EVALUATION OF THE IMPROVEMENT EFFECT OF *GANODERMA LUCIDUM* RESIDUE ORGANIC FERTILISER ON SALINE SOIL

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Abstract. Saline alkali soil is used as spare arable soil, and its improvement is necessary for its development and utilization. There are many research studies on improving saline-alkali soil by using organic wastes produced by various industries, but there are few studies on using wastes produced by traditional Chinese medicine enterprises for saline alkali soil improvement. The purpose of this study was to explore the improvement effect of using *Ganoderma lucidum* residue (GLR) organic fertiliser on saline alkali soil and determine the application amount of GLR organic fertiliser with the best improvement effect. The results showed that the pH, EC and cation leaching loss of the leaching solution of the soil treated with GLR organic fertiliser were significantly higher than those of the unmodified soil. After leaching, the pH, EC, and base ions of the soil were significantly lower than those of unmodified saline alkali soil. The coefficient score of PCA was significantly higher than that of the unmodified saline alkali soil. When the ratio of organic fertilizer to saline-alkali soil was 1:3 and 1:5, the comprehensive evaluation level of the improvement effect was the highest, which could effectively reduce the soil saline-alkali index and promote the leaching of salt in saline-alkali soil.
Keywords: *leaching, saline alkali soil, comprehensive evaluation, soil improvement, saline index*

Introduction

Saline alkali soil is a problematic soil that is widely distributed worldwide. At present, there are approximately 100 million hectares of saline alkali soil in China (Wang et al., 2019). Improving this kind of soil is crucial for agricultural production and food safety. The formation of saline alkali soil is caused by climatic, topographic, and anthropogenic factors. In saline alkali soil, the content of base ions is high, which makes it difficult for plants to absorb water and nutrients from the soil (Kinraide, 1999) and seriously hinders their growth. Soil salinization destroys the soil structure, leads to a decline of soil physical and chemical properties and fertility, inhibits the normal growth and development of plants and microorganisms in the soil, and destroys the benign operation of the soil ecosystem. Saline alkali soil has many negative characteristics, including high pH, electrical conductivity (EC), sodium adsorption rate (SAR) and exchangeable sodium percentage (ESP) (Temiz et al., 2018) which are also important parameters for the identification and classification of saline alkali soil (Sadegh-Zadeh et al., 2018).

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At present, there have been many studies on saline-alkali soil improvement measures, evaluation methods and improvement effects, and the improvement of saline-alkali soil mainly adopts physical, chemical, and biological measures. Among these measures, underground pipes are representative physical improvement measures, physical measures have a long effective period, significant effect of salt discharge, and the salt discharge effect is remarkable, but the engineering quantity is large, the investment cost is high. Physical measures are relatively long-lasting, and they have significant salt removal effects, but they require extensive, costly investments. Chemical measures are widely used. Luo et al. (2015) found that the application of amendments can reduce the pH of soil. Many studies have used acidic or basic chemicals and soluble calcium salts (Tozsin et al., 2015) and inorganic modifiers such as gypsum as amendments for alkaline soil reclamation (Kim et al., 2017; Saifullah et al., 2017; Zhao et al., 2018). However, in terms of improvement effect, Bai et al. (2018). and others found that gypsum alone cannot improve the physical structure of the soil, and it is still easy for salt ions to migrate upwards to the topsoil, resulting in salt accumulation, which will further reduce the nutrient efficiency of the soil (Lakhdar et al., 2009). Therefore, many studies have turned to organic improvers with better improvement effects, which mainly include animal faeces and biochar. Among these improvers, the use of biochar in saline alkali soil is more common (Duan et al., 2019; Zhao et al., 2020). However, these modifiers still have disadvantages of high cost and instability. The application of organic fertilisers has been found to be a good practice for improving soil quality and soil fertility (Ma et al., 2019). On the one hand, organic fertilizer can promote soil aggregation by increasing organic matter, thus improving soil structure, regulating soil microbial community, and improving soil nutrients. On the other hand, organic fertilizer has a significant effect on salt improvement of saline-alkali soil, and organic fertilizer can promote salt leaching. The salt in the soil is lost along with leaching (Tzanakakis et al., 2011; Zhang et al., 2014). At present, the application of green fertilizer is considered a good measure to improve soil fertility and soil improvement, but its effect on the soil is related to the soil type and materials used (Guo et al., 2018), so it is necessary to conduct relevant analysis on the soil improved by the application of organic fertilizer and test the improvement effect.

These saline-alkali soil improvement measures and conditions provide a new idea for our research. Similar to green manure, Traditional Chinese Medicine residue (TCMR) is a solid plant substance produced after extracting medicinal components from herbal materials. *Ganoderma lucidum* residue (GLR) is a kind of TCMR that contains a variety of medicinal components, such as *Ganoderma lucidum* polysaccharide, *Ganoderma lucidum* acid, adenosine, amino acids, trace elements, and cellulose. Ma et al. (2019) found that TCMR improve soil nutrients, enhance soil aggregates, reduce heavy metal content, and increase corn yield. At present, there are few studies on the use of GLR to improve saline alkali soil, and little is known about whether GLR organic fertiliser can improve saline alkali soil or reduce the soil salinity index. Therefore, an indoor soil column leaching experiment was used in this study to compare and analyse the changes in saline alkali indices in the leaching solution and in the soil after leaching. The coefficient score of principal component analysis (PCA) was used to comprehensively evaluate the soil quality after leaching, investigate the leaching effect of GLR organic fertiliser on salt and explore the improvement effect of GLR fertiliser on saline alkali soil.

