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Effect of Biochar Application on Soil Fertility, Nitrogen Use Efficiency and Balance in Coastal Salt-Affected Soil under Barley–Maize Rotation

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Abstract: Coastal lands are often affected by salinization, which leads to a deterioration of soil structure and a decrease in land productivity. As a widely used soil amendment, biochar has been proven to improve poor soil properties and promote crop growth and N adsorption and utilization. However, the effects of biochar on soil fertility, N use efficiency (NUE) and balance in coastal salt-affected soil have rarely been reported. Therefore, we conducted a field micro-plot experiment to study the improvement effects of different biochar rates (0, 13.5, 20.25 and 27 t/ha, corresponding to CK, B1, B2 and B3 treatments, respectively) on coastal salt-affected soil. The results showed that biochar application increased soil water content (SWC) in seasons with abundant rainfall but decreased SWC in seasons with strong evaporation, and the increase or decrease in SWC was greater with the increase in biochar rates. Biochar application increased soil salinity and decreased soil pH, although high rates of biochar increased soil salinity to a lesser extent, while low rates of biochar decreased soil pH most. Biochar application was able to reduce soil bulk density, while B1and B2 treatments decreased it to a higher degree. Moreover, biochar application increased soil macro-aggregates (>0.25 mm) and organic matter, while B2 and B3 treatments increased it to a higher degree. Biochar application improved soil fertility to an extent that crop grain increased yield by 2.84~19.88% in barley season and 12.27~16.74% in maize season. Meanwhile, biochar application also increased NUE because it promoted the increase of yield. In particular, the calculation of N balance between soil and plant systems suggested that biochar application could reduce the apparent N loss during crop planting, and B1 treatment was better at reducing apparent N loss. Overall, our study indicates that biochar application has great potential to improve poor physicochemical properties and N nutrient utilization in coastal salt-affected soil. More importantly, we suggest that biochar application rates should be controlled in coastal salt-affected soil.

Keywords: coastal salt-affected soil; biochar application; soil fertility; N use efficiency; N balance

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1. Introduction

It has been estimated that there are about 1128 Mha of salt-affected soils on earth [1], which is widely distributed across 75 countries on all continents [2]. In the coastal area of China, there are about 2.17×10^6 ha of tidal flats, of which about 1/4 is found in the Jiangsu province. These coastal tidal flats are located in the marine–terrestrial interlaced zone between sea and land, which has high economic value and commercial utilization value [3]. However, excessive salt content in the coastal reclaimed soil often seriously limits the development of agriculture in tidal flat areas [4]. For instance, the accumulation of salt in crop leaves will produce toxicity and lead to the premature senescence of leaves, resulting in a significant reduction of aboveground biomass [5]. In addition, salt-affected soil often shows a lack of soil organic matter (SOM), which is not conducive to the maintenance of soil structural stability [6]. Furthermore, coastal salt-affected soil is greatly affected by seawater, as Na^+ is adsorbed by soil colloids instead of Ca^{2+}, Mg^{2+} and other multivalent cations, and becomes the main body of soil cations. The large hydration radius of Na^+ leads to the relative dispersion of clay particles, which hinder the formation of soil aggregates (SA) [7], restrict the entry of water and air into the soil and are disadvantageous to crop growth. Therefore, eliminating the obstacle of soil salinity and alkalinity and increasing soil fertility and productivity are key points for the amendment and utilization of coastal salt-affected soil.

N is one of the essential macronutrient elements for plants, which has a profound impact on crop growth and yield formation. N is the most important component of protein and protein is the embodiment of life activities, so N is often called the "life element". Plants mainly adsorb N from soil, resulting in a continuous decline in the level of N in soil, which requires supplementation by fertilization (mainly chemical fertilizer). In the past few decades, the application of N fertilizer has not only fed more people in the world, but also led to a large amount of N produced by many anthropic factors entering the air, water and land, resulting in a series of serious environmental and health problems [8]. Ammonia volatilization is the main way for N to enter the environment, and there is a positive correlation between soil total salt content, pH and ammonia volatilization [9,10]. Therefore, it is foreseeable that coastal salt-affected soil with excessive soluble salt and high pH will have extremely high ammonia volatilization [11]. In addition, nitrate reductase has extremely high salt sensitivity. High salt in soil will reduce nitrate reductase activity and increase N_2O emission [12]. Considering these factors, there is a large amount of N loss and low N availability in coastal salt-affected soil. Therefore, increasing N use efficiency (NUE) and reducing its environmental effect are also the key to amending coastal salt-affected soil.

Biochar is a carbon-rich solid residue formed by the high temperature pyrolysis of biomass under anaerobic or limited oxygen conditions. Biochar is mainly composed of stable aromatic organic carbon [13], which is difficult to degrade in soil, so it has great potential to mitigate climate change [14] and long-term nutrient supply capacity [15] when mixed with soil. In addition to being rich in carbon, the biochar produced by pyrolysis of plant residues contains not only a large amount of N and other nutrients related to plant growth, but also a large surface area, which can adsorb these nutrients to prevent them from losing water. Therefore, applying biochar to soil can significantly improve the supply capacity and availability of soil nutrients [16,17], increase crop yield [18] and increase NUE [19,20]. In addition, biochar application can increase the content of Ca^{2+} and Mg^{2+} in soil. On the one hand, this can reduce Na^+ and pH in salt-affected soil, improve soil physical properties [2] and increase the content of SOM and water-stable aggregates. On the other hand, this can also reduce the adsorption of Na^+ by plants, which is beneficial to plant growth and increases crop yield [21]. Moreover, another remarkable feature of biochar is its loose and porous structure, which is perhaps the most beneficial feature of amending salt-affected soil. It has been proven that biochar application in salt-affected soil can improve soil pore structure and hydraulic characteristics, increase soil water retention [22] and water infiltration capacity [23], which creates favorable conditions for salt leaching and crop growth. Recently, some studies have taken into account the effects of biochar application on soil quality and crop N uptake and utilization [24,25]. However, similar studies lack research on salt-affected soil, especially in coastal areas.

