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Biochar Amendment Combined with Straw Mulching Increases Winter Wheat Yield by Optimizing Soil Water-Salt Condition under Saline Irrigation

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Abstract: The freshwater deficit is the major constraint to winter wheat production. Saline water irrigation could alleviate wheat water stress while increasing the risk of soil salinization, which would result in wheat yield reduction due to additional salt stress. The objective of the present study is to explore the effect of a straw-returning mode to promote winter wheat production under saline water irrigation. A field experiment was conducted during the winter wheat growing seasons of 2017–2018 and 2018–2019. Four returning modes were set, based on an equivalent carbon input: straw mulching (SM), biochar amendment (BA), straw mulching combined with biochar amendment (SM+BA), and the control without straw-returning (CK), along with three salinity levels of irrigation water: 0.47 dS m^{-1} (I0, freshwater), 3.25 dS m^{-1} (I1), and 6.75 dS m^{-1} (I2). Saline water irrigation alone triggered soil salt accumulation and reduced the wheat grain yield by 9.43—-18.19%. Returning straw to fields increased soil organic carbon content by 16.41—-52.21% and decreased soil bulk density by 0.69—-1.46%. The highest increase in wheat grain yield (16.60—-21.80%) was always obtained when using treatment SM+BA, due to the increased soil moisture content (3.15—-12.31%) and lower salt levels (24.79—-44.29%) compared to CK. The results of the present study established that SM+BA provided better soil water–salt conditions and nutrient environment for winter wheat growth than a single treatment. Thus, the combined application of SM and BA was shown to be a proper mitigating strategy to cope with the adverse effects of saline irrigation on winter wheat production and to promote the sustainable use of saline water irrigation.

Keywords: saline water irrigation; straw mulching; biochar amendment; wheat yield; soil water-salt distribution

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1. Introduction

Winter wheat (*Triticum aestivum* L.) is an important component of human food consumption that plays a pivotal role in global food security [1]. In China, the area given over to wheat cultivation accounts for 22% of the total arable land, which contributes to 21% of total Chinese grain production [2]. Winter wheat production is highly dependent on irrigation, due to insufficient rainfall during the wheat-growing period [3,4]. However, with the acceleration of modernization processes in China, the demand from municipal and industrial consumers for freshwater is increasing, constantly putting pressure on the available water for agricultural production [5]. Thus, freshwater shortage is becoming the main obstacle to optimal wheat yields [6].

In recent years, unconventional water resources have been explored for agricultural production, in response to a possible food security crisis [7,8]. Saline water is an important component of unconventional water resources and is used to replace freshwater for agricultural irrigation to alleviate freshwater shortages [9]. Cavalcante et al. [10] demonstrated that supplemental irrigation with saline water could reduce plant water stress during drought scenarios, causing an increase in physical water productivity. Wheat is classified as a moderately salt-tolerant crop, with an irrigation-water salinity threshold of about 5–8 dS m^{-1}, so it is often irrigated with saline water during the dry period to ensure a good final yield [11–13]. Wang et al. [14] reported that irrigation with 5 dS m^{-1} of saline water achieved more than 96% of the maximum yield of winter wheat, but also remarkably increased the salinity to a depth of 0–40 cm of topsoil. Long-term saline water irrigation will inevitably intensify the accumulation of soil salt. Excessive salts in the soil will hinder the physiological growth of crops, including inhibiting the uptake of nutrients and creating an internal ion imbalance, thus reducing crop yields [15]. Jiang et al. [16] revealed that soil salt levels notably increased after three years of continuous irrigation with saline water of 3.2–6.1 dS m^{-1}, and the wheat yield reduced by 13.35–21.12%. In addition, continuous saline water irrigation could raise the content of exchangeable sodium in soil, leading to the reduction of soil physiochemical properties, such as soil bulk density, saturated hydraulic conductivity, soil organic carbon, and so forth, which also has a negative effect on wheat production [17,18]. This phenomenon is even more problematic in arid and semi-arid regions. Thus, measures to restrain soil salt accumulation need to be considered in advance when saline water is adopted as an alternative source for agricultural irrigation.

Organic material amendment is considered a convenient and effective agronomic measure by which to enhance the quality of the soil affected by salinization and facilitate wheat production under saline water irrigation conditions [11,19,20]. In China, straw is a common organic material used to improve soil fertility in fields, and its annual production is about 8×10^8 t [21]. Straw is rich in nutrient elements, such as nitrogen (N), phosphorus (P), potassium (K), and carbon ©, which could be released into the soil to promote crop growth when in a straw-returning mode [22,23]. Returning straw to fields not only creates favorable growing conditions for crops by improving the soil water-salt distribution and nutrient content but also replaces lost soil organic carbon; therefore, the scientific and rational use of straw resources is especially important for areas irrigated with saline water [24,25]. Straw mulching has been widely used in arid and semiarid areas to adjust the soil water-salt conditions. Luo et al. [26] demonstrated that straw mulching could prevent soil water from escaping into the atmosphere and improve soil water-holding capacity after straw decomposition, thus increasing wheat productivity in semiarid areas. Paul et al. [24] also reported that straw mulching in salt-affected soil significantly increased the soil water content by 3–9% and promoted sunflower root development, leading to a rise of 23% in sunflower yield. Sarangi [27] confirmed that straw mulching reduced the soil salinity from 5 to 3 dS m^{-1} and conserved soil moisture by 4–8%, thereby increasing potato yield. In summary, straw mulching could decrease soil water loss and restrain soil salt accumulation in the topsoil by shading the topsoil, which could reduce soil surface evaporation and inhibit the salts from moving upward from the subsoil [24,26–29].

Recently, biochar amendment has been considered as an alternative and efficient method by which to combat the decline in salt-affected soil quality [11,19,30]. Biochar is a carbonaceous material produced by the pyrolysis of plant biomass, which has the characteristics of good pore structure, specific surface area, and strong ion exchange capacity [31,32]. Biochar can help increase the porosity of salinized soil, improve soil particle size, and enhance the stability of aggregates [33]. Moreover, biochar can help crops to promote root growth, improve nutrient absorption, alleviate salt stress, and thereby increase crop yield [34]. Previous studies have shown that in current practice, the amount of biochar application is typically distributed between 10 and 75 t ha^{-1}, the ratio of which is influenced by soil texture, biochar raw material, and climate conditions [35–37]. Thus, biochar amendment alone may not be a more suitable choice than straw mulching for field management in a saline environment, considering the benefit ratio of input to output [21,34]. Therefore, it is worthwhile to explore the possibility of using straw in combination with biochar, which may help to reduce the cost of using biochar alone.

Straw-returning practices, including straw mulching and biochar amendment, might be a reasonable choice to improve crop production. However, most of the previous studies have concentrated on utilizing straw mulching or biochar amendment alone for agricultural production, while few of the published reports are related to their combined use in saline environments. Meanwhile, the most suitable returning mode for winter wheat under saline water irrigation is still unknown. The objectives of this study were, firstly, to investigate the changes in soil properties and the resulting wheat yield responses, and secondly, to reveal the potential mechanisms of restraining soil salt accumulation under different straw-returning modes when irrigated with saline water. We hypothesized that: (i) the combined application of biochar amendment and straw mulching is the most suitable straw-returning mode for ensuring wheat production under saline water irrigation; (ii) soil water-salt conditions could be the reason for differences in the wheat yields under different straw-returning modes; (iii) straw-returning practices could mitigate the adverse effect of saline irrigation on soil properties.

