Water Supply

Water Supply Vol 22 No 9, 7242 doi: 10.2166/ws.2022.311

The effect of humic acid on the desalinization of coastal clayey saline soil

Ruirui Huang

State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

E-mail: 2697645518@qq.com

ABSTRACT

There is a lack of research on the effect of humic acid on salinity adsorption and leaching of saline-alkali soil. We used humic acid as a modifier. Saline soil adsorption and leaching tests were carried out in the laboratory and the field to study the effect of humic acid on water, salt, and wheat yield in coastal clay saline soil. Compared to the CK (non-humic acid treatment), the laboratory tests show that soil water content, salt adsorption, salt leaching, and salt removal efficiency, all showed a trend of increasing first and then decreasing, with the increase of humic acid, and increased by 0.1–1%, 0.5–4%, 3–11%, and 1–8% under T1-T8 (humic acid treatments), respectively. Field tests show that in all humic acid treatments soil salinity in 0–20 cm and 0–60 cm was reduced, and the water content and wheat yield was increased, compared to CK. When the humic acid content was 0.149 g/kg (T2 treatment), the soil salt removal effect and wheat yield were optimized. Overall, humic acid can effectively reduce the salinity in clay saline soil, improve its ability to hold water, and inhibit salt accumulation and soil salinization. This research contributes to the improvement of saline-alkali soil in the Yellow River Delta.

Key words: changes of water and salt in field soil profile, clayey saline soil, humic acid, salt adsorption, salt leaching, wheat yield

HIGHLIGHTS

- The mechanism and law of adsorption of water and salt in soil by humic acid were clarified.
- Clarified the influencing mechanism of humic acid on salt removal and reduction in clay saline soil.
- Determine the appropriate amount of humic acid needed to further improve the clay saline soil.

1. INTRODUCTION

The area around the Yellow River Delta is large, has low terrain and poor drainage. Its soil evaporates and salt accumulates in spring and autumn (He *et al.* 2021), leading to high soil salinity. Salinized soil poses serious problems, such as high soil salinity, low organic matter content, difficult crop growth, and low crop yield, which restrict local agricultural production and socio-economic development (Zhang *et al.* 2021). As a result, the improvement and treatment of coastal saline-alkali soil are of great significance to the development and construction of the Yellow River Delta.

Adding amendments is an especially important measure to improve saline-alkali soil (Zheng 2018). Many scholars have conducted research and gained valuable results. At present, materials in the soil are divided into inorganic (such as gypsum, desulfurized gypsum, aluminum sulfate, calcium silicate, etc.) and organic materials (such as biochar, organic fertilizer, humic acid, etc.) (Zhang *et al.* 2019).

Armstrong & Tantonn (1992) used gypsum to improve salinized alkaline soil and studied and analyzed the change in the surface soil salinity. They found that desulfurized gypsum can cause soil desalinization, but its high cost restricted its application in practical production. Sun *et al.* (2011) found that adding aluminum sulfate to the heavy saline-alkali soil in the Songnen Plain can effectively reduce the soil's PH value and cause soil leaching and desalting. However, they also found that the heavy metal ions contained in desulfurized gypsum cannot be controlled, posing a great threat to the soil environment. Yue *et al.* (2015) used biochar as a modifier and studied its influence on the leaching effect of saline-alkali soil through the indoor soil column test. The results showed that the soil column with biochar would not only shorten the leaching time, but also speed up desalination. Nevertheless, its cost was high, and it was not suitable for large-scale research. When Li (2018) studied the combined effect of calcium silicate and a bio-organic fertilizer on saline-alkali soil, they found that the excessive use of the organic fertilizer increases the soil's PH value, despite it causing soil desalinization to a certain extent.

Although the soil fertilizer, farm organic fertilizer, organic waste residue, and other organic substances can significantly improve the fertility of saline-alkali soil and promote salt leaching, these studies (Melillo *et al.* 2002; Jalali & Ranjbar 2009; Sahin *et al.* 2011) uncovered that long-term use pollutes groundwater.

Modified materials can improve soil texture and effectively reduce the soil salinity because they also have low salinity, long survival time in the soil, an appropriate PH value, and cause no secondary damage to the environment (Mahdy 2011; Yazdanpanah & Mahmoodabadi 2013). At present, both organic and inorganic materials can effectively improve soil structure but are costly and cause many problems in practical application, such as secondary damage to the soil and the environment. Likewise, they cannot be applied in a large area. Therefore, a common concern of scholars is to find efficient, cheap, environmentally safe, and practical soil ameliorants.

As a macromolecular organic matter, humic acid is accumulated in the remains of animals and plants through a series of chemical processes, i.e., the decomposition and transformation of microorganisms. Because it is also an organic colloid, it is highly active and has a strong adsorption and condensation capacity. It can bond dispersed soil particles, form soil aggregates with high stability, and improve the physical and chemical properties of the soil (Wang *et al.* 2019). Application of humic acid in soil has attracted the attention of Chinese and foreign scholars. Gao *et al.* (2020) found in studying the influence of humic acid on sunflower yield and soil salt-alkali index that humic acid has significant effects in reducing soil salinity, soil SAR (Sodium Adsorption Ratio) and improving sunflower yield. Chai *et al.* (2021) carried out an investigation experiment on the influence of humic acid on soil chemical characters and grape fruit quality, and found that soil exchangeable Ca^{2+}, Mg^{2+} and organic matter contents were significantly increased, and fruit quality was significantly improved. Xiong (1979) found that adding humic acid can improve the soil organic matter content and soil water retention ability, which can reduce the content of sodium ions and the loss of potassium in the soil. Studies (Chen *et al.* 2002; Wang & Zhu 2021) believed that humic acid could promote seed germination and root growth. Previous studies (Liu & Wang 2020; Yang *et al.* 2021) found that humic acid can help increase the amount of phosphorus in the soil, improve physical and chemical properties, aggregate the stability of the soil, and regulate the soil microbial community.

On the whole, it is a simple and feasible measure to use humic acid materials to improve saline-alkali soil. However, most of the current studies on the improvement of saline-alkali soil by humic acid focus on soil nutrients, soil desalting, soil ion changes, organic carbon and microbial activities, etc. The study on the adsorption and leaching effect of humic acid on saline soil is very limited.

Therefore, this study takes the coastal saline soil of the Yellow River Delta as the research object. Given the problems of large saline-alkali land area, high salinity, poor structure and low fertility, we choose high-quality, environmentally friendly and practical humic acid as improved material. Through the simulated soil column leaching and adsorption experiment and a field test, we mainly study the effect of humic acid on desalination of coastal clay saline soil. The main objectives are as follows:

(1) The effect of humic acid on the adsorption characteristics of water and salt in coastal clay saline soil under saline leaching was analyzed through laboratory tests. And study the mechanism and law of humic acid on soil desalting effect under fresh water leaching.
(2) By analyzing the effect of humic acid on the variation of water and salt in the field and wheat yield, the suitable dosage of humic acid for the improvement of clay saline soil was determined. The relationship and effect of application amount of humic acid on saving water and reducing salt in the improvement of clay saline soil were verified.

