ANALYSIS OF DESALINATION EFFECT OF VARIOUS IMPROVEMENT MEASURES ON THE INTERLAYER OF HEAVILY SALINE-ALKALI SOIL

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Abstract. This paper takes the interlayer soil of heavy saline-alkali soil in Weigan River Irrigation Demonstration base in Aksu District, Xinjiang Province, China as the research object. Through field plot tests, the changes of soil water and salt under different years and winter irrigation quota of 4725 mm·ha^{-1} were studied. Analysis revealed that, after three rounds of irrigation, the control (CK) treatment exhibited soil moisture content 1.4%–16.2% and 2.3%–15.5% higher than that of other treatments at 60–80 cm and 0–100 cm, respectively. Among all treatments, G1 exhibited the highest desalination rate of 75.9%, followed by G6 and G3 at 51.5% and 39.4%, respectively, whereas G2 and G5 were relatively similar at 38.2% and 37.4%, respectively, and G4 showed the lowest desalination rate of 33.9%. Significant desalination effects were observed after two and three winter irrigations, particularly in the 0–20 cm soil layer where salt content decreased from 7.06–11.61 g kg^{-1} before irrigation in 2020 to 2.00–5.91 g kg^{-1} after irrigation in 2022. The desalination rate was between 76.8% and 382.5%, which improved the surface soil from the initial medium to moderate saline–alkali soil to light to moderate saline–alkali soil. The research findings that improvement measures can enhance soil water infiltration and improve soil desalination efficiency.
Keywords: *improvement measures, heavily saline–alkali soil, interlayer soil, desalination effect, water infiltration*

Introduction

Xinjiang, located in the hinterland of Eurasia, faces significant challenges due to its limited precipitation (annual average: 147 mm), high evaporation rates (annual average: 2125 mm) and prominent problems of soil salinisation and secondary salinisation in shallow groundwater areas. It has gained international recognition as the ‘world saline–alkali land museum’. The saline–alkali land area in Xinjiang spans 2181.4 × 10^4 ha, constituting 22.01% of the national saline–alkali soil area (9913 × 10^4 ha) (Mao et al., 2015). The salinised farmland encompasses an area of 233.1 × 10^4 ha in Xinjiang, accounting for 37.7% of the total cultivated land, among which, mild, moderate, and severely salinised farmland covers 76.5%, 20.5% and 3%, respectively, with southern Xinjiang accounting for 49.6% of the total. Soil salinisation has emerged as the primary factor restricting the sustainable development of irrigation agriculture in Xinjiang (Dilinur et al., 2020).

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In certain domestic irrigated areas, uniform flood irrigation with equal quota is used for leaching soil salts in saline–alkali soil. However, determining the appropriate flood irrigation quota is often arbitrary, leading to either excessive or insufficient salt leaching. In Xinjiang, regular flood irrigation is commonly used as a key method for soil desalination. Nevertheless, improper irrigation techniques and quotas during winter and spring result in a detrimental cycle of salt accumulation in the irrigated area, particularly in the 0–60 cm soil layer of cotton fields during the growth period, with the maximum salt accumulation occurring in the 40–60 cm soil layer (Dilinur et al., 2020). In addition, major changes have occurred in the existing tillage mode compared with the traditional mode. The soil profile exhibits a distinctive layered structure known as a "sandwich" formation, comprising the mulching film, ploughing layer and additional ploughing layer. This structure leads to the gradual formation of dense and stable interlayers in the vertical direction at a certain depth below the soil surface (Wei et al., 2021; Dong et al., 2021). These clay-based interlayers hinder effective leaching and improvement of saline soil due to their poor permeability, particularly when located at depths greater than 60 cm and with clay layer thickness exceeding 10 cm. The presence of interlayers not only diminishes water infiltration rates (Lemon, 1956) but also inhibits water evaporation (Miller, 1962), ultimately altering salt migration patterns (Willis, 1960). To address the reduced permeability and evaporation caused by interlayers, researchers have explored various methods, such as burying plastic film 40 cm below the surface of the soil or using *in situ* soil sintering to create interlayers with different materials (Guo et al., 2006; Wen et al., 2008; Leng et al., 2012). These measures have resulted in positive effects in mitigating soil salinity and optimising crop growing environments.

Regarding the law of water and salt transport in interlayer soil, numerous scholars have developed mathematical models that accurately represent the transport of water and salt in layered soil under various conditions (Pan et al., 2017; Shi et al., 2018; Li et al., 2018). Factors considered in these models include soil texture (Lemon, 1956), soil thickness and soil location (Xu et al., 2016; Ge et al., 2019). In terms of improvement measures for layered soil, various techniques, such as subsoiling (turning) (Dilinur et al., 2020), ditching and drainage and drilling and sand irrigation have been used to improve soil desalination rates (Xia et al., 2017; Zhang et al., 2017), yielding promising results.

Considering the practical issues resulting from the poor permeability of irrigation water, low efficiency of salinity leaching and expansion of the layered soil area due to large-scale high-standard farmland construction in southern Xinjiang, field tests were conducted in the present study using various improvement measures, including deep-turning, ditching, drilling, and sand irrigation. The effects of these measures on soil desalination and the law of water and salt migration in interlayer soil were analysed under winter irrigation conditions. Therefore, a simple and practical improvement measure that could be widely applied was explored, and the results of this study provide a reference for the comprehensive treatment, development, and utilisation of interlayer soil in land with heavy saline soil.