2. Materials and Methods

2.1. Study Site Description

A two-year field experiment was conducted at the Water-Saving Park of Hohai University (118°50′ E, 31°57′ N) during the winter wheat growing season (from November 2017 to June 2018 and from November 2018 to June 2019). The climate of the experiment region was characterized by a subtropical monsoon climate with an annual average temperature of 15.3 °C, mean annual precipitation of 1073 mm, and mean annual evaporation of approximately 900 mm [38]. The daily meteorological data during the two winter wheat growing seasons were recorded by an automatic weather station at the experiment site (Figure 1).

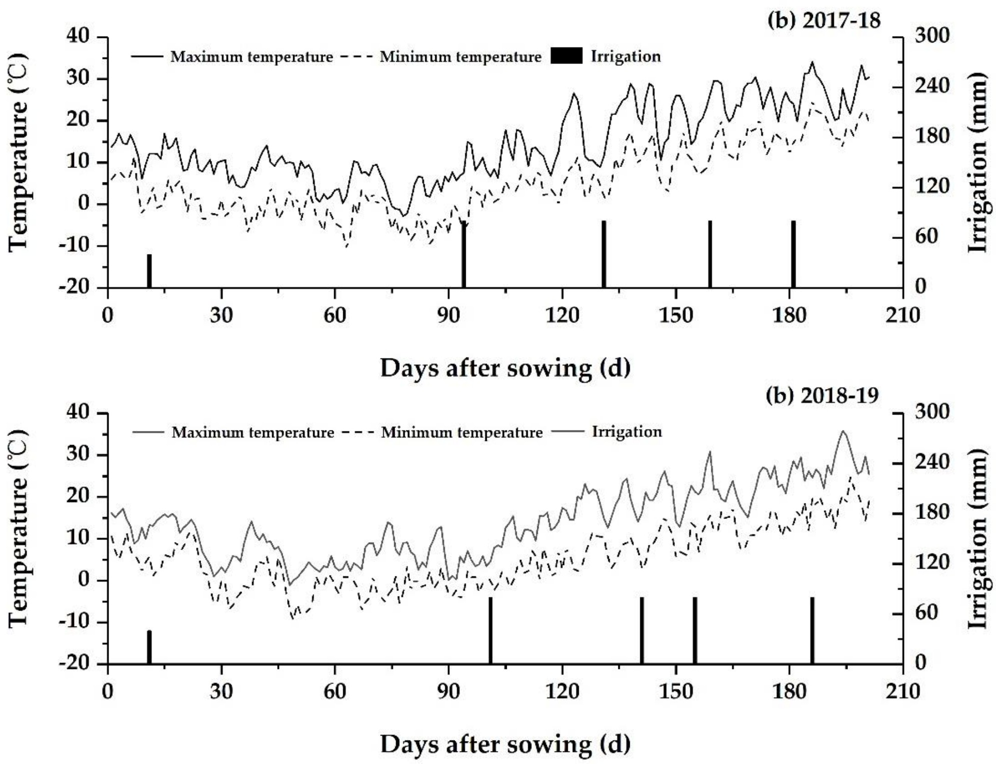

Figure 1. The values recorded for temperature and irrigation events during the experiment.

2.2. Experimental Design

The experiment was established as a 4 × 3 factorial, carried out in a randomized block design with three replications. The treatments tested in the experiment comprised four straw-returning modes (CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment) and three testing the salinity of irrigation water (I0: 0.47 dS m^{-1}, I1: 3.25 dS m^{-1}, and I2: 6.75 dS m^{-1}). Freshwater for irrigation was collected from tap water pumped through pipes from the local waterworks. Na_2SO_4, $CaCl_2$, NaCl, and $MgCl_2$ (2:1:2:1) were mixed with tap water to prepare saline water for irrigation that had a specified salinity, according to the proportion of salt content in the local subsurface saline water. Straw for returning to the field was the rice straw harvested during the previous season from around the study station, while the straw-returning amount was set at 7.5 t ha^{-1} for treatment SM, according to local rice straw production. The content levels of C, N, P, and K in the tested rice straw were 423.9 g kg^{-1}, 6.1 g kg^{-1}, 1.5 g kg^{-1}, and 19.6 g kg^{-1}, respectively. The biochar was prepared via the pyrolysis of rice straw for 4–6 h at a temperature of 550–600 °C and low oxygen conditions. The initially tested biochar properties are shown in Table 1. The biochar dosage was set at 5.5 t ha^{-1} and 2.0 t ha^{-1} in treatments BA and SM+BA, respectively, in order to maintain an equivalent intake of C as far as possible. Slight secondary salinization occurred in the tested soil after years of saline water irrigation experiments. The soil physicochemical properties were measured in the laboratory at the beginning of the present experiment (Table 1).

Table 1. Physical and chemical properties of the initially tested soil (0–15 cm), the biochar, and the straw.

Attribute	Soil	Biochar	Straw
pH	7.76	9.48	–
Electrical Conductivity (dS m^{-1})	1.34	3.92	–
Bulk Density (g cm^{-3})	1.37	0.21	–
Organic carbon (g kg^{-1})	8.0	587.6	423.9
Total nitrogen (g kg^{-1})	1.95	32.6	6.1
Available phosphorus (g kg^{-1})	0.021	11.4	1.5
Available potassium (g kg^{-1})	0.064	48.2	19.6
Calcium (g kg^{-1})	0.018	0.016	–
Sodium (g kg^{-1})	0.105	0.032	–
Magnesium (g kg^{-1})	0.014	0.024	–
Cation exchange capacity (cmol kg^{-1})	18.2	76.1	–
Field capacity (cm^3 cm^{-3})	35.2	–	–
Silt (%)	37.88	–	–
Sand (%)	31.29	–	–
Clay (%)	30.83	–	–

The winter wheat material used was Sumai 10 (*Triticum aestivum* L.), a local cultivar produced by the Fengqing Seed Technical Company (Jiangsu, China). Sumai 10 is usually sown from October to November and is harvested from May to June, with a potential grain yield of 7.3–8.7 t ha^{-1}. The wheat seeds were sown at a density of approximately 300 kg ha^{-1} in a field plot, and each plot size was 2 × 1 m^2. The bottom of each plot was equipped with a gravel layer for free drainage. Before the winter wheat was sown, 0–15 cm of the soil layer of the plot was tilled artificially, then biochar was incorporated into the soil at the same time. Fertilization and other field management methods followed the local practical experience, whereby 600 kg ha^{-1} of compound fertilizers (N:P:K = 21:19:10) was applied in total. Straw-mulching treatments were implemented after the winter wheat was sown. A mobile rain shelter was used to limit the effects of natural rainfall during the growing seasons, in order to accurately explore the effects of saline water irrigation on the soil properties and winter wheat yields. The saline water irrigation events were arranged in the later stages to guarantee the seeding emergence rate [13]. The irrigation regime is shown in Table 2. After the winter wheat was harvested, the wheat straw was removed from the experiment plots. The 2017–2018 trial was repeated in the 2018–2019 season, and all treatment regimens were administered again in the same fixed positions.