2. MATERIALS AND METHODS

2.1. Overview of the study area

The Yellow River Delta is located in the lower reaches of the Yellow River in the northeast of Shandong Province between the longitudes of 117 °31′ and 119 °18′ E and latitudes of 36 °55′ and 38 °16′ N. It is situated in the Bohai Depression, an alluvial plain formed by the deposition of a large amount of sediment from the Yellow River (Figure 1). Its terrain is low and flat with an elevation of 11 m in the southwest. The Yellow River Delta has four distinct seasons with a dry and windy spring and autumn. The average temperature is 10–14 °C, while the average annual precipitation is 584 mm. The rainfall in the delta is much lower than the average level in Shandong Province with an uneven distribution throughout the year, causing drought in spring and autumn and flooding in summer. The dry season lasts up to 8 months per year. The saline-alkali soil in this region is heavy in texture, consists mostly of a clay loam or clay, and contains plenty of soluble salt. In the area, all kinds

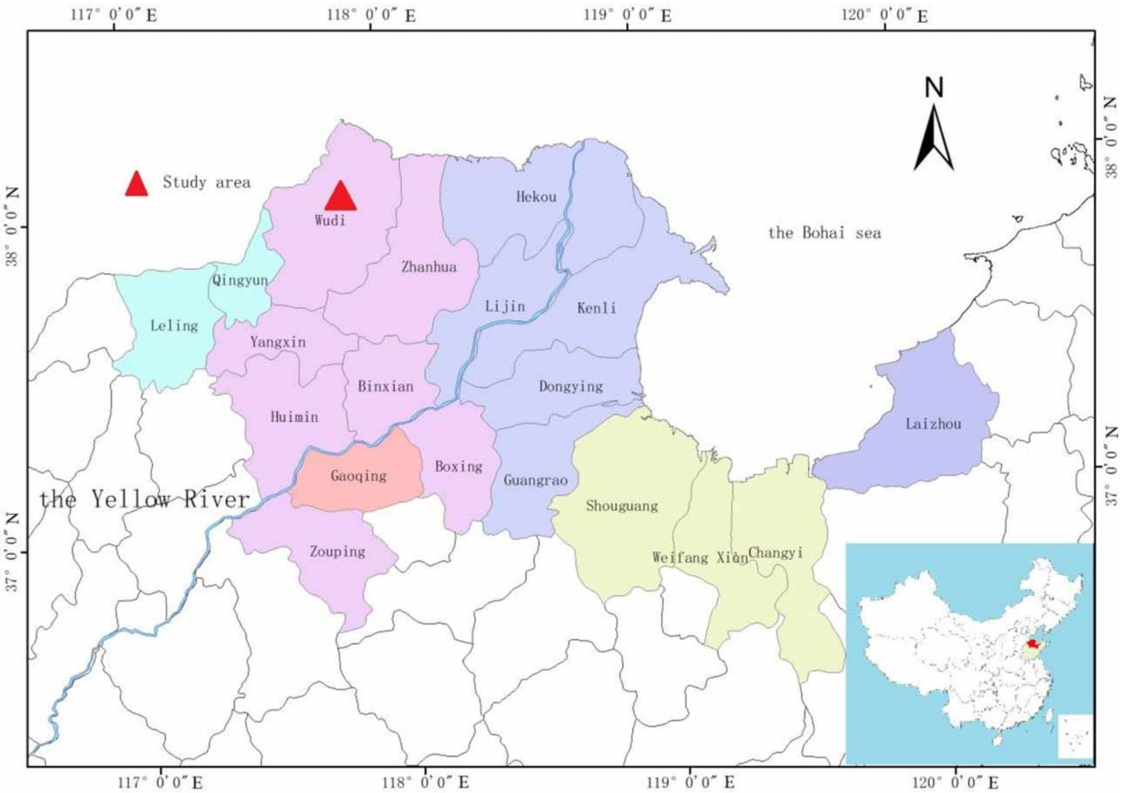

Figure 1 | The location of the study area.

of saline-alkali soils form because the region poorly drains water. Likewise, the water in the area evaporates quickly and the leaching of the soil is weak, so the salts dissolved in groundwater accumulate on the soil surface. Further problems in the Yellow River Delta represent poor soil ventilation and permeability, soil compaction, poor soil structure, low soil water conductivity, etc. (Qadir *et al.* 2001).

2.2. Test design

2.2.1. Simulated soil column salt adsorption and leaching experiment

The ratio of saline soil and humic acid in the simulated soil column is shown in Table 1. CK was used as control treatment and did not contain humic acid. Soil was collected in spring for this laboratory experiment, and the salinity of the initial soil sample was 14.92 g/kg. Due to the small amount of humic acid, its salinity was ignored. CK and T1-T8, all soil columns, underwent the same treatment procedure. The simulated soil column in the laboratory test was divided into 9 groups of treatments, with 3 parallel treatments for each group. Humic acid and saline soil were mixed evenly according to the determined ratio, then filled into a PVC pipe with a diameter of 7 cm at a constant bulk density of 1.49 g/cm^3. The simulated soil column was pressed to a height of 6.5 cm. A total of 27 soil columns were simulated.

Saltwater from the drainage channel and distilled water made in the laboratory were used to simulate leaching soil columns. Table 2 shows the salinity and volume of water used for the two leaching sessions.

Table 1 | The proportion of humic acid and soil in the laboratory test

Treatment	CK	T1	T2	T3	T4	T5	T6	T7	T8
Humic acid (g)	0	0.0748	0.149	0.224	0.299	0.374	0.449	0.524	0.599
Clayey saline soil (g)	372.197	372.112	372.047	371.072	371.897	371.822	371.747	371.672	371.597
Content of humic acids (g/kg)	**0**	**0.20**	**0.40**	**0.60**	**0.80**	**1.00**	**1.20**	**1.40**	**1.60**

Table 2 | Water quantity and salinity in the water samples in the soil adsorption simulation test

Water sample	SW	FW
Water quantity (mL)	250	125
Salinity(g/L)	**7.47**	**0**

The first leach water contained saltwater with a salinity of 7.47 g/L (SW), while the second one contained freshwater with a salinity of 0 g/L (FW)(125 ml is formulated according to irrigation quota of Shandong Province, simulating normal field irrigation). The simulated soil column was rinsed with distilled water for 24 hours after the first rinsing with saltwater. A glass bottle is set under the soil column to collect the filtrate after each leaching, so as to determine its salinity and volume.

2.2.2. The field test

The field test was conducted in the Wudi County in Binzhou City and located at a longitude of 117 °45′29.84″–117 °49′47.19″ E and a latitude of 37 °51′10.01″–37 °53′32.02″ N. The area consists of clay saline soil, while the main crop cultivated there is wheat.

The field experiment was divided into 5 treatments: the control treatment (CK), treatment 1 (T1), 2 (T2), 3 (T3), and 4 (T4). Each treatment was further divided into 3 groups of repeated experiments. The amount of humic acid in different treatments is shown in Table 3 (Under CK,T1-T4 treatment, the ratio of humic acid used in the field was the same as that in the laboratory test).