Materials and Methods

Test conditions

The experimental area is situated in the high-efficiency water-saving experimental demonstration base of Hailou Village, Hailou Town, Weigan River Irrigation Area, Shaya County, Aksu Prefecture, Xinjiang Province, China. In 2019, the irrigation area was

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newly built as a 500,000-mu high-efficiency water-saving and income-increasing pilot project in Shaya. The core experimental area is located on the west bank of Weigan River, approximately 10 km north of Shaya County, with geographical coordinates of 41°14'30" north latitude and 82°43'33" east longitude. The study area experiences a dry climate with limited precipitation (annual average: 47.3 mm) and an annual evaporation of 2000.7 mm. The annual average sunshine is 3031.2 h, and the annual average temperature is 10.7°C. The groundwater depth in the study area is 1.9–2.5 m. The soil texture is characterised as silty loam, with a bulk density of 1.51–1.69 $g \cdot cm^{-3}$. The soil's chemical properties include a total nitrogen content of 0.5 $g \cdot kg^{-1}$, total phosphorus content of 0.75 $g \cdot kg^{-1}$, total potassium content of 19.72 $g \cdot kg^{-1}$, and pH value of 8.75. The clay interlayer is located 60–80 cm below the surface, with a thickness of 15–20 cm. The initial salt content of the soil layer exceeds 10 $g \cdot kg^{-1}$, primarily composed of sulphate–chloride salts, indicating heavily salinised soil conditions (Qian et al., 2019). *Table 1* shows the soil conditions of the test site before the commencement of the experiment.

Table 1. *Soil chemical properties in the experimental area*

Soil depth (cm)	Cl^- ($g \cdot kg^{-1}$)	SO_4^{2-} ($g \cdot kg^{-1}$)	Ca^{2+} ($g \cdot kg^{-1}$)	K^+ ($g \cdot kg^{-1}$)	Mg^{2+} ($g \cdot kg^{-1}$)	Na^+ ($g \cdot kg^{-1}$)	CO_3^{2-} ($g \cdot kg^{-1}$)	HCO^{3-} ($g \cdot kg^{-1}$)	Salt content ($g \cdot kg^{-1}$)
0–10	5.91	2.40	1.07	0.14	0.97	3.46	0.00	0.13	14.09
10–20	3.30	3.24	0.99	0.09	0.80	3.15	0.00	0.12	11.68
20–30	3.03	2.97	0.51	0.05	0.54	3.53	0.00	0.15	10.79
30–40	2.50	4.43	0.59	0.08	1.01	2.11	0.00	0.15	10.86
40–50	3.89	10.30	1.93	0.12	1.16	3.65	0.00	0.13	21.18
50–60	3.63	11.64	2.66	0.08	1.82	4.16	0.00	0.08	24.07
60–70	4.71	15.12	2.95	0.11	2.48	4.47	0.00	0.13	29.97
70–80	4.67	10.36	2.54	0.08	1.96	4.35	0.00	0.09	24.06
80–90	4.51	8.08	1.98	0.04	1.42	3.68	0.00	0.07	19.77
90–100	4.53	5.77	1.08	0.04	1.10	3.53	0.00	0.08	16.12

The meteorological data came from the meteorological station installed in Hailou Town by the Water Resources Bureau of Shazhi County, as shown in *Figure 1*. It can be seen from *Figure 1(a)* that the average temperature in April rose to 15.0°C and 18.4°C, reaching the suitable temperature range for cotton seed emergence. In both years, the temperature reached the maximum value in July, with an average of 26.5°C and 26.7°C respectively, and then began to gradually decrease, with an annual average temperature of 12.7°C and 13.2°C, respectively. As can be seen from *Figure 1(b)*, the average daily humidity has been increasing since April and gradually decreasing after August, with the annual average humidity being 53.3% and 49.7%, respectively. As can be seen from *Figure 1(c)*, the cumulative evaporation in July is the largest, which is 190.3 mm and 180.7 mm, respectively, and the total annual evaporation is 1210.3 mm and 1246.2 mm, respectively. As can be seen from *Figure 1(d)*, the rainfall in May and June of 2021 is relatively large, with 244 mm, accounting for 65.9% of the annual rainfall. The rainfall in June, August and September 2022 is relatively high at 105.3 mm, accounting for 51.7% of the annual rainfall. The total rainfall in 2021 and 2022 will be 370.0 mm and 203.6 mm, respectively.

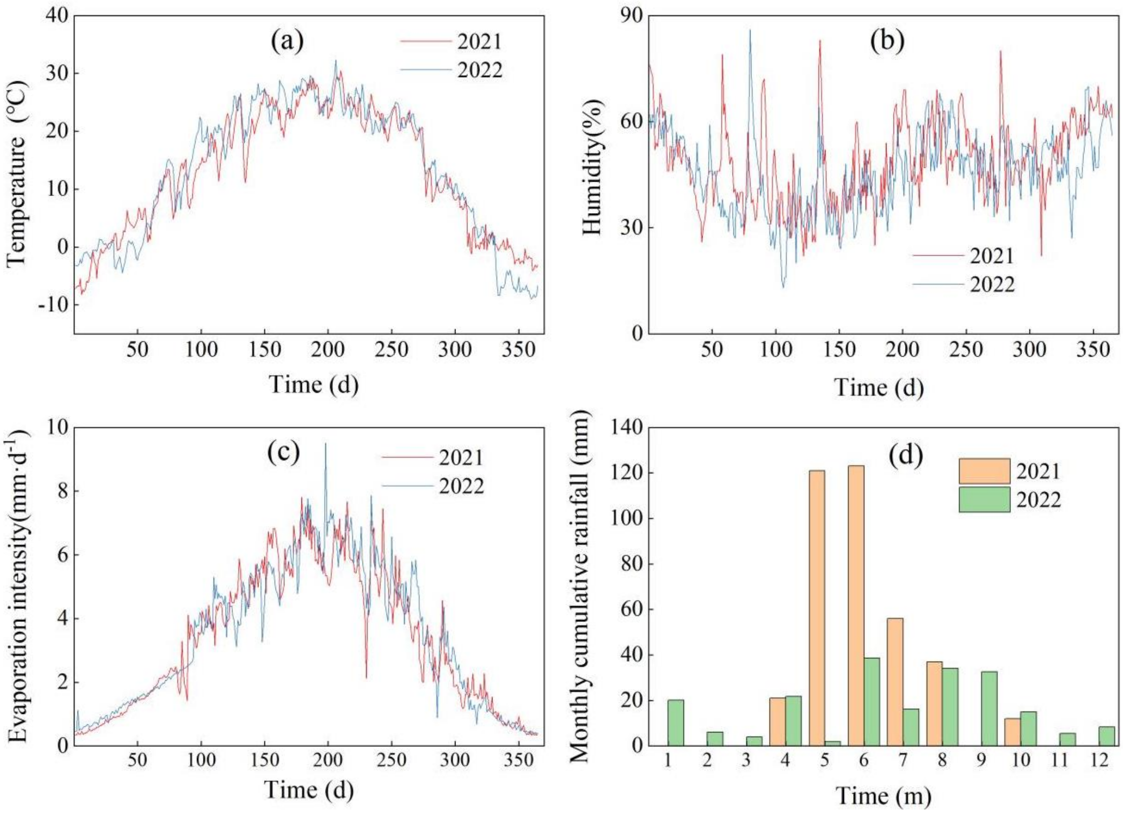

Figure 1. *Characteristics of main meteorological parameters in the study area from 2021 to 2022*

