RESEARCH ARTICLE

Regulation of improved biochar on the geochemical properties of saline alkali land

Bing Qiao*, Zebing Xing

College of Agricultural Engineering, Shanxi Agricultural University, Jinzhong, Shanxi, China

Received: September 10, 2023; **accepted:** November 22, 2023.

Biochar possesses water absorption properties and can impact soil permeability, acidity levels, and other relevant factors. However, its effects are inconsistent as it is highly susceptible to external climatic conditions. Therefore, it is crucial to ensure the stability of biochar during the treatment of saline alkali soil. Achieving this goal requires enhancing the regulation of saline alkali soil and improving the properties of the land, both of which are vital for maintaining optimal conditions for agricultural production. Moreover, research on the use of biochar has predominantly concentrated on acidic or low to medium salt soils with little attention given to soda saline alkali soil. The use of ameliorating agents on saline and alkaline land has been the focus of attention and research, and the application of biochar in most research soils for the acidic or low to medium salt land is a key component in strengthening the regulation of saline and alkaline land and the improvement of land properties to ensure agricultural production. In order to improve biochar, this study suggested applying it to a soda-saline area in Northeast China and adding polymeric aluminum iron sulphate (Pais) for biochar's joint regulation. The study method primarily involved adjusting the pseudo dissociation of various biochar and improvement additives to examine their impact on regulating soil physicochemical properties. The biochar addition amount categorized the groups into Bi0 (0%), Bi1 (1%), Bi2 (2%), and Bi3 (3%). Based on the inclusion of polymeric aluminum iron sulphate modifier, the soil was classified into four groups as Pais0 (0%), Pais1 (1%), Pais2 (2%), and Pais3 (3%). The groups (Bi0 and Pais0) without any added ingredients (0%) were set as controls. The results found that the biochar-enhanced amendment greatly impacted the pH values of the saline-alkali soil. Notably, the soil's bulk density showed a remarkable decrease while its porosity showed a significant increase with the maximum bulk density difference of the groups being 0.43 g/cm^3. Particularly, the improvement effect of the modified proportion (1% and 2%) was outstanding. Comparing various modified biochar ratios to the untreated group, the difference in soil moisture content was essentially greater than 25%, and the saturated water holding capacity of the soil reached its highest value of 45.89% in the modified ratios (2% and 3%). The sodium adsorption ratio of saline-alkaline soil with the improved ratio (1% and 2%) was the smallest (0.1), but the enhanced soil enzyme activity and fungus suppression were both more prominently affected by the improved biochar. The method of preparing this amendment was relatively straightforward, thereby reducing the cost of land treatment significantly. The enhanced biochar exhibited excellent capabilities to alleviate the salt alkalinity of saline land and improve soil fertility. This feat was of great technical significance and should be considered a valuable reference for the agricultural sector.

Keywords: biochar; alkaline soil; regulatory effects; polymeric aluminum iron sulphate; enzyme activity; electrical conductivity.

***Corresponding author:** Bing Qiao, College of Agricultural Engineering, Shanxi Agricultural University, Jinzhong 030801, Shanxi, China. Email: qb18734137262@126.com.

Introduction

Alkaline soil (AS) is characterized by the distribution and accumulation of soluble salts in both the horizontal and vertical dimensions, significantly impacting land growth and can be categorized as having light, medium, or heavy salt content. The formation of AS is influenced by both natural and human-made factors. AS can harm the structural qualities of the soil through the adsorption of metal ions by soil colloids, which can reduce the soil's permeability and enzyme activity (EA) as well as microbial activity. The Soda Saline Alkali Soil (SSAS) type makes up more than 30% of the overall AS distribution area in China, which is quite large and mostly concentrated in arid and semi-arid regions [1, 2]. Saline alkali resistant plant planting and afforestation are the principal biological ways for SSAS improvement and use, together with hydraulic engineering measures, physical and chemical improvement, and biological measures. In contrast, organic materials used in agricultural production, such as fruit peels and crop stalks, disintegrate at high temperatures, and the solid products that remain after the removal of oil and gas have good chemical stability [3]. Numerous studies have been conducted on the use of biochar in soil improvement practices, but few of them have included SSAS. Additionally, high molecular applications of biochar in soil improvement are still very uncommon. It is recommended that biochar is enhanced to regulate the physicochemical characteristics of AS whilst combining polymeric aluminum iron sulphate (PAIS) with AS to optimize desalination outcomes. Ascertaining the optimum ratio of modified biochar for AS management is valuable given that the PAIS preparation process is relatively uncomplicated. Structural degradation and nutrient deficiencies brought about by alkalinity aggregation greatly restrict soil development, while long-term straw biochar application can significantly promote phosphorus conversion in soil and improve AS. Li *et al*. discussed and analyzed the relationship between biochar and soil physicochemical properties, organic acid content, EA, *etc*. to provide a basis for the application of straw biochar in SSAS [4]. Wang *et al*., on the other hand, investigated the effect of biochar and organic fertilizer on the improvement of AS quality and yield and set up a field experiment to test different treatment groups, which showed that both increased the total organic carbon and decreased the pH value in the soil [5]. Ekinci *et al*. analyzed the effect of biochar on the growth of kale seedlings under salt stress with the help of potting experiment and set up different salinity levels and biochar doses for experimental design. The results showed that salt stress would have a greater constraint on the growth parameters such as leaf area and fresh weight of kale seedlings to a greater extent, and the addition of biochar significantly improved the situation and effectively increased the nutrient content and EA of kale seedlings [6]. Kul analyzed the growth properties and physiological and biochemical characteristics of salt-stressed aubergine under inter-root biotrophic bacteria combined with biochar with the help of pot experiment with two salinity levels and three biochar levels. The results showed that water content as well as growth properties of aubergines under salt stress were significantly reduced and transformed, and some EA enhancement and electrolyte leakage were evident. Nutrient uptake of aubergine seedlings was significantly increased under the application of combined amendments and the salt tolerance of the plants was improved [7]. Sodium carbon content in soil can affect AS soil, in order to further determine its appropriate proportion, Wei *et al*. designed a field experiment on the change of two factors including biochar dosage and phosphorus content. The results showed that biochar could effectively increase soil organic carbon content, and its 1% and 3% dosage made its increase value above 95%, and the increase of phosphorus content could also affect soil structure, but its effect was small. The combination of the two could effectively improve the soil structure and enhance its quality [8]. Kul *et al*. conducted a study on biochar affecting the performance of tomato under soil salinity and designed experiments under two salinity conditions and three doses of biochar. The results showed that 5% and 10% biochar applications improved the negative effects of phytogenesis under salt stress by increasing the plant height more than 40% (5% biochar) and the number of leaves more than 24% (10% biochar) [9].

