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RESEARCH ARTICLE

Biochar improves soil quality and wheat yield in saline-alkali soils beyond organic fertilizer in a 3-year field trial

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Abstract

The objective of this study was to examine the effects of biochar compared to organic fertilizer on soil quality and wheat yield in the saline-alkaline lands. A 3-year field trial was conducted on moderately saline-alkaline land in the Yellow River Delta region (YRD) with six treatments: biochar (B1: 5 t, B2: 10 t, B3: 20 t ha^{-1} year^{-1}) and organic fertilizer (OF1: 5 t, OF2: 7.5 t ha^{-1} year^{-1}) as well as control (CK). The results showed that both biochar and organic fertilizer increased total organic carbon (TOC), total nitrogen (TN), NH_4^+-N, and NO_3^--N, and reduced pH, thereby increasing soil microbial biomass carbon (MBC) and nitrogen (MBN), MBC/TOC ratio, and MBN/TN ratio, but organic fertilizer increased soil nutrients and microbial biomass better than biochar. Correlation analysis revealed that soil water content (SWC), soil salt content (SSC), and Na^+ were the most important factors influencing wheat yield. When compared to CK, the SSC and Na^+ decreased by 5.55–7.52% and 3.86–9.39%, respectively, and SWC increased by 5.14–5.62% in the biochar treatment, while they increased by 1.07–10.19%, 1.08–7.58%, and 2.96–3.84% in the organic fertilizer treatment, respectively. Accordingly, wheat yield of biochar treatment was 0.90–14.71% higher than that of organic fertilizer treatment (4.49–4.80 t ha^{-1}) and CK (4.47 t ha^{-1}). Collectively, B2 had the lowest SSC and Na^+ and the highest yield and was significantly better than the organic fertilizer treatment, as well as efficiently increasing soil nutrients and microbial biomass, suggesting that it may be a better agricultural practice for improving soil quality and increasing wheat yield in the YRD.

Keywords Saline-alkali soil · Soil microbial biomass · Yield · Soil nutrients · Soil salinity

Introduction

Soil salinization has become a global problem in the early twenty-first century and is one of the most severe environmental factors impeding agricultural productivity (Tang et al. 2020). Salinity affects approximately 1.13 billion ha of land worldwide (Zhang et al. 2022), and it is growing at a rate of 1–2% each year (Mahmoud et al. 2019). As the youngest coastal ecosystem in China (Luo et al. 2017), the Yellow River Delta region (YRD), which is close to the sea, with shallow groundwater, uneven precipitation, and high evaporation-precipitation ratio (3.5:1), is responsible for the saline-alkali land covering an area of 442,900 ha (Xia et al. 2019). The high salinity-alkalinity of soils can induce issues such as serious degradation of soil structure and fertility, reduction of microbial biomass, and increase of soil osmotic pressure, which limits nutrient and water uptake by plants and sustainable use of saline-alkali lands (Liang et al. 2021; Zhang et al. 2022; Zhou et al. 2021).

Wheat (*Triticum aestivum* L.) is one of the globally important food crops and plays an essential role in maintaining global food security (Yue et al. 2019). China is the world's largest wheat producer, with yield exceeding 133 million tons, contributing 18% of the world's total production (FAO 2021). With the increasing population and food

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demand, YRD has become a major food production base in China with its abundant land resources. However, excellent soil quality is a prerequisite for wheat production (Shi et al. 2017), and the soil salinization had impeded wheat production with yield losses of up to 60% (Dadshani et al. 2019). Therefore, it is necessary to ameliorate saline-alkali land to avoid negative effects of salinity and alkalinity on wheat yield under the background of global food crisis. Existing measures (such as leaching, plant salt-tolerant crops, and foreign soil) for saline-alkali soil improvement are time-consuming, expensive, and ineffective (Cui et al. 2021). A high-efficiency and eco-friendly agricultural strategy to ameliorate saline-alkali soil is urgently required.

Biochar can be produced from biomass under low oxygen condition at 300 to 700 °C and is a material with high porosity and high-specific surface area (Hardie et al. 2014). This porosity and specific surface area gives biochar favorable properties of water retention and ion adsorption, which have positive effects when applied to soil and is considered as a better soil amendment (Atkinson 2018; Li et al. 2020; Piscitelli et al. 2018). Its use on saline-alkali soils has yielded many substantial benefits, include improving soil fertility, alleviating salt stress, increasing soil water, reducing nutrients leaching, lowering Na^+ content, and promoting crop growth and yield (Ali et al. 2017; Shi et al. 2019; Sun et al. 2020; Xu et al. 2018; Zhang et al. 2019). Additionally, biochar can provide a suitable habitat for soil microorganisms by supplying essential nutrients and improving soil properties, thus increasing the microbial biomass in salt-affected soils (He et al. 2020). For example, when applied to saline-alkali soils, biochar increased soil mineral nitrogen and total organic carbon (TOC) (Irfan et al. 2019; Jing et al. 2020; Zhang et al. 2021a) and improved soil water-salt status (Zhang et al. 2021a), thus increasing soil microbial biomass carbon (MBC) and microbial biomass nitrogen (MBN) (Shi et al. 2019; Xu et al. 2018). Chemical fertilizers and pesticides were mostly used in traditional agriculture (Makaju and Kurunju 2021; Xie et al. 2019). However, the long-term use of chemical fertilizers results in the deterioration of soil quality, environmental pollution, and secondary salinization (Pahalvi et al. 2021). Therefore, several researchers have proposed replacing chemical fertilizers with green organic fertilizers in agricultural practice. When applied to soils, organic fertilizer can improve soil physicochemical properties, accelerate microbial growth, and increase crop yield (Chen et al. 2015; Liu et al. 2020; Luo et al. 2017). Likewise, there has been an increase in studies showing that organic fertilizer application on saline-alkali lands brings the benefits in terms of reduced soil salinity, alkalinity, and water evaporation and increased soil nutrients (Chen et al. 2020; Liu et al. 2020; Shi et al. 2019; Xie et al. 2019). These effects favorably reduce the negative effects of soluble salts on plants and microorganisms, and promote crop and microbial growth. (Shi et al. 2019; Wang et al. 2020; Zhou et al. 2021). Consequently, organic fertilizer and biochar could be potentially used to improve soil quality, microbial biomass, and crop yield in saline-alkali soils.

China produces approximately 820 million tons of straw and 3.8 billion tons of livestock manure annually, and 31% of the straw and more than 50% of the manure are not used/disposed in a reasonable way (An et al. 2019; Li et al. 2018), threatening the ecological environment. Therefore, exploring the effects of organic fertilizer and biochar made from straw and manure on saline-alkali lands improvement has great environmental benefits. Unfortunately, most of the current studies on the application of biochar or organic fertilizer to improve saline-alkali soil has been performed under laboratory or greenhouse conditions, which amendment more significantly ameliorates saline-alkali soil water-salt status, nutrients, microbial properties, and quality and then enhances wheat yield in consecutive years of field trial remains largely unclear.

We hypothesized that long-term application of biochar in saline-alkali lands can more effectively ameliorate soil physicochemical properties and increase wheat yield than organic fertilizer, especially soil water-salt status. To validate the hypothesis, we conducted a 3-year field trial on saline-alkali lands in the YRD, with the following objectives (1) to compare the effects of biochar and organic fertilizer on soil water-salt status, alkalinity, Na^+, carbon (C), nitrogen (N), and microbial properties; (2) to determine the optimal amendments and application rate to improve saline-alkali soils by evaluating the potential of biochar and organic fertilizer in ameliorating soil properties and increasing wheat yield. The findings will provide a theoretical basis for using biochar or organic fertilizer to improve saline-alkali soils in the YRD.