Experimental design

The winter irrigation experiment was conducted from December 2020 to January 2023, with a winter irrigation quota of 3150 $m^3 \cdot ha^{-1}$. In 2020, two treatments were implemented: deep-turning (G1) and drilling (G2). The soil layer in the test plot was evenly turned at a depth of 1 m using a Longong LG6060D crawler excavator. For drilling, a Yamaha 159Fv four-stroke ground drill produced by Yingshang Xingyuan Technology Development Co., Ltd. was used. The holes had a diameter of 6 cm, a density of 36 holes/100 m^2 and a depth of 1 m. Each treatment covered an area of 100 m^2 and was repeated twice. In 2021, four additional measures were introduced: hole drilling and sand filling (G3), ditch opening (G4), hole drilling after ditch opening (G5), hole drilling after ditch opening and sand filling after ditch opening (G6). The hole density and hole irrigation were the same as those used in the previous year. Commercial sand with a coarse texture (0.25 to <1 mm), free from salt content, was used for testing. Ditching involved excavating a salt drainage ditch alongside the test area, perpendicular to the agricultural ditch, using the same model of excavator mentioned earlier. The ditch had dimensions of 1 m in width, 2 m in depth and 50 m in length, with a spacing of 6–8 m. The salt drainage ditch was backfilled after two flood irrigation events. The G5 and G6 treatments are based on G4 treatment, and other parameters are the same as G3 treatment. The control (CK) treatment represented conventional heavy saline–alkali land, and each treatment plot covered an area of 100 m^2 (*Figure 2*).

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The research area was treated with deep turning — Ditching was performed in the research area — The research area was drilled — Layered soil profile structure

Figure 2. *Schematic diagram of test treatment and soil interlayer profile in the research area*

Test process

On 12th November 2020, a background investigation was conducted on the core demonstration area for efficient water conservation in Shaya, covering 20,000 ha. After sampling and analysis, a representative cotton field with heavy saline interlayer soil was selected as the test area, encompassing approximately 0.8 ha. In the past three years, the cotton yield in this test area was nearly non-existent. Soil sampling was performed on 1st December 2020, before winter irrigation, which was conducted on 4th December 2020. The irrigation volume during winter was 3150 $m^3 \cdot ha^{-1}$. Due to water immersion, interlayer soil and freezing, the water seepage above 40 cm from the surface was relatively slow. As a result, soil sampling following irrigation was conducted on 4th January 2021. On 13th May 2021, cotton re-seeding was not performed in the adjacent saline–alkali land due to extreme weather conditions, including hail. On 11th July 2021, ditching and drilling operations were conducted, followed by ditching, and drilling again. Soil sampling before winter irrigation was conducted on 5th December 2021, and winter irrigation was performed on December 10, 2021, with an irrigation amount of 3150 $m^3 \cdot ha^{-1}$. Subsequently, soil sampling after winter irrigation was conducted on 10th January 2022. Soil sampling before irrigation was conducted on 28th November 2022, and winter irrigation was conducted on 2nd December 2022, with an irrigation amount of

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3150 $m^3 \cdot ha^{-1}$. Finally, soil sampling after winter irrigation was conducted on 2nd January 2023.

Measuring items and methods

Soil moisture content: Automatic soil moisture monitoring systems (A760 telemetry from ADCON and STEVENSWATER, USA) were used for data collection and transmission. The sensors were installed at ten locations at depths of 0–100 cm, with measurements taken at every 10 cm. Soil moisture content was determined using the drying method for the following treatments: G3, G4, G5, G6 and CK.

Soil conductivity: Soil salinity monitoring in the G1 and G2 treatments was conducted using the same soil moisture monitoring system mentioned above. For the G3, G4, G5, G6 and CK treatments, Dutch drilling was performed, The sampling depth is 100 cm, with 5 layers of 0-20 cm, 20-40 cm, 40-60 cm, 60-80 cm and 80-100 cm, respectively. The soil extract conductivity was determined using a DDSJ-308A conductivity metre (Shanghai Sheng Magnetic Instrument Co., Ltd.).

Soil ions: Chemical analysis was used to determine the content of eight soil ions. Ultraviolet spectrophotometry V-5000 (Shanghai Metash Instruments Co., Ltd) was employed to determine the content of K^+, Na^+, Ca^{2+} and Mg^{2+}. The neutralisation titration method was used to determine the content of CO_3^{2-} and HCO^{3-}, and the silver nitrate titration method was used to determine the Cl^- content. The content of SO_4^{2-} was determined using the EDTA indirect complexometric titration method.

Soil desalting rate: The soil desalting rate refers to the percentage decrease in soil salt content from the initial value in the test plot. It is used to assess the desalting effect of the soil layer under the combined action of leaching and dark pipe. The soil desalting rate has been used in previous studies (Dou et al., 2020; Liu et al., 2021), with the following formula employed to calculate the parameter:

$$N = \frac{S_1 - S_2}{S_1} \% \qquad \text{(Eq.1)}$$

where N represents the soil desalting rate (%), S1 is soil salt content before winter irrigation ($g \cdot kg^{-1}$) and S2 is soil salt content after winter irrigation ($g \cdot kg^{-1}$). The relative desalting rate of a given measure compared with the CK treatment was calculated using the following formula:

$$D_R = (D_G - D_{CK}) / D_{CK} \qquad \text{(Eq.2)}$$

where DR denotes the relative desalting rate, DCK is the desalting rate of the CK treatment (%) and DG is the desalting rate of the given measure (%). DR > 0 indicates relative desalting, whereas DR < 0 indicates relative salting. A larger DR value indicates a better desalting effect.

