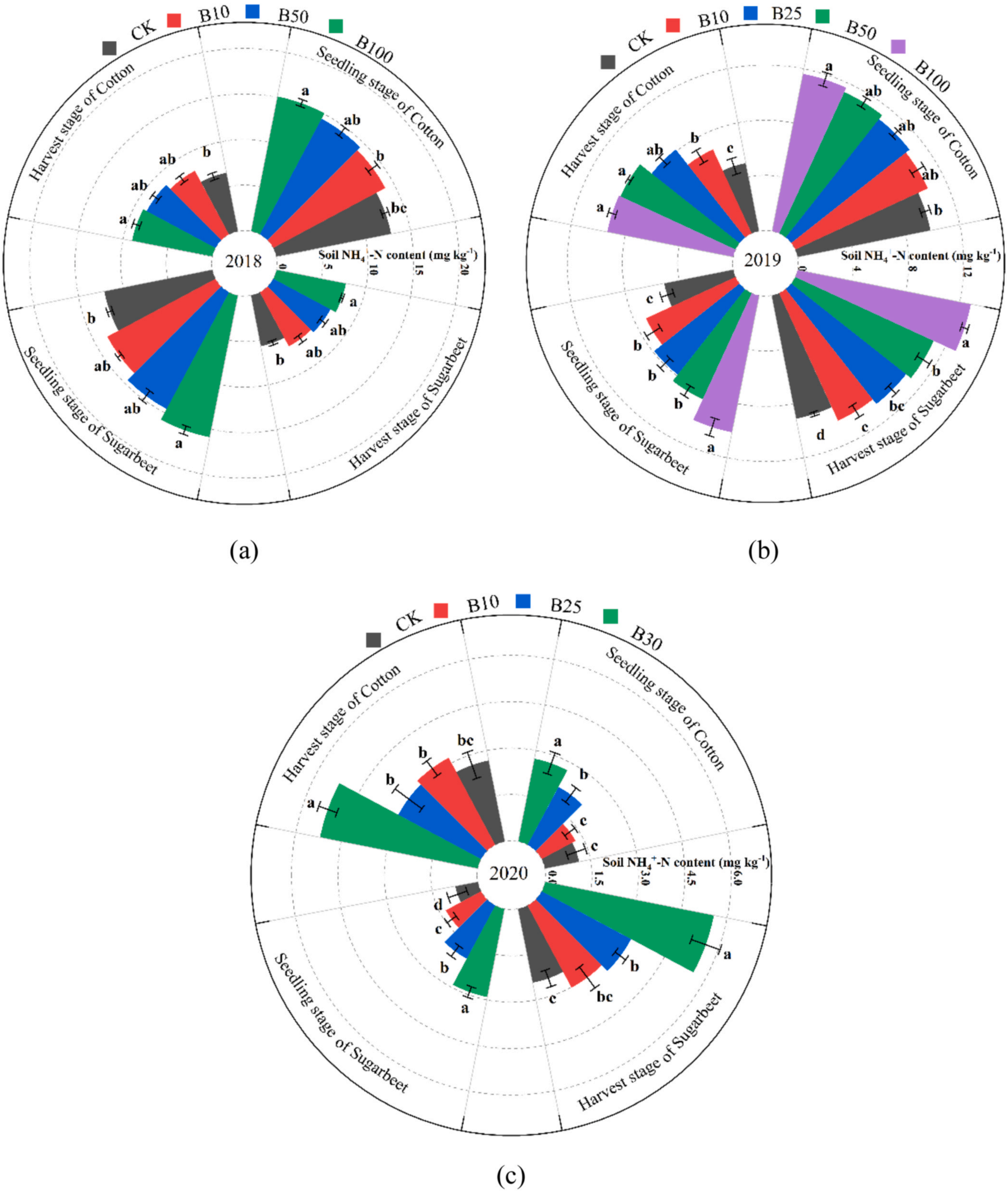


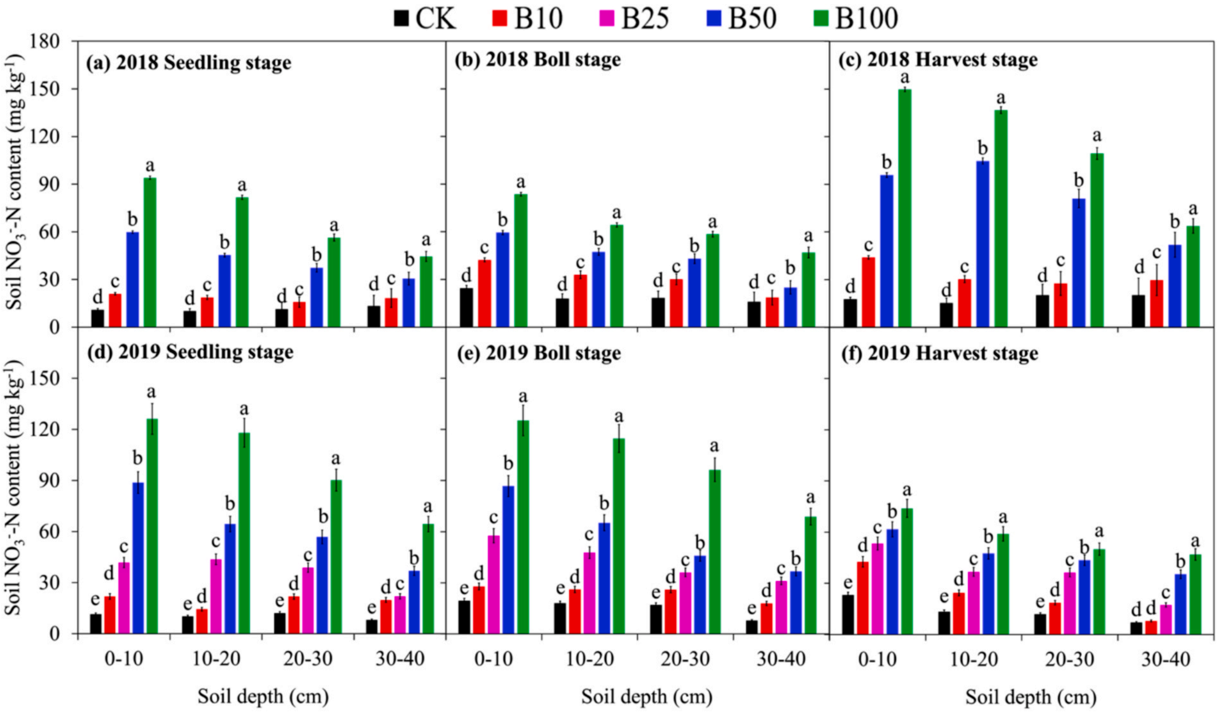
Fig. 6. Comparison of soil NH_4^+-N (mg kg^{-1}) for different biochar application treatments during seedling and harvest stages of cotton and sugarbeet in 2018 (a), 2019 (b), and 2020 (c).