Materials and methods

Experimental site

The field experiment was performed in the Zhong Yu Ecological Industrial Park district in Binzhou, Shandong province (37°29′N, 118°03′E). The region has a temperate continental monsoon climate, with average annual temperatures, rainfall, evaporation, and sunshine hours of 13.9 °C, 691.6 mm, 1805.8 mm, and 2632.0 h, respectively. Since the 1970s, the region has been implementing a winter wheat-summer maize rotation. Before conducting the experiment, we collected soil samples from the industrial park using an auger (5 cm diameter) and ring cutter (100 cm^3) and determined its basic physicochemical properties, which are listed in Table 1. A Malvern laser particle size analyzer was used to determine the soil particle size (Mastersizer 3000,

Table 1 The physical and chemical properties of the test soil before the experiment

Soil property		Value
EC$_{1:5}$ (mS cm^{-1})		0.96
pH		8.19
Soil salt content (g kg^{-1})		2.38
Na^{+} (g kg^{-1})		0.56
Ca^{2+} (g kg^{-1})		0.21
Mg^{2+} (g kg^{-1})		0.03
Sodium adsorption ratio ((mmol L^{-1})$^{0.5}$)		6.16
Exchange sodium percentage (%)		7.26
Bulk density (g cm^{-3})		1.39
Organic matter (g kg^{-1})		13.71
Total N (%)		0.09
Total K (%)		2.10
Field capacity (%)		28.62
Available P (mg kg^{-1})		46.30
Available K (mg kg^{-1})		186.95
Soil particle composition (%)	<0.002 mm	2.96
	0.02–0.002 mm	76.78
	>0.02 mm	2.96

Malvern, UK). The test soils were classified as silty sandy loam and moderately saline-alkali soil, respectively, according to the US Soil Taxonomy (Soil Survey Staff 2014) and the provisional regulations on ecological function zoning provided by the ministry of ecology and environment of the people's republic of China (https://www.mee.gov.cn/gkml/zj/wj/200910/t20091022_172113.htm).

Materials

Powder size biochar (B) was produced from cotton straw by Mingchen Co., Ltd. in Shandong province. Measured by BET-N$_2$ adsorption after degassing at 120 °C for 5 h (ASAP 2020, Micromeritics Instrument, USA), the pore volume and specific surface area were 1.9 mL g^{-1} and 12.5 m^2 g^{-1}, respectively. The dry firing in a muffle furnace at 850 °C for 6 h yielded 25.4% ash content.

Particulate size organic fertilizer (OF) was produced from pig manure by Wengfujingu Co., Ltd in Shandong province. NO$_3^-$-N and NH$_4^+$-N were extracted with 2 M KCl at a ratio of 1 to 5 of OF to water, then determined using an AA3 flow analyzer (Braun and Lübbe, Germany), they were 132.2 and 70.4 mg kg^{-1}, respectively. Organic matter content was greater than 45%. Table 2 outlines the additional characteristics of B and OF.

Field experiments and treatments

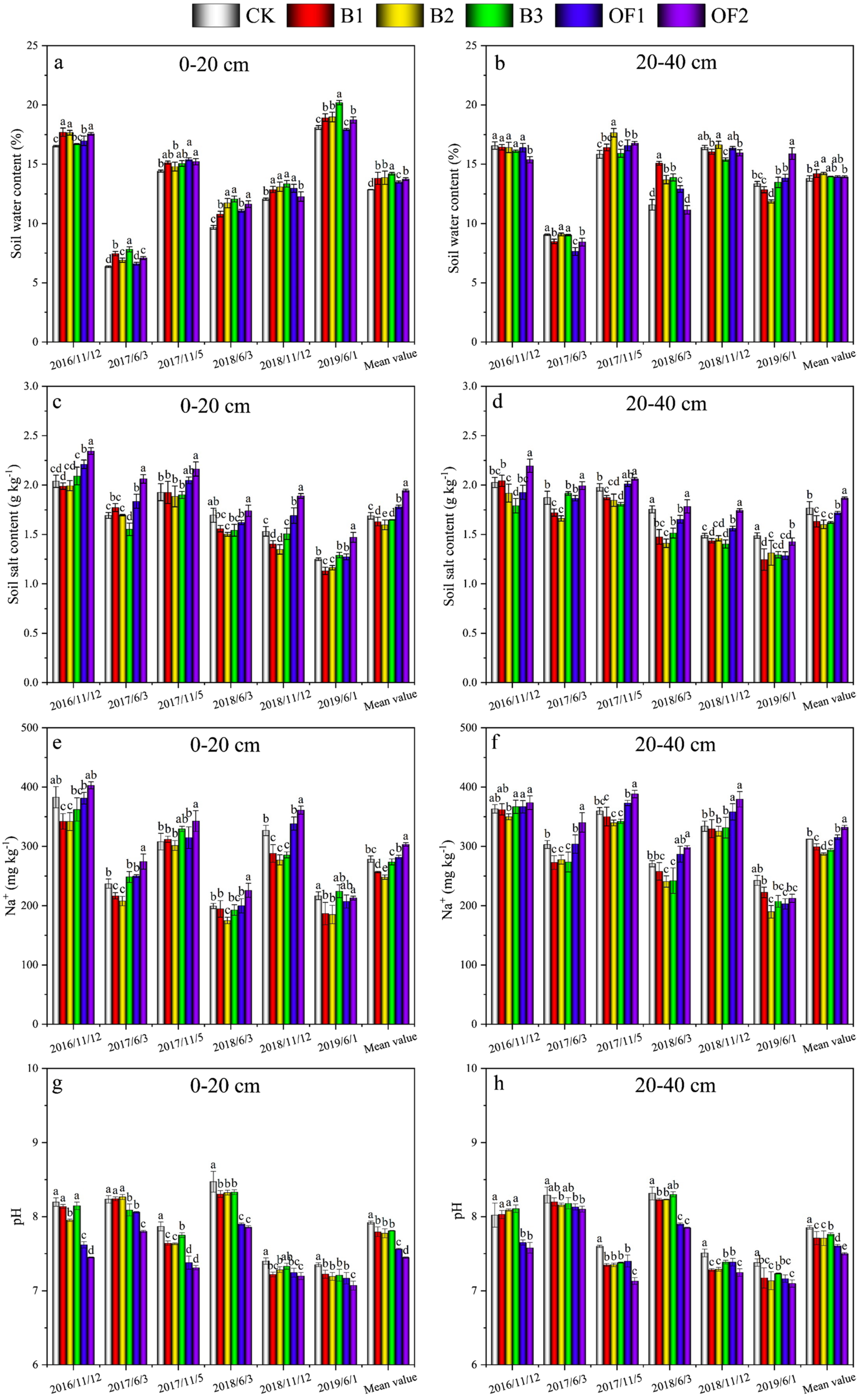
Field experiments were conducted between June 2016 and June 2019. Winter wheat (*Triticum aestivum* L.) was sown in October and harvested in June of the following year; summer maize (*Zea mays* L.) was sown in June and harvested in October. According to the findings of the previous pot and soil column infiltration trials, we established six treatments with three replications: CK; biochar with 5, 10, and 20 t ha^{-1} year^{-1} for B1, B2, and B3, respectively; organic fertilizer with 7.5 and 10 t ha^{-1} year^{-1} for OF1 and OF2, respectively. The field experiment adopted a completely randomized design, the plot area was 14.5 m × 8 m = 116 m^2. Fertilization method: insufficient quantities of N and P$_2$O$_5$ in the B and OF treatments were compensated by applying urea ($N \geq 46\%$) and diammonium phosphate ($P_2O_5 \geq 43\%$, $N \geq 14\%$), respectively, to achieve equivalent levels in each treatment; the levels of N (200 kg ha^{-1} year^{-1}) and P (120 kg ha^{-1} year^{-1}) were consistent in each treatment; no K fertilizer addition due to high soil K content. B, OF, N fertilizer, and P fertilizer were spread evenly on the soil surface before sowing the crop and then tilled using a rototiller to mix them evenly with the soil at a depth of 0–20 cm (B, OF, N fertilizer, and P fertilizer were applied at a 1:1 ratio in the wheat and maize seasons and once a year). Other field management followed local management practice.