Data processing

WPS 365 was used to sort out and analyze the test data, and Origin 2021 was applied to make the graphics.

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Results

Effect of improvement measures on soil moisture content

The transport law of soil water and salt under different non-improvement measures was compared using conventional heavy saline–alkali land as CK treatment. *Fig. 3* illustrates the change in soil moisture content before and after winter irrigation in 2020 under different improvement measures. As shown in *Fig. 3(a)*, among the various improvement measures, G1 exhibited an increase in soil moisture content with increasing depth of the 1 m soil layer in the test area. The 0–20 m soil layer had the lowest moisture content (16.4%), whereas the 80–100 cm soil layer had the highest moisture content (22.6%). Both G2 and CK treatments showed a similar pattern, with moisture content initially increasing and then decreasing with soil layer depth. The maximum water content was observed in the 60–80 cm soil layer, measuring 25.1% and 26.5% for G2 and CK, respectively, whereas water content significantly decreased in the 80–100 cm soil layer to 22.0% and 20.1%, respectively. *Fig. 3(a)* also presents the soil moisture content of each treatment after winter irrigation in 2020.The differences in soil moisture content were observed at different depths. In the 0–80 cm depth range, G1 had the lowest moisture content, followed G2, whereas CK had the highest moisture content. At the 80–100 cm depth, all three treatments exhibited a decreasing soil moisture trend, but CK showed the largest decrease, followed by G2 and G1. The average moisture content before and after winter irrigation for G1, G2 and CK was 20.0%, 20.8% and 21.9%, respectively, whereas after irrigation, it increased to 21.6%, 25.1% and 27.2%, respectively. Overall, the soil moisture content ranking was CK > G2 > G1.

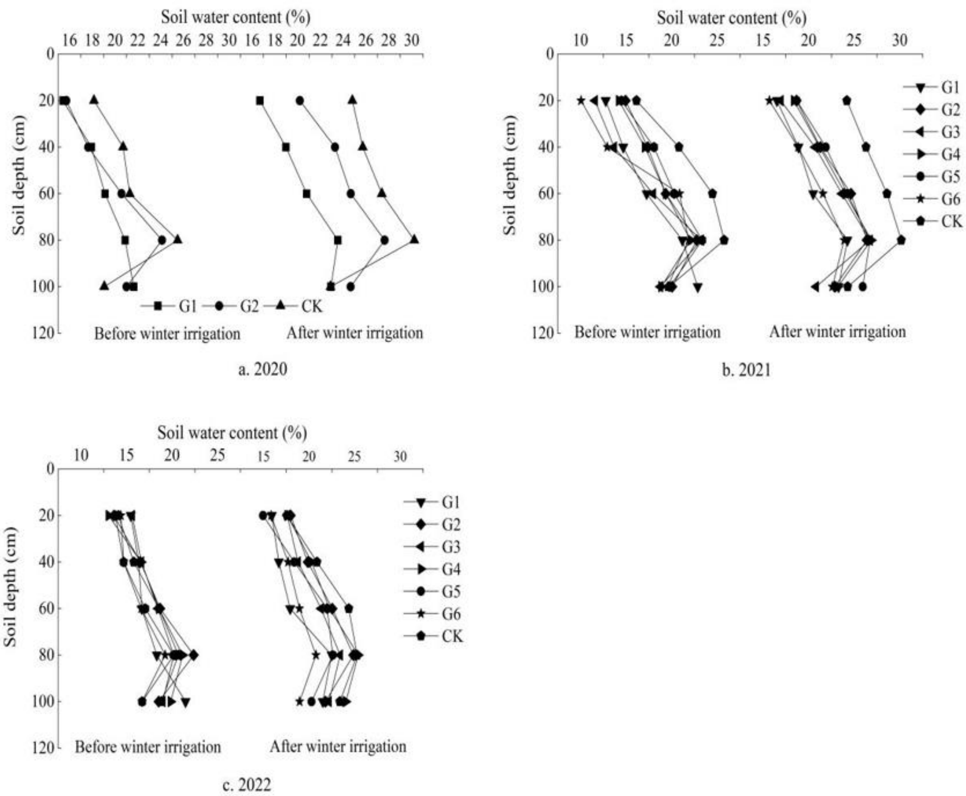

Figure 3. *Changes in soil moisture content before and after winter irrigation in different years under different treatment measures*

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Fig. 3(b) presents the changes in soil moisture content before and after winter irrigation under different treatment measures in 2021. In addition to the existing G1, G2 and CK treatments from 2020, G3, G4, G5 and G6 treatments were introduced in 2021. G1, G2 and CK showed consistent changes in soil moisture content before and after irrigation in both 2020 and 2021. Similarly, G3, G4, G5 and G6 showed the same pattern as G2 and CK treatments in 2020 and 2021. CK exhibited the highest soil moisture content before and after irrigation, with average water content in 2021 at 19.5%–23.9% and 23.3%-28.4%, respectively. In terms of different soil depths, the surface layer (0–20 cm) of each treatment showed the lowest soil moisture content, which was 12.5%–18.6% and 18.2%–26.7% before and after irrigation, respectively. Moisture content increased with increasing soil depth, reaching its maximum at 60–80 cm, with values of 23.7%–28.2% and 26.4%–32.7% before and after irrigation, respectively. At the 80–100 cm depth, water content noticeably decreased, averaging 21.3%–25.4% and 23.3%–28.4% before and after irrigation, respectively.