With the continuous development of economy in coastal areas, the contradiction between human and land has become increasingly prominent. As an important reserve land resource, the rational amendment and utilization of coastal tidal flat soil is of great significance to alleviating the reduction of cultivated land. Based on the above discussion, it can be seen that biochar application is able to improve coastal salt-affected soil, increase crop yield and nitrogen use and reduce nitrogen losses. However, it is unclear as to whether its improvement of coastal salt-affected soil is becoming better as the rates of biochar increase. Therefore, we conducted a micro-plot experiment to study the effect of biochar on the improvement of coastal salt-affected soil under the typical barley–maize rotation system. The objectives of this study are as follows: (1) to investigate the effects of biochar on soil fertility, NUE and N balance in coastal salt-affected soil, and (2) to verify whether the improvement effect of salt-affected soil improves with an increase in biochar rates.

2. Materials and Methods

2.1. Site Description

The study site is located in the Tiaozini Reclamation Area (32°49.9′~32°50.3′ N, 120°56.6′~120°57.4′ E) of the coastal economic development area of Jianggang Town, Dongtai City, central coastal area of Jiangsu Province, China. It is a coastal tidal flat, newly reclaimed in 2013. This site belongs to the transition region between the subtropical and warm temperate zones and has typical monsoon climate characteristics, such as four distinct seasons, the same period of rain and heat, concentrated rainfall, cold winters and hot summers. The annual average temperature is 15 °C, the annual average precipitation is 1061.2 mm and the annual average evaporation is 882.8 mm. Precipitation is unevenly distributed throughout the year. About 70% of the rainfall was concentrated from May to September during the 2000~2015 period. The fact that the annual average precipitation was greater than that of evaporation resulted in the coastal saline soil in this site showing a trend of desalination as a whole. Nevertheless, because the study site is offshore and the terrain is flat with an average elevation of 1.1 m, the groundwater level is high and is greatly affected by sea water, which leads to poor groundwater quality (the annual average electrical conductivity is 7.6 dS/m) [26]. Under the influence of the monsoon climate and ocean tide, the changes in soil salinity in the study site have obvious seasonality. Generally, there is little precipitation and strong evaporation in spring and the salinity accumulation on the soil surface is serious, which significantly harms crop growth. Moreover, the lack of freshwater resources and poor soil quality are also essential factors restricting the development of local agriculture.

2.2. Properties of Soil and Biochar

The soil texture of this study site is silt loam, and the soil type comprises alluvial saline soils (fluvisols, FAO), which are typical muddy coastal salt-affected soil. This study was conducted through micro-plot field experimentation, which took place on the high beach site of the research area. Before this study began, maize had been planted at this site.

The biochar used in this study was purchased from Jiangsu Huafeng Agriculture Bioengineering Co., Ltd (Zhenjiang, China). The raw biochar material was straw, which was formed by high temperature anaerobic pyrolysis, and the pyrolysis temperature was 550 °C. The basic properties of the soil and biochar are given in Table 1.

Table 1. The basic properties of soil and biochar in this study.

	EC	**pH**	**SOM**	**TN**	**TP**	**NH_4^+-N**
	(μS/cm)		**(g/kg)**	**(g/kg)**	**(g/kg)**	**(mg/kg)**
0–20 cm	346.1 ± 38.5	8.84 ± 0.10	8.37 ± 1.24	0.40 ± 0.15	0.68 ± 0.04	3.48 ± 0.34
20–40 cm	544.1 ± 72.3	9.20 ± 0.14	5.25 ± 0.64	0.26 ± 0.03	0.57 ± 0.02	2.31 ± 0.27
Biochar	7581.5 ± 81.3	9.13 ± 0.05	719.3 ± 65.4	6.64 ± 0.12	3.32 ± 0.13	35.01 ± 1.65

Note: The data are mean ± standard deviation (n = 3). EC: electrical conductivity, SOM: soil organic matter, TN: total nitrogen, TP: total phosphorus.

2.3. Experimental Design

In this study, a winter barley (*Hordeum vulgare* L.) and summer maize (*Zea mays* L.) rotation was adopted. The barley seeds and maize seeds were provided by Shanghai Haifeng Dafeng Seed Industry Co., Ltd. (Shanghai, China), and Shanghai Huanghai Seed Industry Co., Ltd. (Shanghai, China), respectively.

There were six treatments in the field experiment, each treatment contained three replicates and the arrangement was completely random. The specific experimental designs are listed in Table 2. Before the beginning of this experiment, the land was leveled and the micro-plots were divided. The size of each micro-plot was 3 m × 4 m, and each micro-plot was surrounded by a 0.2 m wide drainage ditch. Before sowing, biochar and chemical fertilizer were evenly spread on the soil surface and mixed with the topsoil. Biochar was only applied once before barley planting. Urea was selected as N fertilizer and applied according to the base-topdressing ratio of 4:3:3. The P fertilizer was calcium superphosphate, which was applied as basal fertilizer. No K fertilizer was applied in this experiment. The type, rates and application methods of the chemical fertilizers were the same during barley and maize planting. Barley was the first crop planted in this experiment, and its planting period was from November 2018 to May 2019. After the barley harvest, soil preparation, the removal of debris and straw, the application of basal fertilizer and other steps were carried out and then maize was sown. The maize planting period was from June 2019 to October 2019. Barley and maize were not irrigated during the growth period, and weeding and pest control followed local practices.

Table 2. Micro-plot experiment design.

Treatment	Code Name	Biochar Rates (t/hm^2)	Chemical Fertilizer Rates (kg/hm^2)
Low biochar rates + fertilizer	B1	13.5	
Medium biochar rates + fertilizer	B2	20.25	N:225
High biochar rates + fertilizer	B3	27	P_20_5:105
Fertilizer	CK	0	
No N fertilizer	N0P	0	P_20_5:105
No fertilizer	N0P0	0	0

2.4. Soil and Plant Sampling

Soil samples were taken from 0~20 cm and 20~40 cm soil layers with a soil drill for the determination of soil water content (SWC), electrical conductivity (EC), pH and organic matter. In addition, the ring knife samples from the 0~20 cm soil layers were taken to determine soil bulk density (BD), and bulk soil samples from the 0~20 cm soil layers were excavated with a shovel for determining SA.