Materials and methods

Materials

Saline alkali soil sample was obtained from a saline alkali soil improvement site in the village of Dabusutai in Jiuyuan District, Baotou city, Inner Mongolia. Soil was taken at fixed points on the saline alkali land at an approximately 20 cm depth. The soil collected at each point was fully mixed after collection and then dried in a cool place. The GLR organic fertilizer for the laboratory homemade, compost using natural compost, covering nano compost cloth, compost time for 42 days, specific compost conditions refer to Shi et al. (2022). See *Table 1* for the physical and chemical properties of the soil and GLR organic fertiliser.

Table 1. *Physicochemical properties of the experimental soil and GLR organic fertiliser*

(a) Saline soil		**(b) GLR organic fertiliser**	
Index		**Index**	
pH	9.35	Total humus/%	35.05
Electrical conductance (EC) ms/cm	18.10	Humic acid/%	12.99
Na^+ (g/mg)	18309.34	Fulvic acid/%	22.06
K^+ (g/mg)	51.22	EC (uS/cm)	46.70
Mg^{2+} (g/mg)	70.93	Free humic acid/%	23.36
Ca^{2+} (g/mg)	14.478	Aqueous humic acid/%	8.88
Available phosphorus (mg/kg)	15.15	pH	6.40
Hydrolysed nitrogen (g/kg)	1.63	Organic matter/%	80.65
Organic matter (/%)	0.542		

Leaching experiment

Six treatments were designed, including a control (CK), in which no GLR organic fertiliser was applied, and five experimental treatments, Groups T1, T2, T3, T4, and T5, in which the dry weight ratios of GLR organic fertiliser and saline-alkali soil 1:3, 1:5, 1:7, 1:9, and 1:11, respectively. Each treatment was repeated three times.

Leaching device (*Fig. 1*): A leaching device was made of PVC pipe with an outer diameter of 110 mm and a height of 40 cm. The upper part was sealed with fresh-keeping film to prevent water loss, and the bottom was sealed with two layers of medical gauze. Approximately 2 cm of deep-sea sand was placed at the bottom of the device. The height of the soil column was 22 cm. A funnel with a diameter of 15 cm and a 500 ml beaker were placed at the lower part to collect the drenching solution. After the drenching solution was collected, it was placed into a clean plastic bottle and stored in a refrigerator or a cool place for later analysis.

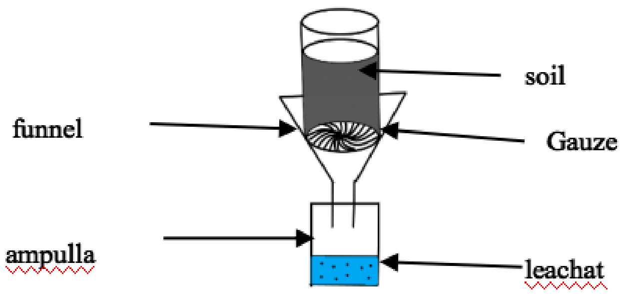

Figure 1. *Leaching device*

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After the soil sample and GLR organic fertiliser were dried in the shade and screened through a 3 mm sieve, they were mixed into the leaching device in different proportions. Pure water was added to reach the maximum field water capacity (30%). The leaching experiment began 7 days after culture. The samples were leached six times, once every 24 hours for a total of six leaching cycles. The amount of leached water was calculated according to the average annual rainfall in Baotou, Inner Mongolia, and by the number of leaching cycles and surface area of the leached water. The annual precipitation in Baotou, Inner Mongolia, is approximately 300 mm (Hao et al., 2016), and the amount of leached water during each rain event is 235.5 ml.

Sampling and measurement

Sample collection

Soil leachate was collected once a day. At the end of leaching, soil was collected from the 10-20 cm soil layer in the soil column, and each treatment was repeated three times.

Index determination

The soil pH was measured by a hand-held pH metre, and the soil water mass ratio was 1:2.5. The EC of the soil was measured with a handheld conductivity metre, and the soil water mass ratio was 1:5. The total salt content of the soil was determined by the gravimetric method, and the soil water mass ratio was 1:5; Ca^{2+} and Mg^{2+} were determined by atomic absorption spectrophotometry (Huang et al., 2013); Na^{+} and K^{+} were measured by a fp640 fire spectrophotometer (Mahmoodabadi et al., 2013); available phosphorus was determined by molybdenum antimony anti spectrophotometry; sulfate radicals were titrated by EDTA; chloride ions were titrated with silver nitrate; and the sodium adsorption ratio (SAR) was determined according to Kharel et al. (2018) and calculated as:

$$\mathrm{SAR} = \mathrm{c(Na^{+})}/\sqrt[2]{\mathrm{c(Ca^{2+})} + \mathrm{c(Mg^{2+})}/2} \tag{Eq.1}$$

where C (Na^{+}), C (Ca^{2+}) and C (Mg^{2+}) represent the content of each ion in each litre of solution.

The indicators of saline alkali soil were normalized, and the normalized conversion function of the maximum value was as follows (Xia et al., 2019):

$$X^{*} = (X - X_{min})/(X_{max} - X_{min}) \tag{Eq.2}$$

where X_{max} is the maximum value of the sample data and X_{min} is the minimum value of the sample data.

Based on the variance contribution of the 1st and 2nd principal components, the evaluation function was used to find the composite score of each treatment. The evaluation function was as follows:

$$\mathrm{F} = \sum \mathrm{a_i}\, \mathrm{F_i} \tag{Eq.3}$$

where a_i denotes the variance contribution of the principal component and F_i denotes the score of the i^{th} principal component (i=1, 2).

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Statistical analyses

The statistical software Excel was used for basic data processing, SPSS 23.0 and Excel were used for statistical analysis, and the least significant difference (LSD) test was used ($p<0.05$). $P < 0.05$ indicates that the difference is statistically significant.