Fig. 3(c) presents the changes in soil water content before and after winter irrigation with different measures in 2022. The water content at different depths before and after irrigation in each treatment were largely consistent with those observed in 2021. Specifically, the water content of each treatment before and after irrigation was 15.5%-24.9% and 17.5%–27.9%, respectively. The average moisture content in the 100 cm soil layer was 18.8%–20.5% and 20.9%–24.4% before and after irrigation, respectively. At different soil depths, the surface layer (0–20 cm) of each treatment had the lowest moisture content before and after irrigation, with values of 15.5%–18.1% and 17.5%–20.5%, respectively. Moisture content increased with increasing soil depth, reaching its maximum level at 60–80 cm, with values of 20.8%–24.9% and 23.3%–27.9% before and after irrigation, respectively. At the 80–100 cm depth, water content decreased, averaging 19.2%–25.4% and 23.3%–28.4% before and after irrigation, respectively. After irrigation, the soil moisture content at 0–100 cm ranked as follows: CK (24.79%) > G4 (24.41%) > G2 (23.91%) > G3 (23.15%) > G5 (22.14%) > G1 (21.4%) > G6 (20.94%).

As shown in *Fig. 3(a)–(c)*, consistent patterns in moisture content changes before and after irrigation were observed across different years. Before irrigation, all treatments, except G1, showed an increasing trend with soil depth in the 0–80 cm soil layer, reaching maximum values in the 60—80 cm interlayer. Subsequently, moisture content decreased at the 80–100 cm depth. After irrigation, the water content of each treatment showed a consistent pattern across different years, increasing with depth above the interlayer soil and decreasing below it. Notably, the water content fluctuation at the 0–60 cm depth was significantly greater than that at the 60–80 cm and 80–100 cm depths, indicating the considerable influence of the interlayer at the 60–80 cm depth on soil moisture content changes. Additionally, the presence of the interlayer soil had a substantial impact on the moisture content of the upper layer at the 0–60 cm depth, which decreased with increasing depth. Furthermore, due to the physical characteristics of interlayer soil, the water infiltration rate through the interlayer was slower, resulting in relatively smaller changes in moisture content below the interlayer.

Winter irrigation significantly improved the soil moisture content after one winter offseason compared with that before irrigation. For example, the average moisture content after irrigation under the G1, G2 and CK treatments measures in 2020 was 24.6%, representing a 3.7% increase compared with before winter irrigation. Similarly, the average moisture content after irrigation in 2021 and 2022 was 4.2% and 3.1% higher than that before irrigation, respectively. Among the different treatments, CK consistently

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exhibited higher soil moisture content before and after three rounds of winter irrigation, whereas G1 showed lower levels, indicating that the physical characteristics of the original soil had been altered by breaking the interlayer soil, influencing the magnitude and distribution of overall soil moisture content.

Effect of improvement measures on soil salinity

The soil salinity changes before and after irrigation under different treatment measures from 2020 to 2022 are shown in *Fig. 4*. *Fig 4(a)* shows that, in 2020, the soil salt variation with depth in each treatment before irrigation was similar to the variation in water content. Before irrigation, G1 exhibited a gradual increase in soil salinity with depth, with salt content of 9.64 $g{\cdot}kg^{-1}$ and 12.65 $g{\cdot}kg^{-1}$ in the 0–20 cm and 80–100 cm layers, respectively. Before irrigation, G2 and CK showed an initial increase in soil salinity followed by a decrease with increasing depth; salt content was lowest in the 0–20 cm layer (11.51 $g{\cdot}kg^{-1}$ and 11.61 $g{\cdot}kg^{-1}$, respectively) and highest in the 60–80 cm layer (15.43 $g{\cdot}kg^{-1}$ and 17.92 $g{\cdot}kg^{-1}$, respectively), whereas this content was about 13.11 $g{\cdot}kg^{-1}$ in the 80–100 cm layer. Overall, soil salinity at all depths followed the order CK > G2 > G1. The mean values of soil salinity in the entire 0–100 cm soil layer under G1, G2 and CK treatments were 11.25 $g{\cdot}kg^{-1}$, 13.39 $g{\cdot}kg^{-1}$ and 14.78 $g{\cdot}kg^{-1}$, respectively.

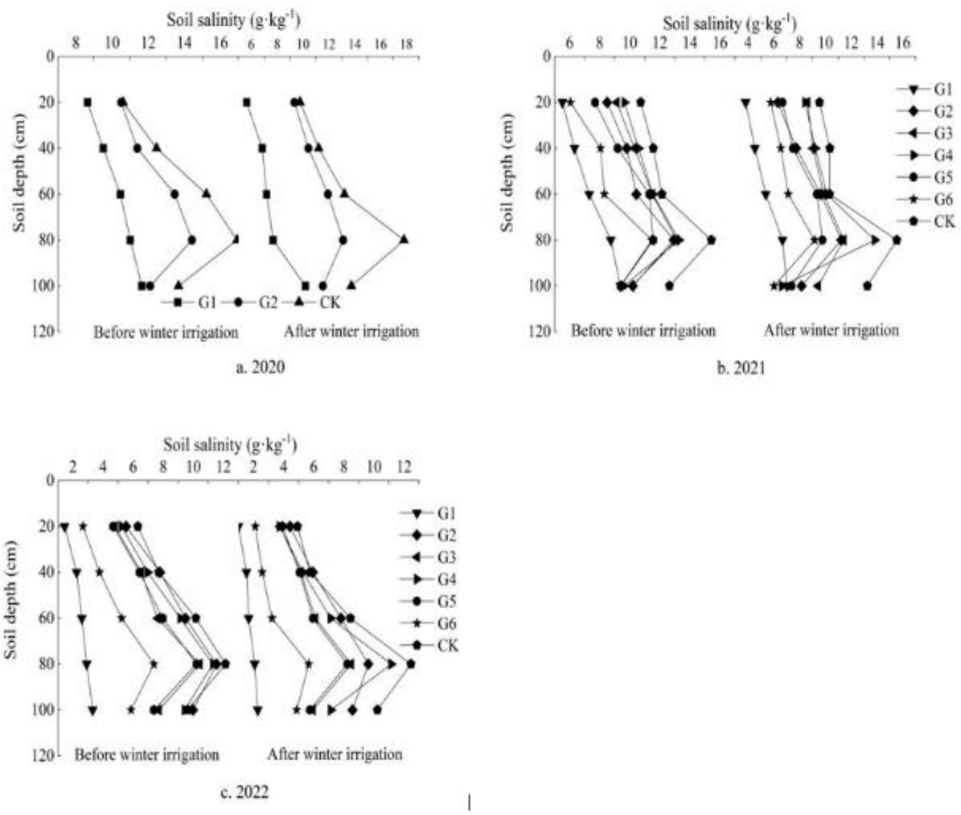

Figure 4. *Changes in soil salt content before and after winter irrigation in different years under different treatment measures*