Each test plot is designed to be 120 m long and 10 m wide to enable modern agricultural machinery to operate in the field. In the field experiment, the sowing, irrigation, and fertilizer amount, tillage and fertilization method, and irrigation time under different treatments were consistent with the local wheat planting method. In accordance with the determined amount, humic acid was evenly spread on the soil surface before sowing the winter wheat. The earth was then ploughed 4 times with a rotary plow until the humic acid was evenly mixed with the soil at a depth of 0–20 cm in the test plot. The same ploughing method was used for the control group. The field experiment started in October 2016 and ended in June 2019. For soil and wheat yield sampling,6 representative points were selected according to the shape of 'S', as shown in the following Figure 2. The field soil sampling was divided into 5 soil layers of 0–20, 20–40, 40–60, 60–80 and 80–100 cm.

2.3. Sampling and measurement

2.3.1. Test materials

Soil samples were taken from plots 30–5 in the Bohai Granary Project test area. The soil sampling depth was 0–40 cm. After retrieving soil samples, they were air-dried and cleaned of impurities in the laboratory. After the soil sample is fully mixed, it is screened by a 2 mm sieve for reserve use.

Table 3 | The amount of humic acid in each treatment in the field test

Treatment	CK	T1	T2	T3	T4
Humic acid dosage (kg/mu)	0	40	80	120	160
Humic acid content in soil (g/kg)	0	0.2	0.4	0.6	0.8

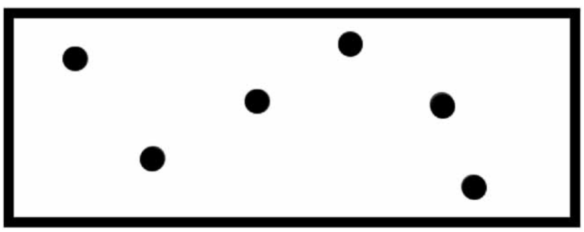

Figure 2 | Field soil and wheat yield sampling locations.

The water samples used in the laboratory test were taken from the drainage channel in the test area and the salinity of the water samples were measured prior to each test.

Humic acid used in the laboratory and field tests was provided by commercial companies. In the soil column adsorption and leaching simulation test, the leach water was deionized water made in the laboratory.

2.3.2. Test items and methods

The measurement items mainly include soil salinity and water content before and after humic acid treatment, the volume and salt content of soil leaching filtrate, and wheat yield.

(1) Soil salinity: To measure the soil salinity, soil samples screened by a 1 mm sieve were mixed with deionized water in a ratio of 1:5. The soil extract was obtained after centrifugation. The filtrate of soil was then filtered, and the conductivity value of the filtrate was measured by the DDB-2 conductivity meter. After recording the electrode constant, the soil salinity was calculated according to the standard curve formula determined by laboratory technicians. The electrode constant was 1.028. The conversion formula between the soil conductivity measured by the electrode and the soil salinity is shown in Formula (1).

$$y_0 = 0.2157x \tag{1}$$

where y_0 is the soil salinity, g/kg; X is the conductivity value at 25 °C, DS m^{-1}

(2) Desalination rate:

$$r = 100\frac{y_1 - y_2}{y_2} \tag{2}$$

where r is the desalination rate (%); y_1 is the soil salinity before leaching; y_2 is the soil salinity after leaching.

(3) Soil water content is determined through the drying method. The aluminum box was weighed and marked as $M_{0.}$ Afterward, the weight of the aluminum box and air-dried soil was weighed and marked as M_1. The aluminum box was then placed into the oven at 105 °C. After 4 hours, it was taken out, weighed, and marked as M_2. According to Formula (3), the water content θ was obtained:

$$\theta = \frac{M_2 - M_0}{M_1 - M_0} \times 100\% \tag{3}$$

(4) Soil bulk density: To determine the soil bulk density, samples were taken with a soil ring knife from soil at a depth of 0–20 and 20–40 cm at each sampling point (100 cm^3). Three parallel samples were taken from each test plot, sealed, stored, and brought back to the laboratory. The soil bulk density was calculated after drying the soil in an oven at 105 °C until it achieved a constant weight.

(5) Salinity of leaching solution and soil salinity after leaching: The electrode constant of 0.977 was used to determine the salinity in the leached liquid. The conversion formula between the conductivity measured by the electrode and the salinity is described in Formula (4). The salinity of the filtrate and the leached liquid product were calculated according to this formula, Then the soil salinity of simulated soil column after leaching is calculated according to the volume of leaching liquid, and the calculation formula is as follows (5) and (6):

$$M = 0.625\sigma \tag{4}$$

$$y_1 = \frac{250 * 7.47 + 372.197 * y_0 - V_1 * M_1}{372.197} \tag{5}$$

$$y_2 = \frac{372.197 * y_1 - V_2 * M_2}{372.197} \tag{6}$$

where M is the salinity of the filtrate (g/L); σ is the conductivity value at 25 °C ($\mu s/cm^{-1}$) $\cdot$ y_1 and y_2 are the soil salinity of the simulated soil column after each leaching, respectively, (g/kg); V_1 and V_2 are the volume of filtrate collected after each wash, respectively, (L); M_1 and M_2 are respectively the salinity values (g/L) of the filtrate collected after each leaching, which are calculated according to Equation (4).

The specific determination method is as follows:

(1) Two pieces of circular filter paper with a diameter of 7 cm were placed at the bottom of the soil column to prevent the loss of soil particles during the test. At the same time, two screens were placed on the surface of each soil column to avoid soil depression caused by a water impact.
(2) The installed soil column was placed horizontally on the test table, the leach water was slowly and evenly poured into the soil column through the glass rod, and the upper water layer in the soil sample was kept stable when adding more water.
(3) The leachate was collected in the beaker after the leaching process ended. The leachate volumes V_1, V_2 and the conductivity value σ of the leachate were measured.
(6) Salt removal efficiency or desalting efficiency refers to the amount of salt discharged per unit of water volume.

$$P = \frac{M}{V} \tag{7}$$

where P is the salt removal efficiency (g/L); M is content in the filtrate (g/kg); V is the amount of leaching.
(7) Wheat yield: Six different representative points were selected for each treatment according to the 'S' type. The effective panicle number and the 1,000-grain weight and average panicle number of wheat per mu were calculated, after which the wheat yield of different treatments was calculated in the field test.

2.4. Data processing and analysis

The data processed in the experiment were standardized by Microsoft Excel 2010 and the data in the chart were the mean $\pm$ standard deviations of the three repetitions. The curve fitting of the mathematical models was plotted using Origin 2017(IBM, USA). A one-way analysis of variance (one-way ANOVA) followed by LSD (Least Significant Difference) test was used to determine the statistical significance of each parameter in SPSS (IBM, USA). In the figures for each assay, values followed by different letters are significantly different at $p \leq 0.05$.

3. RESULTS

3.1. Soil adsorption of water and salt in the laboratory test

Figure 3 shows the changes of soil water content (Figure 3(a)) and salinity (Figure 3(b)) under SW (Salinity: 7.47 g/L; water: 250 ml) leaching of each treated soil column.