soil layer by 28.4%, 57.8%, and 129.7% for cotton and 30.3%, 62.7%, and 111.8% for sugarbeet; the 0–100 cm soil layer by 31.8%, 49.1%, and 98.9% for cotton and 26.7%, 46.5%, and 84.2% for sugarbeet, respectively, relative to CK.

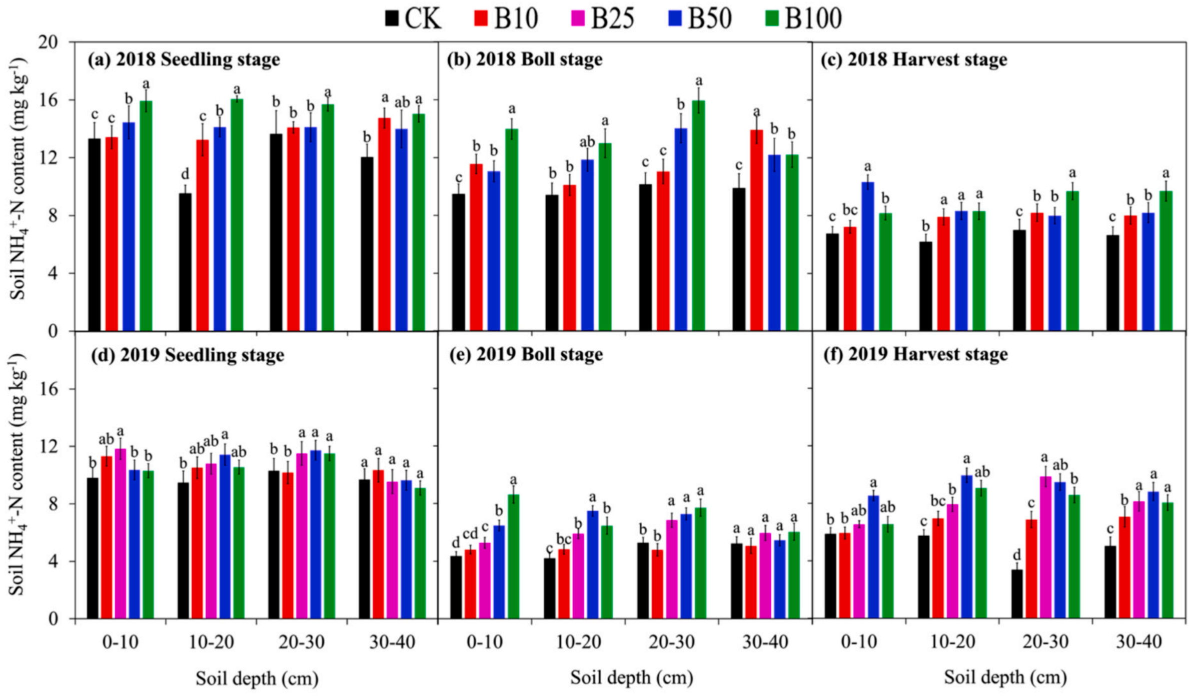
4. Discussion

4.1. Impact of biochar on soil chemical environment

Soil chemical environment is an important factor affecting soil



(a) NO_3^--N



(b) NH_4^+-N

Fig. 7. Effect of different biochar application amounts on soil (a) NO_3^--N and (b) NH_4^+-N contents at different soil depths during different cotton growth stages in 2018 and 2019. Error bars are standard errors. Different letters above the bars indicate statistical differences among treatments at $p < 0.05$ with LSD test.

aggregate structure, biological activity, physical properties, and crop growth (Abad et al., 2023). Planting salt-tolerant crops such as cotton and sugarbeet in saline soils combined with soil amendments can improve soil quality. This study investigated the effects of different BAR on ion contents, nutrients, salt distribution, and salt storage in saline-alkali soils in cotton and sugarbeet fields in southern Xinjiang for three consecutive years. Biochar application significantly increased soil ion contents, promoted soil Na^+ and K^+ movement horizontally and