Soil sampling

Wheat is a moderately salt-tolerant crop and the root system is primarily concentrated in the 0–40 cm soil layer. At the seedling stage, salt stress can easily result in weak seedlings or a low survival rate. Soil data at harvest can reflect the soil improvement effect and provide data for summer maize planting. Consequently, soil samples (0–20 cm and 20–40 cm depths) were collected at the seedling and harvest stages. The collection method was based on a five-point sampling method using a 5 cm diameter soil auger to drill the soil. All fresh soil samples will be divided into two parts after passing through a sieve (2 mm) (eliminate crop debris, stones, and other impurities), (1) placed at 4 ℃ for measuring soil water content (SWC), microbial biomass carbon

Table 2 The physical and chemical properties of soil amendments

Amendments	EC$_{1:5}$ (mS cm^{-1})	Ion concentration (mg kg^{-1})			pH	Total C (%)	Total N (%)
		Na^{+}	Ca^{2+}	Mg^{2+}			
Biochar	1.56	38.98	134.55	21.61	8.50	68.70	0.33
Organic fertilizer	18.36	963.22	227.76	175.60	6.70	15.90	1.11


CK
B1
B2
B3
OF1
OF2
a
0-20 cm
b
20-40 cm
Soil water content (%)
0
5
10
15
20
25
c
0-20 cm
d
20-40 cm
Soil salt content (g kg^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
e
0-20 cm
f
20-40 cm
Na$^+$ (mg kg^{-1})
0
100
200
300
400
500
g
0-20 cm
h
20-40 cm
pH
6
7
8
9
10
2016/11/12
2017/6/3
2017/11/5
2018/6/3
2018/11/12
2019/6/1
Mean value

◂**Fig. 1** Dynamics of soil water content, soil salt content, Na^+, and pH under biochar and organic fertilizer treatments at 0–20 cm and 20–40 cm depths

(MBC), microbial biomass nitrogen (MBN), NH_4^+-N, and NO_3^--N, (2) natural air-drying for measuring soil salt content (SSC), Na^+, pH, total organic carbon (TOC), and total nitrogen (TN). All indicators that required the use of fresh soil samples were measured within 1 week of sampling.

Measurement methods

The SWC (%) was determined by drying in an oven at 105 °C for 12 h. Na^+ was extracted at a soil–water ratio of 1:5 and then measured using the photometer method described by Bao (2005). pH value in a soil–water suspension (1:2.5) was determined using a pH meter (Fe28, Mettler, Switzerland). SSC (g kg^{-1}) was calculated using Eq. (1) from previous research results (Liu et al. 2018), where $EC_{1:5}$ (mS cm^{-1}) was measured in soil–water suspension (1:5) using an EC meter (DDS-11A, Leici, China).

$$SSC = 2.160 \times EC_{1:5} + 0.303 \tag{1}$$

where SSC is soil salt content (g kg^{-1}), $EC_{1:5}$ is electrical conductivity value (mS cm^{-1}).

TOC (g kg^{-1}) was determined using the combustion method of the C/N analyzer (multi C/N 2100S, Jena, Germany) after adding an excess of hydrochloric acid to remove inorganic carbon from the soil. TN (g kg^{-1}) was determined using the semi-micro Kjeldahl method described by Bao (2005). The NH_4^+-N and NO_3^--N (mg kg^{-1}) were extracted at a ratio of 1:5 soil to 2 M KCl solution and analyzed using AA3 flow analyzer (Braun and Lübbe, Norderstedt, Germany). The MBC and MBN (mg kg^{-1}) concentrations were determined using the fumigation-extraction method described by Shi et al. (2019). SWC of samples was initially adjusted to 40% of the field moisture capacity and then cultivated in incubator at 25 °C for 7 days. After cultivation, the soil was divided into two equal parts, one of which was fumigated with chloroform under – 0.07 Mpa pressure (Fumigation under light-proof conditions for 24 h), and the other of which was not fumigated. After fumigation, the total carbon (TC) and TN concentrations in the soil were extracted at a ratio of 1:4 soil to 0.5 M K_2SO_4 solution and then quantified using a TC/TN analyzer (multi N/C 2100S, Jena, Germany). MBC and MBN were determined using Eq. (2) (Shi et al. 2019).

$$MBC(MBN) = \frac{40 \times [C(N)_{\text{fumigated}} - C(N)_{\text{unfumigated}}]}{K_{C(N)} \times M/(1 + N)} \tag{2}$$

where $C_{(N)}$ is total carbon (nitrogen) content (mg kg^{-1}), K_C and K_N are conversion coefficients with values of 0.45 and 0.54, respectively, M is fresh soil weight (g), N is soil water content (%).

Wheat yield Wheat was harvested from a randomly selected area of 4 m^2, dried at 110 °C for 12 h, and then weighed to determine the wheat yield.

Statistical analyses

All data in this study are shown as the mean of three replicates. Data were statistically analyzed using SPSS (version 22) (IBM Software, Chicago, IL, USA). One-way analysis of variance (ANOVA) and LSD were used to determine the statistically differences among various treatments. The influence of the treatments on soil data and wheat yield was measured using repeated ANOVA with time (first to third year) as within factor. Pearson correlation analysis was used to determine the correlation among the soil physicochemical properties, soil microbial properties, and wheat yield. Figures were plotted using Origin 2021 (Origin Lab, USA).

Results

Variations in SWC, SSC, pH, and Na^+

Changes in SWC throughout the experiment are shown in Fig. 1a–b. As expected, the interannual variability of SWC for each treatment was high and exhibited a significant increasing trend ($P < 0.05$), with 20.97–29.67% more SWC in the third year compared to the first. In 0–20 cm, B and OF treatments significantly increased the mean SWC ($P < 0.05$) in a concentration-dependent manner, reaching a maximum at B3 (14.20%) and OF2 (13.75%), respectively. In 20–40 cm, B1 and B2 treatments significantly increased the mean SWC ($P < 0.05$), with B (13.96–14.22%) being more effective than OF (13.93–13.96%) and CK (13.80%) in increasing SWC.