As can be seen from Figure 3(a), the soil water content under T1-T8 was higher than that under the CK treatment. It showed a trend of first increasing and then decreasing with the increase of the humic acid content. The soil water content gradually

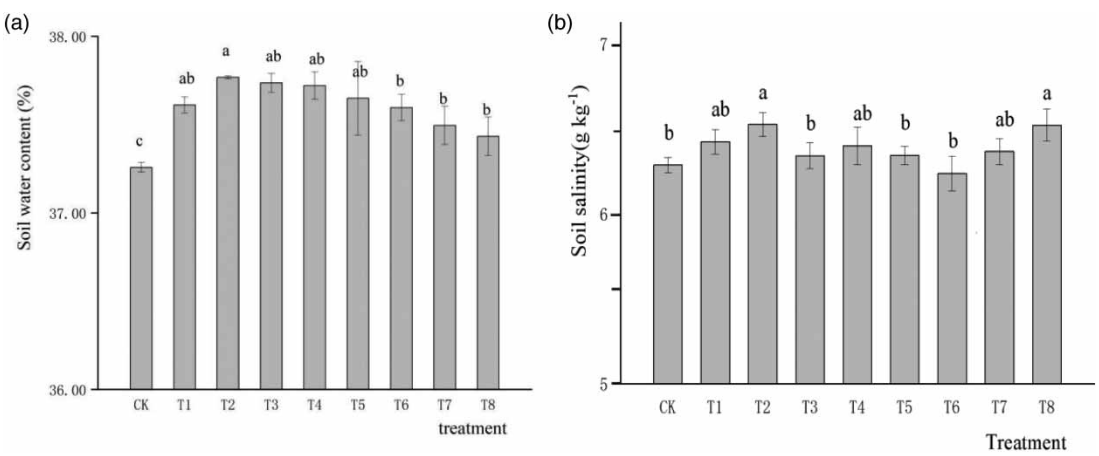

Figure 3 | The effect of humic acid on the soil water adsorption.

increased under T1 and T2 and decreased under T3-T8. Compared to the CK treatment, the soil water content under T1-T8 increased by 0.7%, 1.0%, 0.8%, 0.9%, 0.7%, 0.3%, 0.3%, and 0.1%, respectively. The difference between T1-T5 and the CK treatment was significant ($p < 0.05$). However, no significant difference was observed in the soil water content between T6-T8 and the CK treatment. When the soil was treated with humic acid, the soil water content was the highest in T2 (37.75%), followed by T4 (37.72%), but it was the lowest in T8 (37.43%).

It can be seen from Figure 3(b) that the soil salinity had the concentration of 14.9 g/kg and 6.5 g/kg before and after salt leaching, respectively. Thus, the soil salinity was greatly reduced. After leaching, the soil salinity showed a multivariate change because it first increased, then decreased, and then again increased (Figure 3(b)). Under the CK and the T1-T2 treatments, the soil salinity rose, but gradually decreased under T3-T6. The change in the soil water content in the early stage of the experiment was consistent with that in the soil. Compared to the CK treatment, the salinity in T1-T8 increased by 2.19%, 3.80%, 0.88%, 1.82%, 0.91%, −0.79%, 1.27%, and 3.74%, respectively. In addition, there were significant differences between treatments T2-T8 and the CK treatment ($p < 0.05$), while no significant difference was observed in the salinity between treatments T1 and T3-T7 and the CK treatment. When the soil was treated with humic acid, the soil salinity under T2 was the highest (6.52 g/kg), followed by T8 (6.51 g/kg). It was the lowest under T6 (6.23 g/kg), even lower than under the CK treatment. However, the two treatments showed no significant difference between each other.

3.2. Soil salt leaching in the laboratory test

Figure 4 shows the change in the soil desalinization rate after FW (salinity: 0 g/L, water: 125 mL) leaching. This procedure was adopted to clarify the response of soil desalinization to the amount of humic acid in each treatment.

The soil salinity had a concentration of 6 g/kg before leaching and 4 g/kg after leaching. It significantly decreased under all treatments in which desalting occurred to a certain extent, too. However, the desalting effect was different due to the different amounts of humic acid. As shown in Figure 4, the desalting rate under the CK and the T1-T8 treatments decreased by 31.01%, 34.24%, 35.16%, 35.23%, 35.28%, 36.38%, 36.76%, 35.46%, 34.07%, respectively, when increasing the amount of humic acid. Overall, the rate of desalination first increased and then decreased. The difference in the desalting rate between the T1-T8 and the CK treatments reached a significant level ($p < 0.05$). T6 had the highest desalting rate, followed by T5, while T8 had the lowest desalting rate.

3.3. Soil salt removal efficiency

Desalting efficiency is an important index that measures the desalting capacity per unit water. Figure 5 shows the change in the soil salt removal efficiency in freshwater leach under different treatments (salinity = 0 g/L, water volume = 125 mL). According to the agricultural irrigation water quota of Shandong Province, the amount of leach water was 125 mL. It was used to simulate the effect of humic acid on the salt removal efficiency of coastal clay saline soil under normal field irrigation.

As shown in Figure 5, the salt removal efficiency first increased and then decreased with an increase in humic acid. The soil salt removal efficiency was concentrated at 6–7 g/L in 125 mL freshwater leach. Compared to the CK treatment, the salt removal efficiency under the T1-T8 treatments increased by 3.23%, 7.55%, 6.36%, 6.76%, 5.10%, 3.20%, 2.31%, and

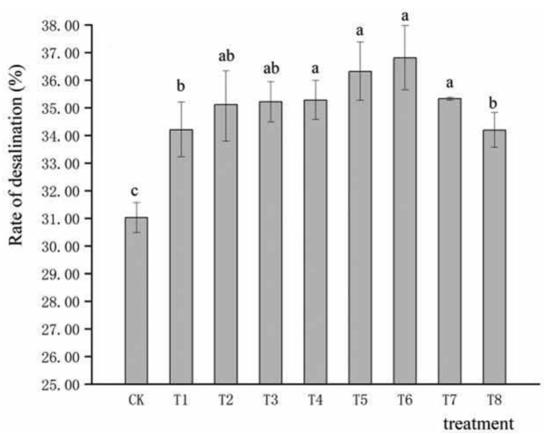

Figure 4 | The changes in the soil desalting rate under different humic acid treatments.

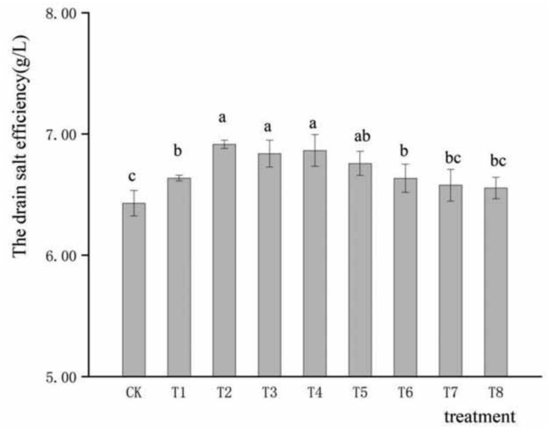

Figure 5 | The effect of humic acid on soil salt removal efficiency.

1.95%, respectively. The results indicate that adding humic acid can improve the efficiency of soil salt removal, which was the highest in T2, followed by T4, and the lowest in T8.

On one hand, the T2-T4 treatments showed a significant difference in the salt removal efficiency compared to T1. The salt removal efficiency increased with the increase of humic acid at T1-T4 treatments. On the other, the salt removal efficiency in the T4-T8 treatments gradually decreased. The difference in the salt removal efficiency in the T6-T8 treatments reached a significant level compared to T4. At T6-T8 treatments, the soil salt removal efficiency gradually decreased with the increase of humic acid.