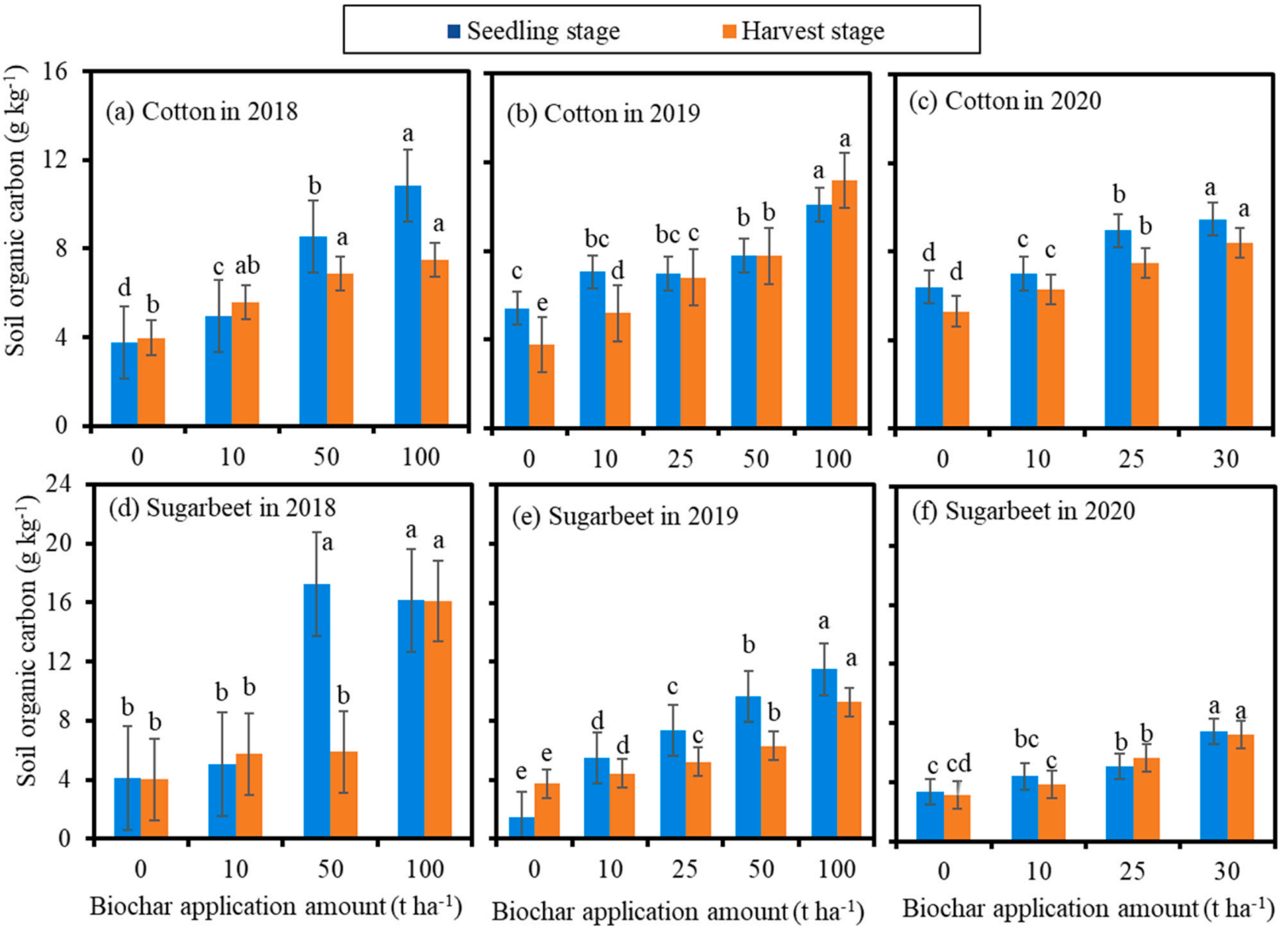


Fig. 8. Comparison of soil organic carbon contents (g kg^{-1}) for different biochar application treatments during seedling and harvest stages of cotton and sugarbeet in 2018, 2019, and 2020.

vertically, and accumulated soil Na^+ and K^+ in the 0–60 cm surface layer. The 0–20 cm soil depth had the highest Na^+ and K^+ contents, consistent with the findings of Li et al. (2018) and Zhao et al. (2020), and likely due to the unique properties of biochar, which can change soil physical properties and promote the movement of soil ions with soil water (Liang et al., 2021; Wang et al., 2022). Moreover, biochar contains plant ash, mostly in the form of soil inorganic salts, increasing the content of soil salt ions (Saifullah et al., 2018). Biochar application also significantly increased soil nutrients (NO_3^--N, NH_4^+-N, SOC, available potassium, and available phosphorus) from 0 to 40 cm depth in cotton and sugarbeet fields, which positively correlated with BAR, primarily because biochar adsorbs nutrients through its large specific surface area under complexation and electrostatic and capillary forces (Liu et al., 2017). Biochar-added soil immobilizes nutrients while promoting their cycling to reduce N and P loss and improve soil fertility (Zhao et al., 2023) At the same time, the multiple functional groups of biochar are the key reason for its nutrient retention. Studies have shown that biochar application improved soil quality, increased soil nutrient and water holding capacity, and improved soil bulk structure, thus increasing soil retention and crop utilization of nutrients such as N, P, and K. However, excessive biochar application (more than 10%, mass ratio) can inhibit plant growth by increasing soil salinity, as demonstrated by Luo et al. (2016). Zhang et al. (2016) also reported that biochar application increased soil salinity in different soils (sandy loam and clay loam), consistent with this study's soil salinity accumulation and distribution. In this study, biochar's contribution to WAPSSS mainly occurred in the upper soil layer, close to the initial application location. Biochar application in farmland has been shown to reduce soil bulk density (improving water holding capacity) and increase porosity (promoting water and salt transport), which are intrinsic mechanisms affecting soil physicochemical properties. In addition, the large amounts of exchangeable cations and organic substances in biochar can further change the distribution of soil salinity.