2.3. Sampling and Measurements

Soil samples were collected before wheat sowing and after harvesting. Three soil samples were collected with a soil auger at intervals of 15 cm (0–15 cm, 15–30 cm, 30–45 cm, and 45–60 cm) in each plot and were mixed for soil moisture and salt content measurement. One of the collected soil samples was placed in a 105 °C oven and dried for 24 h to achieve a constant weight for calculating the soil gravimetric moisture content using the weighing method, while the other samples were air-dried to pass through a 1 mm sieve for measuring the electrical conductivity of a 1:5 ratio of soil-water leachate ($EC_{1:5}$) using a conductivity meter (DDBJ-350, Shanghai, China). Three undisturbed soil cores were collected using a cutting ring (100 cm^3) at 0–20 cm depth in each plot for determining soil bulk density (BD).

Table 2. Irrigation regime for winter wheat growth during two growing seasons.

Year		Sowing	Greening	Jointing	Heading	Filling	Total
		Fresh Water		Saline Water			
2017–2018	Date	21 Nov.	12 Feb.	21 Mar.	18 Apr.	10 May	
	Amount	40 mm	80 mm	80 mm	80 mm	80 mm	360 mm
2018–2019	Date	21 Nov.	19 Feb.	31 Mar.	14 Apr.	15 May	
	Amount	40 mm	80 mm	80 mm	80 mm	80 mm	360 mm

Composite soil samples were collected using an auger from the upper 20 cm layers on three random points in each plot and were then mixed thoroughly. The air-dried composite soil sample was ground and passed through a 0.15 mm sieve for the determination of soil chemical properties. Organic content was detected using the $K_2Cr_2O_7$ titration method [39]. The total nitrogen content was determined using the Kjeldahl method [40]. The available phosphorus was measured using the Olsen method [41]. The available potassium was analyzed using the ammonium acetate extraction method [42].

At harvest, all the plants were collected from each field plot to determine the above-ground biomass, spike numbers, 1000-grain weight, and grain yield. The kernel number per spike was measured additionally by selecting 10 plants randomly from the harvested plants. Before all measures were taken, the harvested plant samples were oven dried at 105 °C for 30 min to halt biological enzyme activity and were then dried at 75 °C for about two days until they were a constant weight.

2.4. Evaluation Methods

The soil salt content was calculated using the following empirical formula, which was developed in the local laboratory (Figure 2):

$$SS_i = 3.203EC_{1:5,i} + 0.103$$

where $EC_{1:5,i}$ is the electrical conductivity of the 1:5 soil-water leachate in layer i, in mS cm^{-1}. SS_i is the soil salt content of layer i, in g kg^{-1}.

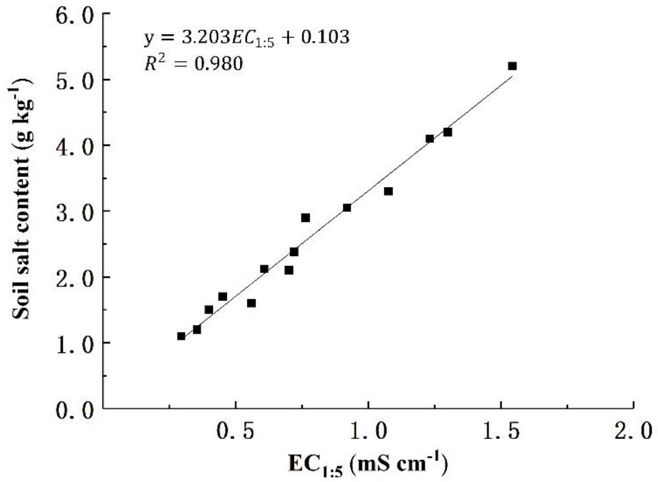

Figure 2. Relationship between the electrical conductivity of 1:5 soil-water extract ($EC_{1:5}$) and soil salt content.

2.5. Statistical Analysis

An analysis of variance (ANOVA) was conducted with the SPSS 18.0, and the least significant difference (LSD; $p < 0.05$) was used to detect the statistical significance of the treatment effects.

3. Results

3.1. Effects on Soil Moisture Content

The soil moisture content was significantly affected by the straw-returning modes, as shown in Figure 3, but no significant difference was found among the irrigation water salinity levels. Soil moisture content distribution within the 60 cm profile indicated that no matter what straw-returning mode was adopted for the treatments, the soil moisture content was higher than in the control treatment with no straw. For the entire 60 cm soil profile, the average soil moisture content of SM, BA, and SM+BA increased by 2.84%, 1.48%, and 3.48% compared to CK in 2017–2018 and increased by 3.99%, 2.12%, and 4.25% in 2018–2019, respectively. In addition, the soil moisture contents of I1 and I2 were 1.40% and 2.12% lower than I0 in 2017–2018, and 1.82% and 2.60% lower in 2018–2019, respectively. However, no significant difference was found among irrigation water salinity levels. Compared with the no-straw-mulching treatments (CK and BA), the mean soil moisture content of the upper 15 cm profile under two straw mulching treatments (SM and SM+BA) increased by 4.43% in 2017–2018 and by 5.35% in 2018–2019. Similar results were found in the 15–30 cm layers, but the soil moisture content of SM was lower than that of SM+BA in 2017–2018, while it was higher in 2018–2019. However, the average soil moisture content below 30 cm in depth when given no biochar amendment (CK and SM) was lower than that when under treatments with biochar amendment (BA and SM+BA).

3.2. Effects on Soil Salt Content

3.2.1. Vertical Distribution of Soil Salt

The vertical distribution of soil salt in the 60 cm soil profile was significantly affected by both the straw-returning modes and irrigation water salinity, as shown in Figure 4. Treatments with all saline water irrigation treatments had a similar vertical distribution of soil salt. In particular, the soil salt content decreased with increasing soil depth; the highest soil salt value was always found in the uppermost topsoil layer of 0–15 cm. In addition, soil salt content within the 0–15 cm soil layer increased significantly with the increase in irrigation water salinity. For the upper 15 cm profile, the mean soil salt contents of I1 and I2 were 1.75 g kg^{-1} and 3.37 g kg^{-1} higher than that of I0 in 2017–2018, and 2.31 g kg^{-1} and 4.52 g kg^{-1} higher in 2018–2019, respectively. A significant difference in soil salt content within the upper 15 cm profile was also observed between the straw-returning modes, especially during the harvesting stage of 2018–2019, under irrigation salinity with I2 (Figure 4f). For instance, the soil salt content of SM, BA, and SM+BA in the upper 15 cm profile significantly decreased, on average, by 1.88 g kg^{-1}, 3.16 g kg^{-1}, and 4.06 g kg^{-1}, compared with that of CK in 2018–2019, respectively. Similar results were found in 2017–2018 (Figure 4c), but no significant differences among the straw-returning treatments were observed.