After barley matured, 1 m^2 was selected in each micro-plot for yield measurement and plant sample collection. After the maize had matured, all the maize cobs and straws in the whole micro-plot were obtained. After plant sampling was completed, the straw and grain were separated, killed green at 105 °C and then dried at a constant temperature of 70 °C until they reached a constant weight in the oven. The yield was measured by 1% balance. Some representative crop samples of each treatment were ground and sieved (0.25 mm) for determining the total N in crop straws and grains.

2.5. Measurement and Calculation of Related Indexes

2.5.1. Measurement of Related Indexes

The soil samples obtained during crop growth were divided into two parts, one of which was stored in a 4 °C refrigerator and the other part was air-dried and sieved (2 mm). SWC was measured by oven drying. The soil was extracted by the ratio of soil to water at 1:5 (w/v), and soil EC and pH were measured by an electrical conductivity meter and a pH meter (Multiparameter SevenExcellence™, Mettler Toledo, Shanghai, China), respectively. The soil NH_4^+-N and NO_3^--N were extracted by the ratio of soil to 2 M potassium chloride solution at 1:10 (w/v), in which NH_4^+-N was measured by indophenol blue colorimetry and NO_3^--N was measured by ultraviolet spectrophotometry. Soil total N was measured using the Kjeldahl method. Soil total P was measured through the acid-soluble molybdenum antimony resistance colorimetric method. SOM was measured using the potassium dichromate oxidation external heating method. The total N of straw and grain was measured by indophenol blue colorimetry after digesting with H_2SO_4-H_2O_2. Soil BD was measured using the ring knife method. Refer to [27] for the detailed operation steps of the above indicators. SA was measured according to the protocol described by [28].

2.5.2. Calculation of Related Indexes

The percentage of SA of each particle size was calculated as follows:

$$wA_i(\%) = \frac{x_i}{\Sigma x_i} \times 100 \quad (1)$$

where wA_i is the content of SA with different particle sizes; x_i is the drying weight of SA of each particle size; and Σx_i is the drying weight of all SA; i = >5 mm, 2~5 mm, 1~2 mm, 0.5~1 mm, 0.25~0.5 mm, <0.25 mm.

Related indexes of NUE and N balance were calculated as follows [29]:

Apparent N fertilizer use efficiencies (NUE, %) = (aboveground N uptake in N application treatment − aboveground N uptake in control treatment)/N application rates × 100. (2)

N fertilizer agronomic efficiency (NAE, kg/kg) = (grain yield in N application treatment − grain yield in control treatment)/N application rates. (3)

N fertilizer partial factor productivity (NPFP, kg/kg) = grain yield in N application treatment/N application rates. (4)

N uptake efficiency by plant (NUEP, %) = aboveground N uptake in the N application treatment/N application rates × 100. (5)

N harvest index (NHI, %) = grain N uptake/aboveground N uptake × 100. (6)

Soil residual inorganic N (kg/hm^2) = soil residual NO_3^--N + soil residual NH_4^+-N. (7)

Net mineralization of soil N(kg/hm^2) = aboveground N uptake in the treatment without N fertilizer + soil residual inorganic N in the treatment without N fertilizer − initial inorganic N accumulation in the treatment without N fertilizer. (8)

Apparent N loss (kg/hm^2) = N application rates + initial soil inorganic N accumulation + net soil N mineralization − plant N uptake − soil inorganic N residue after crop harvest. (9)

2.6. Statistical Analysis

Microsoft Excel 2016 and Origin 2016 were used for data processing and drawing, respectively, and IBM SPSS Statistics 24 was used for statistical analysis. The LSD method was used for multiple comparisons ($p < 0.05$).

3. Results

3.1. SWC, Salinity and pH

SWC, EC and pH are shown in Figure 1. Because it was more susceptible to rainfall and crops, SWC in the 0~20 cm soil layer changed significantly from month to month, while SWC in the 20~40 cm soil layer changed more gradually and to a lesser extent between months, and in general, SWC in the 20~40 cm soil layer was higher than that in the 0~20 cm soil layer. For the 0~20 cm soil layer, SWC reached the maximum in January, but SWC in March was significantly lower than that in January. From April to September, SWC saw only limited changed, but in October, SWC was significantly lower than that of the previous month, which was related to the large evaporation and low rainfall in the autumn. The SWC of the 0~20 cm and 20~40 cm soil layers responded differently to biochar application. For the 0~20 cm soil layers, biochar application reduced SWC in March, and SWC decreased more with the increase of biochar rates. However, biochar application had a positive effect on SWC in other months, and SWC generally increased with the increase in biochar rates.

For the 20~40 cm soil layer, biochar application increased SWC, but there was no significant difference ($p < 0.05$) between different biochar rates.