The enhancement of soil physiochemical traits and AS stress tolerance by means of biochar has been thoroughly elucidated. The complex mechanisms of biochar amendments necessitate an investigation of the interactions between biochar and soil organisms in diverse environments, offering practical value and immense significance [3]. The application and amendment of biochar played an important role in reducing the negative effects of salt stress on plants, which was analyzed by Ghassemi-Golezani *et al*. with the help of potting experiments with different biochar treatment groups and salt stress conditions. It was found that biochar treatment was effective in sodium content in plant tissues and bacterial improvement based on biochar increased the yield of oilseed rape by more than 50% in all cases [10]. Soliman *et al*. affected the yield and leaf growth performance of wheat under salinized soil and showed that salt stress greatly inhibited plant photosynthesis and caused osmotic damage. The decline in crop yield due to physiological damage was significant at the nutrient stage and maturity with values of more than 40% [11]. Alfadil *et al*. analyzed the improvement of salt tolerance in maize with the help of pot experiments and set up three different levels of bio-addition for controlled experiments. The results showed that the addition of biochar could effectively improve the soil properties, in which 10% addition could greatly improve the salt tolerance of maize, and the improvement effect was outstanding for maize with high evapotranspiration [12]. Malik *et al*. conducted an analysis on the restoration of saline soils using biochar and humic acid. They performed a pot experiment in a greenhouse and found that salt stress detrimentally impacted the dry weight, chlorophyll, and water relations of maize seedlings. The harmful effects were more pronounced under high salt stress conditions. The application of biochar and humic acid could guarantee the growth performance of maize, and the combined application could effectively improve the accumulation and uptake of Na^+, the proportion of which was more than 10%, which alleviated the salt-induced oxidative damage to plants. The application of biochar could effectively alleviate the oxidation of plants and improve their EA [13]. Wang *et al*. studied the role of biochar and organic fertilizer on soil property changes and analyzed a three-year experiment on a Delta AS. The results showed that both amendments could increase crop yield, and had obvious enhancement effect on soil water content, calcium, phosphorus, and nitrogen, and effectively improved soil salinity [14]. Zhou *et al*. studied the soil properties of rhododendron under different temperatures of pyrolysis-amended biochar with the help of potting experiments. The results showed that the biochar at 350°C and 550°C had obvious promotional effects on photosynthesis of rhododendron and the biomass, and to a certain extent could reduce soil acidity and mycorrhizal infestation rate. Therefore, biochar had obvious application effects in promoting the growth of acidophilous plants and improving soil quality [15].

The improvement of most AS sites is mostly done with the help of biochar for salt tolerance modulation, and less research involves SSAS. This study proposed the combination of PAIS, which had a simple preparation technique, and biochar to better realize the performance modulation of AS, and thus improved its salt tolerance. The objective of the study was to examine the regulatory effect of enhanced biochar in saline alkali soils with particular emphasis on enhancing their physicochemical characteristics. To achieve this, a comparative experimental design analysis was carried out utilizing an improved biochar in conjunction with the incorporation of polymeric aluminum iron sulfate. The results would provide critical technical reference value for agricultural production and a reduction in land management costs.

Materials and Methods

Research area and soil sample collection

The research area is in a typical agricultural pastoral ecotone in Jilin Province, China (44°47'N, 123°25'E). The area is a typical continental monsoon climate and the annual precipitation in the region is mainly concentrated in the summer with the average annual evaporation more than 1,500 mm. The topography of the area is mostly of plain type and the soil is alkaline in nature. The study gathered saline alkaline "soda" soil from this region at a depth of 0-20 cm. The collected soil samples underwent stone and impurity removal, air drying, uniform grinding into powdered form, and preparation *via* a 2 mm sieve. The pH value and organic matter content of the collected soil samples were 10.55 and 3.48 g/kg. A soil unit (200 m × 200 m) with 3-7 sampling areas (30 m2) were set up by using multi-point sampling technique to ensure that the sampling interval of soil did not exceed 2 m, adhering to the principles of comprehensiveness, representativeness, objectivity, and feasibility as experimental requirements.

Experimental design

Biochar and polymeric aluminum iron sulphate (PAIS) were obtained from Jinhefu Agricultural Technology Co., Ltd., Jilin, China and Xinbang Environmental Protection Technology Co., Ltd., Jilin, China, respectively. The biochar category was equal to corn stover, in which the content of organic carbon, total nitrogen, phosphorus, and potassium were 600 g/kg, 12.8 g/kg, 0.21 g/kg, and 43.29 g/kg, respectively. Meanwhile, the biochar had a specific surface area and average pore diameter that surpassed 8.5 m^2/g and 16 nm, respectively. The content of alumina and iron in PAIS as a polymer coagulant was 16.5% and 0.57%, respectively. The experimental groups were classified based on variable levels of biochar and modified additives, which included four biochar groups of Bi0 (0%), Bi1 (1%), Bi2 (2%), and Bi3 (3%), and four modified agent groups of Pais0 (0%), Pais1 (1%), Pais2 (2%), and Pais3 (3%). Bi0 group without any added ingredients (0%) and Pais0 group (0%) were the controls. When adding improved additives to biochar, the control group was Bi0+Pais0, and a total of 10 treatment groups were formed. Each treatment was repeated three times. The volume of the soil samples tested was consistent across all trials, and the experiments were conducted using one tenth of the total amount of soil available. The changes in soil physical and chemical properties under different treatment were observed to determine any alterations.

(1) Soil column drenching

The experiment was carried out with the help of the soil column drenching method to elute pollutants from the soil with the help of drenching agents such as acid and alkaline solutions or surfactants. In the experiment, AS without any addition of substances was set as a control group. Glass tubes with height and internal diameter of 40 cm and 7.5 cm, respectively were set up with nylon mesh and quartz sand laid inside the glass tubes to better achieve the percolation of the soil samples. Different proportions of biochar and amendments were then mixed into the soil samples, and the same treatment solution collector was placed at the bottom of each soil column device. Distilled water was added consecutively to the glass tube apparatus at the same level. The soil layer, which was lined with filter paper, underwent static treatment and drenching. The resulting solution was collected and tested to determine the acidity and alkalinity, as well as the levels of relevant metals [16]. Some soil samples were then selected for the determination of physicochemical properties of the drenched soil.

(2) Soil nutrient determination

Soil samples mixed with biochar or amendments were analyzed. The sample was kept at a constant temperature (28℃) in a GHP-250 light incubator (Shanghai Yiheng Scientific Instruments Co., Ltd., shanghai, China) with breathable and light-proof environment (avoiding a completely dark) for 30 hours. The soil samples were hydrated daily according to the gravimetric method to ensure that the water content of the soil was 50% of its maximum water holding capacity. At the end of incubation, the soil samples were divided into two portions and sent to Shanghai Meiji Biopharmaceutical Technology Co., Ltd., Shanghai, China for diversity determination and air drying for physicochemical property determination.