SSC and Na^+ levels gradually decreased over the 3 years of the experiment, reaching a minimum value in June 2019, and were higher at the seedling stage than at the harvest stage (Fig. 1c–f). Compared to CK, B significantly ($P < 0.05$) reduced the mean SSC of 0–20 and 20–40 cm depths to a minimum value at B2 (1.59 g kg^{-1} and 1.60 g kg^{-1}) and then increased with increasing application of B; whereas OF treatment increased the SSC level, increasing by 0.02–0.18 g kg^{-1} (mean value of 0–40 cm depth). The mean SSC at the 0–40 cm soil layer was in the order of OF2 > OF1 > CK > B3 > B1 > B2. The effect of B and OF on Na^+ was comparable to that of SSC. In 0–40 cm layer, the mean Na^+ content of B1, B2, B3, OF1, and OF2 changed by – 5.88%, – 9.39%, – 3.86%, 1.08%, and 7.58%, respectively, compared to CK. B was more effective than

OF treatment in reducing SSC and Na^+, with B2 treatment being the most desirable.

Application of B and OF significantly reduced the pH of the 0–20 cm and 20–40 cm soil layer over time ($P < 0.05$, Fig. 1g–h), with 7.51–11.38% less pH in 2019 than in 2017. The mean pH value of 0–40 cm depth was in the order of CK > B3 > B1 > B2 > OF1 > OF2, where the pH value of OF treatment (7.47–7.58) was significantly lower than those of B treatment (7.74–7.79) ($P < 0.05$).

Variations in TOC, TN, NH_4^+-N, and NO_3^--N

Figure 2 shows the dynamic of TOC and TN. The values of TOC and TN significantly increased by B and OF amendments from 2016 to 2019, with both reaching a maximum in the third year ($P < 0.05$, Fig. 2a–b). It is noteworthy that TOC and TN were higher in the seedling stage than in the harvest stage until the end of experimental period (June 2019). For the mean value of 0–20 cm depth, the TOC (B 7.29–8.35 g kg^{-1}, OF 8.35–8.85 g kg^{-1}) and TN (B 0.93–1.06 g kg^{-1}, OF 1.08–1.16 g kg^{-1}) in the soil treated with B and OF were significantly ($P < 0.05$) higher than those in CK (TOC 7.18 g kg^{-1}, TN 0.88 g kg^{-1}), and they are all in order of OF2 > OF1 > B3 > B2 > B1 > CK. A similar phenomenon was observed in the 20–40 cm soil layer. Compared with CK, the mean TOC values of 0–40 cm depth increased by 6.50–19.83% (B) and 25.32–34.54% (OF), whereas mean TN values increased by 6.81–15.82% (B) and 22.55–29.48% (OF).

As shown in Fig. 3a–b, the variation trend of NO_3^--N and NH_4^+-N with respect to time is consistent with TOC and TN. In the third year of the experiment, the

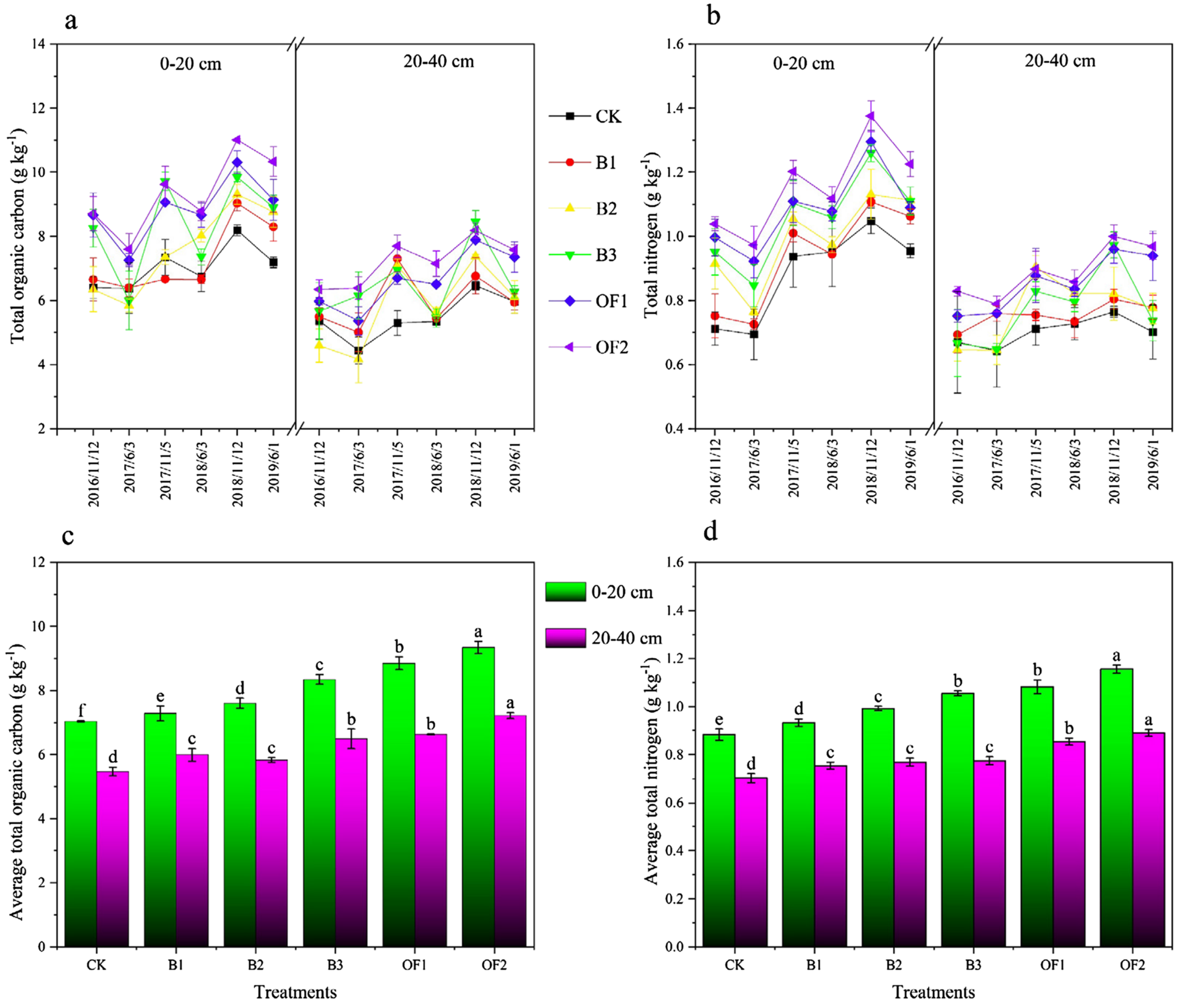


Fig. 2 Dynamics of total organic carbon and total nitrogen under biochar and organic fertilizer treatments at 0–20 cm and 20–40 cm depths