After irrigation in 2020, the variation pattern of soil salt under each treatment remained consistent with that before irrigation, with a ranking of CK > G2 > G1 and average soil salt content of 14.15 $g{\cdot}kg^{-1}$, 12.27 $g{\cdot}kg^{-1}$ and 8.5 $g{\cdot}kg^{-1}$, respectively, as shown in

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Fig. 4(a). Compared with before irrigation, the average salt content of G1, G2 and CK treatments after irrigation decreased by 24.5%, 8.4% and 4.2%, respectively. For G1, G2 and CK, salt content in the 0–20 cm surface soil was 6.63 g·kg^{-1}, 10.34 g·kg^{-1} and 10.77 g·kg^{-1}, representing reductions of 31.3%, 10.2% and 7.3%, respectively, compared with the content observed before irrigation.

Fig. 4(b) illustrates the soil salt content changes under different treatments in 2021. The changes before and after irrigation were consistent across treatments. Only G1 exhibited an increase with increasing depth, whereas the other treatments generally showed an increasing trend followed by a decreasing trend. The highest soil salt content was observed at 60–80 cm. The average salt content in the entire 0–100 cm soil layer under G1, G2, G3, G4, G5, G6 and CK treatments decreased by 1.98 g·kg^{-1}, 1.76 g·kg^{-1}, 1.17 g·kg^{-1}, 1.29 g·kg^{-1}, 1.70 g·kg^{-1}, 1.74 g·kg^{-1} and 0.7 g·kg^{-1}, respectively.

Fig. 4(c) shows the soil salt content changes before and after winter irrigation in 2022. The salt content variations at different soil depths were consistent across all treatments. Desalination occurred in the 0–100 cm soil layer for all treatments, and the average salt content in this soil layer decreased by 0.79 g·kg^{-1}, 1.59 g·kg^{-1}, 1.53 g·kg^{-1}, 1.52 g·kg^{-1}, 1.56 g·kg^{-1}, 1.29 g·kg^{-1} and 0.83 g·kg^{-1} for G1, G2, G3, G4, G5, G6 and CK, respectively. These results indicate that, compared with conventional treatment, the improvement measures contribute to reducing soil salt content after winter irrigation.

Fig. 4 shows a significant decrease in soil content after three winter irrigations in 2020, 2021 and 2022 under G1, G2 and CK treatments. The average soil salt content under G1 and G2 decreased from 11.25 g·kg^{-1} and 13.39 g·kg^{-1} before winter irrigation in 2020 to 2.71 g·kg^{-1} and 8.27 g·kg^{-1} after winter irrigation in 2022, representing decreases of 8.54 g·kg^{-1} and 5.12 g·kg^{-1}, respectively, and the most substantial reduction occurred in the 0–20 cm soil layer (7.64 g·kg^{-1} and 6.09 g·kg^{-1}, respectively). For CK, the average salt content decreased from 14.78 g·kg^{-1} to 9.35 g·kg^{-1} after three winter irrigations, indicating a 36.7% reduction. After two winter irrigations under G3, G4, G5 and G6 treatments, the average soil salt content in 2022 decreased by 4.08 g·kg^{-1}, 4.04 g·kg^{-1}, 4.05 g·kg^{-1} and 4.97 g·kg^{-1} compared with that before irrigation in 2021. Additionally, the soil salt content in the 0–40 cm soil layer exhibited significant decreases, reaching 5.45 g·kg^{-1}, 5.51 g·kg^{-1}, 5.49 g·kg^{-1} and 3.34 g·kg^{-1} in G3, G4, G5 and G6 after irrigation, respectively. The results also showed that two winter irrigations led to a reduction in surface salt content from moderate-to-severe salinisation to mild salinisation. However, CK exhibited moderate-to-severe salinisation levels after three winter irrigations. These findings highlight the effective reduction of soil salt content and significant decrease in surface salt content achieved through different interlayer treatments.

Effect of improvement measures on soil desalination effects

Table 2 presents the effects of different measures on soil desalination. In 2020, G1 exhibited a significantly higher desalting rate (24.93%) compared with G2 (8.34%) and CK (4.67%). In 2021, G1 showed the highest desalting rate (23.4%) among the seven treatments, followed by G6 (18.0%), G5 (15.7%), G2 (15.5%), G4 (10.9%) G3 (9.9%) and CK (5.2%). After winter irrigation in 2022, G1 had the highest desalting rate (22.52%), CK had the lowest desalting rate (9.8%), and the other treatments showed desalting rates of 16.5%–21.5%. Following three winter irrigation treatments, a noticeable soil desalting effect was observed. The average soil salt content under G1 and G2 treatments decreased from 11.25 g·kg^{-1} and 13.39 g·kg^{-1} before winter irrigation in 2020 to 2.71 g·kg^{-1} and 8.27 g·kg^{-1} after winter irrigation in 2022, resulting in desalting

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rates of 75.9% and 38.2%, respectively. For CK, the salt content decreased from 14.78 g·kg^{-1} before the first winter irrigation to 9.35 g·kg^{-1} after the third winter irrigation, resulting in a desalting rate of 36.7%. The desalting rates under G3, G4, G5 and G6 treatments were 41.8%, 33.9%, 37.4% and 51.4%, respectively, between 2021 before winter irrigation and 2022 after winter irrigation. Notably, despite having undergone only two rounds of winter irrigation, the desalting rates of G3 and G6 surpassed that of G2 after three winter irrigations. G5 and G2 exhibited slightly higher desalting rates compared with CK, indicating that overall soil stirring, hole drilling and sand irrigation, (G3) and ditch drilling and sand irrigation (G6) were the most effective measures for soil desalination. These findings highlight the significant improvement in desalting heavy saline–alkali soil through deep-turning, hole drilling and sand irrigation.