(3) Microbial diversity determination

The soil microbial DNAs were extracted by using Soil Genomic DNA Extraction Kit (Solebao Technology Co., Ltd., Beijing, China) following the manufacturer's instructions. The primers of bacterial V3-V4 variable region of the 16S rRNA gene were applied for polymerase chain reaction (PCR) with the forward and reverse primers' sequences as 338F (5' – ACT CCT ACG GGG GGC AG - 3') and 806R (5' – GAC TAC HVG GGT WTT AAT - 3), where H could be A, C, or T; V could be A, C, or G, and W could be A or T. Bomeilun PCR detection kit (Annolen Biotechnology Co., Ltd., Beijing, China) was applied for PCR reactions following manufacturer's instructions. ABI 2720 Thermal Cycler (Applied Biosystems, Waltham, MA, USA) was employed with the program as 96°C for 5 minutes followed by 27 cycles of 96°C for 30 seconds, 55°C for 30 seconds, and 72°C for 30 seconds. An additional 72°C for 10 minutes was applied before the final preservation at 4°C. For soil fungi detection, the primers ITS1F (5' – CTT GGT CAT TTA GAG GAA GTA A - 3') and ITS2R (5' – GCT GGT TCT TCA TCG ATG C – 3') were used to amplify fungal ITSr DNA fragments under the program of 96°C for 5 minutes followed by 27 cycles of 96°C for 30 seconds, 55°C for 30 seconds, 72°C extension for 45 seconds. An additional 72°C for 10 minutes was performed before the amplified products were maintained at 4°C conditions. The PCR products were examined by using 1% agarose gel electrophoresis before being sent to Meigi Biomedical Technology Co., Ltd. (Shanghai, China) for DNA sequencing. The resulted DNA sequences were analyzed by using Quantitative Insights Into Microbial Ecology (QIIME) software (https://qiime2.org) for sequence partitioning, sample sequence statistics, and species classification. The sequences were grouped based on the similarity of 97% and compared for classification, resulting in the results of Operational Taxonomic Units (OTU) clustering analysis.

Measurement of experimental data

For the determination of soil physical properties, the collected soil samples were dried at 105°C in an HZQ-QX full temperature oscillator (Jintan Jinda Manufacturing Co., Ltd., Changzhou, Jiangsu, China) to remove excess water and weighed to calculate the bulk weight and soil porosity. The nitrogen (N), phosphorus (P), and potassium (K) were calculated by alkaline diffusion, sodium bicarbonate leaching, and ammonium acetate-flame photometric methods. The porosity of the soil was calculated as follows.

$$Porosity(\%) = (1 - SBD / SPD) \times 100 \qquad (1)$$

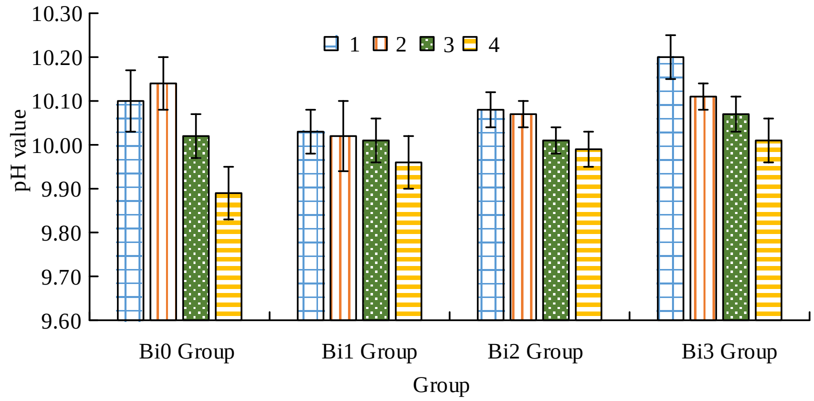
where *SBD* was the soil bulk weight and *SPD* was the soil particle density. The pH of the soil was determined by a pH meter using a water-soil ratio of 2.5:1 and the capacitance was determined by using a conductivity meter (Shanghai Yidian Scientific Instruments Co. Ltd., Shanghai, China). Soil cation exchange was calculated using sodium acetate monoflame photometric method. The soil alkalinity expression was shown as:

$$ESP(\%) = (ESC / CEC) \times 100 \qquad (2)$$

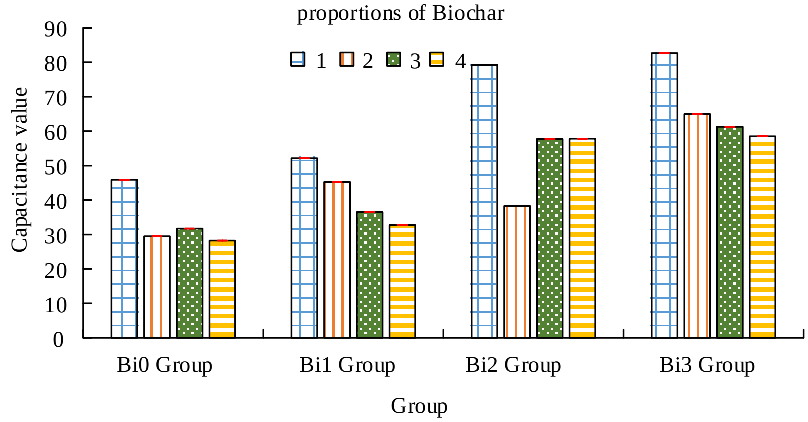
where *ESC* was the exchangeable sodium content and *CEC* was the cation exchange quantity.

Statistical analysis

SPSS software (IBM, Armonk, NY, USA) and R language (https://www.r-project.org/) were employed in this study. Single factor analysis of variance was conducted on each measurement index. Mean standard deviation values were used to represent the experimental data. Significance of differences between different treatments was determined by employing Duncan's new complex range method with $P < 0.05$. The two-way analysis of variance was employed to examine the impact of biochar and amendments on the



(a) Change of soil pH value after treatment with different proportions of Biochar



(b) Change of soil capacitance after treatment with different proportions of Biochar

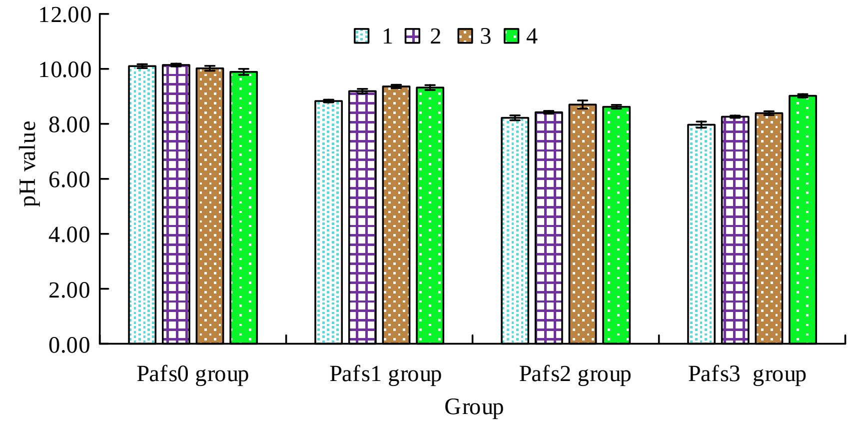
Figure 1. Changes of soil salt ions under different Biochar.

physical and chemical characteristics of alkali soil with soda saline.