3.2.2. Soil Salt Content within the 0–60 cm Soil Profile

The soil salt content within the 0–60 cm soil profile was influenced by the straw-returning modes and irrigation water salinity (Figure 5). In particular, the average soil salt content in the 0–60 cm soil depth showed a significant increasing trend as irrigation water salinity increased, while the mean value of soil salt content with all treatments in 2018–2019 was 0.21 g kg^{-1} higher than that in 2017–2018. Within each saline water irrigation treatment, the application of straw-returning resulted in lower soil salt content compared with the no-straw control, and soil salt content within the 60 cm soil profile showed a rule of CK > SM > BA > SM+BA. The highest (3.36 $\pm$ 0.09 g kg^{-1}) and lowest (1.30 $\pm$ 0.11 g kg^{-1}) soil salt content values were observed for treatment CK with I2 in 2018–2019 and SM+BA&I1 in

2017–2018, respectively. However, no significant differences were found among SM, BA, and SM+BA under irrigation water salinity with I1 in 2017–2018. Significant differences were obtained among all treatments when only under irrigation water salinity of I2 in 2018–2019. In particular, SM, BA, and SM+BA decreased the soil salt content within the 60 cm soil profile by 0.73 g kg^{-1}, 1.04 g kg^{-1}, and 1.49 g kg^{-1}, compared to CK under irrigation water salinity with I2 in 2018–2019, respectively.

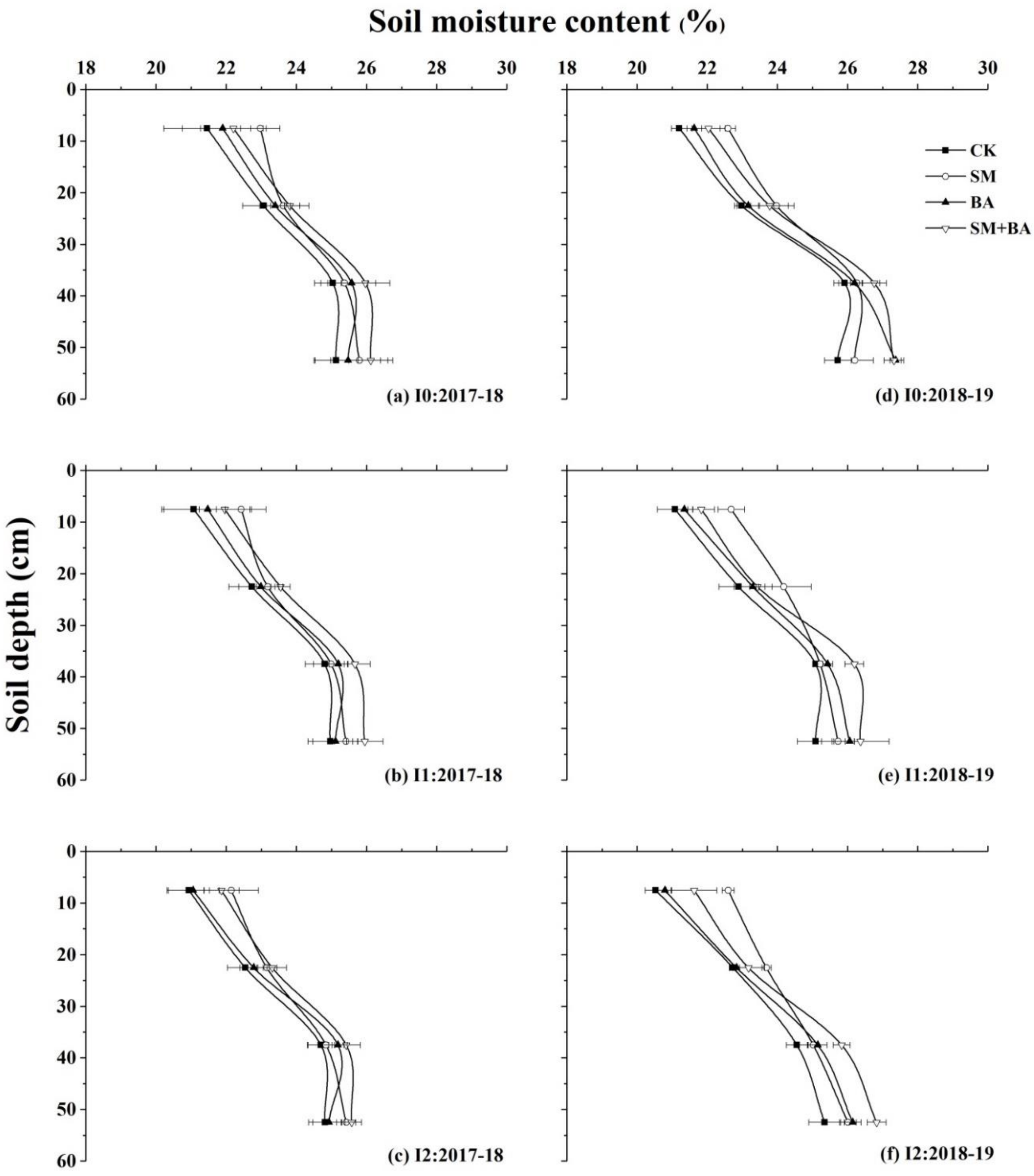

Figure 3. Vertical distribution of soil moisture content within the 0–60 cm soil profiles under different straw-returning modes and irrigation water salinity levels at the time of winter wheat harvest during the 2017–2018 and 2018–2019 growing seasons, respectively. The values are means of three replications ± standard deviation. CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment; I0, I1, and I2 indicate an irrigation salinity of 0.47 dS m^{-1}, 3.25 dS m^{-1}, and 6.75 dS m^{-1}, respectively.