4.2. Sugarbeet played a vital role in decreasing soil salinity

Soil salinization is a major challenge for agriculture in arid and semi-arid regions (Li et al., 2020; Qiu et al., 2021), driven by factors such as climate change, human activities, and farming patterns (Du et al., 2023; Mukhopadhyay et al., 2021; Thiam et al., 2019; Xiao et al., 2023). Common remediation methods such as irrigation leaching and chemical remediation are limited in arid and semi-arid areas due to water shortages and poor economies (Yan et al., 2021a), highlighting the need for new approaches to improve soil quality and food security. In this study, adding biochar and using salt-tolerant crops (cotton and sugarbeet) reduced soil salinity and improved soil quality. Notably, sugarbeet played a particularly important role in reducing soil salt ions (Na^+ and K^+) and increasing the accumulation of soil nutrients (NO_3^--N, NH_4^+-N, organic carbon, available potassium, and available phosphorus). Studies have shown that salt-tolerant crops reduce soil salinity mainly by absorbing salt ions in their roots (Liu et al., 2023). Yan et al. (2021a) showed that the interaction of irrigation and N application in saline fields in South Xinjiang promoted Na^+, K^+, Ca^{2+}, and Mg^{2+} uptake by all sugarbeet organs, and Zhang et al. (2023b) reported that salt stress promoted the accumulation of allantoin in sugarbeet, enhancing salt tolerance. Liu et al. (2023) showed that salt stress modulates reactive

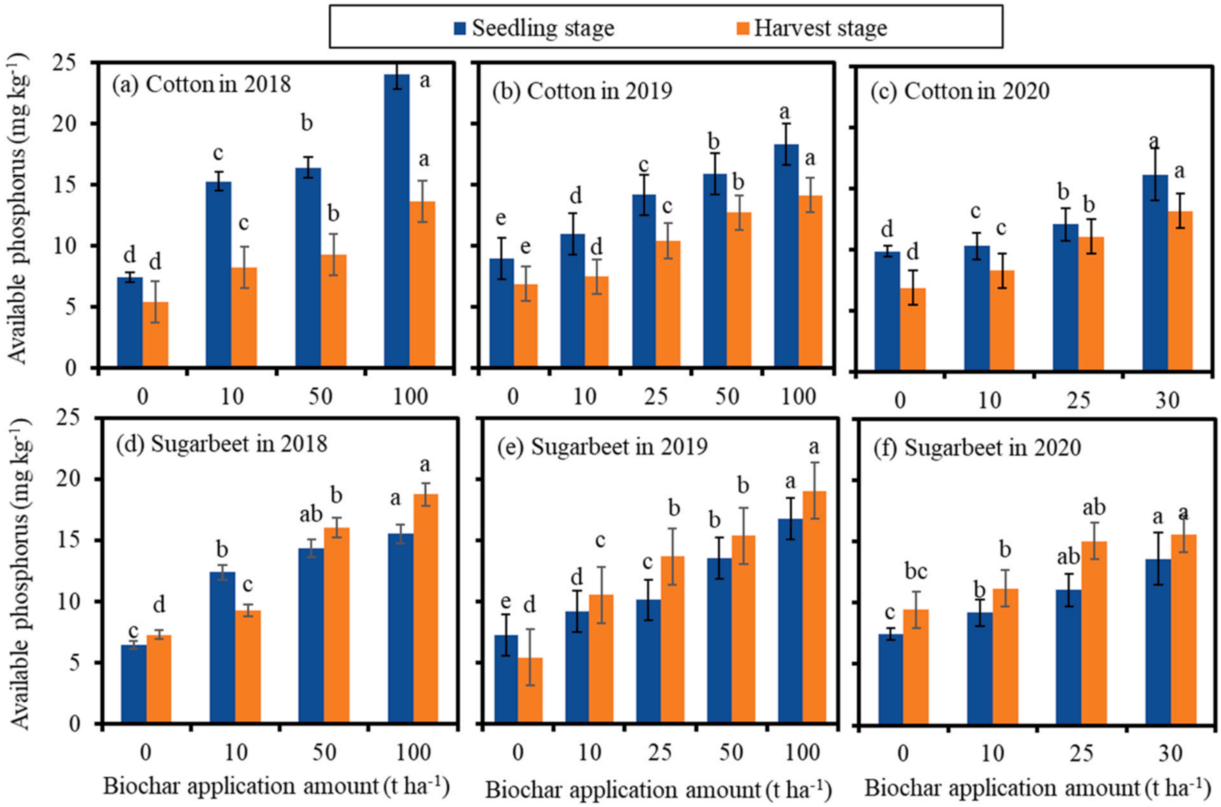


Fig. 9. Comparison of soil available phosphorus contents (mg kg^{-1}) for different biochar application treatments during seedling and harvest stages of cotton and sugarbeet in 2018, 2019, and 2020.