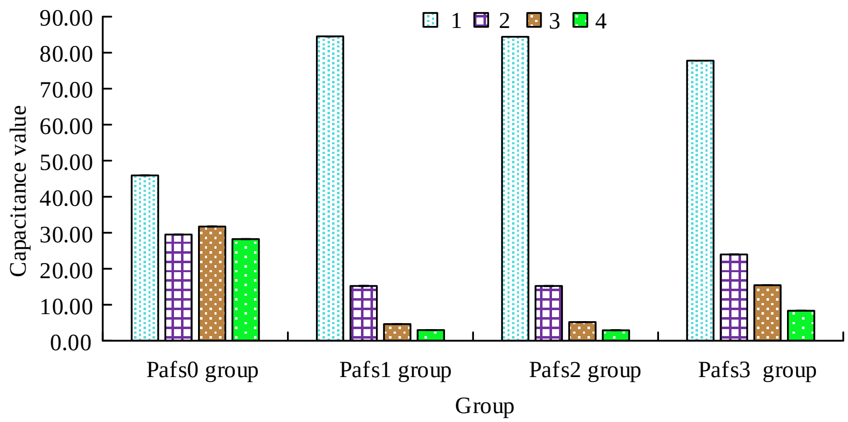
Results and discussion

Changes in saline alkali geochemical properties under single treatment

In order to better analyze the physicochemical properties of biochar improver on alkaline soil (AS), this study, based on the design of the experimental program, analyzed the changes in salt ions in the drenched solution after adding different proportions of biochar and improved biochar treatment by choosing the solution pH as well as capacitance. The results demonstrated that there was no significant impact on the alteration of soil pH by either the control group (Bi0 group) or the experimental groups (Bi1, Bi2, and Bi3) (Figure 1a). The pH measurements of soil samples collected from the control group and the three types of drenching solutions were 10.10, 10.05, 10.07, and 10.20, respectively. Although there were fluctuations in the pH value changes at different experimental intervals, the differences observed between the groups were not statistically significant. While there were variations in pH values during different experimental periods, the overall differences in pH between the groups did not appear to be significant. The capacitance values of control and the three experimental groups showed differences with the values of 46.12 mS/cm, 53.01 mS/cm, 80.03 mS/cm, and 82.74 mS/cm, respectively (Figure 1b). Notably, as the number of experiments increased, the gap between values of different groups decreased. Moreover, the maximum difference between values from



(a) Changes in soil pH value after treatment with different proportions of additives



(b) Changes in soil capacitance values after treatment with different proportions of additives

Figure 2. Salt ion changes in soil treated with different proportions of amendments.

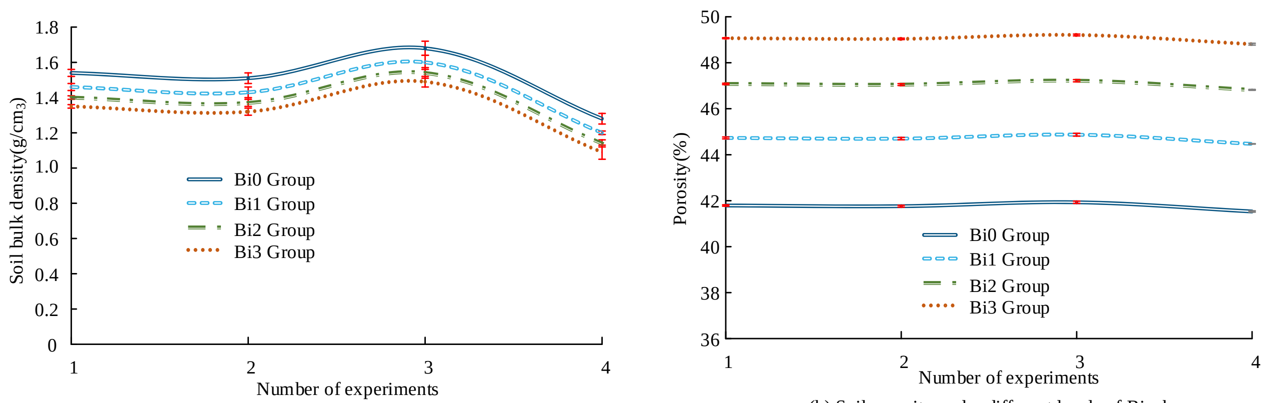
the third and fourth experiments was less than 3 mS/cm. The results suggested that the increase of biochar was not a significant change in pH values between groups. However, the addition of biochar improved the salt-based ions in the soil. Subsequently, the changes in soil salt ions with the improved additives were analyzed (Figure 2). The results showed that the changes in soil pH between the Pais0 and the other groups were significant, and the decrease in pH between the control group and the experimental group at the first experiment was more than 10% with a maximum of 20.89% between Pais0 and Pais3 groups. The data of capacitance value changes during the first experiment demonstrated a more than 65% increase between the control and experimental groups. As the number of experiments increased, the capacitance value of the experimental group declined significantly compared with that of the control group, and this decline continued over time.

Changes in saline alkali geochemical properties under combined treatment

The pH and capacitance values of the soil with improved biochar treatments were listed in Table 1. The results showed that, under the integrated amended biochar, AS soil showed more obvious changes in pH values, and the group differences in values under different experimental times were obvious with the maximum values of group differences under different experimental times reaching 2.2, 2.58, 2.31, and 2.07, respectively. With the increase between the number of

Table 1. pH and capacitance values of soil under the action of improved biochar.