3.4. Variation of soil salinity and water contents in the field test

Spring is the most intense season of evaporation in the Yellow River Delta region, and also the most obvious time of soil resalinity, which is the key period of soil salinity control in the improvement of saline-alkali soil. We took the soil from April 30, 2017, to study the effect of humic acid on soil water and salinity under natural conditions in the field, and to explore the effect of humic acid on soil resalinity in spring. From 15 April to 30 April, there was no irrigation or rainfall, and soil water content was in a constant state of evaporation. The results indicate that the field was not irrigated, there was no rain, and soil water content constantly evaporated from April 15 to 30, 2017.

(1) Changes in soil water content and salt salinity at a depth of 0–20 cm

Within the soil depth of 0–20 cm, the soil water content had a concentration of 15–19% under each treatment (Figure 6(a)). The soil water content under the humic acid treatment was higher than that under the CK treatment. It increased under

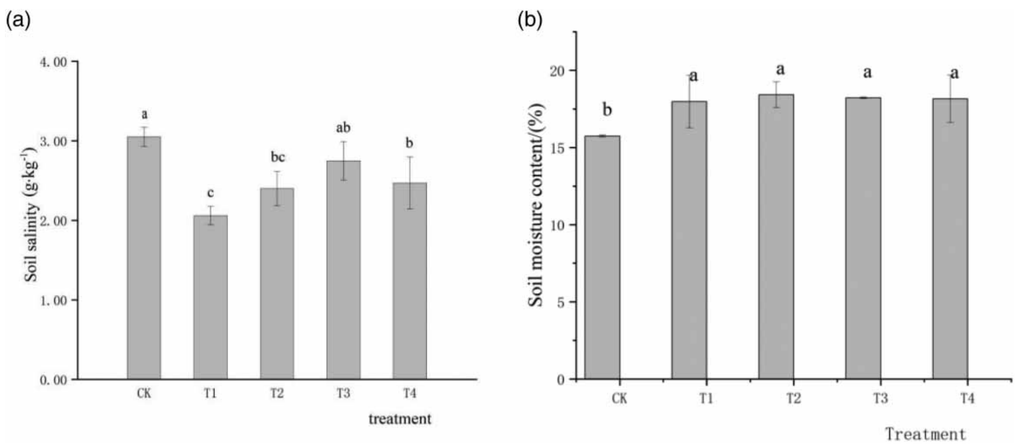

Figure 6 | The soil water content and salinity at a depth of 0–20 cm under different treatments.

treatments T1, T2, T3, and T4 by 14.12%, 17.02%, 15.73%, and 15.39%, respectively, compared to the CK treatment. The soil water content was the highest in T2. However, the soil salinity under the humic acid treatment was lower than that under the CK treatment (Figure 6(b)), which were 2.06 g/kg, 2.40 g/kg, 2.75 g/kg, and 2.47 g/kg, respectively, and decreased by 47.86%, 27.35%, 10.92%, and 23.57%, respectively, compared to the CK treatment. The soil desalting rate was the highest in T1 and the lowest in T2. The changes in the soil salinity under the humic acid treatment were significantly different from the CK treatment ($p < 0.05$).

(2) Changes in soil water and salinity at a depth of 0–60 cm

Crops are cultivated at the depth of 0–60 cm, so it is significant to study the changes in the water and salinity in the soil at this depth. At this depth, the soil water content under each treatment had a concentration of 25%, higher than that at a 0–20 cm depth. Compared to the CK treatment, the water content of T1-T4 treatments increased by 6.40%, 7.14%, −1.04%, and 5.34%, respectively. T1 and T2 treatments were significantly different from the CK treatment. The highest water content was in T2 and the lowest in T3. At a 0–60 cm depth, the soil salinity under the CK, T1, T2, T3, and T4 treatments was 2.34 g/kg, 1.79 g/kg, 1.72 g/kg, 2.11 g/kg, and 2.09 g/kg, respectively. The soil salinity in T1 and T2 decreased by 23.76% and 26.71%, respectively, with a significant difference compared to the CK treatment. The soil salinity in T3 and T4 decreased by 9.82% and 10.68%, respectively, with no significant difference (Figure 7).

(3) Changes in soil water content and salinity at a depth of 0–1 m.

The main purpose of improving saline soil is to reduce the amount of salt in the soil by treating it with humic acid, provide a suitable environment for crops to grow, and realize high crop yield. The change in soil salinity at a depth of 0–1 m is an important index that shows the improvement of saline-alkali soil.

(4) Changes in the water content and salinity in the soil under different treatments (Figure 8)

With the increase of soil depth, the variation in soil water content treated with different humic acids was basically the same since it first increased and then decreased (Figure 8(a)). At a 0–40 cm depth, the soil water content gradually increased with the increase of soil depth, while at a 40–100 cm depth, it gradually decreased with the increase of soil depth. The maximum water content had a concentration of 30–35% at a 40–60 cm depth, while the minimum water content was concentrated 15–18% at a 0–20 cm depth. The soil water content under the humic acid treatment was higher than that under the CK treatment.

With the increase of soil depth, the soil salinity under each treatment first decreased, then increased, and then decreased again (Figure 8(b)). The soil salinity gradually decreased at a 0–20 cm depth, then it increased at a 20–40 cm depth, and then again decreased and continued to do so at a 40–100 cm depth. The salinity on the soil surface was mainly concentrated at a 0–20 cm depth, followed by a 40–60 cm depth. The salinity in each layer under the humic acid treatment was lower than that under the CK treatment.

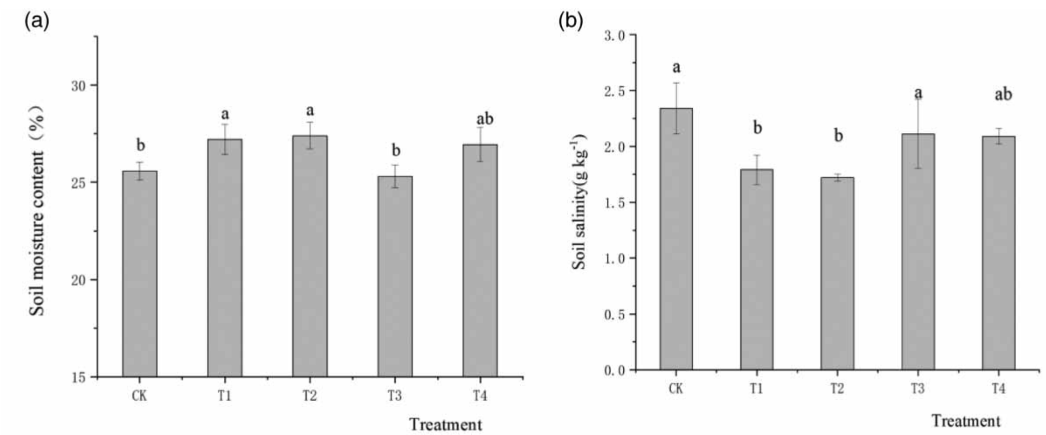

Figure 7 | The variation of soil water content and salinity at a depth of 0–60 cm under different treatments.