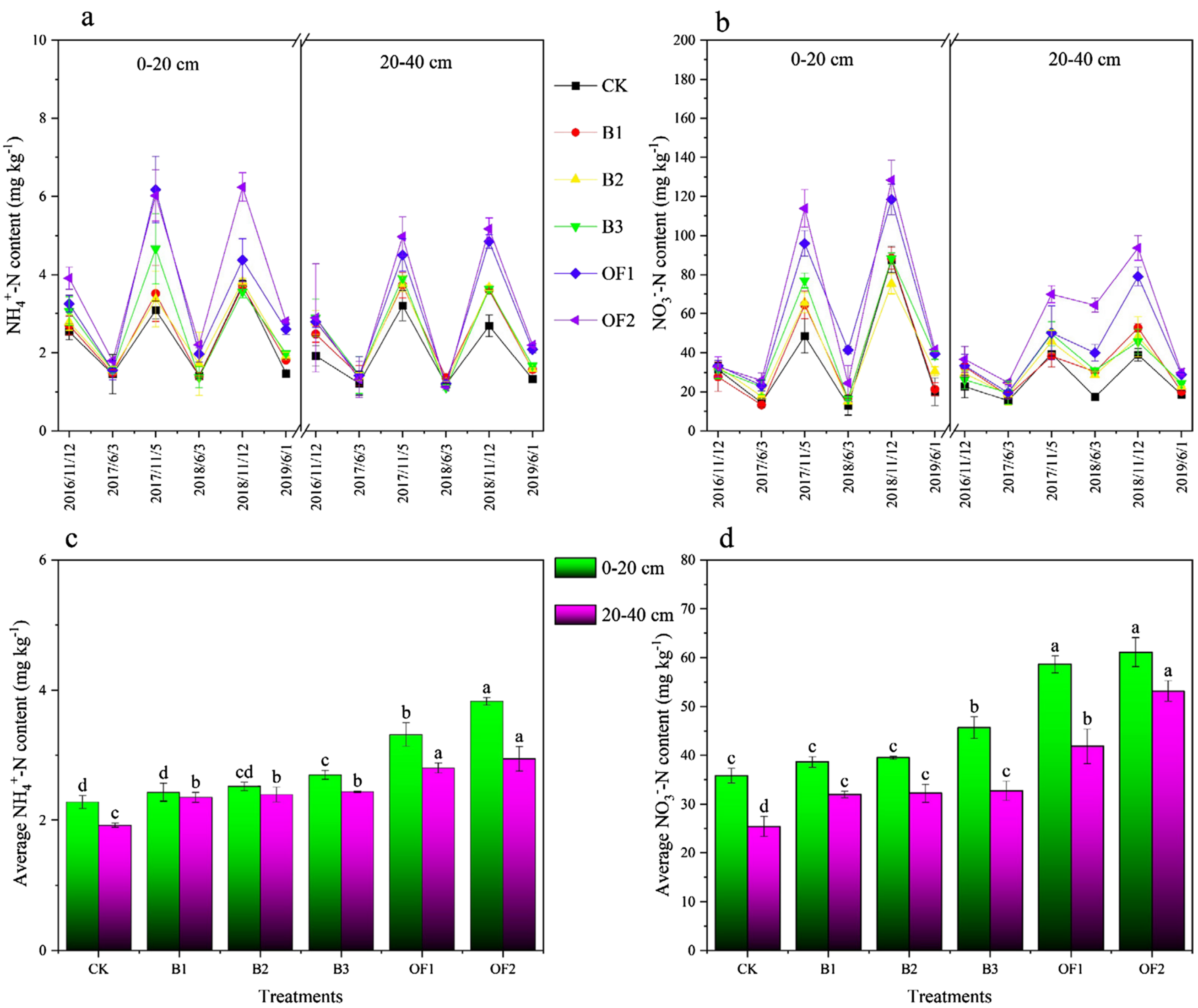


Fig. 3 Dynamics of NH_4^+-N and NO_3^--N under biochar and organic fertilizer treatments at 0–20 cm and 20–40 cm depths

NH_4^+-N and NO_3^--N contents were 29.43–65.76% and 96.91–145.01% higher than in the first year, respectively. In Fig. 3c–d, B and OF increased NH_4^+-N and NO_3^--N of all soil layers, with 14.01–22.36% and 15.32–27.93% in the B treatment and 45.84–61.27% and 63.98–86.46% in the OF treatment relative to CK, respectively; they are all in order of OF2 > OF1 > B3 > B2 > B1 > CK. The NH_4^+-N and NO_3^--N content of B3 and OF at 0–20 cm and those of each treatment at 20–40 cm were significantly ($P < 0.05$) different from CK. These results demonstrated that B and OF amendments were effective in increasing TOC, TN, NH_4^+-N, and NO_3^--N in the 0–20 cm and 20–40 cm soil layers, with the OF treatment having significantly higher TOC, TN, NH_4^+-N, and NO_3^--N contents than B treatment, and with the OF2 having the greatest effect ($P < 0.05$, Figs. 2 and 3).

Changes in MBC and MBN

As shown in Fig. 4a–b, MBC and MBN contents of all treatments gradually increased with time and were 13.10–40.79% and 24.68–67.52% higher in the third year compared to the first year, respectively. The MBC (B 156.51–262.19 mg kg^{-1}, OF 192.96–220.87 mg kg^{-1}) and MBN (B 25.17–40.04 mg kg^{-1}, OF 40.85–82.21 mg kg^{-1}) in soil treated with B and OF were significantly higher than in CK (MBC 173.92 mg kg^{-1}, MBN 24.68 mg kg^{-1}) ($P < 0.05$, Fig. 4c–d). In the 0–20 cm soil layer, the mean MBC value was increased by 6.26% (B1), 13.37% (B2), 27.09% (B3), 38.83% (OF1), and 50.38% (OF2) compared to CK, whereas the mean MBN value increased by 19.45% (B1), 28.25% (B2), 37.80% (B3), 92.28% (OF1), and 182.90% (OF2). Similarly, in the 20–40 cm soil layer, B and OF also significantly

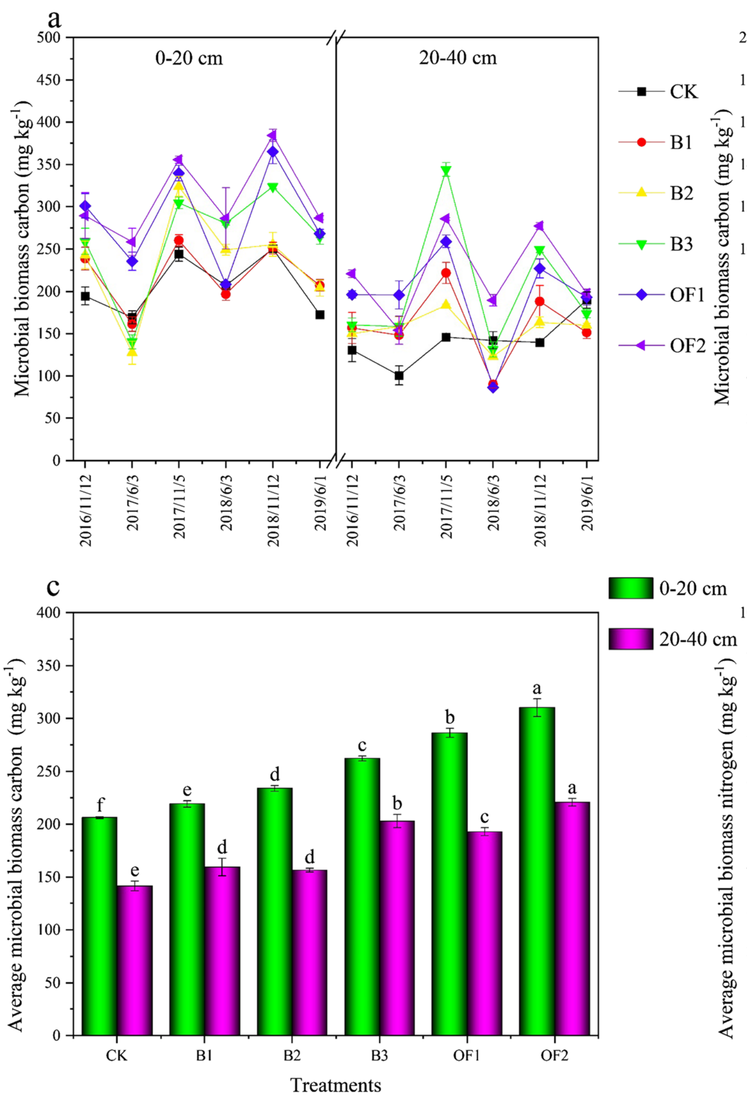


Fig. 4 Dynamics of microbial biomass carbon and microbial biomass nitrogen under biochar and organic fertilizer treatments at 0–20 cm and 20–40 cm depths

increased MBC (B 10.58–43.40%, OF 33.33–56.04%) and MBN (B 23.95–60.54%, OF 101.12–160.11%) ($P < 0.05$). In terms of increasing soil MBC and MBN levels, the OF was significantly better than the B, particularly the OF2 treatment.