Results

Leachate

Ion content

Fig. 2A shows that the mass change of Mg^{2+} in the leaching solution of the treatment with GLR organic fertiliser was higher than that of the CK, and the content of Mg^{2+} in the leaching solution of Treatment group T3 was the highest at the first leaching, reaching 390.80 mg/L. The amount of Na^{+} leached out from each treatment with GLR organic fertiliser was higher than that of the CK in the six leaching cycles (see *Fig. 2B*). The Na^{+} content in the leaching solution of Treatment group T3 was the highest in the first leaching, reaching 145.64 mg/L. The change in the K^{+} mass in the leaching solution of the treatment group with added GLR organic fertiliser was greater than that of the CK (see *Fig. 2C*). The K^{+} concentration in the treated leachate peaked at the second leaching cycle at 120.96 mg/L. The Ca^{2+} content in the leached solution of the treatment with added GLR organic fertiliser was higher than that of the CK (see *Fig. 2D*). The peak value of Treatment Group T2 was the highest, which was 3.873 mg/L. The $Cl^{—}$ content of the drenching solution of the treatment group with added GLR organic fertiliser was higher than that of the CK (see *Fig. 2E*). the peak value of the T3 treatment group was 12442.21 mg/L at the first leaching. In *Fig. 2F*, the change trend of each treatment group was basically consistent with that of the CK curve as a whole, and the T1, T2, and T4 treatment groups and CK all reached their peaks during the second leaching. The peak values of T3 and T5 treatment groups were reached at the fifth and first leaching, respectively.

Cumulative quantity

In *Fig. 3*, Compared with the control, the total amount of Mg^{2+} leaching in each treatment increased significantly, with an increase range of 25.82%-46.49%. Compared with the CK, the total Na^{+} leaching amount in the treatments with GLR organic fertiliser increased significantly, with an increase range of 56.24%-96.29%.

In the whole leaching process, the total amount of K^{+} leached in each treatment increased compared with the CK. The growth range is 148.80% to 320.75%.

The accumulation of Ca^{2+} in the leaching solution of treatments with GLR organic fertiliser was significantly higher than that in the CK, the range was between 243.24% and 277.13%.

The treatment groups supplemented with GLR organic fertiliser had significantly higher $Cl^{—}$ accumulation in the drenching solution than CK, with an increase range of 101.70% - 204.55%. *Fig. 3F* shows that except for Treatment Group T2, the total accumulation of SO_4^{2-} in the leaching solution of the treatment groups was lower than that of the CK. The total accumulation of SO_4^{2-} in the leaching solution of Treatment Group T2 increased by 5.38% compared with that of the CK.

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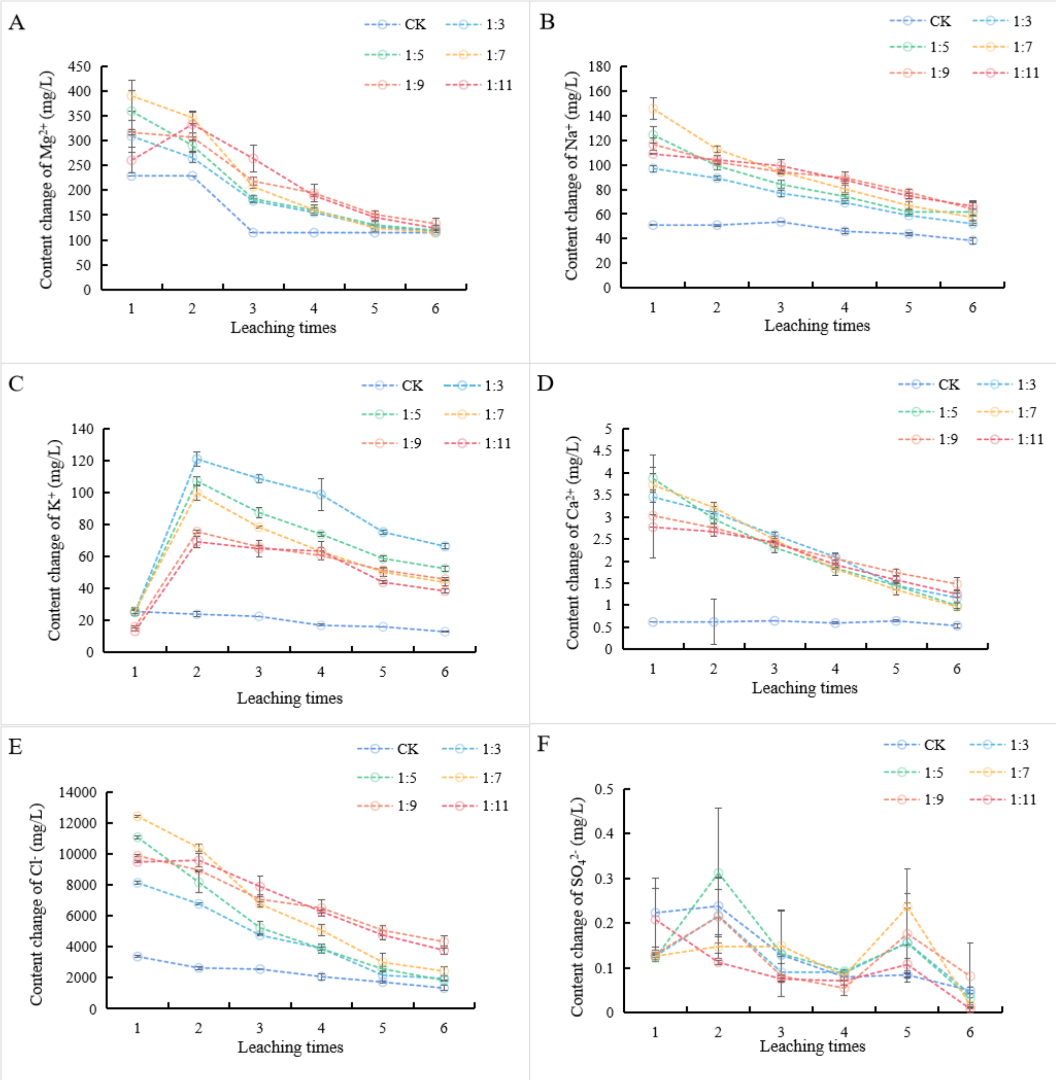