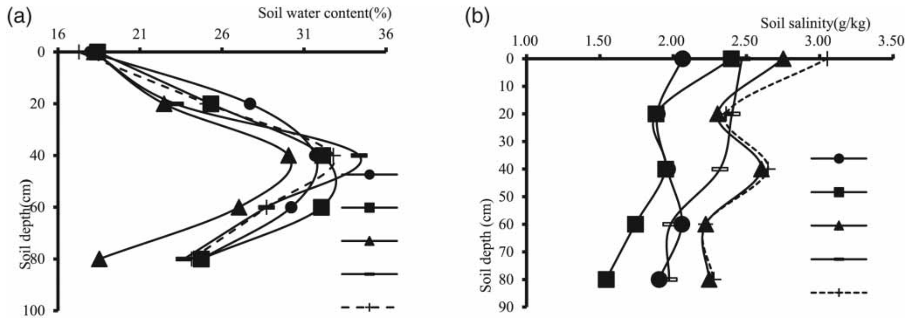

Figure 8 | Changes in the water content and salinity in the soil under different treatments.

3.5. Wheat yield

Wheat is one of the main crops cultivated in the Yellow River Delta. However, soil salinization is seriously affecting the delta, so most of the land consists of medium-to-low-yield fields. Research on the effect of humic acid on yield is another indicator that can reflect the improvement of saline-alkali soil under the humic acid treatment.

Overall, wheat yield changed similarly in 2017 and 2018 with the increase of humic acid. It first increased and then decreased and was the highest in T2 (Figure 9). In 2017, wheat yield was 3,172.87 kg/hm^2, 6,219.14 kg/hm^2, 6,760.24 kg/hm^2, 5,597.76 kg/hm^2, and 5,712.69 kg/hm^2 under the CK, T1, T2, T3, and T4 treatments, respectively. It increased under T1-T4 treatments by 96%, 113, 76, and 80%, respectively, with significant differences compared to the CK treatment ($p < 0.05$). In 2018, wheat yield was 3,732.42 kg/hm^2, 7,910.35 kg/hm^2, 9,134.93 kg/hm^2, 8,551.62 kg/hm^2, and 8,429.50 kg/hm^2 under the CK, T1, T2, T3, and T4 treatments, respectively. It increased by 111%, 144, 129, and 125% under T1, T2, T3, and T4,

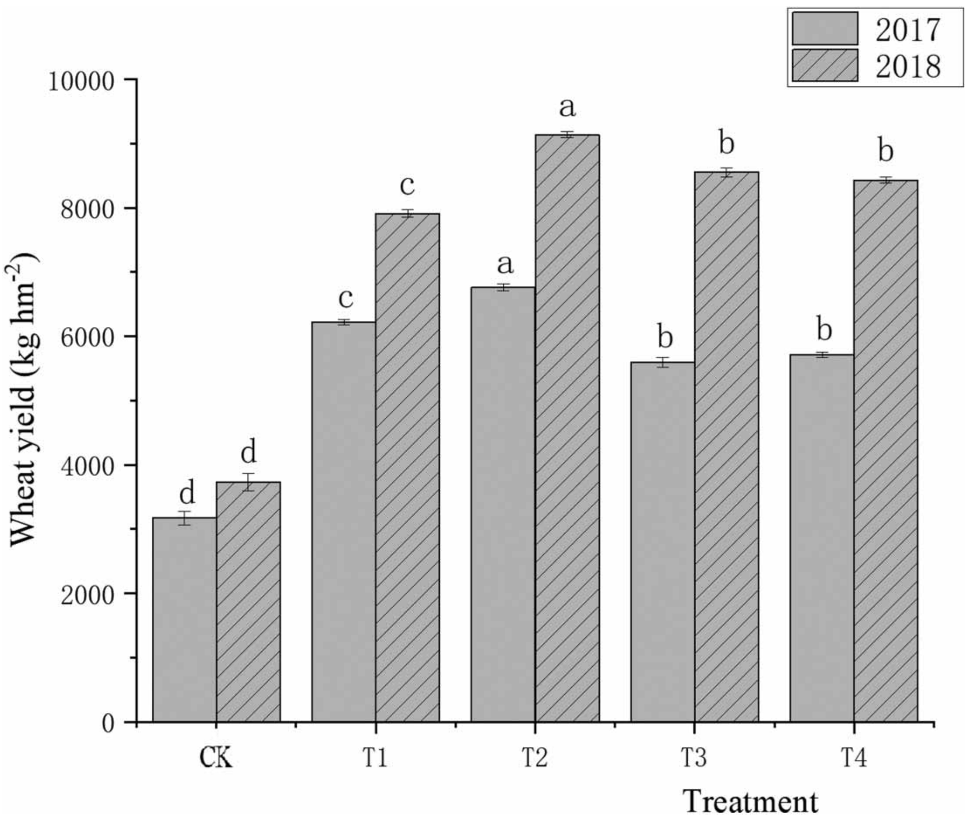

Figure 9 | The effect of humic acid on wheat yield.

respectively, with significant differences compared to the CK treatment ($p < 0.05$). Compared with 2017, crop yield in CK and T1-T4 treatment increased by 17.63%, 27.19%, 35.12%, 52.76% and 47.55% in 2018, respectively.

4. DISCUSSION

4.1. The effect of humic acid on the adsorption and leaching of water content and salinity in soil

Soil water is the solvent and carrier of salt. As it flows, it carries the salt with it (Zhang *et al.* 2015). To study the change in soil salinity, we must first see how the water content changes.

This research found that humic acid can improve soil adsorption, increase the saturated water content in the soil, and improve the soil's capacity to hold water (Figure 3(a)), which is consistent with the findings reported by Gu Xin *et al.* (Li 2012; Gu *et al.* 2017). This phenomenon can be interpreted as the combination of humic acid dissolved in water with soil minerals or other interactions that change the original structure of the soil. In addition, the soil salinity in the Yellow River Delta was mainly NaCl, accounting for 70% of the total salinity. As a soil dispersant, Na^+ will lead to the dispersion of aggregates and clay particles, resulting in the collapse of soil macropores and small voids, and hinder the movement of gas and water. The decrease of Na^+ can increase the number and stability of soil aggregates (Li *et al.* 2004). Some studies (Zhang *et al.* 2019; Gao *et al.* 2022) have shown that, Ca^{2+} and Mg^{2+} contained in humic acid can displace Na^+ into soil solution, which significantly reduces the adsorption of Na^+ to soil. In addition, humic acid as an organic colloid, produces a certain number of colloids, binds dispersed soil particles, forms a soil granular structure with high stability, and helps increase the content and proportion of soil pores, thus enhancing the soil's capacity to hold water. With the continuous increase of humic acid, the soil water content gradually increased under T1 and T2. It reached the maximum in T2, but decreased in T3-T8, possibly because the humic acid increased soil pore content and improved soil water permeability. Although humic acid can somewhat improve the soil's capacity to hold water, adding it excessively can cause water loss. Likewise, the humic acid would only be wasted, and the optimal effect would not be achieved.