Group	pH value				Capacitance value			
	1	2	3	4	1	2	3	4
Bi0+Pais0	11.11±0.15	11.15±0.13	11.02±0.11	10.879±0.11	50.49±0.11	32.450±0.13	34.903±0.11	31.075±0.1
Bi1+ Pais1	9.43±0.13	10.13±0.14	10.36±0.13	10.384±0.13	77.693±0.11	15.480±0.18	3.949±0.10	3.399±0.11
Bi1+Pais2	9.24±0.14	9.438±0.12	10.043±0.12	9.691±0.12	101.288±0.15	17.853±0.11	6.039±0.11	3.245±0.1
Bi1+Pais3	9.108±0.15	8.987±0.11	8.789±0.14	8.459±0.14	90.145±0.13	17.640±0.11	7.942±0.11	5.313±0.12
Bi2+Pais1	9.449±0.13	9.834±0.14	9.922±0.13	10.428±0.12	147.675±0.12	32.175±0.13	12.1±0.11	8.074±0.11
Bi2+Pais2	9.13±0.14	9.438±0.13	9.757±0.13	9.537±0.12	89.925±0.11	18.128±0.11	7.084±0.10	3.696±0.10
Bi2+Pais3	8.943±0.12	8.877±0.12	8.712±0.15	8.525±0.13	91.905±0.11	18.92±0.10	8.558±0.11	5.698±0.11
Bi3+Pais1	9.482±0.13	10.241±0.11	10.472±0.13	10.472±0.12	71.478±0.11	9.152±0.12	4.653±0.11	3.971±0.10
Bi3+Pais2	9.218±0.15	9.46±0.12	9.405±0.14	9.174±0.12	89.705±0.11	15.73±0.11	5.896±0.10	3.15±0.12
Bi3+Pais3	8.91±0.13	9.119±0.12	9.317±0.12	8.80±0.13	74.756±0.11	61.743±0.13	32.912±0.1	13.442±0.11

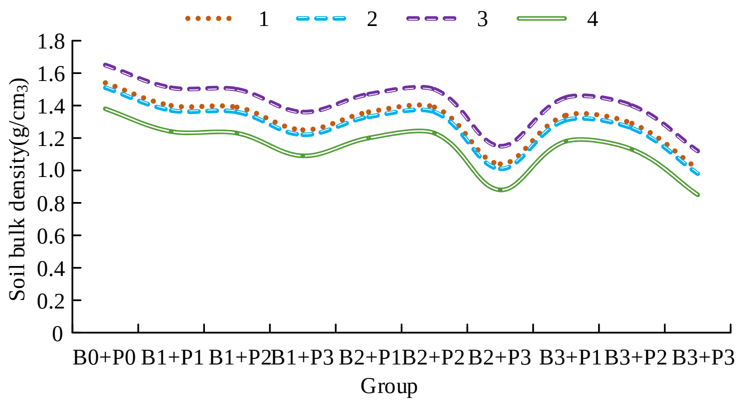


(a) Soil bulk density under different levels of Biochar treatment

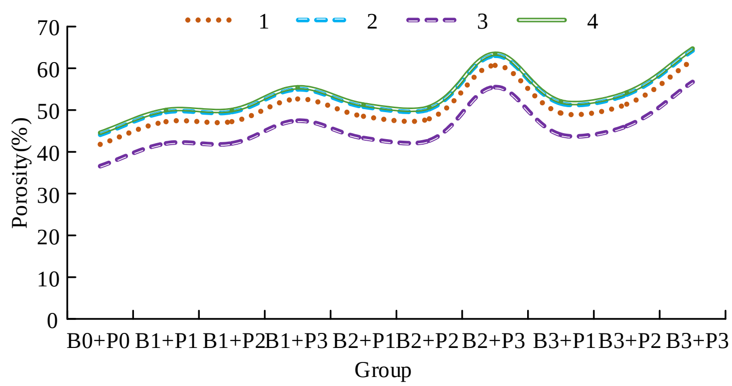
(b) Soil porosity under different levels of Biochar treatment

Figure 3. Change of soil bulk density and porosity under single biochar treatment.

experimental times, the pH values of the Bi0+Pais0 group were greater than those of the other groups. The data between groups with different additives of charcoal differed significantly, and the addition of additives significantly reduced the pH value of AS. In terms of capacitance value, the soil under mixed biochar could make a significant increase. However, the increase under different groups decreased with the increase of the number of experiments. Subsequently, the physical properties of the soil under different rinsing solutions were analyzed including soil bulk weight and pore extent. The soil bulk weight can reflect the moisture content and structure of the soil to a certain extent, and a small bulk weight indicates that the soil is loosened and has a good degree of fertility. The results demonstrates that biochar had an impact on the bulkiness of AS soil (Figure 3). The bulkiness value of the Bi0 group was higher than that of Bi1, Bi2, and Bi3 groups during multiple experiments, which suggested that biochar played a role in determining the bulkiness of the soil. In terms of changes in porosity, the differences between the groups were significant and the average range of values for Bi1, Bi2, and Bi3 groups were basically 44.67%, 47.12%, and 49.02%, respectively, which suggested that the use of biochar improved soil structure. There was a significant decrease in the soil capacity under the use of modified biochar with a significant increase of the porosity (Figure 4). The maximum difference in soil capacity between the group without any addition and the other groups reached 0.43 g/cm^3, and the improvement in soil capacity was most prominent when the addition ratio of biochar and amendment was 1% and 2%, respectively. In



(a) Comprehensive ratio of soil bulk density under different experimental times



(b) Comprehensive ratio of soil porosity under different experimental times

Figure 4. Changes in soil bulk density and porosity under comprehensive ratio.

terms of porosity, the addition of modified biochar made the soil have different degrees of improvement, and the mixed application of biochar could effectively improve the soil structure. The results also demonstrated that the combination of biochar could considerably enhance soil water holding capacity (Figure 5). Compared to the control group, the average values of saturated, capillary, and field water holding capacity under varying quantities of modified biochar were increased with all groups exceeding 30%, 30%, and 29%, correspondingly. Moreover, the saturated water holding capacity of the soil in the Bi2+Pais3 group demonstrated the highest value, approximately 45% with the difference to Bi0+Pais0 group exceeding 50%. The capillary water holding and field water holding capacities in Bi2+Pais3 group were also higher than that in other groups (Figure 5a). Meanwhile, from the standard deviation, the values of each group under the three indicators had certain differences, and the significance effect between the experimental group and the control group was obvious (Figure 5b).

The changes in soil chemical property content under different groups were listed in Table 2. The results showed that the groups utilizing upgraded biochar at varied ratios displayed a noteworthy increase in numerical values in comparison to the group which did not incorporate any additives (Bi0+Pais0) with the minimum rise of available nitrogen among the groups being over 25%. In general, the level of soil eutrophication in the saline alkali soil had considerably improved under the refined treatment. Subsequently, the physicochemical properties of soda saline alkali soil were analyzed using the two factor variance. The results showed that the application of biochar could significantly affect the soil bulk