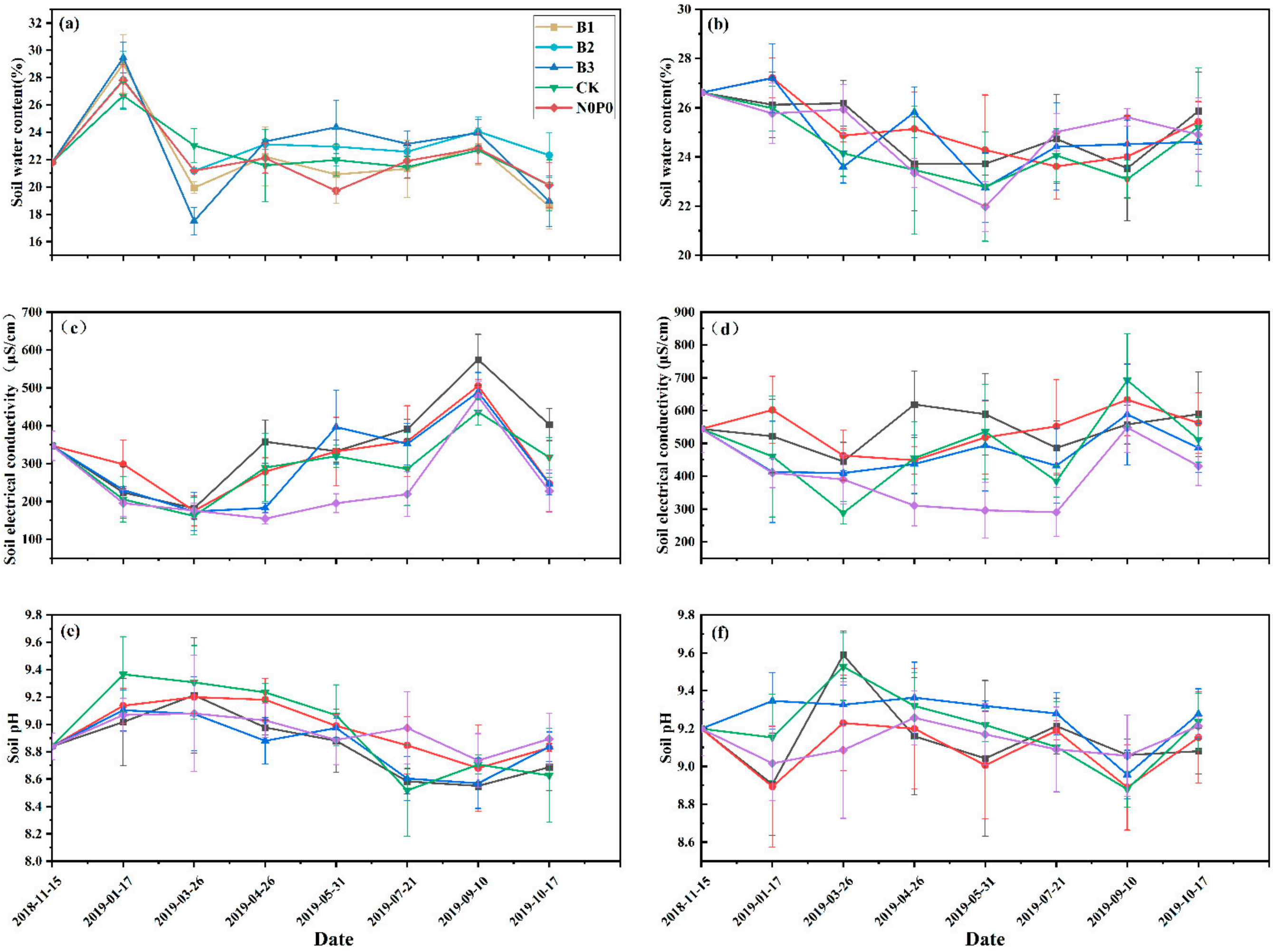

Figure 1. Soil water content, electrical conductivity and pH of 0~20 cm (**a**,**c**,**e**) and 20~40 cm (**b**,**d**,**f**) soil layers during barley and maize growth under different treatments. Error bars indicate the standard deviation for three replications.

Because there was a good linear correlation between soil EC and salinity in coastal salt-affected areas ($n = 110$, $R^2 = 0.96$, $p < 0.001$), we used soil EC to characterize salinity [30]. As with SWC, the soil EC and pH varied significantly from month to month during the year, and the changes were more dramatic for the 0~20 cm soil layer. For the 0~20 cm soil layer, soil EC was highest in September, while soil pH was higher in winter and spring (November to May of the next year for barley) than in summer and autumn (July to October for maize). Soil EC and pH of the 20~40 cm soil layer were higher than the 0~20 cm soil layer. Soil EC and pH in the 0~20 cm soil layer ranged from 154.43 to 574.87 μS/cm and 8.48 to 9.39, respectively, while the soil EC and pH in the 20~40 cm soil layer ranged from 288.1 to 692.5 μS/cm and 8.88 to 9.59, respectively. Compared with the CK treatment, the different application rates of biochar increased the soil EC of 0~20 cm and 20~40 cm soil layers to a certain extent, and generally, the medium and low rates of biochar increased more, while the high rates of biochar increased less. Contrary to the effect of biochar application on soil EC, after three different rates of biochar were added to the soil for a period of time, the soil pH of the 0~20 cm soil layer was reduced compared with the CK treatment; the longer the application time, the better the effect of reducing soil pH, and overall, the lower the rates of biochar, the more the soil pH was reduced. In general, the application of high rates of biochar increased the soil pH more in the 20~40 cm soil layer.

3.2. Soil Fertility

In order to clarify the improvement effect of biochar on soil fertility, we measured the soil BD, SOM and SA after the barley and maize harvest (Figure 2). Biochar application reduced soil BD, increased SOM and promoted the formation of SA after harvest in two crops. However, the effect of different biochar rates on the three soil fertility indexes were different, and there were differences between the two crops.