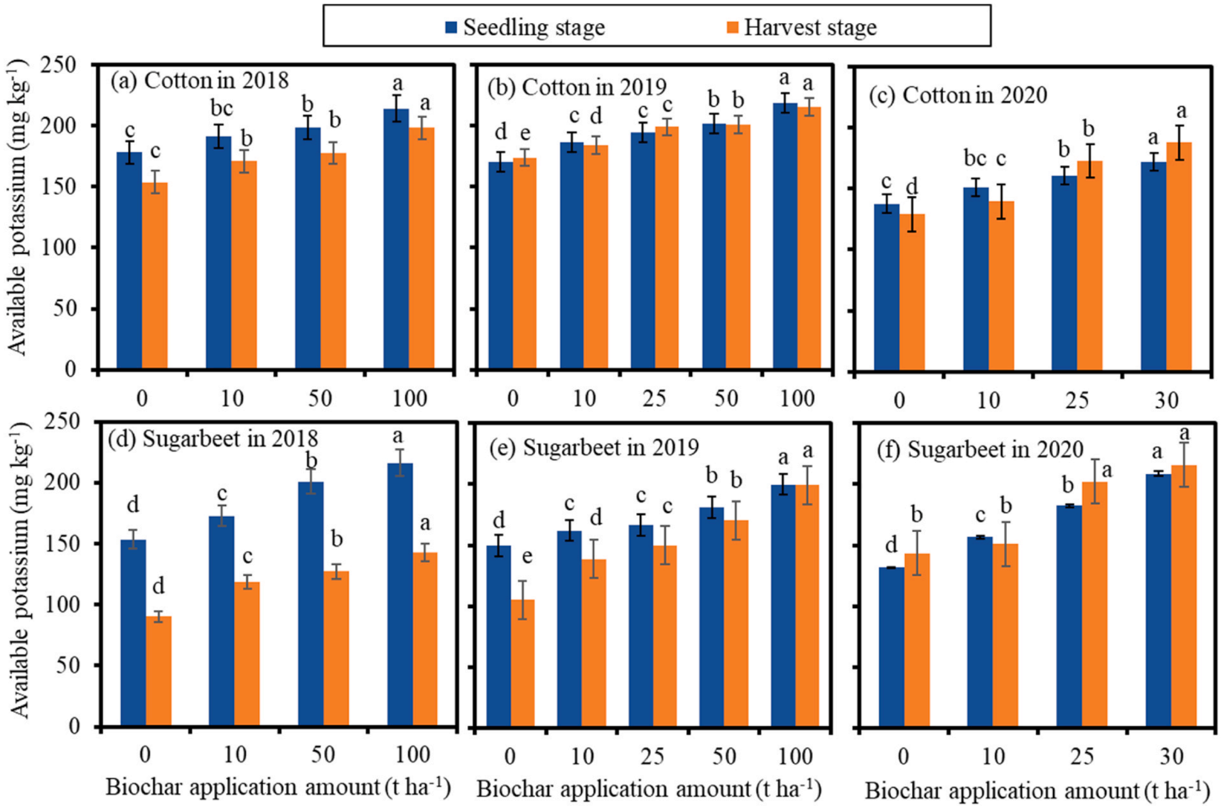


Fig. 10. Comparison of soil available potassium contents (mg kg^{-1}) for different biochar application treatments during seedling and harvest stages of cotton and sugarbeet in 2018, 2019, and 2020.

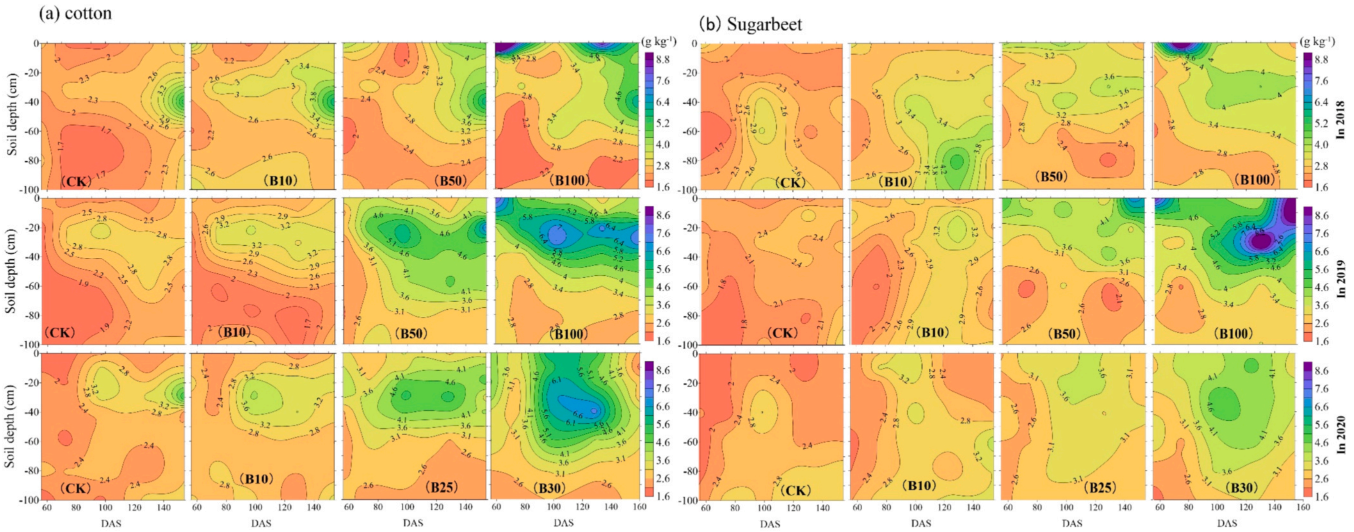


Fig. 11. Soil salt content over time showing the influence of various biochar application rates in the 2018–2020 crop growing seasons.