Figure 2. *Change of ion content in leaching solution, (A) Mg^{2+}, (B) Na^{+}, (C) K^{+}, (D) Ca^{2+}, (E) Cl^{-}, (F) SO_4^{2-}*

pH, conductivity, and leaching volume

Fig. 4A shows the change in the leaching solution volume under different treatments. Compared to the CK, the total volume of leaching solution in Treatment groups T1, T2 and T5 decreased by 0.83%-5.84%, but the volume of the leaching solution in Treatments groups T3 and T4 increased by 3.38% and 0.90%, respectively.

Fig. 4B shows the change trend of the pH value of the leaching solution under the different treatments. Compared with the CK, the pH value of the leaching solution of each treatment decreased. The pH value of Treatment Group T1 was the lowest in the first three leaching processes.

Fig. 4C shows that the GLR reduces the conductivity of soil. During the leaching process, ions flow out with the leaching solution, and the salt content in the soil continues to decrease.

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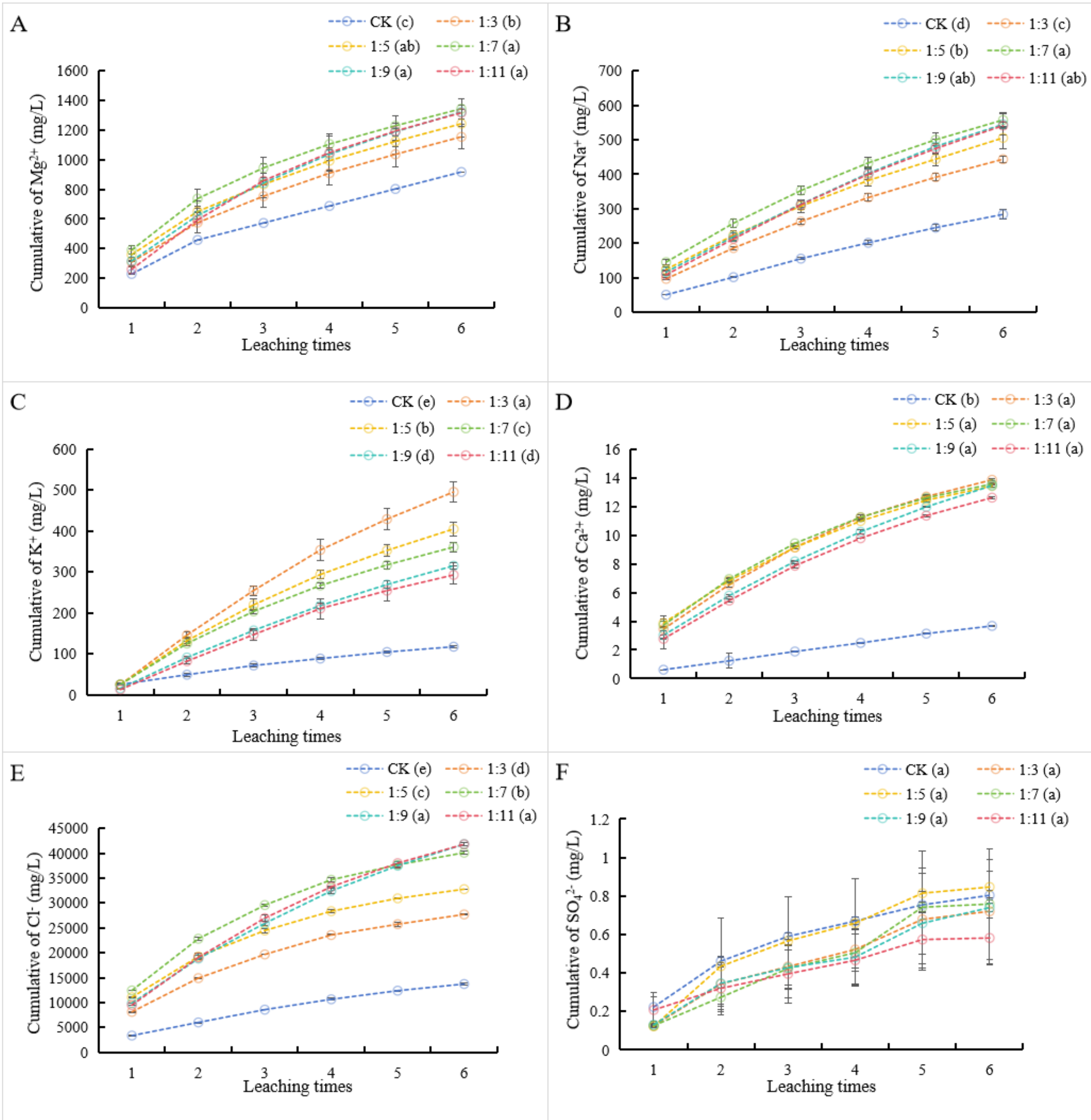

Figure 3. *Ion Cumulative quantity in the leaching solution, (A) Mg^{2+}, (B) Na^{+}, (C) K^{+}, (D) Ca^{2+}, (E) Cl^{-}, (F) SO_4^{2-}. Different lowercase letters indicate significant differences ($p < 0.05$) in the six leaching accumulations of ions between groups by using the LSD test*

Changes in soil physical and chemical properties before and after leaching

pH and conductivity

Fig. 5A shows that after adding GLR organic fertiliser in different proportions, the soil pH of each treatment group was lower than that of the control group. Treatment Group T1 had the best effect on soil pH improvement. The soil pH was 6.34, which was 28.52% lower than that of the CK.