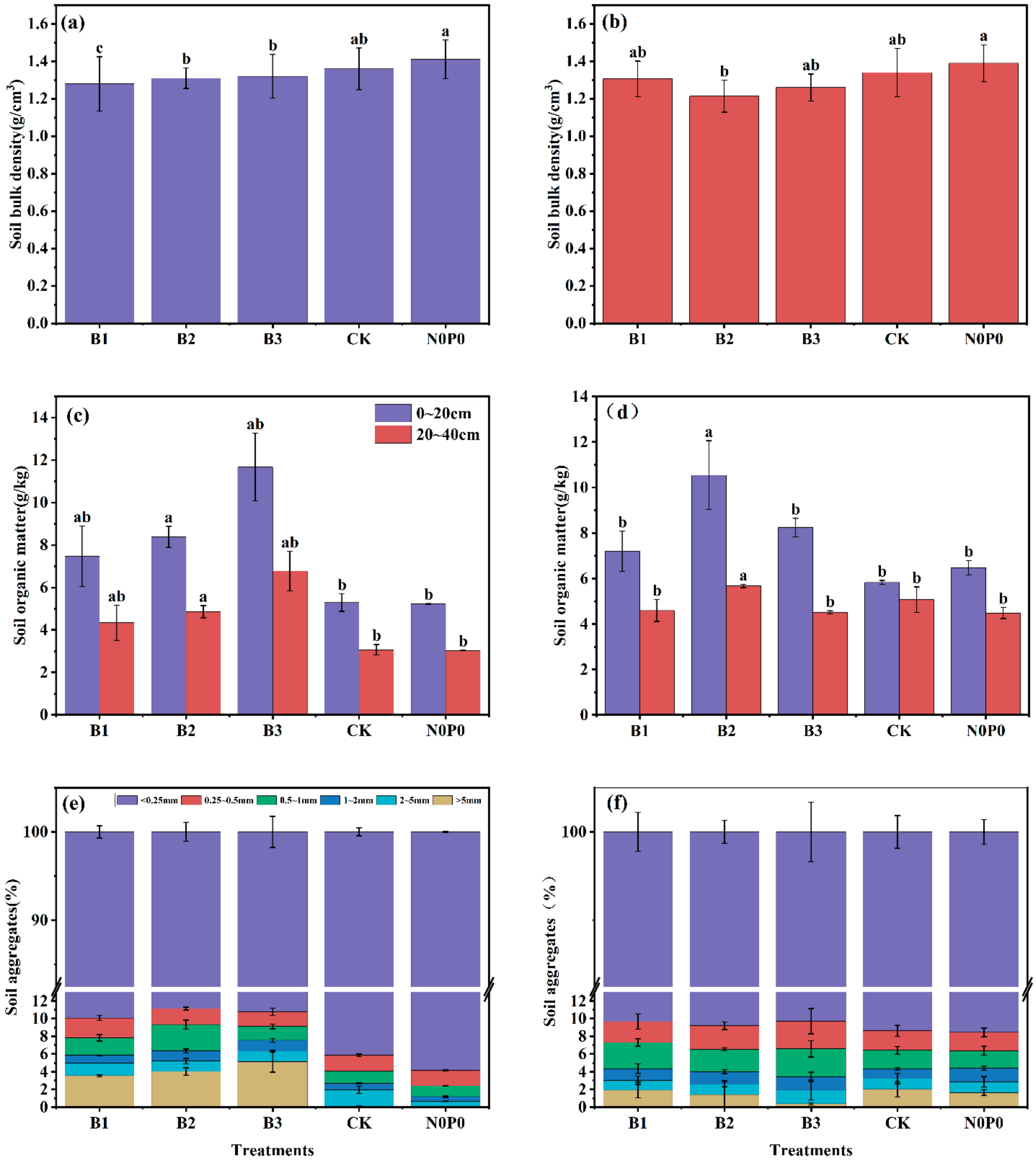

Figure 2. Soil bulk density, soil organic matter and soil aggregates after barley (**a**,**c**,**e**) and maize (**b**,**d**,**f**) harvest under different treatments. Error bars indicate the standard deviation for three replications, different lowercase letters indicate significant difference among different treatments ($p < 0.05$).

For the soil BD, compared with CK treatment, B1, B2 and B3 treatments significantly decreased by 5.88%, 3.68% and 2.94%, respectively, in the barley season ($p < 0.05$), while in the maize season, it decreased by 2.49%, 9.45% and 5.97%, respectively, but only the difference between B1 and CK treatment was significant ($p < 0.05$). In the barley season, the content of SOM in the 0~20 cm layer increased with the increase of biochar rates, which demonstrated that the B1, B2 and B3 treatments increased by 41.23%, 58.31% and 121%, respectively, compared with CK treatment. However, in the maize season, the SOM in the 0~20 cm layer did not increase with the increase in biochar rates; yet, medium biochar rates increased most, specifically, B1, B2 and B3 treatments increased by 23.5%, 80.79% and 41.34%, respectively, compared with CK treatment. In addition, among the three treatments, only the B2 treatment increased significantly compared with CK treatment ($p < 0.05$). After two crops were harvested, biochar application improved the content of soil macro-aggregates (>0.25 mm). Compared with CK treatment, the soil macro-aggregates of B1, B2 and B3 treatments increased by 71.72%, 89.95% and 83.65% in the barley season, respectively, while in the maize season, it only increased by 12.18%, 6.84% and 12.65% respectively. In particular, the composition of soil macro-aggregates was different between the two crops. Biochar application significantly increased the content of the 0.25~1 mm and over 5 mm layer macro-aggregates in the barley season, while in the maize season, biochar application increased the content of 0.25~1 mm macro-aggregates to a higher degree.

3.3. Crop Yield and N Uptake

The effects of biochar application on barley and maize yield and N uptake are shown in Table 3. Biochar application was helpful for increasing grain and straw yield. The grain yield of barley and maize increased with the increase of biochar rates, compared to CK, B1, B2 and B3 treatments increased barley grain yield by 2.84%, 16.16% and 19.88% and maize grain yield by 12.27%, 15.27% and 16.74%. Biochar application also increased straw yield; however, the highest straw yield in two crops resulted from B2 treatment, which increased barley straw yield by 9.73% and maize straw yield by 26.71%. The effect of biochar on the N content of grain and straw was inconsistent with two seasonal crops, and there was no significant difference ($p < 0.05$) between different nitrogen fertilizer treatments except B1 treatment. Moreover, compared with CK treatment, all biochar treatments improved the N content of barley straw and grain; however, for the maize season, only B1 treatment increased the N content of straw and grain, while B2 and B3 treatments decreased or increased slightly. According to the yield and N content of the crop, we calculated its N accumulation. Biochar application increased the N accumulation of two crops, but only the increase in the barley season was significant ($p < 0.05$). Moreover, the N accumulation of crops in both seasons increased less through B3 treatment, while B1 treatment increased it most in the barley season and B2 treatment increased it most in the maize season.

Table 3. Effects of different treatments on yield and nitrogen uptake of barley and maize.