Effect of B and OF on MBC/TOC ratio, MBN/TN ratio, and MBC/MBN ratio

As shown in Fig. 5a–b, increasing doses of B and OF amendments induced an increase in the MBC/TOC ratio and MBN/TN ratio, which reached their highest values at B3 (MBC/TOC ratio 3.09%, MBN/TN ratio 4.00%) and OF2 (MBC/TOC ratio 3.15%, MBN/TN ratio 6.52%), respectively. In the 0–20 cm soil layer, the MBC/TOC ratio ranged from 2.93 to 3.32% and the MBN/TN ratio ranged from 3.29 to 7.12%, whereas in the 20–40 cm depth, the MBC/TOC ratio ranged from 2.49 to 3.03% and the MBN/TN ratio ranged from 2.89 to 5.93%. Compared to CK, the MBC/TOC ratio and MBN/TN ratio increased by 3.49–13.91% and 14.21–29.47% for the B treatment and 11.99–16.15% and 61.06–111.16% for the OF treatment, respectively. Collectively, the MBC/TOC ratio and MBN/TN ratio of OF treatment were higher than those of B treatment, which were particularly pronounced in the MBN/TN ratio ($P < 0.05$).

As shown in Fig. 5c, B and OF amendments significantly decreased the MBC/MBN ratio in the 0–20 cm and 20–40 cm depths compared to CK ($P < 0.05$). Increasing doses of B provoked a decreasing and then increasing trend in MBC/MBN ratio, with MBC/MBN ratio between 6.10

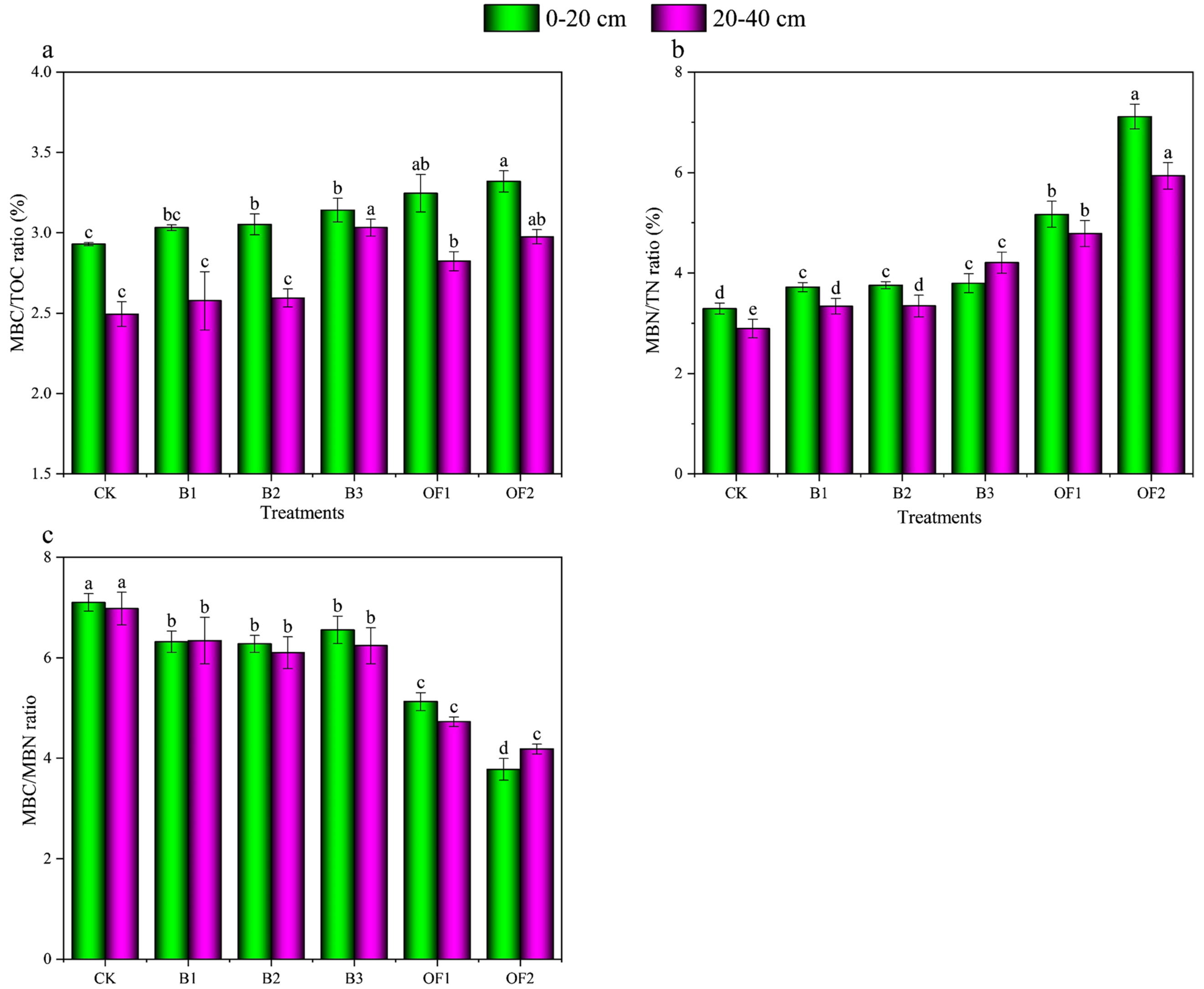


Fig. 5 MBC/TOC ratio, MBN/TN ratio, and MBC/MBN ratio under biochar and organic fertilizer treatments at 0–20 cm and 20–40 cm depths

and 6.56, whereas OF treatment showed a decreasing trend, with MBC/MBN ratio between 3.78 and 5.13. The MBC/MBN ratio of the OF amended soil was significantly lower than that of the B amended soil, with OF2 (3.78) having the lowest soil MBC/MBN ratio ($P<0.05$).

Variations in the of wheat yield

As shown in Table 3, the wheat yield of each treatment ranged from 3.64 to 5.94 t ha^{-1}. The wheat yield of CK, B1, B2, B3, OF1, and OF2 increased over time, with the third-year yield being 34.86%, 36.57%, 47.55%, 45.87%, 24.29%, and 9.09% greater than the first-year yield, respectively. Wheat yield of B treatment in the first, second, and third years were higher than CK (first year: 3.64 t ha^{-1}; second year: 4.84 t ha^{-1}; third year: 4.91 t ha^{-1}) by 8.94–10.67%, 6.38–11.80%, and 10.30–21.06%, respectively, while that of OF treatment increased by 17.11–18.27%, −0.26 to 7.93%, and −4.35 to 7.91%, respectively. The mean wheat yield of each treatment was in the order of B2 > B3 > B1 > OF1 > OF2 > CK. Compared to CK, B application in the soil significantly increased wheat yield (8.35–14.71%, $P<0.05$) and B2 provided the highest yield (5.13 t ha^{-1}), whereas only OF1 significantly increased wheat yield among OF treatments (7.30%, $P<0.05$). Collectively, B was more beneficial than OF in increasing wheat yield, and B2 produced the best outcomes.