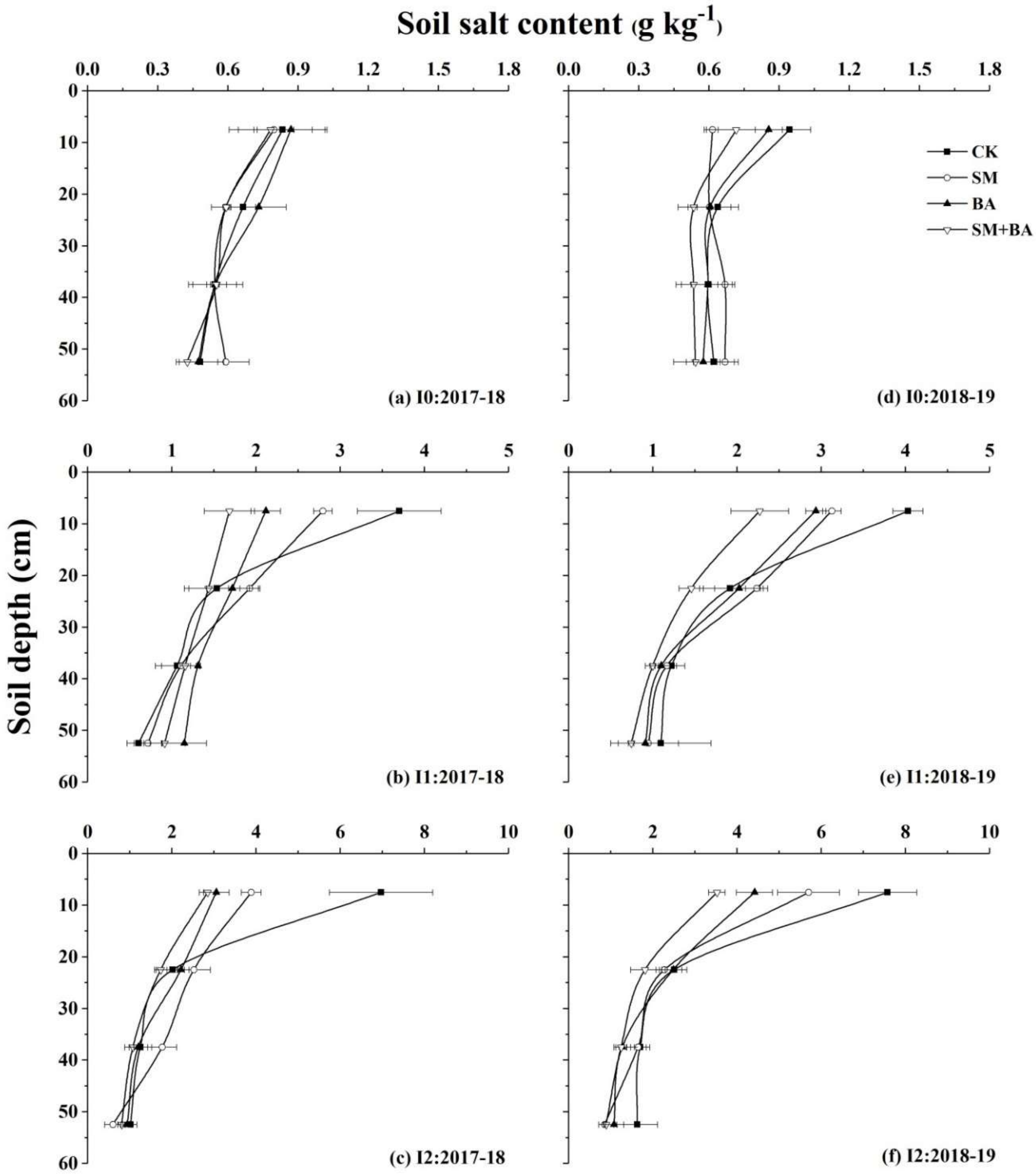

Figure 4. Vertical distribution of soil salt content within the 0–60 cm soil profiles under different straw-returning modes and irrigation water salinity levels at winter wheat harvest during the 2017–2018 and 2018–2019 growing seasons, respectively. The values are means of three replications ± standard deviation. CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment; I0, I1, and I2 indicate an irrigation salinity of 0.47 dS m^{-1}, 3.25 dS m^{-1}, and 6.75 dS m^{-1}, respectively.

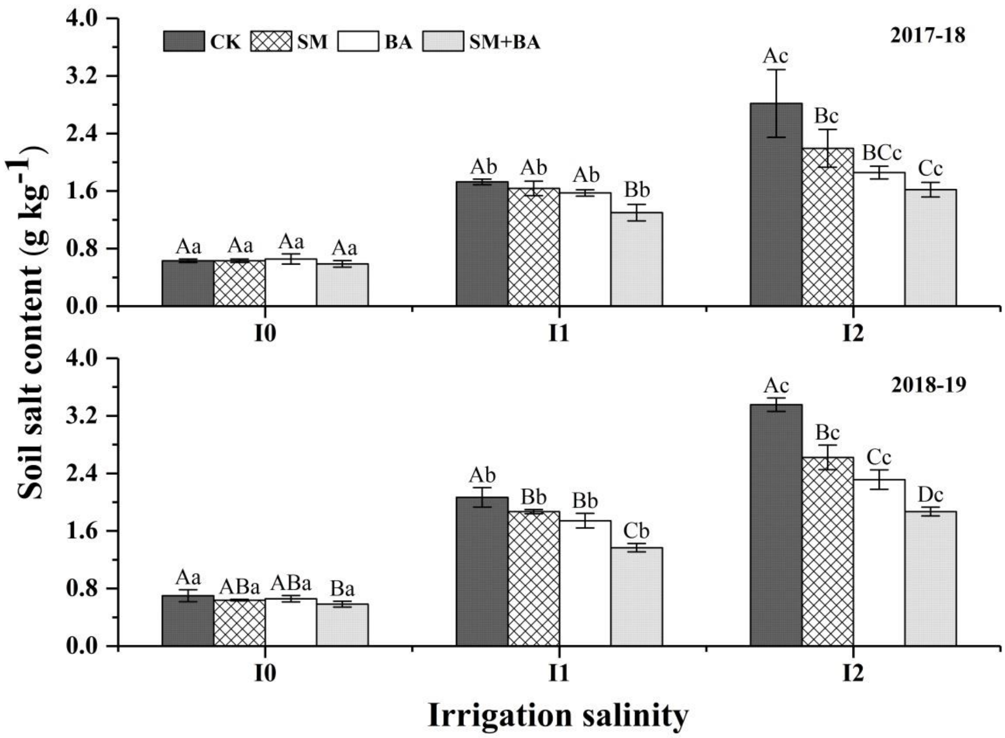

Figure 5. The effects of straw-returning modes and irrigation water salinity on soil salt content in 2017–2018 and 2018–2019, respectively. The values are means of three replications, ± standard deviation. For each growing season, different uppercase and lowercase letters indicate a significant difference ($p < 0.05$) among straw-returning modes (for a given irrigation regime) and irrigation water salinity levels, respectively. CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment; I0, I1, and I2 indicate an irrigation salinity of 0.47 dS m^{-1}, 3.25 dS m^{-1}, and 6.75 dS m^{-1}, respectively.

3.3. Effects on Soil Organic Carbon and Bulk Density

3.3.1. Soil Organic Carbon (SOC)

As presented in Figure 6, the soil organic carbon (SOC) content was significantly affected by the straw-returning modes, saline water, and salinity. The SOC content decreased significantly with the increasing salinity of the saline water. For instance, the SOC content of I1 and I2 was 0.49 g kg^{-1} and 1.64 g kg^{-1} lower than that of I0 in 2017–2018, and 1.17 g kg^{-1} and 2.20 g kg^{-1} lower in 2018–2019, respectively. Nonetheless, the application of the straw-returning treatment to fields significantly increased the SOC content. The highest value (12.85 ± 0.37 g kg^{-1}) of SOC content was found for treatment BA with I0 in 2018–2019, while the lowest value (6.35 ± 0.24 g kg^{-1}) was obtained for treatment CK with I3 in 2018–2019, respectively. When the salinity level of irrigation water was at the same level, the lowest SOC content was always found in treatment CK, which might be due to the absence of direct carbon intake. Treatment BA was observed to be the most effective in enhancing SOC content, but there was no significant difference between treatments BA and SM+BA in 2018–2019. The SOC contents of SM, BA, and SM+BA increased by 16.41%, 40.70%, and 29.39% in 2017–2018, and 31.03%, 54.23%, and 52.21% in 2018–2019, respectively, in comparison with that in treatment CK, on average.