Treatments	Yield (kg/hm^2)		N content (g/kg)		N accumulation (kg/hm^2)		
	Straw	Grain	Straw	Grain	Straw	Grain	Plant
			Barley				
B1	15340.7 ± 1850.2 a	4345.9 ± 375.9 ab	6.15 ± 1.13 a	24.17 ± 0.63 a	94.28 a	105.03 a	199.31 a
B2	15559.9 ± 1098.1 a	4908.9 ± 121.3 ab	5.84 ± 0.44 a	21.55 ± 0.95 b	90.80 ab	105.77 a	196.57 a
B3	14039.0 ± 1142.5 a	5066.2 ± 552.2 a	5.98 ± 1.02 a	21.65 ± 0.25 b	84.02 ab	109.66 a	193.68 a
CK	14180.2 ± 812.7 a	4226.0 ± 635.4 b	5.13 ± 0.48 a	21.25 ± 0.41 b	72.81 b	89.81 b	162.62 b
N0P	7065.4 ± 190.8 b	2707.2 ± 49.0 c	3.93 ± 0.10 a	14.96 ± 0.16 c	27.75 c	40.50 c	68.25 c
			Maize				
B1	7622.5 ± 710.1 bc	5194.2 ± 79.6 b	9.71 ± 1.53 c	16.93 ± 0.74 b	76.21 c	87.85 a	164.06 b
B2	8951.2 ± 47.7 c	5332.9 ± 154.3 b	8.72 ± 0.15 bc	16.68 ± 0.46 b	78.08 c	88.99 a	167.08 b
B3	8514.5 ± 609.8 c	5400.7 ± 211.0 b	7.58 ± 0.57 abc	16.73 ± 0.8 b	65.25 bc	90.03 a	155.28 b
CK	7064.4 ± 755.2 abc	4626.4 ± 145.4 b	9.49 ± 0.29 c	16.70 ± 0.34 b	67.31 bc	77.37 ab	144.68 b
N0P	5578.2 ± 792.9 a	3351.0 ± 707.2 a	6.48 ± 0.50 ab	15.52 ± 1.31 ab	35.97 ab	51.66 ab	87.63 a

Note: Different letters after the same column of data indicate that the differences between different treatments are significant ($p < 0.05$).

3.4. N Fertilizer Use Efficiency

Table 4 shows the effects of different treatments on N fertilizer use efficiency, which could be used to characterize the agronomic effects of N fertilizer. NUE is the main basis to evaluate the agronomic effect of N, and its value is greatly affected by N application and N loss. Compared to CK treatment, B1, B2 and B3 treatments increased NUE by 38.89%, 35.98% and 32.93%, respectively, in the barley season and by 33.95%, 39.24% and 18.57%, respectively, in the maize season, but there was no significant difference ($p < 0.05$) between different treatments in the maize season. NAE and NPFP could be used to evaluate the contribution of N fertilizer to crop grain yield. We can see that the three application rates of biochar all increased these two indexes in the two season crops, and with the increase in biochar rates, these two indexes increased correspondingly. NUEP and NHI reflect the contribution of the N fertilizer to crop N uptake and the proportion of N adsorbed by crop reproductive organs to the total N uptake of crop, respectively. Biochar application can promote the adsorption of N by crops and improve the NUEP. Furthermore, compared to CK treatment, the NUEP of the B1 and B2 treatments increased more in both crops. As for NHI, compared to CK treatment, of the three biochar treatments, only the B3 treatment increased, while the other two biochar treatments decreased or had no significant effect.

Table 4. Effects of different treatments on N fertilizer use efficiency of barley and maize.

Treatments	NUE (%)	NAE (kg/kg)	NPFP (kg/kg)	NUEP (%)	NHI (%)
			Barley		
B1	58.25 a	7.28 a	19.31 a	88.58 a	52.70 b
B2	57.03 a	9.79 a	21.82 a	87.36 a	53.81 ab
B3	55.75 a	10.48 a	22.52 a	86.08 a	56.62 ab
CK	41.94 b	6.75 a	18.78 a	72.28 b	55.23 ab
N0P	-	-	-	-	59.34 a
			Maize		
B1	33.97 a	8.19 a	23.09 a	72.92 a	53.55 a
B2	35.31 a	8.81 a	23.70 a	74.26 a	53.26 a
B3	30.07 a	9.11 a	24.00 a	69.01 a	57.98 a
CK	25.36 a	5.67 b	20.56 b	64.30 a	53.48 a
N0P	-	-	-	-	58.95 a

Note: Different letters after the same column of data indicate that the differences between different treatments are significant ($p < 0.05$). NUE: Apparent N fertilizer use efficiencies, NAE: N fertilizer agronomic efficiency, NPFP: N fertilizer partial factor productivity; NUEP: N uptake efficiency by plant; NHI: N harvest index.

3.5. N Balance

According to N input and output, we calculated the N balance during the planting period of two crop seasons (Table 5). In the N input, fertilizer N occupied a dominant position, accounting for more than 70% of N input. Biochar application decreased the content of soil inorganic N, thus reducing the initial inorganic N in the maize season. In addition, the mineralization of organic N in maize season was higher than that in the barley season. In the N output, the main factor was crop adsorption, accounting for 53~84% of N adsorption by crop in the barley season and 42~90% in the maize season. Apparent N loss accounted for a large proportion during the period of two seasonal crops, which accounted for 26~36% in barley season and 34~46% in maize season. Biochar application reduced N loss, and compared to CK treatment, the apparent N loss in the barley season decreased by 27.83%, 21% and 25.35%, respectively, while that in the maize season decreased by 27.22%, 15.43% and 4.49%, respectively.

Table 5. Effects of different treatments on nitrogen balance between barley and maize and soil.

Treatments	N Input (kg/hm^2)			N Output (kg/hm^2)		
	Fertilizer N	Initial Inorganic N	Net Mineralization	Residual Inorganic N	Plant Uptake	Apparent N Loss
			Barley			
B1	225	28.46	53.10	26.59 ab	199.31 a	80.66 b
B2	225	28.46	53.10	21.70 b	196.57 a	88.29 ab
B3	225	28.46	53.10	29.44 ab	193.68 a	83.44 b
CK	225	28.46	53.10	32.17 a	162.62 a	111.77 a
N0P	0	28.46	53.10	13.31 b	68.25 b	0
			Maize			
B1	225	26.59	82.32	54.22 a	164.06 b	115.63 a
B2	225	21.70	82.32	27.58 b	167.08 b	134.36 a
B3	225	29.44	82.32	29.73 b	155.28 b	151.75 a
CK	225	32.17	82.32	35.93 b	144.68 b	158.88 a
N0P	0	14.53	82.32	9.22 c	87.63 a	0

Note: Different letters after the same column of data indicate that the differences between different treatments are significant ($p < 0.05$).

4. Discussion

4.1. Effect of Biochar Application on SWC, EC and pH in Coastal Salt-Affected Soil

In this study, the response of SWC to biochar application (Figure 1a,b) was affected by both climate and biochar properties. Specifically, in the spring drought period, biochar application deepened the color of the soil surface, increased the solar radiation absorbed by the soil surface and led to a decrease in water viscosity and surface tension, thus accelerated soil water evaporation [31]. Furthermore, biochar might also contain hydrophobic functional groups [32]. Therefore, biochar application decreased SWC, and SWC decreased more as the rates of biochar increased. However, throughout most of the rest of the planting period, biochar application promoted the retention of soil water and SWC increased with the increase in the rates of biochar, which might be related to the micropore structure on the surface of biochar and its ability to absorb water [33].