Table 2. *Desalination rates of different soil layers under different treatment measures*

Treatments	Year	Soil depth(cm)					Average desalting rate (%)
		0–20	20–40	40–60	60–80	80–100	
G1	2020	31.28	25.39	28.62	27.73	11.62	24.93
	2021	26.38	24.60	23.31	21.25	22.74	23.65
	2022	18.28	22.03	25.43	21.61	23.90	22.25
	Average value	25.31	24.00	25.79	23.53	19.42	23.61
G2	2020	10.20	7.93	10.66	8.57	4.36	8.34
	2021	5.31	11.11	13.13	12.06	6.37	9.60
	2022	17.09	21.08	16.02	15.30	12.80	16.46
	Average value	10.87	13.37	13.27	11.98	7.84	11.47
G3	2021	22.78	19.33	6.99	12.13	18.27	15.90
	2022	17.82	18.49	17.61	17.04	20.37	18.27
	Average value	17.16	17.06	12.62	13.71	15.49	17.08
G4	2021	20.78	20.53	11.40	−3.85	9.25	11.62
	2022	24.10	21.09	19.84	1.22	21.87	17.62
	Average value	20.68	19.56	14.62	3.69	15.54	14.62
G5	2021	11.84	16.86	15.93	14.23	19.42	15.66
	2022	13.35	18.56	22.65	17.72	19.56	18.37
	Average value	15.29	18.33	17.74	11.88	18.17	17.01
G6	2021	4.19	16.74	12.75	18.54	32.40	16.93
	2022	15.04	25.07	32.20	20.53	14.48	21.47
	Average value	11.51	20.05	20.89	16.99	21.69	19.20
CK	2020	7.25	9.21	12.41	−5.03	−0.47	4.67
	2021	10.09	9.69	13.85	−0.68	−4.40	5.71
	2022	19.09	22.56	15.57	−2.37	−5.84	9.80
	Average value	12.14	13.82	13.94	−2.70	−3.57	6.73

The desalting rates at different soil depths under G1, G2 and CK treatments in 2021 were consistent with those in 2020 and 2022. Therefore, the desalting rates of different soil depths treated with various measures in 2021 were analysed. Desalting rates varied slightly across different depths under G1 treatment, with the highest desalting rate observed in the surface layer (0–20 cm). The desalting rates at the 20–80 cm depth were 21.3%–24.6%, whereas the desalting rate at the 80–100 cm depth was 22.7%. The comprehensive and uniform turning of the entire 0–100 cm soil layer under G1 treatment altered the physical properties of deep soil, particularly the interlayer, resulting in distinct

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salt movement characteristics compared with other measures. Under the CK treatment where no improvement measures were employed, significant soil salt fluctuations were observed. The desalting state was 9.7%–13.9% at depths of 0–60 cm, whereas the salt accumulation state prevailed at depths of 60–100 cm, with salt accumulation rates of −0.7% – −4.4%. This can be attributed to the poor permeability and infiltration capacity of the soil clay in the 60–80 cm interlayer, which slows water infiltration and salt migration, ultimately leading to salt accumulation within a specific period. A similar pattern was observed under the G4 treatment where the highest desalting rate (20.8%) was achieved in the surface layer, followed by salt accumulation (−3.9%) in the 60–80 cm depth and desalting (9.3%) in the 80–100 cm depth. This may be due to the wide spacing between trenches (6–8 m) and the sampling point at the centre of the test area. Consequently, after irrigation, water near to the trench infiltrated more rapidly, whereas water farther away from the trench exhibited slower infiltration. As a result, the movement of water and salt in the interlayer position resembled that under the CK treatment. The desalting rates after three winter irrigations ranked as follows: G1 > G6 > G3 > G2 > G5 > CK > G4.

Effects of improvement measures on the soil desalination effect in the interlayer

The desalting rate and relative desalting rate of interlayer soil under different improvement measures, after 2–3 rounds of winter irrigation, are shown in *Fig. 5*. It was evident that the desalting rate at the 60–80 cm interlayer depth was significantly higher under the G1 treatment (74.4%) than under the other treatments, with the next highest desalting rates observed under G6 (46.6%), G3 (31.9%), G2 (31.2%), G5 (26.5%), CK (24.9%) and G4 (14.9%) treatments. In terms of the relative desalting rate, only G4 was negative (−0.4), whereas the other treatments showed positive rates (0.1–2.0).

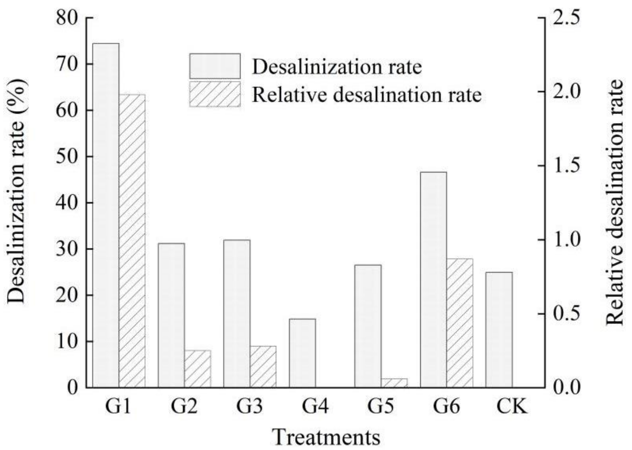

Figure 5. *Comparison of the desalination effects of different treatment measures on interlayer soil*

Considering the previous analysis of average water and salt contents in the soil, it was apparent that the physical properties of interlayer soil impede water infiltration and salt leaching. However, various improvement measures can improve the water and salt conditions of the interlayer and correspondingly promote water infiltration and salt leaching throughout the entire soil layer. Notably, the desalting rates under G1, G6 and G3 treatments at the interlayer position surpassed those observed under other treatments,

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correspondingly leading to an improved average desalting rate for the entire 0–100 cm soil layer. This highlights that, in the case of heavy saline–alkali soil containing interlayers, soil desalting primarily revolves around interlayer soil desalination. These results reveal that G1, G6 and G3 treatment measures effectively enhance interlayer soil desalination and yield positive outcomes for interlayer improvement in heavy saline-alkali soil.