Compared to the CK treatment, the soil salinity significantly increased under the humic acid treatment (Figure 3(b)).This may be because salt is dissolved in water and salt moves with water, forming a transient salt retention due to the increased water-holding capacity of the soil. With the increase of humic acid, the soil salinity gradually increased under T1 and T2 and decreased under T2-T6, which was similar to the change in the soil water content.This phenomenon further indicates that the change of soil salinity is closely related to water movement.The increase of the soil salinity under T6-T8 indicated that the change in the soil salinity was more complicated than that in the water content. At the same time, studies (Nong *et al.* 2022) have also shown that when the salinity of water is high (greater than 6 g/L), organic matter cannot play an effective role in reducing salinity. Moreover, humic acid itself will carry a small amount of salt, salt water irrigation, especially high salinity water will also introduce a large number of Na^+ and Cl^- and other ions. All of these may lead to the retention of salt in humic acid-treated soil.

However, it can be confirmed that this does not affect the active desalting effect of humic acid under freshwater leaching. The desalting efficiency (Figure 5) and desalting rate (Figure 4) of soil under humic acid treatment are higher than those under CK treatment. However, further studies will be conducted to investigate the specific internal ion changes, the internal interaction between brackish water irrigation and humic acid, and whether the effect of humic acid on soil salinity is negative under high salinity brackish water leaching.

The desalting of soil is the result of the complex reaction of humic acid in soil under the washing of fresh water. However, it is well known that organic matter promotes the structure of saline soil. As for the mechanism of organic matter on soil structure, more people believe that organic ions can improve the composition of exchangeable ions through complexation, reduce the number of dispersed ions, and increase the number of soil clay and aggregate stability (Barzegar & Nelson 1997; Li *et al.* 2002). In laboratory experiment, salt removal efficiency was the highest under T2 and the lowest under T8 (Figure 5). Not only was the adsorption of water and salt relatively high under T2, but the leaching effect was high, as well. Generally, salt removal efficiency was relatively good.

This research found that the soil salinity decreased significantly under highly salinized saltwater leach (Figure 3(b)). This indicates that when soil salinity is high, salt water with high salinity can have a certain leaching effect on salt in the soil and reduce its salinity and the salt stress on crops. Because the research area is located at the end of the irrigation area in the Yellow River Delta, it faced the problem of insufficient quantities of fresh and saltwater. How to effectively realize the desalination of clay saline soil and improve the efficient utilization of freshwater is particularly important for the improvement of saline-alkali soil in this area. Therefore, this research proposes treating the saline-alkali wasteland containing large amounts of salt with highly salinized saltwater to effectively improve the wasteland, turn it into a medium-to-low-yield farmland, and increase the available land area in the Yellow River Delta.

4.2. Changes in the water content and salinity and wheat yield in the field test

The humic acid dosage of CK, T1-T4 in field experiment and CK, T1-T4 in laboratory experiment were consistent. The laboratory experiment is a simple simulation of the field experiment to explore the law of soil desalting and salt adsorption by humic acid under fresh and salt water leaching. The field experiment is the application of laboratory test and verify, exploring in complex nature condition, the effect of humic acid on soil water and salt and production change. Differently from the laboratory experiment, the variation of water and salt in the field is affected by climate, rainfall, groundwater and many other factors. In the laboratory test, the leaching of fresh water and salt water was only carried out, and the simple mechanism analysis was carried out from the perspective of water salt. Therefore, the specific changes of field results may be slightly different from those of laboratory experiments.

The soil layer of 0–20 cm and 0–60 cm has a great influence on the growth of crops. This time, the soil was collected in the spring without rain for a long time. Under the effect of long-term evaporation, the soil salting effect was the most obvious. The soil salinity in the humic acid treatment group was lower than that in CK treatment group, and the soil water content was higher than that in CK treatment group. This phenomenon indicates that humic acid has a positive effect on the regulation of water and salt under evaporation condition. Humic acid can not only increase the water holding capacity of soil, but also effectively promote soil desalting, which is consistent with the results of laboratory tests that humic acid improves the desalting effect. It is worth mentioning that the results of laboratory salt adsorption test and field soil desalting process are two completely different processes, so it is of little significance to compare the results.

In the field results, we found that there was no significant difference in the variation of surface soil water content between 0 and 20 cm under each treatment (Figure 8(a)). This is mainly because, compared with other soil layers, the 0–20 cm soil is most affected by external factors such as rainfall and evaporation, and the soil moisture changes sharply, and the influence of humic acid dosage is not obvious.

The yield data (Figure 9) showed that compared with CK treatment, the plots under humic acid treatment all obtained higher wheat yield. In humic acid treatment, wheat yield first increased and then decreased with the increase of humic acid content, and the wheat yield under T2 treatment was the highest.Humic acid has a great contribution to increase crop yield, which is consistent with the results of previous studies (Yang 2012; Zhang *et al.* 2014).Similar to the effect of soil desalting in laboratory experiments, humic acid did not increase yield linearly. Beyond a certain point, the improvement effect of humic acid may gradually decline. Liu (2021) and Lal (2020) reported this similar phenomenon in their experiments. They believed that SOM (soil organic matter content) was closely related to crop yield, but there was a threshold. The threshold value depends on the nature of soil and tillage system, beyond which SOM has no obvious effect on yield.

4.3. The optimum application of humic acid

Generally, gypsum and furfural slag are used in the improvement of clay saline soil (Armstrong & Tantonn 1992; Cheng *et al.* 2014; Cui *et al.* 2014). Although these materials are effective in improving soil structure and reducing soil salinity, there are single improvement effects, only salt washing, no fertilizer, or secondary damage to the ecology, which makes it difficult to achieve long-term ecological improvement and sustainable development of the saline-alkali soil. In this research, humic acid was used to treat the coastal clay saline soil. The results indicate that humic acid could not only affect the adsorption of water and enhance the soil's capacity to hold water, but also improve and increase the adsorption and leaching of salt. Humic acid can also effectively reduce the soil salinity, inhibit soil salinization, and improve wheat yield. It was found that humic acid increased the adsorption of soil water, and also increased the adsorption of soil salt.

This research also observed that the soil's capacity to hold water, desalination efficiency, and wheat yield did not increase with the increase of humic acid. In the field experiment, the wheat yield (Figure 9) under T2 treatment was the highest, and in the laboratory experiment, the soil desalting efficiency (Figure 5) under T2 treatment was the highest. Although the desalting rate (Figure 4), of T6 was the highest considering the cost, the dosage of humic acid under T2 treatment was the most reasonable. As a result, the optimal amount of humic acid used in this research was 0.149 g/kg.

5. CONCLUSION

In combination with the simulated soil column adsorption and leaching tests, this research conducted the humic acid test on wheat in the field. Likewise, it analyzed the variation and distribution of the soil water content and salinity and wheat yield. The results indicate that humic acid had positive effects on the water content and salinity and wheat yield. It was also found that humic acid can improve the physical and chemical properties of the soil, effectively increase the soil water content, reduce the soil salinity, inhibit soil salinization, and increase wheat yield. Using humic acid to improve saline-alkali soil can realize the comprehensive regulation of water conservation, salt reduction, and yield increase. These findings have important theoretical and practical significance for the improvement of saline-alkali soil in the Yellow River Delta.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Armstrong, S. B. & Tantonn, T. W. 1992 Gypsum applicantions to aggregated saline- sodic clay topsolis. *Journal of Soil Science* **43** (2), 249–260.