As shown in *Fig. 5B*, the soil conductivity of all treatment group after leaching was lower than that of the CK, and the overall change trend showed that the conductivity of the saline alkali soil decreased with increasing amount of GLR residue organic fertiliser.

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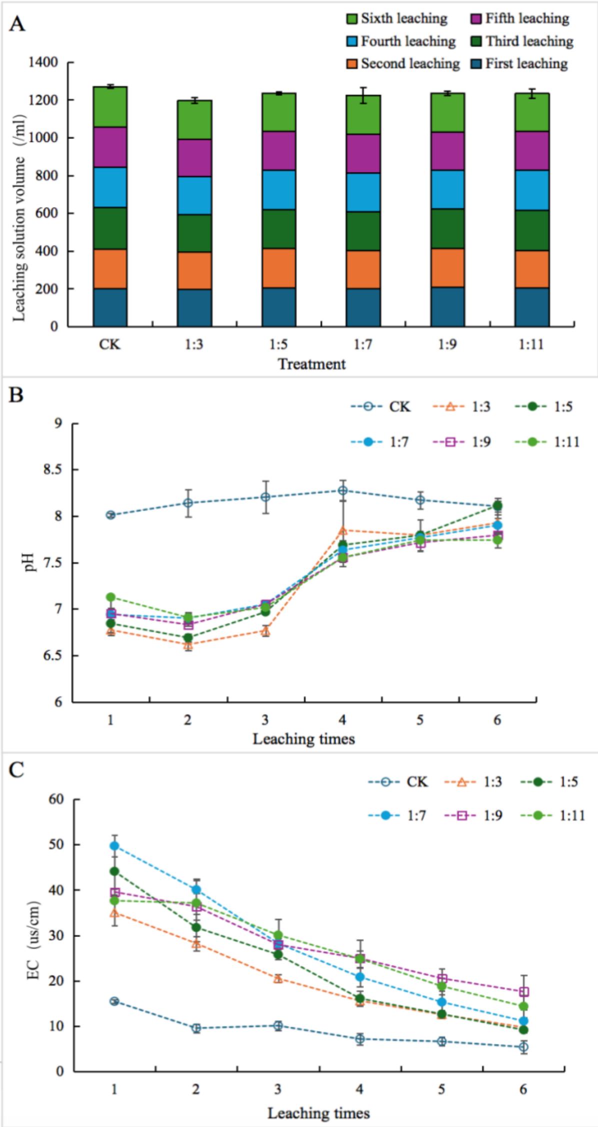

Figure 4. *Changes in leaching solution volume, pH and conductivity. (A) leaching solution volume; (B) pH of leaching solution; (C) conductivity of leaching solution*

Ion change

As shown in *Fig. 6*, Treatment group with added GLR organic fertiliser showed a significant decrease in cations in the soil after drenching compared to the CK. In *Fig. 6A*, the soil in Treatment Group T4 had the lowest Mg^{2+} content of 1.32 mg/kg after leaching. The K^{+} content of the soil in each treatment group increased significantly before drenching and increased with the increase in the fertiliser, but the K^{+} content in the soil changed little after leaching. The K^{+} content of the soil in Treatment Group T4 was the lowest after leaching at 57.57 mg/kg. Among the soils supplemented with organic fertiliser of GLR, the lowest Na^{+} content was 2914.04 mg/kg in Treatment Group T1 after leaching. The overall trend showed that as the amount of organic fertiliser applied to the GLR increased, the soil Na^{+} content decreased. The Ca^{2+} content in the soil increased with the increase in GLR organic fertiliser before leaching, and the soil in Treatment Group T4 had the lowest Ca^{2+} content of 5.16 mg/kg after leaching.

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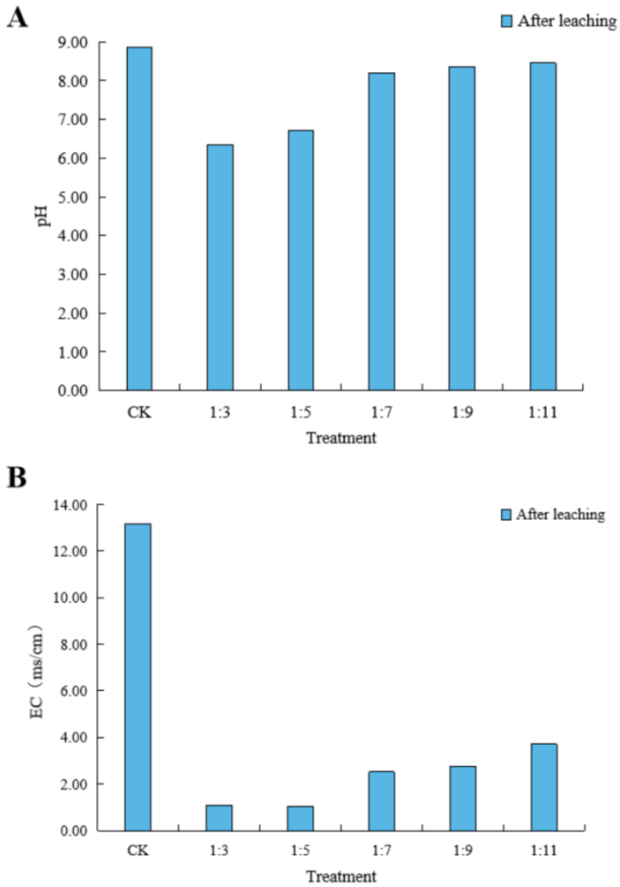

Figure 5. *(A) The pH of soil after leaching in different treatment groups; (B) The conductivity of soil after leaching in different treatment groups*

As shown in *Fig. 6B*, the Cl^- content in the soil of the GLR treatment groups was lower than that of the CK, and the lowest Cl^- content after leaching was Treatment Group T1, which was 95.48% lower than that of the CK. As shown in *Fig. 6B*, the SO_4^{2-} in the soil before leaching was positively proportional to the amount of added GLR organic fertiliser. After leaching, the SO_4^{2-} content in the soil was the lowest in Treatment Group T2, with a 94.86% reduction compared to the CK. After leaching, the CO_3^{2-} content in the soil of Treatment groups T1, T2, and T3 were 0. The HCO_3^- content in the soil increased by 1060.63 mg/kg and 1543.67 mg/kg in the CK and T5 treatment groups, respectively.