Table 4
Biochar application effects on soil salt content (g kg^{-1}) at 0–40 cm soil depth during the cotton seedling and boll-open stages in 2018, 2019, and 2020.

Year	Treatment	Seedling stage			Boll-open stage			Average	Change (%)
		Wide row	Narrow row	Bare soil	Wide row	Narrow row	Bare soil		
2018	CK	2.13c	2.33c	2.69d	3.53d	3.43d	4.13c	3.04c	-
	B10	2.58bc	2.86bc	3.77c	3.96c	4.66c	4.77c	3.77c	24.0
	B50	2.91b	3.27b	4.69b	4.68b	5.10b	7.13b	4.63b	52.3
	B100	6.06a	5.75a	7.14a	5.16a	7.05a	8.84a	6.67a	119.4
2019	CK	1.98b	2.01d	2.51e	2.69d	2.99d	4.15e	2.72e	-
	B10	2.14ab	3.08 cd	3.58d	3.10d	3.37 cd	4.68d	3.33d	22.4
	B25	2.30ab	3.52c	4.26c	3.93c	3.93c	5.34c	3.89c	43.0
	B50	2.62ab	4.12b	6.23b	4.94b	5.79b	6.50b	5.03b	84.9
	B100	5.18a	5.29a	7.68a	5.60a	8.46a	7.40a	6.60a	142.6
2020	CK	2.06d	2.31d	2.45d	2.55d	3.33d	3.51d	2.70d	-
	B10	2.71c	3.24c	3.34c	3.08c	4.00c	4.16c	3.42c	26.7
	B25	3.62b	4.27b	4.96b	3.94b	4.78b	5.54b	4.52b	67.4
	B30	4.47a	5.34a	5.97a	4.63a	5.61a	6.28a	5.38a	99.3
Multi-year mean	CK	2.06	2.22	2.55	2.92	3.25	3.93	2.82	-
	B10	2.48	3.06	3.56	3.38	4.01	4.54	3.51	24.4
	B25	2.96	3.895	4.61	3.935	4.355	5.44	4.205	55.2
	B50	2.77	3.70	5.46	4.81	5.45	6.82	4.83	68.6
	B100	5.62	5.52	7.41	5.38	7.755	8.12	6.635	131.0

Table 5
Biochar application effects on soil salt content (g kg^{-1}) at 0–40 cm soil depth during the sugarbeet seedling and sugar accumulation stages in 2018, 2019, and 2020.

Year	Treatment	Seedling stage		Sugar accumulation stage		Average	Change (%)
		Plastic mulching zone	Bare soil	Plastic mulching zone	Bare soil		
2018	CK	2.13c	3.10c	2.00c	2.16c	2.25c	-
	B10	2.56bc	4.02b	2.92b	2.95b	2.99bc	32.9
	B50	2.91b	5.20ab	3.29ab	3.47ab	3.51b	56.0
	B100	4.37a	5.77a	3.74a	3.99a	4.33a	92.4
2019	CK	2.18c	3.27d	2.58d	2.45d	2.54d	-
	B10	2.53c	4.95c	3.06d	2.81d	3.16d	24.4
	B25	2.97bc	7.33b	4.56c	4.97c	4.56c	79.5
	B50	3.56b	7.84b	5.19b	6.87b	5.37b	111.4
	B100	5.02a	13.92a	7.41a	11.93a	8.45a	232.7
2020	CK	1.74b	1.88d	2.22b	3.03b	2.14b	-
	B10	2.18b	2.33c	2.36b	3.27ab	2.44b	14.0
	B25	2.57ab	3.26b	2.81ab	3.83ab	2.97ab	38.8
	B30	3.08a	4.11a	3.30a	4.53a	3.56a	66.4
Multi-year mean	CK	2.02	2.75	2.27	2.55	2.31	-
	B10	2.42	3.77	2.78	3.01	2.86	23.8
	B25	2.77	5.30	3.69	4.40	3.77	59.2
	B50	3.24	6.52	4.24	5.17	4.44	83.7
	B100	4.70	9.85	5.58	7.96	6.39	162.6