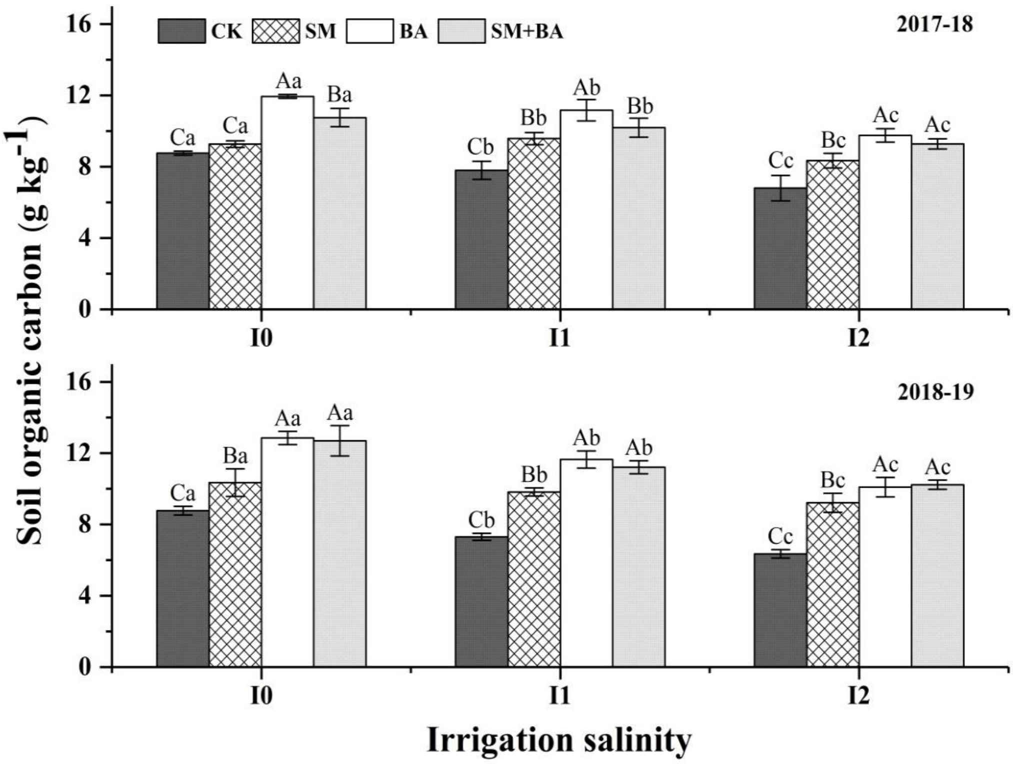

Figure 6. The effects of the straw-returning modes and irrigation water salinity on soil organic carbon (SOC) levels in 2017–2018 and 2018–2019, respectively. The values are means of three replications ± standard deviation. For each growing season, the different uppercase and lowercase letters indicate a significant difference ($p < 0.05$) among straw-returning modes (for a given irrigation regime) and irrigation water salinity levels, respectively. CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment; I0, I1, and I2 indicate irrigation salinity levels of 0.47 dS m^{-1}, 3.25 dS m^{-1}, and 6.75 dS m^{-1}, respectively.

3.3.2. Soil Bulk Density (BD)

As demonstrated in Figure 7, both straw-returning modes and irrigation water salinity influenced the soil bulk density (BD). With an increase in irrigation salinity level, the soil BD of I1 and I2 increased by 0.95% and 2.05% in 2017–2018 and by 0.55% and 1.37% in 2018–2019, respectively in comparison with treatment I0. Saline water irrigation caused a significant increase in soil BD, while straw-returning could minimize the negative effect of saline water irrigation on soil BD. Compared to the no straw-returning (CK) tests, the soil BD values of SM, BA, and SM+BA decreased by 0.69%, 1.47%, and 1.46% in 2017–2018, and by 0.80%, 1.41%, and 1.21% in 2018–2019, respectively. Although the straw-returning treatments could notably reduce the soil BD, the difference among straw-returning mode treatments was not quite significant, especially for the SM and SM+BA, which showed a significant difference only under the conditions of the I1 treatment in 2018–2019.

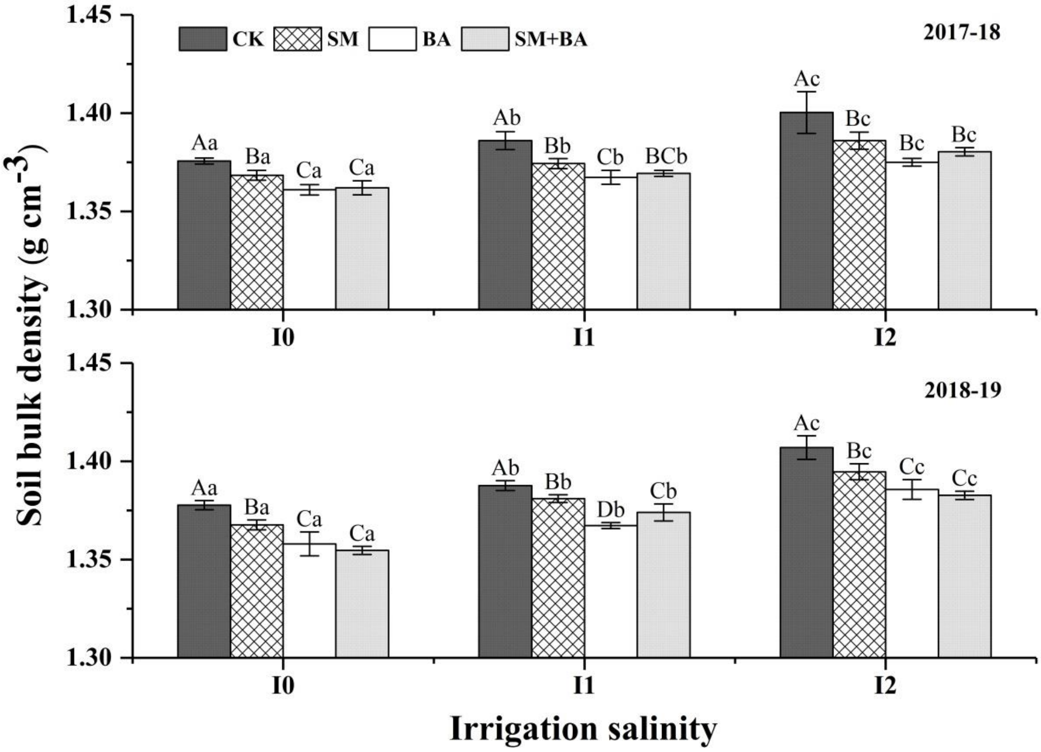

Figure 7. Effects of straw-returning modes and irrigation water salinity on the soil bulk density (BD) in 2017–2018 and 2018–2019, respectively. The values are the means of three replications ± standard deviation. For each growing season, the different uppercase and lowercase letters indicate a significant difference ($p < 0.05$) among the straw-returning modes (for a given irrigation regime) and irrigation water salinity levels, respectively. CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment; I0, I1, and I2 indicate irrigation salinity levels of 0.47 dS m^{-1}, 3.25 dS m^{-1}, and 6.75 dS m^{-1}, respectively.