Comprehensive evaluation of soil after leaching

Principal component analysis

The results of the PCA extraction of all the indicators of saline soil improvement using SPSS 23.0 statistical software are shown in *Table 2*. The component matrix showed that sodium ions, pH, electrical conductivity, and sodium adsorption ratio were the main indicators on the 1st principal component, and in the 2nd principal component, potassium ions and calcium and magnesium ions were the main indicators.

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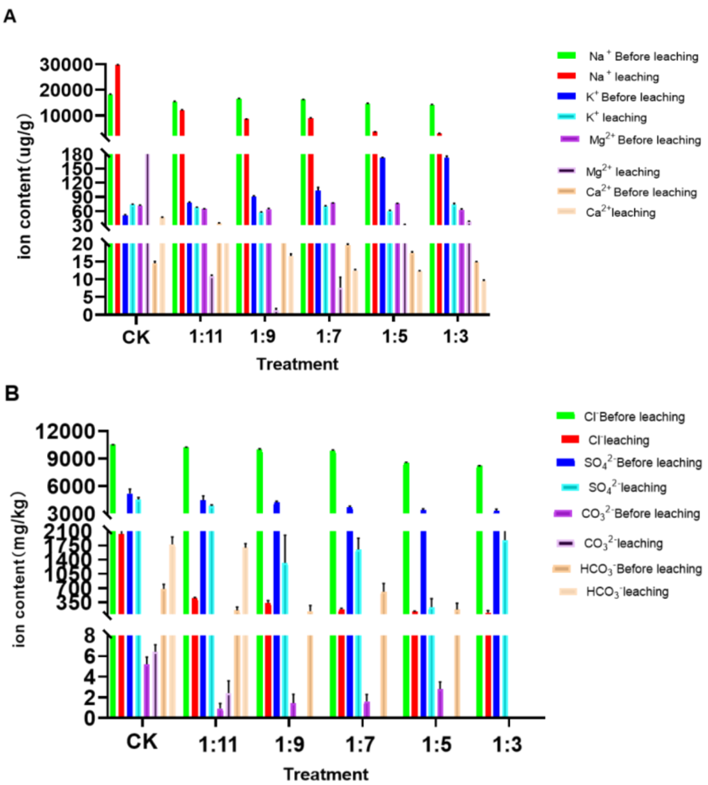

Figure 6. *Changes in (A) soil cations and (B) soil anions before and after leaching in different treatment group*

Table 2. *Principal component analysis of each index*

Parameter		Principal Component 1	Principal Component 2
Index	Potassium ions	-0.058	0.942
	Calcium ion	0.083	0.881
	pH	0.997	0.061
	Electrical conductivity	0.964	0.241
	Sodium ion	0.983	0.14
	Magnesium ion	-0.391	0.77
	Sodium adsorption ratio	0.974	-0.152
Initial Eigenvalue	Eigenvalue	3.580	2.371
	Percent	57.163	33.727
	Cumulative percentage	57.163	90.890
Load variance	Variance contribution rate	57.163	33.727
	Cumulative variance contribution rate	57.163	90.890

Comprehensive scores

Based on the coefficient score matrix of the two principal components, the functional expressions of each principal component score were obtained as follows:

$$F_1 = 0.025X_1 + 0.058X_2 + 0.251X_3 + 0.25X_4 + 0.25X_5 - 0.065X_6 + 0.236X_7$$

$$F_2 = 0.398X_1 + 0.369X_2 + 0.001X_3 + 0.078X_4 + 0.035X_5 + 0.334X_6 + 0.088X_7$$

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The calculated comprehensive scores of saline soil improvement by GLR organic fertiliser with different addition ratios (*Table 3*) showed that the comprehensive improvement effect of each treatment was ranked in the following order from highest to lowest improvement: Treatment Group T1 > Treatment Group T2 > Treatment Group T4 > Treatment Group T3 > Treatment Group T5. When the comprehensive score was set to different evaluation levels, i.e., >0.8 is level 1, 0.1-0.8 is level 2, and <0.1 is level 3, the results of this study showed that Treatment groups T1 and T2 were in level 1, Treatment groups T3, T4 and T5 were level 2, and the CK treatment was level 3, among which, Treatment Group T1 had the best comprehensive effect in improving saline soil.