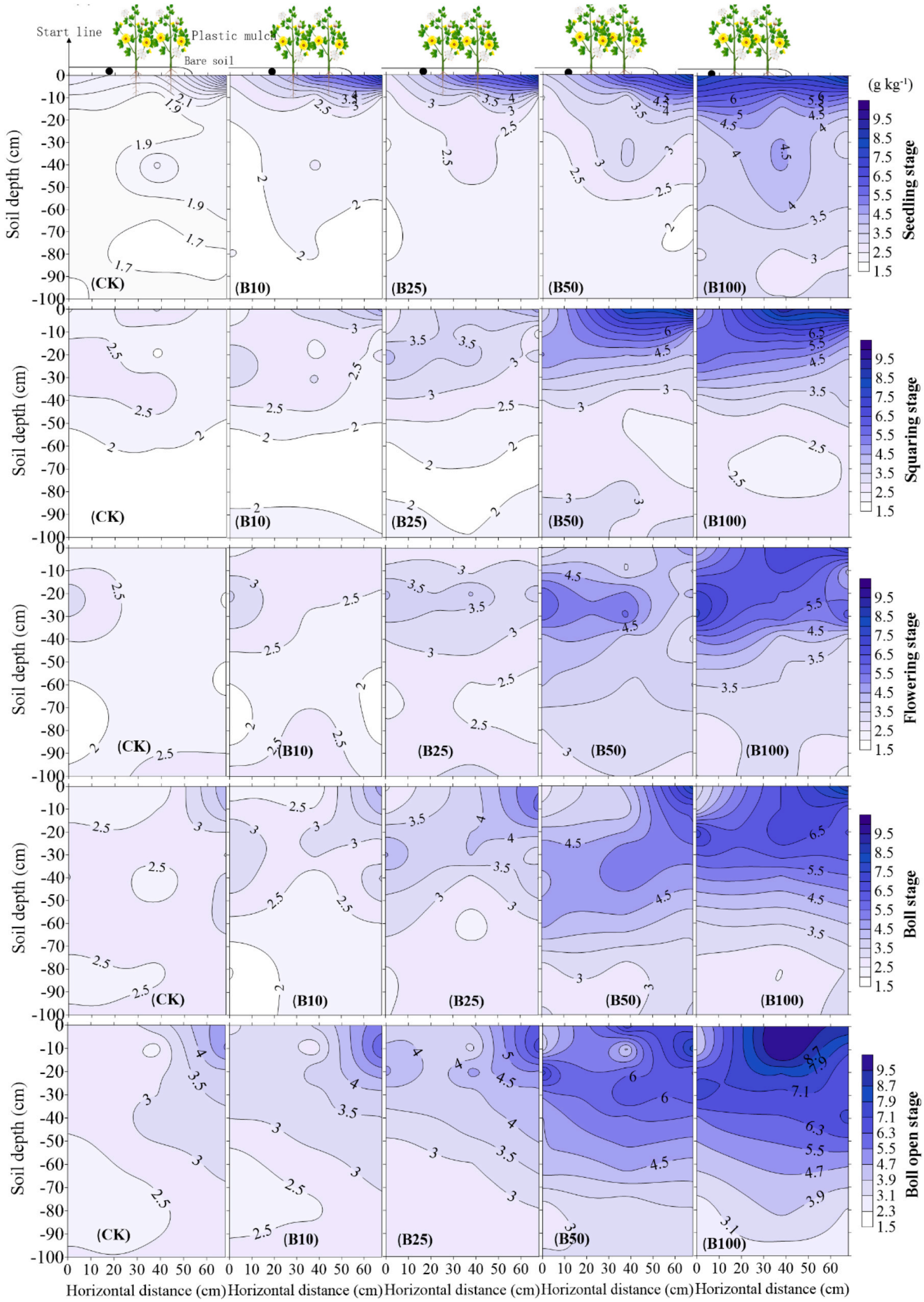


Fig. 12. Contour maps of soil salt content in the XOZ plane for various biochar application rates at key cotton growing stages in 2019.

oxygen metabolism, carbohydrate metabolism, and hormone signaling pathways, increasing the stress resistance of sugarbeet. Our study further supports the advantages of sugarbeet in improving saline-alkali soil quality and reducing soil salinity. Furthermore, biochar addition may enhance the salt tolerance and salt absorption of sugarbeet by promoting the adsorption of various ions and nutrients near the roots. Conversely, high salt stress promoted the synthesis of salt-tolerant hormones (such as allantoin) in sugarbeet, affecting the expression