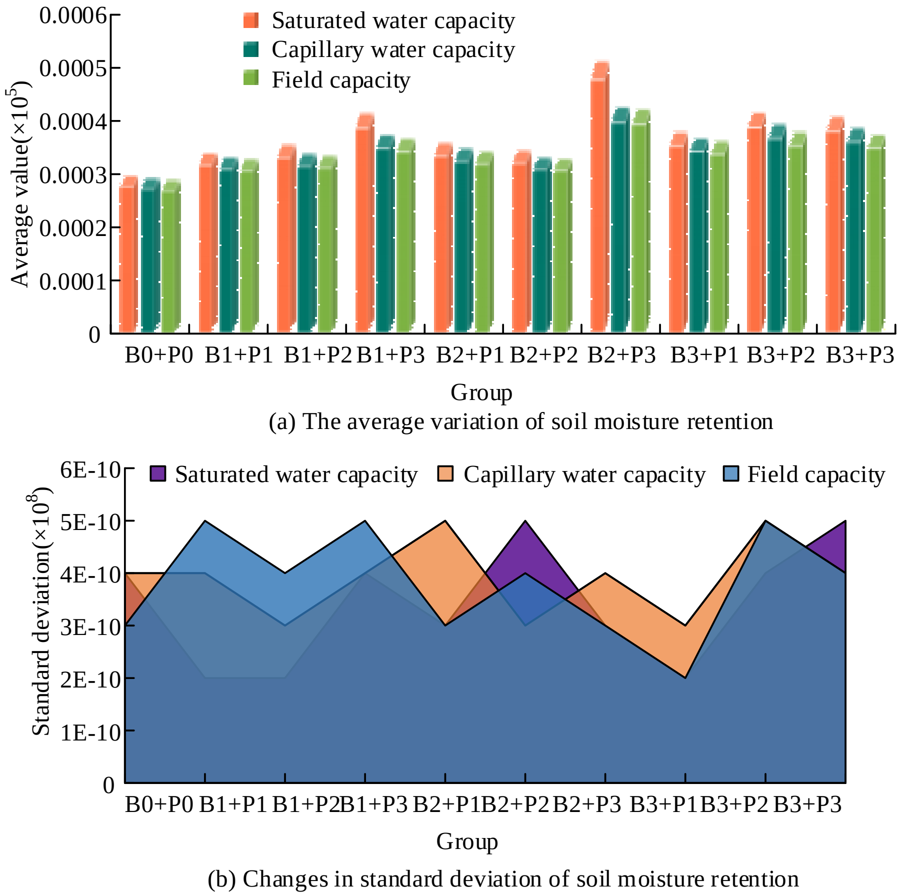


Figure 5. Water retention of soil under improved biochar structure.

Table 2. Changes in soil chemical property content under different groups.

Group	Organic matter		N		P		K	
	M	SD	M	SD	M	SD	M	SD
Bi0+Pais0	12.76	1.71	109.75	2.88	103.84	1.06	108.68	18.28
Bi1+Pais1	16.09	0.86	144.4	1.09	188.1	4.9	361.64	18.28
Bi1+Pais2	19.92	1.85	155.84	5.29	250.2	4.04	626.66	10.64
Bi1+Pais3	23.25	0.76	182.09	4.39	322.55	2.78	867.58	18.28
Bi2+Pais1	16.37	1.35	129.82	1.26	182.2	7.51	373.69	21.08
Bi2+Pais2	19.58	0.5	151.99	4.71	240.84	3.08	632.68	18.28
Bi2+Pais3	23.65	2.05	174.62	0.56	305.2	2.59	885.65	18.28
Bi3+Pais1	15.51	2.22	127.37	1.74	184.28	4.55	295.39	10.64
Bi3+Pais2	19.24	0.73	145.34	1.09	246.04	7.69	445.97	10.64
Bi3+Pais3	22.45	0.47	163.65	4.11	315.78	1	632.68	18.16

Notes: N, P, and K represented available nitrogen, phosphorus, and potassium, respectively. M and SD represented the mean value and standard deviation.

density of saline alkali soil ($P < 0.05$), but not on soil porosity and water capacity. The variance results of the mixed saline alkali soil after the application of polymeric aluminum iron sulfate were significant, and its F-values in soil capacity, porosity, and water capacity were greater than

Table 3. Two factor analysis of variance.

Physical and chemical properties	Biochar		Biochar + Pais	
	F	*P*	F	*P*
Soil bulk density	6.189	0.013	11.052	0.002
Soil porosity	1.267	0.297	6.577	0.006
Water holding capacity	3.149	0.159	10.234	0.005
pH	1.514	0.261	10.034	0.000
Organic matter	0.769	0.554	10.069	0.022
N	6.877	0.013	4.177	0.016
P	3.166	0.216	20.314	0.020
K	2.143	0.128	5.698	0.011

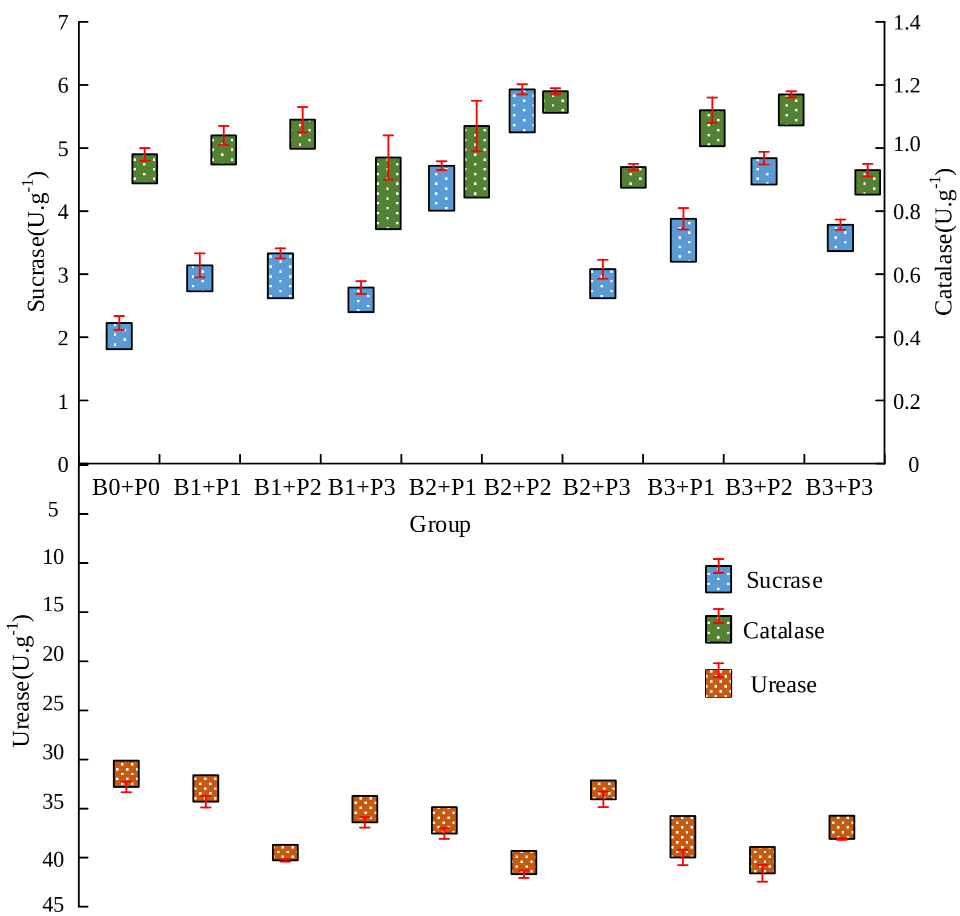


Figure 6. Effect of improved biochar on soil enzyme activity.

those of the single application of biochar. The application of biochar only significantly affected the water-soluble K component of soda saline alkali soil (*P* < 0.05), while the effect on P and N plasma in the soil was not significant. On the other hand, adding polymeric aluminum iron sulfate could significantly affect the pH value (*P* < 0.01) and P, N plasma (*P* < 0.05) of saline alkali soil (Table 3). The results indicated that the application of polymeric aluminum iron sulfate could effectively improve the physical and chemical properties of saline alkali soil.