Barzegar, A. R. & Nelson, P. 1997 Organic matter, sodicity, and clay type: influence on soil aggregation. *Soil Science Society of America Journal* **61** (4), 1131–1137.

Chai, Y. Z., Zhang, Y. Y. & Ma, J. W. 2021 Effects of isoacidic amendments on vineyard soil and grape quality. *Soil and Fertilizer Science in China* **02**, 102–107.

Chen, F. S., Chen, G. S., Zeng, D. H. & Liang, C. 2002 Effects of peat and weathered coal on the growth of Pinus sylvestris var. mongolica seedlinggs on aeo-lian sandy soil. *Journal of Forestry Research* **13**, 251–254.

Cheng, J. R., Chen, X. H. & Liu, Z. H. 2014 Experimental study on desalting process and effect of desulfurized gypsum in improving coastal saline-alkali soil. *Chinese Environmental Science* **34** (06), 1505–1513.

Cui, X. C., Hu, J. L. & Lin, X. G. 2014 Effects of papermaking powder and furfural residue on maize growth and soil microbial characteristics in coastal saline-alkali land. *Journal of Ecology and Rural Environment* **30** (3), 331–335.

Gao, H. M., Wang, X. P. & Qu, Z. Y. 2020 Effects of different amendments on soil saline-alkali indexes and crop yield in Hetao irrigation area. *Chinese Journal of Soil Science* **51** (05), 1172–1179.

Gao, X. L., Mao, W. B. & Sun, Y. X. 2022 Effect of potassium humate on adsorption and leaching of major salt ions in coastal clay soils. *Water Saving Irrigation* **04**, 77–82.

Gu, X., Ren, C. M., Yang, L. & Wang, X. Z. 2017 Study on the amelioration effect of natural coal humic acid on saline-alkali soil. *Journal of Irrigation and Drainage* **36** (09), 57–61.

Jalali, M. & Ranjbar, F. 2009 Effects of sodic water on soil sodicity and nutrient leaching in poultry and sheep manure amended soils. *Geoderma* **153**, 194–204.

Lal, R. 2020 Soil organic matter content and crop yield. *Soil and Water Conservation Society* **75** (2), 27––232.

Li, J. 2012 *Study on Changes of Soil Quality in Protected Land and Effects of Different Measures on Soil Improvement*. Master's Thesis, Northeast Agricultural University.

Li, K. 2018 *Study on the Effect of Combined Application of Calcium Silicate and bio-Organic Fertilizer on Saline-Alkali Soil Improvement. PhD Thesis*, Inner Mongolia Agricultural University, Inner Mongolia, China.

Li, X. G., Cui, Z. J. & Wang, L. Y. 2002 Effects of salinization and organic matter on soil structural stability and Atterberg limit. *Acta Pedologica Sinica* **04**, 550–559.

Li, X. G., Cao, J. & Li, F. M. 2004 Sodium salt and qualitative impact on soil physical properties. *Journal of Soil Bulletin* **01**, 64–72.

Liu, L. 2021 Correlation between soil organic matter content and crop yield. *Applied Technology of Soil and Water Conservation* **01**, 20–22.

Liu, M. & Wang, C. 2020 Saline-alkali soil applied with vermicompost and humic acid fertilizer improved macroaggregate microstructure to enhance salt leaching and inhibit nitrogen losses. *Applied Soil Ecology* **156**, 103705.

Mahdy, A. M. 2011 Comparative effects of different soil amendmentson amelioration of saline-sodic soils. *Soil and Water Research* **6**, 205–216.

Melillo, J. M., Steudler, P. A. & Aber, J. D. 2002 Soil warming and carbon-cycle feedbacks to the climate system. *Science* **298**, 2173–2176.

Nong, W. L., Shao, G. C. & Wu, S. Q. 2022 Effects of biochar application on soil salinity distribution and aggregate structure under brackish water irrigation. *China Rural Water and Hydropower* **06**, 154–161.

Qadir, M., Schubert, S., Ghafoor, A. & Murtaza, G. 2001 Amelioration strategies for sodic soils: a review. *Land Degradation & Development* **12**, 357–386.

Sahin, U., Eroglub, S. & Sahinb, F. 2011 Microbial application with gypsum increases the saturated hydraulic conductivity of saline-sodic soils. *Applied Soil Ecology* **13**, 247–250.
Sun, Y. N., Geng, Y. H. & Zhao, L. P. 2011 Changes of ions in saline-alkali soil modified by aluminum sulfate. *Chinese Agricultural Science Bulletin* **27**, 255–258.
Wang, Y. S. & Zhu, Y. F. 2021 Research on preparation and properties of a multifunctional superabsorbent based on semicoke and humic acid. *European Polymer Journal* **159** (45), 110750.
Wang, Q. Z., Wang, Y., Sun, Z. M. & Xue, C. 2019 Application of humic acid to ameliorate saline-alkali land. *Chinese Journal of Applied Ecology* **4**, 1–13.
Xiong, Y. 1979 The composition of soil colloid and compound. *Journal of Soil Bulletin* **05**, 1–8 + 28.
Yang, D. C. 2012 *Effects of Combined Application of Organic and Inorganic Fertilizer on Physicochemical Properties and Yield of Alkalized Meadow Soil*. *PhD Thesis*, Northeast Agricultural University, Hei Longjiang, China.
Yang, F., Sui, L. & Tang, C. 2021 Sustainable advances on phosphorus utilization in soil via addition of biochar and humic substances. *Science of The Total Environment* **768**, 145106.
Yazdanpanah, N. & Mahmoodabadi, M. 2013 Reclamation of calcareous saline-sodic soil usingdifferent amendments: time changes of soluble cations in leachate. *Arabian Journal of Geosciences* **6**, 2519–2528.
Yue, Y., Lin, Q. M., Guo, W. N., Li, G. T. & Zhao, X. R. 2015 Effects of biochar addition on salinity leaching in different soil layers. *Agricultural Research in the Arid Areas* **33**, 62–67.
Zhang, M. M., Chen, C. & Liu, G. M. 2014 Suitable fertilizer and amendment to improve physical and chemical properties of saline-alkali soil and increase crop yield. *Transactions of the Chinese Society of Agricultural Engineering* **30** (10), 91–98.
Zhang, J. P., Liu, Z. G. & Sun, J. S. 2015 Effects of different water and mulching treatments on growth and water use of winter wheat. *Journal of Irrigation and Drainage* **34** (08), 7–11.
Zhang, Q., Feng, G. Y. & Wang, S. L. 2019 Change of salinity in coastal saline-alkali soil by desalting and supplementing. *Water Saving Irrigation* **4**, 56–59.
Zhang, L., Zhao, Y., Shi, W. W. & Wang, Q. W. 2021 Research and application of modern saline-alkali soil remediation technology system in Yellow River Delta. *China Rural Water and Hydropower* **07**, 151–154.
Zheng, Q. K. 2018 Effect of sand mixing improvement on water and physical properties of coastal clayey saline soil. *Shandong Agricultural University*, 1–20.

First received 16 May 2022; accepted in revised form 21 August 2022. Available online 27 August 2022