Table 3. *Combined score for each treatment*

Treatment group	First principal component score	Second principal component score	Comprehensive score	Ranking	Grade
CK	0.03	0.04	0.0288	6	3
T1	1.00	0.98	0.9038	1	1
T2	0.89	0.96	0.8333	2	1
T3	0.25	0.40	0.2788	4	2
T4	0.21	0.51	0.2933	3	2
T5	0.19	0.46	0.2627	5	2

Discussion

Effect of GLR residue on the pH and conductivity of saline soils

The pH of the drench solution of Treatment Group T1 was lowest during the first three drenching cycles and that of Treatment Group T5 was lowest during the last drenching cycle (*Fig. 4B*). The pH of the drench solution treated with GLR organic fertiliser decreased compared to that of the CK, which may be due to the decomposition of organic matter in GLR that produces organic acids. There was a gradual increase in the pH of the drench solution after the fourth drenching cycle for each treatment, which may be due to the decrease in calcium concentration in the pore water caused by drenching, thus leading to the dissolution of carbonate minerals in the soil, as indicated by Gu et al. (2018). Soil pH is critical for plant growth and soil fertility and is one of the important chemical properties used to assess soil quality (Chen et al., 2020a). The decomposition of soil organic matter, dissolution of minerals, coalescence and dispersion of colloids are all related to soil pH (Tibbett et al., 2019). In this study, the pH of the soil after the addition of GLR organic fertiliser was found to be significantly lower than that of CK. This may be because GLR improves the nutrients in the soil and significantly increases the contents of organic matter, total nitrogen, available phosphorus, available nitrogen, and available potassium in the soil. These organic substances produce large amounts of organic acids to enhance the replacement of adsorbed sodium in the soil (Chen et al., 2020b), resulting in a decrease in pH and an increase in CEC, which is consistent with the results of Chen et al. (2020b). In addition, it is also possible that the addition of GLR organic fertilisers increased Ca^{2+} in the soil. Ca^{2+} underwent a replacement reaction with Na^{+} in the saline soil, displacing a large amount of Na^{+} in the saline soil and effectively lowering the pH of the soil (Smaoui-Jardak et al., 2017).

EC represents the dissolution conditions and ion exchange capacity of water-soluble ions in the soil (Huang et al., 2013). The results of the present study revealed that the EC of the drench solution of each treatment was significantly higher than that of the CK,

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indicating that the addition of GLR organic fertiliser enhanced the evolution of salt-based ions from the soil, which is similar to previous research results (Gharaibeh et al., 2009). The EC values of the soils were lower than those of the CK after leaching, probably because the ions that were easily leached from the soils treated with GLR were more thoroughly leached when leaching ended, and the cementation and agglomeration of soil particles changed the soil pore conditions and promoted the leaching effect, resulting in lower EC values of the soils treated with GLR after leaching. The second possibility is that the negatively charged carboxyl groups in the humus adsorbed some soil cations, resulting in lower soil EC values, which is consistent with the findings of Motojima et al. (2012). The trend of the volume of the drench solution reflected the water holding capacity of the soil. In this study, the volume of leaching solution in Treatment Group T1 was the smallest, indicating that the water holding capacity in the soil was greater. This may be because the humic acid in the GLR organic fertiliser reduces the content of water-soluble salt in the soil, increases the aggregate structure in the soil, and increases the organic matter in the soil. After the organic matter is decomposed, the surface oxidation groups and carboxyl groups increase, which improves the water holding capacity of saline alkali soil, which is consistent with the research results of Chen et al. (2020b).

Effect of GLR organic fertiliser on saline soil cations under leaching conditions

The cation content and size of the ratio have different degrees of negative effects on the physical properties of the soil. The main cation in saline soils is Na^+ (Li et al., 2019). In this study, as seen in *Fig. 6A*, the amount of Na^+ in the soil before and after leaching was above 10,000, which was much higher than that of other ions. The Na^+ content in the drench solution of the treatment groups with the addition of GLR organic fertiliser was significantly higher than that of the CK, and the accumulated amount of Na^+ leached out was also higher than that of the CK. The above results show that the GLR organic fertiliser promoted a leaching effect of Na^+ in the soil, probably because the increased Ca^{2+} of the GLR replaced Na^+ (Ahmad et al., 2016). Ca^{2+} has a stronger charge and replaces Na^+ at the exchange site in the form of leachable Na_2SO_4, a form of Na_2SO_4 that can be easily removed, which is consistent with previous findings (Abate et al., 2021). The Na^+ content in the soil with GLR fertiliser was significantly reduced after leaching compared with that of the CK. Among the treatments, the soil in Treatment Group T1 had the lowest remaining Na^+ content after leaching, which effectively reduced the Na^+ content in the soil and alleviated the salinization of the soil.

The K^+ leaching ability is important because it affects the efficiency of organic fertiliser use (Jalali et al., 2008). Yazdanpanah et al. (2013) found that the potassium content in the soil is affected by the chemical composition of the organic amendments used. During the six leaching cycles in treatment Group T1, the K^+ content of the leaching solution was significantly higher than that of the other treatments. The possible reason was that K^+ was greatly affected by water movement (Wang et al., 2017). This study showed that the treatments with different percentages of GLR organic fertiliser had an effect on the K^+ content in the soil, and the K^+ content in the soil of the treatment groups with GLR organic fertiliser was significantly higher than that of the CK before leaching, probably because the addition of GLR organic fertiliser increased the humic acid and organic matter of the soil, and the K^+ produced by the decomposition of organic matter was released into the soil, increasing the K^+ content in the soil. This is consistent with the study of Imbute et al. (2005) and others.

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Mg^{2+} and Ca^{2+} have similar exchange properties in soil and can also exchange with Na^{+} (David et al., 2002). The Mg^{2+} content in the soils with the addition of organic fertiliser increased substantially after drenching, indicating that drenching alone could not remove the Mg^{2+} in the soils, and after the addition of organic fertiliser, the Mg^{2+} in the soils was significantly reduced after drenching, indicating that the treatments with added GLR organic fertiliser effectively reduced the Mg^{2+} content in the soils, among which the Mg^{2+} content in the soils in Treatment Group T4 was the lowest after drenching and the most effective.