Correlation analysis

As shown in Fig. 6, MBC, MBN, MBC/TOC ratio, and MBN/TN ratio exhibited highly significant

Table 3 The wheat yield in 2017, 2018, and 2019

Treatments	Yield (ton ha^{-1})			
	2017	2018	2019	Mean value
CK	3.64 ± 0.08^{c}	4.84 ± 0.08^{b}	4.91 ± 0.13^{c}	4.47 ± 0.09^{c}
B1	3.97 ± 0.29^{b}	5.15 ± 0.24^{ab}	5.42 ± 0.23^{b}	4.84 ± 0.18^{b}
B2	4.03 ± 0.05^{ab}	5.41 ± 0.08^{a}	5.94 ± 0.33^{a}	5.13 ± 0.08^{a}
B3	3.95 ± 0.16^{b}	5.19 ± 0.25^{ab}	5.77 ± 0.31^{ab}	4.97 ± 0.21^{ab}
OF1	4.26 ± 0.14^{a}	4.83 ± 0.27^{bc}	5.30 ± 0.22^{bc}	4.80 ± 0.12^{b}
OF2	4.31 ± 0.11^{a}	4.46 ± 0.23^{c}	4.70 ± 0.31^{c}	4.49 ± 0.20^{c}

The lowercase letters represent the differences among different treatments at the same column ($P < 0.05$) in Table 3. *CK*, control; *B1*, 5 t ha^{-1} year^{-1} biochar; *B2*, 10 t ha^{-1} year^{-1} biochar; *B3*, 20 t ha^{-1} year^{-1} biochar; *OF1*, 7.5 t ha^{-1} year^{-1} organic fertilizer; *OF2*, 10 t ha^{-1} year^{-1} organic fertilizer. Values are means ± SE ($n = 3$)

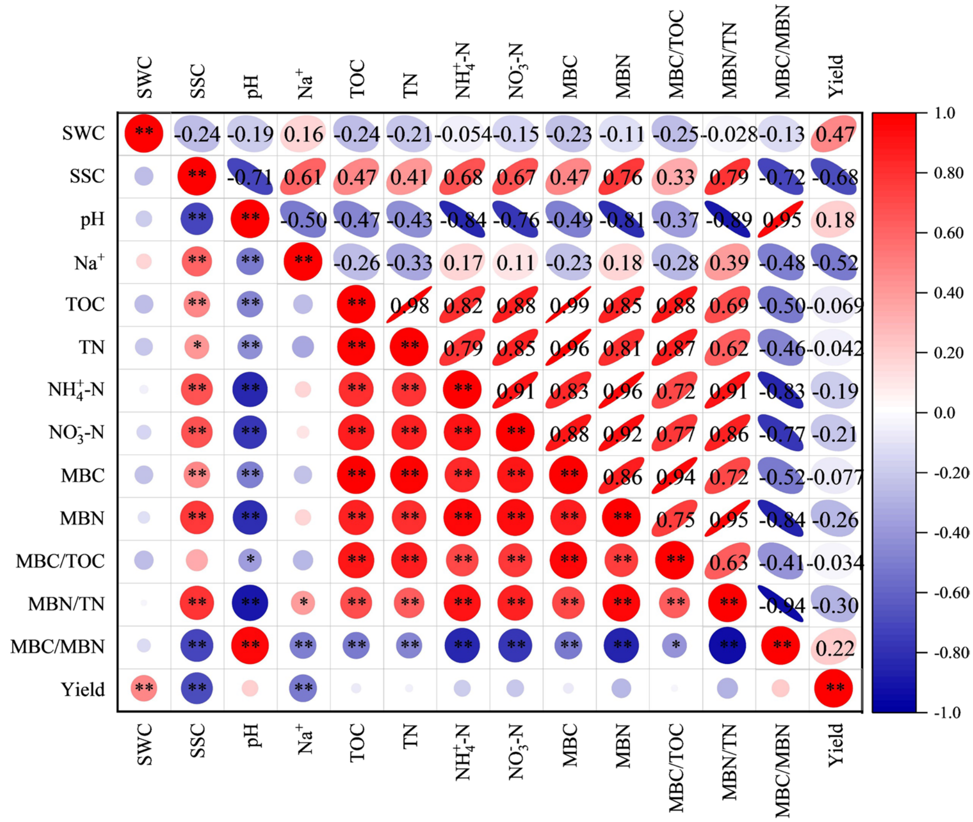


Fig. 6 The correlation analysis of soil physicochemical properties with soil microbial characteristics and wheat yield

positive correlations with TOC, TN, NH_4^+-N, and NO_3^--N ($P < 0.01$). MBC, MBN, and MBN/TN ratio displayed a highly significant positive correlation with SSC and a negative correlation with pH ($P < 0.01$). The MBC/TOC ratio had a significant negative correlation with pH ($P < 0.05$). The wheat yield had a highly significant negative correlation with SSC and Na^+ and a highly significant positive correlation with SWC ($P < 0.01$); there was no significant relationship with other indicators.

Discussion

Effects of B and OF on soil physical and chemical properties

Soil water-salt status is an important factor limiting agricultural production in saline-alkali farming (Liang et al. 2021). In this study, the addition of B and OF amendments for three consecutive years resulted in an increase in SWC (Fig. 1a–b), which was consistent with the results of previous studies (Atkinson 2018; Hardie et al. 2014). The increase in SWC could be attributed to the following mechanisms: (1) the application of B amendment in saline-alkali lands benefited to increase soil porosity (Hardie et al. 2014; Toková et al. 2020), thus allowing the soil to hold more water (Blanco-Canqui 2017; Liang et al. 2021); (2) soil aggregates play an essential role in regulating soil moisture loss, OF amendment could reduce water loss and increase SWC by contributing to soil aggregates formation (Brar et al. 2015; Chen et al. 2021). However, the SWC of the OF-amended soil was less than that of the B-amended soil, which was attributed to the fact that Na^+ is a highly dispersed substance and can cause fragmentation of soil aggregates, while OF application increased SSC and Na^+ (Fig. 1c–f), thus limiting soil water retention (Bronick and Lal, 2005). The increase of SSC and Na^+ in OF treatment was mostly attributable to its high soluble substances and Na^+ content (Table 2). Higher SWC facilitates dissolving more soil salts and leaching them deeper into the soil under gravity (Chu et al. 2022). Exogenous Ca^{2+} and Mg^{2+} could displace the Na^+ on the ion exchange sites, thus promoting soil flocculation and increasing soil permeability (Zhao et al. 2020). In the present study, B itself contained some amount of Ca^{2+} and Mg^{2+} and increased SWC (Fig. 1a–b, Table 2), which explains why B reduced SSC and Na^+. B addition decreased soil pH, which may be since H^+ on acidic functional groups in B can be released in the soil by cation exchange (Shi et al. 2019; Liang et al. 2021). However, B owned an ash content of 25.4% and a pH of 8.5 (Table 2). This illustrates why the pH of B3 treatment was greater than B1. OF treatment lowered soil pH probably because its own acidic characteristics neutralized the soil alkalinity (Table 2).