Some studies have shown that biochar application was able to reduce soil salinity for the following reasons: (1) Biochar application can increase soil porosity and hydraulic conductivity and accelerated soil salinity leaching. (2) The abundant functional groups on the surface of biochar can adsorb Na^+, and the porous structure of biochar can also physically envelop certain salt ions, which can reduce soil salinity. (3) Biochar application can improve soil structure, reduce soil evaporation and thus reduce salt accumulation in the soil surface layer [34,35]. However, our study suggested that biochar application increased soil EC at different levels in different periods, and in general, low and medium rates of biochar increased more and high rates of biochar increased less (Figure 1c,d). On the one hand, biochar itself contains a large amount of soluble salts and applying it to soil with low buffering capacity will increase soil salinity [36]. Furthermore, salt ions (such as Na^+) adsorbed by biochar may also reenter soil solution [6]. On the other hand, biochar application promoted the growth of crops (Table 3), so the water requirement of crops increased, and under the effect of transpiration pull, the salts of the subsoil rose together with the water to the surface soil and accumulated. The high rates of biochar induced the least increase in soil EC, probably because it was more conducive to the formation of soil macro-aggregates (Figure 2e,f), the effect of increasing rainfall infiltration and salt leaching was better and soil salinity also decreased more. From the seasonal difference of soil EC, the highest soil EC was found in September in autumn, which was related to low rainfall, high temperature, intense evaporation and salt accumulation in the soil surface.

Biochar contains many mineral elements, and carbonates composed of these elements often make biochar alkaline, so it is possible that biochar application will increase soil pH [37]. However, our study showed that biochar application could significantly reduce soil pH (Figure 1e,f). There are three main mechanisms for biochar application to reduce soil pH: (1) Biochar application can reduce exchange sodium percentage and reduce soil pH by increasing the adsorption of Na^+, increasing surface charge density and Ca^{2+} content in the soil to replace Na^+ adsorbed on soil colloids, increasing soil porosity and hydraulic conductivity and promoting Na^+ discharge from the soil [21,38]. (2) Biochar has a high cation exchange capacity, which can stimulate crops to adsorb Ca^{2+} and Mg^{2+} and release H^+ [39]. (3) After biochar is added to soil, some acidic functional groups are formed by oxidation. In addition, high rates of biochar weaken the effect of alkalinity reduction, which is related to the alkaline property of biochar, and with the increase in biochar rates, the disturbance to soil pH would also increase. We also found that the response of soil pH to biochar application varied depending on the crop types, that is, the soil pH of the 0~20 cm soil layer in the barley season was higher than that in the maize season. We hypothesized that this might be related to changes in soil salinity composition during the two cropping seasons. In the barley season, because the strong alkaline biochar was first added to the soil, soil pH showed a relative increase. In the maize season, with the continuous rainfall and evaporation, salts also continuously migrated up and down in the soil, which changed the composition of salt ions in the soil, resulting in the change of soil pH.

4.2. Effect of Biochar Application on Soil Fertility in Coastal Salt-Affected Soil

Soil BD is a very important index to reflect soil fertility. If the soil BD is too high, it will reduce the infiltration rate of soil water and nutrients, and thus hinder the growth and extension of plants. Unfortunately, salt-affected soil is usually associated with high BD. Previous studies have demonstrated that due to the loose and porous nature of biochar, it was able to dilute soil compaction when applied to the soil [40]. In the present study, biochar application also decreased soil BD, which was consistent with previous studies in this experimental area [41]. Moreover, in the research of [42], when the rates of biochar increased from 3 t/ha to 12 t/ha, the soil BD decreased at the same time. However, our results showed that the soil BD did not decrease with the increase of biochar rates (Figure 2a,b). We speculate that this might be due to the large rates of biochar used in this study and that the experimental area was located in a coastal zone, which had a strong weathering effect. Through mechanical crashing and physical weathering, biochar particles became smaller. These cracked biochar particles entered soil pores, thus resulting in a relative increase in soil BD.

SOM plays a key role in determining soil fertility. Biochar itself is rich in organic carbon (OC), which can be divided into labile and stable OC. Labile OC accounts for only a small part of the OC in biochar, and it is quickly mineralized by soil microorganisms when added to soil [43], while the stable OC, which accounts for a large proportion of biochar, is mineralized slowly by soil microorganisms. Therefore, the input of biochar into soil can effectively supplement the soil C pool [44]. In addition, biochar application can indirectly affect SOM by changing soil porosity, aggregates, pH, microbial community structure, etc. For instance, the addition of biochar increases soil porosity, which helps more OC to be adsorbed and captured by soil, thus preventing microorganisms from oxidizing OC. Moreover, there are abundant polyvalent cations on the surface of biochar, which can increase the flocculation of soil clay and combine with organic matter to form a biochar–mineral–organic matter complex and promote the formation of SA. Furthermore, biochar can increase the hydrophobicity of soil, which can prevent water from entering and destroying SA, thus protecting SA [45]. SA can protect SOM from two main aspects: one is the reduction of the degradation of SOM through physical protection and the other is the change in the community structure of microorganisms, thus reducing the flow of oxygen and decreasing the oxidation of SOM [46,47]. In this study, when biochar rates increased, the content of SOM also increased after the barley harvest (Figure 2c,d). [48,49] had the same research results. However, although all three different rates of biochar treatments increased SOM after the maize harvest compared to the CK treatment, the SOM under the high rates of biochar treatment decreased to a certain extent compared with the medium rates of biochar treatment. It might be that biochar application slightly increased soil pH in the maize season. Soil pH affects the abundance of bacteria and fungi, thereby affecting the formation of SOM [50,51]. For SA (Figure 2e,f), our results showed that biochar application resulted in no significant increase ($p < 0.05$) of the formation of SA, which might be due to the fact that our study was based on a short-term field experiment and the SA formed in the early stages would have been destroyed by tillage and rainfall [52]. The formation of SA takes a long time. According to [53], comprising research from a five-year experiment, biochar treatment significantly increased the formation of soil water-stable aggregates. In addition, biochar application in this study promoted the increase of SA in the barley season better than that in the maize season, probably because the strong and intensive rainfall in the maize season was more destructive to SA.