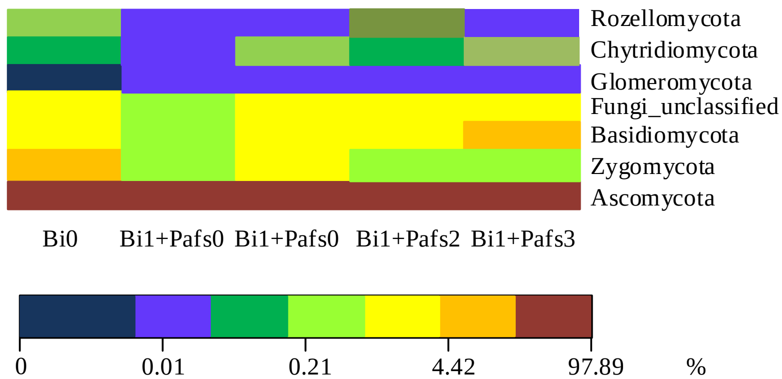


Figure 7. Distribution hotspots of fungal abundance in different soil samples.

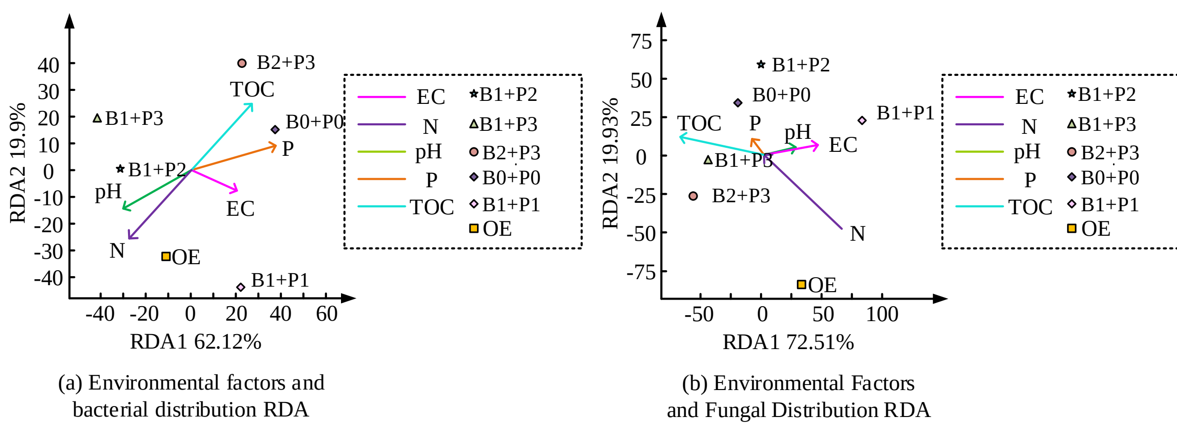
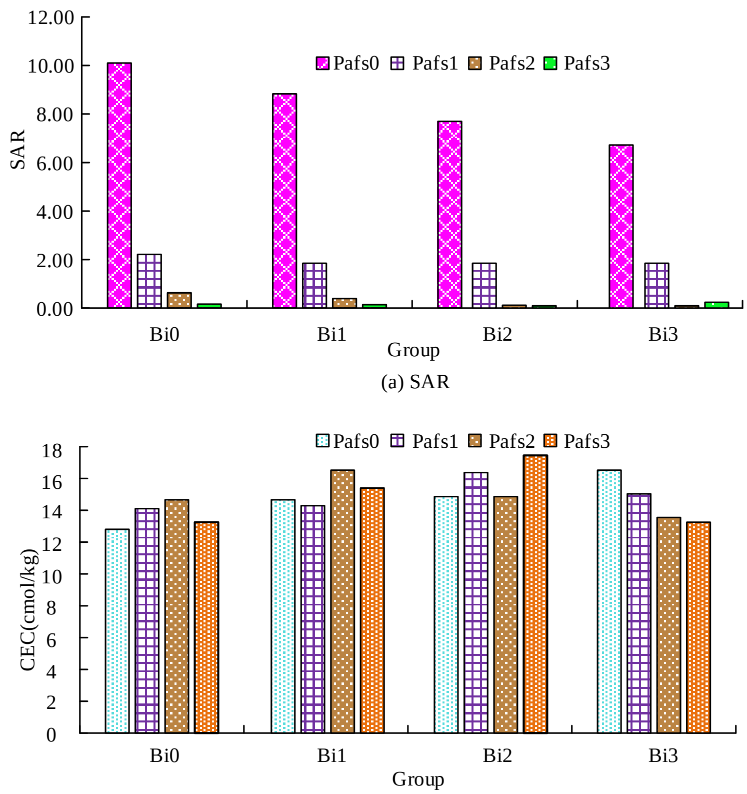


Figure 8. Redundancy analysis of fungal community structure and environmental factors under different treatments. The red arrow was the response or explanatory variables.

The soil enzyme activity (EA) was analyzed, and the results showed that the soil EA increased and then decreased with the application of biochar, while, under the same dosage, the EA of the experimental group with different modified biochar ratios was higher than that of the control group with the improvement effect of at least more than 10%, and the overall difference was significant (Figure 6).

Four main fungal phylum in the different samples were selected and analyzed by using Heatmap graph (Figure 7). The results showed that the application of modified biochar could effectively make the relative abundance of fungal phyla decrease, in which *Rhodococcus* phyla was obviously suppressed in the group, and the numbers of its effective sequences were obviously reduced, while *Coccidioides* phyla only existed in a small portion of the blank control group, which indicated that the biochar water extract had a significant fungal inhibition effect. The redundancy between bacterial community structure and environmental factors under different treatments was also analyzed. The designed environmental factors included acidity and alkalinity values, nitrogen, phosphorus, and conductivity values, which were important factors affecting fungal communities. The results indicated that there was a positive correlation between conductivity and phosphorus content with the distribution of microorganisms in each group (Figure 8). Additionally, the difference between the control and experimental groups'



(b) CEC

Figure 9. Effect of different treatments on sodium adsorption ratio and cation in alkali soil.

factors was significant. Subsequently, the sodium adsorption ratio of AS, an important indicator for assessing the salinity of the land, demonstrated that the biochar under different treatment levels caused different effects on the sodium adsorption ratio of the land (Figure 9). The results revealed that the group that did not receive any treatment presented the highest adsorption ratio with a value over 9.5. In contrast, the groups treated only with biochar displayed adsorption ratios of 8.64, 7.89, and 6.67, which all declined by over 5% compared to the untreated group and the disparity between them was significant. Additionally, PAIS alone demonstrated a better difference effect with the untreated group. However, the adsorption ratio of the 1% biochar treatment and the 2% PAIS treatment was the smallest with a value less than 0.1 and the greatest variation in difference. Therefore, the refined biochar could effectively achieve the improvement of land salinization. The cation exchange also showed that the combination of biochar and PAIS was effective in improving the fertility of the soil with values that were more than 20% higher than those of the untreated group.