C and N are important nutrients that determine crop productivity (Jing et al. 2020). In the present study, the application of B and OF in saline-alkali soils increased soil C and N content and this phenomenon had a multi-year cumulative effect (Figs. 2 and 3), which was consistent with previous studies (Jing et al. 2020; Zhao et al. 2020). The explanation for the increase in TOC, TN, NO_3^--N, and NH_4^+-N could be attributed to several aspects. First, both B and OF are rich in C (Table 2); hence, the soil TOC content must increase following their application. Second, B and OF could inhibit soil denitrification by improving soil structure and aeration (Chen et al. 2021; Shi et al. 2019), thus reducing N loss. Interestingly, the TOC, TN, NO_3^--N, and NH_4^+-N contents were higher in OF treatments than in B treatments. This could be explained by the fact that the application of OF to the soil is equivalent to the direct addition of exogenous organic carbon to the soil due to its inherent characteristics (Table 2). Secondly, the pH of the soil treated with OF is significantly lower than that of the soil treated with B (Table 2), which may have contributed more to the reduced N loss via volatilization owing to the liming effect (He et al. 2020).

Effects of B and OF on soil microbial biomass

In this study, B and OF administration increased MBC and MBN levels in a concentration-dependent manner, which is agreement with findings by He et al. (2020), Lehmann et al. (2011), and Zhang et al. (2021b). Compelling evidence shows that B and OF affect soil microbial activity by modifying the nutrient levels and soil quality to increase MBC and MBN (Chen et al. 2015; Lehmann et al. 2011). Correlation analysis also found similar results (Fig. 6). In the present study, B and OF administration increased soil nutrients (TOC, TN, NO_3^--N, and NH_4^+-N), provided the microorganisms with sufficient C and N, and decreased the soil pH (Figs. 1, 2, and 3), thus increasing MBC and MBN. Studies have shown that microorganisms are highly sensitive to exogenous N and they can temporarily fix N by assimilation and enhance C utilization (Chen et al. 2015; Dempster et al. 2012). Therefore, another explanation for the increase in MBC and MBN in this study could be that B and OF increased TN content and the continuous supply of N, thus promoting N assimilation and stimulating C utilization by microorganisms (Fig. 2). Further analysis found that OF was more effective in increasing MBC and MBN compared with B, which may be due to the following reasons. First, the contents of C and N were higher in OF treatment than in B treatment (Figs. 2 and 3), which could provide a richer source of C and N for microorganisms. Secondly, the high amount of organic matter in OF implies that many microorganisms are needed to decompose it effectively.

The MBC/TOC ratio and MBN/TN ratio can be used as indicators of C and N utilization by soil microorganisms (He 1997; Shi et al. 2019). Higher values indicate that the soil environment is more favorable for microbial growth and less energy is required to sustain the same number of microorganisms (Chodak et al., 2003). In the present study, application of B and OF increased MBC/TOC ratio and MBN/TN ratio in a concentration-dependent manner, which was consistent with previous studies (Bera et al. 2016; Fatima et al. 2021; Wankhede et al. 2021). Correlation analysis revealed that TOC, TN, MBC, MBN, NO_3^--N, NH_4^+-N, SSC, and pH were the main factors affecting the MBC/TOC ratio and MBN/TN ratio of saline-alkali soils (Fig. 6). Therefore, the increase in MBC/TOC ratio and MBN/TN ratio in this study indicated that application of B and OF improved soil fertility and quality (Figs. 5 and 6). In comparison, the MBC/TOC ratio and MBN/TN ratio of OF-treated soils were higher than those of B-treated soils, which was explained by the fact that microorganisms could use the large amount of organic matter contained in OF as an energy substrate to enhance C and N utilization (Wankhede et al. 2021; Wen et al. 2014).

The MBC/MBN ratio can be used to indicate changes in soil microbial community structure. Some studies have shown the MBC/MBN ratio is 3–6 and 7–12 for bacteria and fungi, respectively (Anderson and Domsch 1980; Jenkinson 1976). In present study, application of B and OF significantly reduced the MBC/MBN ratio, approaching 6:1 and 4.5:1, respectively, indicating that B and OF treatments changed the microbial community structure and increased the predominance of bacteria. Similar results were observed in several previous studies (Domene et al. 2015; Chen et al. 2015). Application of B and OF increased TN, NO_3^--N, NH_4^+-N, and MBN/TN ratio (Figs. 2, 3, and 5), which increased the microbial utilization of N, thus inducing a decrease in the MBC/MBN ratio. Besides, the intensity of bacterial leaching can also be reduced by the adsorption properties of B (Pietikäinen et al., 2000). Irfan et al. (2019) and Wu et al. (2011) found that soils with higher N fixation, N supply capacity, and N effectiveness possessed lower MBC/MBN ratio. In this study, OF application significantly increased the N supply capacity and was higher than B (Figs. 2 and 3), which explains why the MBC/MBN ratio of the OF treatment was lower than that of the B. Besides, the decomposition of organic materials could also affect the species and abundance of bacteria (Liu et al. 2007). In this regard, we need to further verify this through molecular biology.

Effects of B and OF on wheat yield

High soil salinity-alkalinity and low soil fertility have been shown to have a negative impact on the crop growth and yield (Zhang et al. 2021b; Zhou et al. 2021). In the present study, correlation analysis showed that SWC, SSC, and Na^+ were the key factors affecting wheat yield in saline-alkali soils, whereas soil fertility had no significant effect on wheat yield (Fig. 6). Wheat yields were significantly increased in the B treatment in this study, with B2 treatment inducing the highest yield (Table 3), due to the decline in SSC and Na^+, increase in SWC, and improvement in soil quality induced by the application of B in saline-alkali soils. Notably, wheat yield following OF treatment was lower than that of B treatment and decreased with increasing OF application. This was mainly because OF application increased the SSC and Na^+, resulting in increased uptake of SSC and Na^+ by the crop, and then affecting wheat yield (He et al. 2020). In summary, these results showed that B was superior to OF in increasing wheat yield in saline-alkali soils.

Conclusion

This study investigated whether continuous application of both B and OF in saline-alkali land can improve saline-alkali soils and increase wheat yield. The results showed that B application reduced SSC, pH, and Na^+ and increased SWC, TOC, TN, NO_3^--N, NH_4^+-N, MBC, MBN, MBC/TOC ratio, and MBN/TN ratio. Compared with CK and B, OF was more effective in increasing soil fertility but did not reduce SSC and Na^+. Correlation analysis revealed that SWC, SSC, and Na^+ were the key factors affecting wheat yield. Correspondingly, the SSC and Na^+ content of B-treated soil was significantly lower than those of OF, and the SWC was higher than that of OF. Consequently, wheat yield was significantly higher following B application compared with OF treatment, especially at a rate of 10 t ha^{-1} $year^{-1}$ in saline-alkali lands. These results indicate that B has potential application value and is superior to OF in improving soil properties and increasing wheat yields in saline-alkali lands. Given the advantages of OF in increasing soil fertility and B in reducing soil salinity and Na^+ and increasing yield, in future, we will explore the long-term effects of the combined application of B and OF on saline-alkali soil quality.

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Data availability Data will be available upon request.

Declarations

Ethics approval and consent to participate Not applicable.

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