4.3. Effect of Biochar Application on Crop Yield in Coastal Salt-Affected Soil

It is controversial as to whether biochar application can improve crop yield. According to the relevant reports [54], when biochar rates increase from less than 1 t/ha to more than 100 t/ha, the corresponding yield increases from less than 10% to more than 200%. The difference may be a result of different biochar types, soil and crops used in different studies. The authors of [18] pointed out that the yield increased significantly when biochar was used in the tropics, but it did not increase significantly when used in temperate regions. This is mainly because there is heavy rainfall in the tropics and a high level of nutrients are leached, so the soil often displays strong acidity, and biochar application can neutralize acidity and provide nutrients (i.e., N, P, Ca) for crop growth, thus increasing crop yield [55]. In temperate regions, however, biochar application raises soil pH too much, thereby causing a large quantity of nutrients to be fixed (P) and lost (ammonia), which does not promote (or even reduce) the yield [56]. However, a study found that biochar application on acid soil did not promote the growth of crops, which might be due to the sufficient supply of nutrients and water in the experiment and the short experiment period (91 days) [57]. Moreover, the authors of [58] demonstrated that applying certain rates of biochar increased crop yield in salt-affected soil, but excessive application of biochar had a negative effect on crop yield. We reached similar conclusions in the current study (Table 3), i.e., that biochar application increased crop yield in coastal salt-affected soil, which was related to a decrease in soil BD, increase in SOC and promoted the formation of SA. Interestingly, grain yield increased with the increase of the rates of biochar, while straw yield increased more with medium and low rates of biochar. We speculated that excessive biochar application might reduce the availability of nutrients in soil, and the adsorption of nutrients by plants would give priority to grain growth, resulting in a decrease in nutrients allocated to straw growth.

4.4. Effect of Biochar Application on N Use Status and N Balance in Coastal Salt-Affected Soil

The N adsorbed by crops is mainly inorganic N, and biochar affects the content of inorganic N in soil by regulating the transformation of N in soil and chemical fertilizer and then affects the adsorption of N by crops. When biochar was applied to acid soil and the application rates were low, the ammonia volatilization loss of N was increased due to its lime effect [59]. Similarly, the incubation experiments of [11] in this experimental area revealed that ammonia volatilization loss increased with the increase in biochar application. However, some studies demonstrated that biochar application reduced ammonia volatilization through the adsorption of ammonia on its surface cation exchange sites and the gradual neutralization of carbonates and alkaline oxides [60,61]. Biochar application has a positive effect on the soil retention of NO_3^--N. On the one hand, biochar adsorbs NO_3^--N indirectly through the electrostatic bridge connection of multivalent cations on its surface. On the other hand, biochar reduces water leakage by increasing soil water retention capacity, thus blocking the leaching of NO_3^--N [62]. In the present study, different rates of biochar treatments had a trend of reducing the residual inorganic N in soil after the two crops were harvested (Table 5). We assumed that the strong alkalinity of coastal salt-affected soil led to strong ammonia volatilization and biochar application also increased ammonia volatilization [11], so the superposition effect of two factors made soil NH_4^+-N at a low level. Furthermore, the intensive rainfall in the study area might also have weakened the retention of NO_3^--N by biochar. Through the analysis of crop N uptake, we found that there was no significant difference ($p < 0.05$) in crop N content among different treatments on the whole, but biochar application greatly improved crop N uptake and N use efficiency (Tables 3 and 4), which we suspected to be related to the improvement of crop yield by biochar in this study. Overall, biochar application showed a significant improvement in N adsorption and use of crops. The difference with our current findings was that previous studies attributed the improvement of crop N uptake and N use efficiency by biochar to increasing the retention and supply time of N in soil by reducing N_2O emission [63] and ammonia volatilization [64]. Interestingly, in this study, NAE and NPFP increased with the increase in biochar rates, while the effects of different biochar treatments on NUE, NUEP and NHI were inconsistent, which was mainly related to the effect of biochar on crop straw and grain yield.

In the agroecosystem, the main paths of N loss are runoff and the leaching loss of nitrate N, ammonia volatilization and the gaseous loss of nitrification/denitrification. In the present study, the apparent loss of N between soil and plant systems was relatively large (Table 5), which included the large loss of ammonia volatilization and rainfall leaching mentioned above. Moreover, in order to prevent waterlogging caused by intensive rainfall in the study area, drainage ditches had been built between each micro-plot, which might also indirectly increase the loss of N through runoff. Biochar application reduced N loss, and the effect of high rates of biochar on reducing N loss was not as good as that of medium and low rates, which was related to the relative decrease of straw yield by high biochar rates. Furthermore, biochar application had a better effect on reducing N loss in the barley season, which might be related to the high biomass of barley and the relatively mild climate during its growing period. It can be seen that biochar application has different effects on the improvement of N fertilizer use efficiency and the prevention and control of N loss [65]; therefore, a reasonable application strategy should be specified in different areas according to local conditions.

5. Conclusions

In conclusion, our field experiments demonstrated that biochar application increased SWC except in the spring with dry climate, increased soil salinity and decreased soil pH. In addition, biochar application reduced soil BD, increased SOM and soil macro-aggregate content. Due to the improvement of the above soil physicochemical properties, biochar application increased crop yield and nitrogen uptake and use, reducing apparent nitrogen loss. This achieved our first objective in this research work. As for the second objective of this study, we found that the high rates of biochar were able to better promote the leaching of salts by precipitation, increase SWC, SOM and soil macro-aggregate content, and therefore increase yield by a higher degree. However, it was not as effective as low and medium rates of biochar in reducing soil pH, BD, and apparent nitrogen loss, as well as in improving crop nitrogen uptake and nitrogen use. Therefore, based on the consideration of economic and environmental benefits, the B2 treatment (20.25 t/ha) in this study was more effective in amending coastal salt-affected soil. Moreover, we suggest that the application rates of biochar should be controlled when they are used to amend soil in coastal areas susceptible to salinization.

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