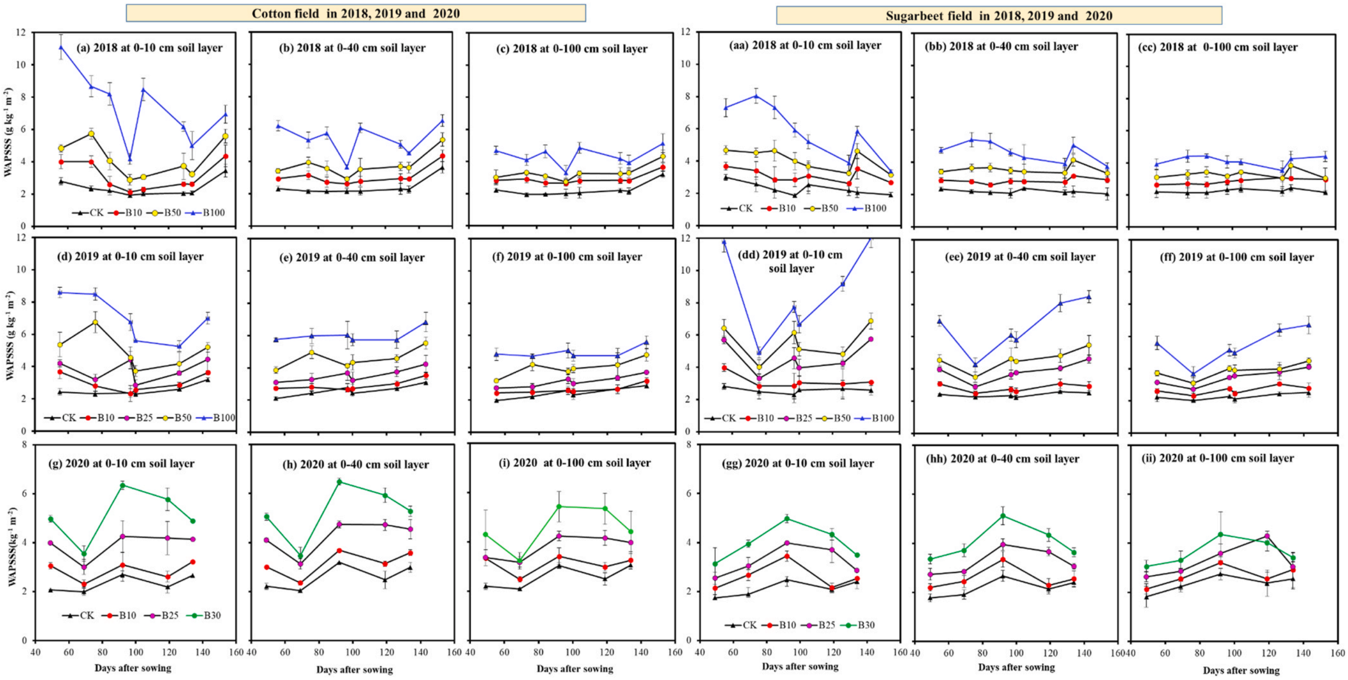


Fig. 13. Variations in weighted-average planar soil salt storage (WAPSSS) for different biochar application treatments during the 2018, 2019, and 2020 cotton and sugarbeet growing seasons.

patterns of related genes and forming a virtuous circle of 'salt stress–self-feedback–salt tolerance' (Zhang et al., 2023b).

4.3. *Most appropriate BAR for saline-alkali soils*

Determining the appropriate BAR is key to improving the soil environment (Li et al., 2022b). Previous studies have shown that biochar has unique advantages in improving soil quality, crop yield, and crop quality (Li et al., 2023; Liang et al., 2021). Biochar application has shown particular promise in improving the quality and yield of cultivated land affected by salinization, especially in saline-alkali soils (Wang et al., 2022; Zhang et al., 2023c). However, the high cost of biochar and its negative impact on the environment limit its widespread use, especially in arid and semi-arid regions with saline-alkali farmland (Yan et al., 2021a). Thus, it is necessary to explicit the optimal BAR in these regions to improve the economic benefits of agricultural production. Previous studies on different BAR in saline-alkali land focused on the impact on crop growth (Zhao et al., 2022), soil hardness (Liang et al., 2021), and soil moisture (Hou et al., 2022). Our three-year study on BAR in southern Xinjiang showed that different application rates significantly affected soil chemical properties in saline-alkali cotton and sugarbeet fields. Biochar also significantly affected the distribution and migration of soil salinity and nutrients. Within a specific application rate range, soil physical and chemical properties will significantly improve with increasing BAR, mainly due to the original biochar properties (Nascimento et al., 2023). However, this also means higher cost inputs, potentially reducing economic benefits. The risk of soil quality decline such as excessive soil salt storage, high nutrient concentration and heavy metal hazards also increases with increasing BAR. Based on our findings, we recommend a BAR of 10 t ha^{-1}, consistent with Wang et al. (2022) in a cotton–sugarbeet intercropping system and Li et al. (2022d) in sugarbeet fields.

5. Conclusions

Biochar application positively affected soil chemical environment in cotton and sugarbeet fields. Biochar application significantly increased soil Na^+ and K^+ contents at different crop growth stages. In the horizontal direction, plastic mulched zones generally had lower Na^+ and K^+ contents than bare soil, while in the vertical direction higher values were observed at the 0–40 cm soil layer.

Sugarbeet reduced soil ion contents more than cotton, while biochar application significantly increased soil nutrient contents (NO_3^--N, NH_4^+-N, SOC, available phosphorus, and available potassium), more so in the sugarbeet field except for NO_3^--N. Soil nutrient accumulation improved the most with 10 t ha^{-1} of biochar. Biochar application also significantly increased soil salinity and the salinity distribution at different directions was changed in the first year, but soil salinity in the crop cultivation layer (0–60 cm) was reduced with the cooperation of irrigation measures at 2019 and 2020. In our research, the BAR of 10 t ha^{-1} Significantly improved the soil chemical environment and was recommended. However, further experiments with more crops and longer durations are needed to understand the long-term effects of biochar application in saline-alkali land.

CRediT authorship contribution statement

Xingyun Qi: Conceptualization, Methodology, Software, Formal analysis, Investigation, Writing – original draft. **Guang Yang**: Resources, Investigation. **Yi Li**: Conceptualization, Methodology, Writing – review & editing, Supervision. **Zhenan Hou**: Conceptualization, Methodology, Supervision. **Penghui Shi**: Data curation. **Shibin Wang**: Investigation. **Xiaofang Wang**: Investigation, Data curation. **Jiaping Liang**: Conceptualization, Investigation, Data curation. **Benhua Sun**: Validation. **Kadambot H.M. Siddique**: Writing – review & editing. **Shufang Wu**: Methodology. **Hao Feng**: Project administration. **Xiaohong Tian**: Methodology. **Qiang Yu**: Methodology. **Xiangwen Xie:** Methodology.

Declaration of Competing 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.

Data Availability

Data will be made available on request.

Acknowledgments

This research was jointly supported by the National Key Research and Development Program of China (No. 2022YDF1900401), the Key Research and Development Program of Xinjiang (No. 2022B02020-2), and the High-end Foreign Experts Introduction Project (G2022172025L).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105893.

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