3.4. Effects on Winter Wheat Yield

Table 3 listed the effect of straw returning modes and irrigation water salinity on the winter wheat yield parameters, including aboveground biomass, grain yield, spike number, kernel number, and 1000-grain weight in 2017–2018 and 2018–2019. The main effects of the straw-returning modes and irrigation water salinity on these yield indicators were detected, except for identifying the kernel number, but no interaction effect was found. With the increase in irrigation water salinity, the aboveground biomass, grain yield, spike number, and 1000-grain weight decreased remarkably. For example, under the conditions of no straw-returning, the winter wheat yield of I1 and I2 decreased by 9.43% and 17.26% in 2017–2018, and by 10.40% and 18.19% in 2018–2019, respectively, in comparison with that testing I0. Although saline water irrigation also reduced the average kernel number, no significant differences were found, except under the I2 conditions in 2018–2019. Similarly, the straw-returning modes did not have a significant effect on kernel number, but all the yield indicators of winter wheat were improved under an additional treatment with straw-returning, compared to saline water irrigation alone, especially in the presence of biochar addition. For instance, under the condition of treatment I2, the grain yield of winter wheat for SM, BA, and SM+BA increased by 7.22%, by 14.61%, and 20.55%, compared with that for CK in 2017–2018, respectively. The maximum yield was always obtained for the treatment with SM+BA, regardless of the salinity level of saline water irrigation. Compared to CK, SM+BA increased the winter wheat yield by 17.60% and 20.55% in 2017–2018, 21.80%, and 21.24% in 2018–2019 under a water salinity of I2 and I3, respectively.

Table 3. Mean values of the winter wheat grain yield parameters, including the aboveground biomass, grain yield, spike number, kernel number, and 1000-grain weight for the different straw-returning modes and irrigation water salinity in 2017–2018 and 2018–2019.

Irrigation Salinity	Straw Treatment	Aboveground Biomass ($t\ ha^{-1}$)		Grain Yield ($t\ ha^{-1}$)		Spike Number (m^{-2})		Kernel Number ($spike^{-1}$)		1000-Grain Weight (g)	
		2017–2018	2018–2019	2017–2018	2018–2019	2017–2018	2018–2019	2017–2018	2018–2019	2017–2018	2018–2019
I0	CK	15.23 ^{aC}	14.89 ^{aC}	7.53 ^{aB}	7.31 ^{aB}	504 ^{aC}	510 ^{aC}	33.70 ^{aA}	34.10 ^{aA}	42.48 ^{aB}	41.93 ^{aB}
	SM	15.91 ^{aB}	16.02 ^{aB}	7.63 ^{aB}	7.76 ^{aB}	527 ^{aAB}	532 ^{aB}	34.80 ^{aA}	33.93 ^{aA}	43.56 ^{aA}	43.77 ^{aA}
	BA	16.32 ^{aA}	16.62 ^{aA}	8.12 ^{aAB}	8.37 ^{aA}	525 ^{aB}	543 ^{aAB}	34.87 ^{aA}	34.73 ^{aA}	44.08 ^{aA}	44.60 ^{aA}
	SM+BA	16.72 ^{aA}	16.92 ^{aA}	8.50 ^{aA}	8.63 ^{aA}	540 ^{aA}	558 ^{aA}	34.87 ^{aA}	34.97 ^{aA}	44.31 ^{aA}	45.60 ^{aA}
I1	CK	14.29 ^{bD}	13.62 ^{bD}	6.82 ^{bC}	6.55 ^{bD}	493 ^{bB}	487 ^{bC}	33.77 ^{aA}	30.83 ^{abA}	41.55 ^{bC}	40.88 ^{bC}
	SM	14.78 ^{bC}	14.79 ^{bC}	7.33 ^{bBC}	7.27 ^{bC}	496 ^{bB}	496 ^{bBC}	33.47 ^{aA}	33.33 ^{abA}	42.35 ^{bBC}	42.20 ^{bB}
	BA	15.42 ^{bB}	15.42 ^{bB}	7.72 ^{bAB}	7.49 ^{bB}	504 ^{bB}	514 ^{bAB}	33.97 ^{aA}	32.43 ^{abA}	43.18 ^{bAB}	43.88 ^{bA}
	SM+BA	16.05 ^{bA}	15.95 ^{bA}	8.02 ^{bA}	7.99 ^{bA}	522 ^{bA}	523 ^{bA}	34.37 ^{aA}	33.97 ^{abA}	44.01 ^{bA}	44.38 ^{bA}
I2	CK	12.98 ^{cD}	12.10 ^{cD}	6.23 ^{cD}	5.98 ^{cD}	462 ^{cC}	463 ^{cD}	31.30 ^{aA}	29.60 ^{bA}	40.12 ^{cC}	39.09 ^{cD}
	SM	13.40 ^{cC}	13.32 ^{cC}	6.68 ^{cC}	6.33 ^{cC}	484 ^{cB}	472 ^{cC}	32.43 ^{aA}	32.37 ^{bA}	41.09 ^{cB}	40.35 ^{cC}
	BA	14.27 ^{cB}	14.32 ^{cB}	7.14 ^{cB}	6.88 ^{cB}	491 ^{cB}	490 ^{cB}	32.97 ^{aA}	31.93 ^{bA}	41.85 ^{cAB}	41.11 ^{cB}
	SM+BA	14.98 ^{cA}	14.87 ^{cA}	7.51 ^{cA}	7.25 ^{cA}	510 ^{cA}	498 ^{cA}	34.03 ^{aA}	33.10 ^{bA}	42.73 ^{cA}	42.07 ^{cA}
Salinity		**	**	**	**	**	**	ns	*	**	**
Straw		**	**	**	**	**	**	ns	ns	**	**
Salinity × Straw		ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

Note: Mean values of the wheat yield parameters, including aboveground biomass, grain yield, spike number, kernel number, and 1000-grain weight for the different straw-returning modes and irrigation water salinity in 2017–2018 and 2018–2019, respectively. Different uppercase and lowercase letters in each column indicate a significant difference ($p < 0.05$) among straw returning modes (for a given irrigation regime) and irrigation water salinity levels, respectively. Analysis of variation (ANOVA): ns indicates that values are not significant, * and ** indicate values that are significant at $p < 0.05$ and $p < 0.01$. Salinity and Straw represent the main effects of irrigation salinity levels and straw-returning modes, respectively. Salinity × Straw represents the interaction effect between the irrigation salinity levels and straw-returning modes. CK: no straw-returning, SM: straw mulching, BA: biochar amendment, SM+BA: straw mulching with biochar amendment; I0, I1, and I2 indicate an irrigation salinity of 0.47 dS m^{-1}, 3.25 dS m^{-1}, and 6.75 dS m^{-1}, respectively.

4. Discussion

Saline water and salinity determine the extent of soil salt accumulation. This is consistent with previous studies [11,14,20] reporting that with an increase in the salinity of irrigation water, the degree of soil salt accumulation is greater due to greater salt intake into the field when the saline water was irrigated with equal amounts. Meanwhile, the distribution of salt in the soil profile showed a pattern where the soil salt content decreased with increasing soil depth (Figure 4), and most of the salt was concentrated in the area where the wheat's root system grew. Similar results were demonstrated by Wang et al. [14], who reported that the surface soil layer contained the highest amount of salt. Salt migrated toward the surface layer along with the water, in response to water uptake by the crop roots and high evaporation rates [17,20]. Salt accumulation in the soil profile due to saline water irrigation, especially in the root zone, could have a negative effect on crop yield through osmotic and ion toxicity [15]. However, the straw-returning application in the study significantly restrained salt accumulation during the two seasons in comparison to the levels in the unamended plots.