The Ca^{2+} content in the drench solution of the treatment groups with added GLR organic fertiliser was significantly higher than that of the CK (*Fig. 2d*), which indicated that the addition of GLR organic fertiliser promoted the effect of Ca^{2+} drenching, probably because the fertiliser increased Ca^{2+} concentration, promoted water infiltration, and thus increased salt drenching, which is consistent with the findings of Fouladidorhani et al. (2020). In addition, organic acids promoted the dissolution of calcium carbonate in soil, which may be one of the reasons (Zhou et al., 2021). The Ca^{2+} content of the soil in the treatment groups with GLR organic fertiliser was significantly lower than that of the CK after leaching, probably because Ca^{2+} and humus added to the soil with GLR organic fertiliser formed an organic-mineral complex soil complex in the form of a cationic "bridge", which was conducive to the formation of a soil agglomerate structure. Moreover, the Ca^{2+} content in the soil of the treatment groups with GLR increased with the addition of organic fertiliser before leaching, but after leaching, it was discharged from the soil in large quantities. Li et al. (2020) showed that K^{+} solubility is much higher than calcium solubility, so Ca^{2+} lympholysis is much lower than K^{+}, which is consistent with the results of the present study.

The above results show that the addition of GLR organic fertiliser not only effectively improved the ionic composition of the soil and the structure of the soil, but it also increased salt leaching from the soil, improved the cation composition and content ratio of the soil, effectively reduced the salt-based ion concentration in the saline soil, reduced the saline index of the soil, and improved the saline soil.

Effect of GLR organic fertiliser on saline soil anions under leaching conditions

Li et al. (2019) found that the main anions of saline alkali soil in the Yellow River Delta are mainly composed of Cl^{-}/SO_4^{2-}, which is similar to the saline alkali soil used in this study. The change in the Cl^{-}/SO_4^{2-} ratio can reflect the change in the soil anion composition. Moreover, Cl^{-} easily moves with water, while SO_4^{2-} cannot. Therefore, the ratio of Cl^{-}/SO_4^{2-} can reflect the leaching state of salt. As shown in *Fig. 6B*, the Cl^{-}/SO_4^{2-} ratio in treatment Group T1 was 2.46 before leaching and decreased to 0.04 after leaching. After leaching, the ratio of Cl^{-}/SO_4^{2-} in the soil decreased to 0.04, indicating that the addition of GLR organic fertilizer made the main base ion Cl^{-} in the saline-alkali soil more easily leached, and the saline-alkali soil could stably maintain desalination state. It also enabled the saline soil to maintain a stable desalination state. In this experiment, the main components of anions in the leaching solution were SO_4^{2-} and Cl^{-}. The amount of Cl^{-} leaching in the drench solution of the treatment with GLR organic fertiliser was significantly higher than that of the CK by 2-3 times, and the total amount of Cl^{-}leaching in the T5 treatment group was the highest, 3.04 times higher than that of the CK treatment. The reason may be that the main salt ions in the soil move quickly with water, and the addition of the GLR organic fertiliser improved the permeability of the soil, thus accelerating the leaching of Cl^{-} from the soil.

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As shown in *Fig. 2F*, in the first drenching cycle, the SO_4^{2-} leaching content of the treatment groups with GLR organic fertiliser was lower than that of the CK, but in the second drenching cycle, the SO_4^{2-} leaching content in treatment Group T2 peaked and was significantly higher than that of the CK in the subsequent drenching cycle, and the total SO_4^{2-} leaching in Treatment Group T2 was the highest among the six leaching treatments, while the total SO_4^{2-} leaching in the remaining treatment groups was lower than that of the CK. This is probably because SO_4^{2-} has a strong ability to be absorbed by soil colloids and is not easily excreted from the soil with leaching (Yang et al., 2021). The SO_4^{2-} concentrations in the soils of Treatment groups T1 and T2 were higher than those of the CK after leaching, but the mass concentrations were significantly lower than those before leaching, probably because a certain amount of SO_4^{2-} was added to the soil in the GLR and was not discharged from the soil in large quantities with leaching.

Comprehensive evaluation of the effect of GLR organic fertiliser on saline soil improvement

The results of PCA showed that pH, conductivity, sodium adsorption ratio, K^+, Na^+, Ca^{2+}, and Mg^{2+} could be used as evaluation indices for the effect of GLR organic fertiliser on saline soil improvement. The two principal components derived from the PCA are evaluated based on the eigenvalues of the initial factors. When the eigenvalues of the principal components are greater than 1, the principal components can be used as a basis for evaluating the effectiveness of soil improvement. The results of this study showed that the use of PCA to evaluate the effect of different proportions of GLR organic fertiliser on soil improvement could convert multiple evaluation indicators into one comprehensive principal component evaluation variable of the improvement effect without an excessive loss of information of the original indicators. The combined principal components of the improvement effect in this study could represent 90.89% of the information on the variability of the effect of different proportions of GLR organic fertilisers on soil improvement. In the first principal component, Treatment groups T1 and T2 scored higher, indicating that those treatments had the greatest effect on sodium ions, pH, EC, and sodium sorption ratio. In the second principal component, Treatment groups T1 and T2 also scored the highest, indicating that they had the greatest total effect on potassium ions and calcium and magnesium ions. From the overall score, the improvement effects of Treatment groups T1 and T2 on saline soil were at the same level, among which Treatment Group T1 had the best improvement effect on saline soil.

Conclusions

This study showed that the addition of GLR organic fertiliser could effectively improve saline soil, reduce soil pH and conductivity, promote the leaching of eight ions (Na^+, Mg^{2+}, K^+, Ca^{2+}, Cl^-, SO_4^{2-}, CO_3^{2-}, HCO_3^-) in the soil, inhibit an anti-salt effect, and reduce soil salinity. The best ratios of organic fertiliser and saline-alkali soil dry weight were 1:3 and 1:5, respectively, when the improvement effect had the highest comprehensive evaluation level and the best improvement effect on saline-alkali soil was achieved.

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