Conclusion

Enhancing AS management is an essential research topic since AS has a significant detrimental influence on both the quality of the land and crop productivity. The results of this study suggested enhancing biochar to achieve its management of soil physicochemical properties and found that the soil electrical conductivity could be increased by using biochar alone. Additionally, a significant difference in soil pH was shown between the group of Pais0 and other Pais groups. Under the integrated amended biochar, the AS soils exhibited more pronounced changes in pH values. The soil capacity significantly decreased when improved biochar was used. The maximum capacity difference between the group without additives and the other groups was 0.43 g/cm^3. Furthermore, increasing the additive ratio resulted in a higher pH value. The difference between the groups of the same biochar with different additives was also obvious. The saturated water holding capacity of the soil in the Bi2+Pais3 group reached the maximum value of approximately 45.89%, and the EA of the experimental group with different modified biochar ratios was high. The soil capacities of capillary water holding, field water holding, and saturated water holding under different modified biochar ratios were all improved by 29-30% compared with the control group. All treatment groups showed a noticeable fungal inhibitory impact, at the very least, of greater than 10%. The untreated group had the highest adsorption ratio (>9.5), while the treatment of 1% biochar and 2% PAIS had the lowest adsorption ratio with a value of less than 0.1. The cation exchange of the modified biochar treatment was significantly higher than that of untreated group by more than 20%.

Acknowledgement

The research was supported by Science and Technology Innovation Fund Project of Shanxi Agricultural University (Grant No. 2018YJ52), Shanxi Province Outstanding Doctor to Jin Work Award Fund Research Project (Grant No. SXYBKY2019014), and Shanxi Science and Technology Project - 1331 Project “Quality and Efficiency Improvement Project".

References

1. Li Y, Li G. 2022. Mechanisms of straw biochar’s improvement of phosphorus bioavailability in soda saline-alkali soil. Environ Sci Pollut R. 29(32):47867-47872.
2. Xu Y, Zheng C, Liang L, Yi Z, Xue S. 2021. Quantitative assessment of the potential for soil improvement by planting Miscanthus on saline-alkaline soil and the underlying microbial mechanism. GCB Bioenergy. 13(7):1191-1205.
3. Egamberdieva D, Alaylar B, Kistaubayeva A, Wirth S, Bellingrath-Kimura S. 2022. Biochar for improving soil biological properties and mitigating salt stress in plants on salt-affected soils. Commun Soil Sci Plan. 53(2):140-152.
4. Li Y, Li G. 2022. Mechanisms of straw biochar’s improvement of phosphorus bioavailability in soda saline-alkali soil. Environ Sci Pollut R. 29(32):47867-47872.
5. Wang S, Gao P, Zhang Q, Shi Y, Guo X, Lv Q, *et al*. 2023. Biochar improves soil quality and wheat yield in saline-alkali soils beyond organic fertilizer in a 3-year field trial. Environ Sci Pollut R. 30(7):19097-19110.
6. Ekinci M, Turan M, Yildirim E. 2022. Biochar mitigates salt stress by regulating nutrient uptake and antioxidant activity, alleviating the oxidative stress and abscisic acid content in cabbage seedlings. Turk J Agric For. 46(1):28-37.
7. Kul R. 2022. Integrated application of plant growth promoting rhizobacteria and biochar improves salt tolerance in eggplant seedlings. Turk J Agric For. 46(5):677-702.
8. Wei W, Zhang S, Wu L, Cui D, Ding X. 2021. Biochar and phosphorus fertilization improved soil quality and inorganic phosphorus fractions in saline-alkaline soils. Arch Agron Soil Sci. 67(9):1177-1190.
9. Kul R, Arjumend T, Ekinci M, Yildirim E, Turan M, Argin S. 2021. Biochar as an organic soil conditioner for mitigating salinity stress in tomato. Soil Sci Plant Nutr. 67(6):693-706.
10. Ghassemi-Golezani K, Abdoli S. 2023. Alleviation of salt stress in rapeseed (*Brassica napus L.*) plants by biochar-based rhizobacteria: new insights into the mechanisms regulating nutrient uptake, antioxidant activity, root growth and productivity. Arch Agron Soil Sci. 69(9):1548-1565.
11. Soliman MH, Alnusairi GSH, Khan AA, Alnusaire T, Fakhr M, Abdulmajeed A, *et al*. 2023. Biochar and selenium nanoparticles induce water transporter genes for sustaining carbon assimilation and grain production in salt-stressed wheat. J Plant Growth Regul. 42(3):1522-1543.
12. Alfadil AA, Xia J, Shaghaleh H, Ibrahim Y, Nourain J, Amar Ali Adam H, *et al*. 2021. Wheat straw biochar application improves the morphological, physiological, and yield attributes of maize and the physicochemical properties of soil under deficit irrigation and salinity stress. J Plant Nutr. 44(16):2399-2420.
13. Malik Z, Malik N, Noor I, Kamran M, Parveen A, Ali M, *et al*. 2023. Combined effect of rice-straw biochar and humic acid on growth, antioxidative capacity, and ion uptake in maize (*Zea mays L.*) grown under alkaline soil conditions. J Plant Growth Regul. 42(5):3211-3228.
14. Wang S, Gao P, Zhang Q, Shi Y, Guo X, Lv Q, *et al*. 2022. Application of biochar and organic fertilizer to saline-alkali soil in the Yellow River Delta: Effects on soil water, salinity, nutrients, and maize yield. Soil Use Manage. 38(4):1679-1692.
15. Zhou H, Li X, Li C, He L, Liu X, Xiao X, *et al*. 2021. Biochar pyrolyzed at low temperature enhanced acidophilous plant growth by promoting *Rhizospheric* microbes in a slightly alkaline urban soil. Biochar. 3(4):603-614.
16. Wu Z, Zhao Y, Zhang N. 2023. A literature survey of green and low-carbon economics using natural experiment approaches in top field journal. Green Low-Carbon Econ. 1(1):2-14.