The possible mechanisms for restraining salt accumulation via straw-returning under saline water irrigation included: (a) inhibiting the upward movement of salts due to soil water evaporation; (b) promoting salt leaching by improving the soil properties. In this study, straw mulching and biochar amendment were investigated; the coupling of the two modes might be a better choice under saline water irrigation. This might be attributed to the fact that SM+BA had the advantages of both SM and BA in optimizing soil water-salt conditions. On the one hand, SM formed a physical barrier on the soil surface, which reduced the energy exchange between the soil and atmosphere more effectively than BA, thus hindering salt accumulation in the topsoil layer, due to soil water evaporation [28]. On the other hand, BA was better than SM at reducing the soil bulk density (Figure 7). Soil BD is an important indicator by which to evaluate saline soil quality, as it may promote the leaching of soil salts due to an increase in soil pore space [43]. However, BA might be a double-edged sword since BA itself contains a certain amount of soluble salt, which would increase the salt content of the topsoil due to the large application amount of 30 to 75 t ha^{-1} [35–37]. The amount of biochar applied in the present study (5.5 and 2.0 t ha $^{-1}$ in treatment BA and SM+BA, respectively) was much smaller than that applied in previous studies, and the salt intake into the soil from biochar was less than that via saline irrigation, so no significant elevation in soil salt content induced by biochar amendment was detected after the wheat harvest. In addition, Liao et al. [28] found that straw mulching was able to trap and store part of the water during irrigation and would gradually release this part of water after an irrigation event, thus prolonging the leaching time to obtain a better performance in terms of salt leaching. Therefore, the combined application of SM and BA was more effective in inhibiting soil salt accumulation in the crop root zone than with each variable alone.

In this study, the soil BD increased significantly with the rise in the salinity level of irrigation water. This finding is consistent with those of Singh et al. [11], who reported that the large amount of sodium ions contained in saline water increases the exchangeable sodium content of soil solution, resulting in the fragmentation of soil particles and the consequent increase in the content of dispersed clay particles. Straw returning could reduce the soil BD by increasing the content of SOC, which could promote the formation of soil aggregates [33,44]. In this study, SM increased the SOC content by 11.9% on average, compared to the no-straw control, which is similar to the research by Dong et al. [29] showing that straw mulching led to a 16.9% SOC content increase. However, SM achieved the lowest positive benefit on soil BD and SOC among the straw-returning treatments in this study. Compared with biochar, which can be added directly into the soil as a carbon source to enrich the soil carbon pool in the short term, straw in its mulching form needs to take quite a long time to complete its decomposition, thus increasing the SOC content, which is undoubtedly slow in improving soil quality [45,46]. Meanwhile, biochar itself is also a porous material and has a smaller bulk density compared to soil (Table 1), so the soil BD amended by biochar will be lower than that without biochar amendment. In this study, biochar amendment, including treatment BA and SM+BA, increased the SOC content by 29.39–54.23%, which is in line with previous studies [11,45]. Although the average value of soil BD under SM+BA was lower than that under BA in this study, there was no significant difference between them. The reason may be due to the fact that SM could create a more favorable moisture environment and increase microbial activity, thus promoting organic carbon decomposition and providing better nutrient conditions for crop root growth [45], and thereby, soil BD reduction.

Saline water irrigation and straw-returning modes both affect the final yield of winter wheat crops. Although saline water irrigation can alleviate the problem of crop yield reduction due to water deficit [13], it does not always guarantee the optimal crop yield in response to its negative effects on crop growth, such as osmotic stress and ion toxicity [15]. At the same time, the adverse effects on soil quality due to saline water irrigation can cause problems for sustainable farming at a later stage. Jiang et al. [16] conducted a three-year experiment and found that with the continuous use of saline water, the differences between saline water treatments and the salinity levels in winter wheat yield were gradually significant, and wheat yield reduced by 13.35% and 21.12% at irrigation water salinity levels of 3.2 dS m^{-1} and 6.1 dS m^{-1} in the third year, respectively, compared to freshwater irrigation. A similar result was obtained in our study, which showed that the winter wheat yield decreased by 5.95–8.64% and 13.28–17.56% when the irrigation water salinity level reached 3.25 dS m^{-1} and 6.75 dS m^{-1}, respectively. However, Mosaffa and Sepaskhah [12] concluded that the use of saline water with a salinity level of 3.36 dS m^{-1} did not cause a significant decrease in winter wheat yield. The reason for this difference may be due to the fact that the soil in the present experiment was not leached by natural rainfall during the winter wheat growing period, so the salt level was always in a highly tense state. Similar experimental results can be corroborated by other studies where the experiments were conducted in a greenhouse [43,44].

Saline water irrigation decreases the soil water potential due to higher ion concentrations in terms of soil moisture, which can create a barrier for crops extracting water and nutrients from the soil for growth, triggering physiological drought [47]. The application of straw-returning techniques could help winter wheat to alleviate the salt stress and increase the final yield. This might be the reason why straw-returning could increase soil water potential by decreasing the soil salt content and could increase the soil moisture content of the crop root zone. In addition, the application of straw-returning techniques improved the soil's organic content, which was the main source of energy for crop growth [34]. In the present study, treatments with biochar amendment, such as BA and SM+BA, showed a better performance than SM in increasing wheat grain yield. Similar results were reported by Ma et al. [48], who suggested that the crop yield increase with biochar amendment was higher than that in straw mulching, due to a greater improvement in the contents of soil organic carbon, nitrogen (N), phosphorus (P), and potassium (K). Meanwhile, BA provided additional N fertilizer (Table 1), which could reduce the microbial competition for N in the soil during straw decomposition and carbon mineralization [11,49]. However, the yield increment under SM+BA was the highest (16.60–21.80%), mainly due to better soil water–salt conditions, where high water and a low-salt environment would favor wheat growth. Moreover, lower biochar usage might be more acceptable for farmers and government agencies when using saline water for irrigation, considering the economic issues [34]. Although a promising winter wheat yield was obtained under SM+BA, long-term field experiments are still recommended in more regions, considering the differences in climatic and hydrological conditions.

5. Conclusions

The straw-returning treatment increased the soil organic carbon and decreased the soil bulk density, thus suppressing the soil salt accumulation caused by saline water irrigation. Furthermore, the straw-returning treatment increased the soil moisture content and caused lower soil salt levels, which helped the winter wheat to alleviate salt stress under saline water irrigation. In the present study, both straw mulching and biochar amendment notably increased the wheat grain yield compared to no straw control. Meanwhile, straw mulching and biochar amendment could promote each other, so as to provide a better soil water-salt condition and nutrient environment for wheat growth than with a single-treatment use. The results showed that biochar amendment that combined the straw mulching would be a proper strategy for winter wheat production under saline water irrigation.

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