Relationship between soil moisture content and salt increments

The relationship between water and salt changes following winter irrigation was analysed. As shown in *Fig. 6*, a significant correlation between soil salt increment and moisture content increment at the 60 – 80 cm interlayer depth was observed under each treatment after irrigation (R^2 = 0.933, P < 0.05). This relationship indicates that as moisture content increment increases, the salt increment decreases. The observed pattern of soil salt increment is consistent with the aforementioned desalting rate findings: treatments with higher desalting rates exhibit greater salt increments at the interlayer with smaller corresponding water content increments, whereas treatments with lower interlayer salt increments show larger water content increments. For example, in 2021, the salt increment under the G1 treatment was 2.07 g·kg^{-1}, accompanied by a 3.1% water content increment. Under the CK treatment, the salt increment was −0.11 g·kg^{-1} and the water content increment was 4.4%. This can be attributed to the blocking effect of clay interlayers in layered soil on water and salt migration (Zhao et al., 2015), resulting in slow penetration of water in the interlayer soil. As water accumulates, salt also accumulates, establishing an inverse relationship between salt increment and water content increment. Consequently, these findings provide further evidence of the impediment of water and salt movement by interlayer soil.

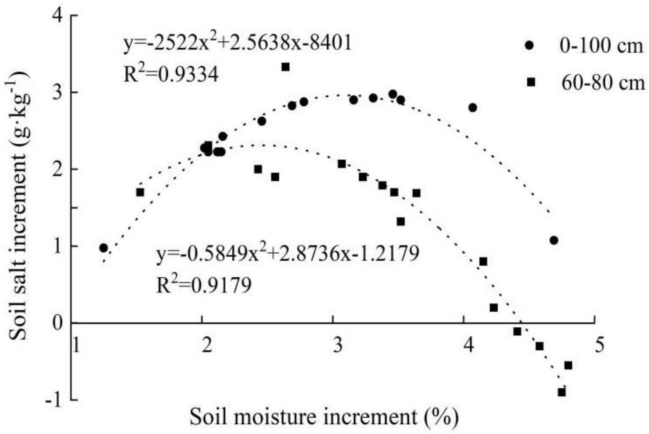

Figure 6. *Relationship between changes in soil salinity and in soil moisture content*

Discussion

Improvement measures enhance interlayer soil water infiltration after irrigation

Winter and spring irrigation are commonly used for salt leaching in saline–alkali land in Xinjiang. However, the effectiveness of conventional saline irrigation in winter varies owing to the influence of meteorological and geographical factors in different regions. For example, the winter irrigation quota in the Mosuowan irrigation district of Manas

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River in northern Xinjiang is 2800 $m^3 \cdot ha^{-1}$ (Feng et al., 2022), and the suitable winter irrigation quota in the Kaikong River basin in southern Xinjiang is 3600 $m^3 \cdot ha^{-1}$ (Zhang et al., 2016). The present study used a winter irrigation quota of 3150 $m^3 \cdot ha^{-1}$ in the Weigan River irrigation district, and the desalting rate of the CK treatment after three winter irrigation cycles from 2020 to 2022 was found to be 36.7%. The limited desalting effect in the CK treatment is primarily attributed to the inhibitory effect of water and salt in the interlayer soil.

Various research studies have investigated the physical and chemical properties of interlayer soil and their impact on water infiltration characteristics, considering factors such as location and depth (Wang et al., 2019; Wei et al., 2021; Dong et al., 2021). These investigations showed that interlayer soil can impede water migration and reduce the rate of water infiltration. The infiltration rate has been observed to initially increase and then decrease with increasing interlayer depth (Wang et al., 2019). Dong et al. (2021) found that slower water infiltration rate and longer infiltration time in ‘sandwich’ structures led to a 22.5%–29.3% increase in soil moisture content in the cultivated layer. Wang et al. (2019) analysed the infiltration characteristics and moisture content distribution after installing the interlayer at different positions, confirming a similar infiltration rate pattern. In the present study, the interlayer depth of around 60 cm corresponds to the infiltration characteristics of soil water in typical farmland.

After the implementation of improvement measures, notable differences were observed in the variation of soil water content in the deep-turning treatment before irrigation compared with the other treatment measures. The deep-turning treatment resulted in a uniform soil state before irrigation, leading to increased water infiltration with depth under the influence of gravity. However, changes occurred in the interlayer after irrigation where each treatment showed an increasing trend followed by a decreasing trend with an increase in depth. The slow infiltration properties of interlayer soil resulted in differences in average water content between the CK treatment and the improvement measures. The CK treatment consistently exhibited higher average water content compared with the other treatments before and after winter irrigation in 2020, 2021 and 2022. This can be attributed to the interlayer soil not being replaced by the deep-turning measures, but rather being evenly turned. After irrigation, the interlayer soil gradually moved downwards owing to the physical structure of the soil and clay properties of the interlayer, promoting water infiltration and transfer. Consistent with previous studies, the change in soil moisture content at the interlayer exhibited the highest moisture content. In 2020, after irrigation, the CK treatment exhibited water content 21.4% and 8.3% higher than that of the G1 and G2 treatments, respectively. Similarly, in 2021 and 2022, the CK treatment exhibited 10.1%–19.2% and 1.4%–16.2% higher moisture content, respectively, compared with the other measures. These results indicate that the improvement measures can effectively enhance water infiltration in the interlayer soil.

Improvement measures enhance interlayer soil desalination

This study tested various improvement measures, including deep digging, drilling and sand irrigation, similar to the research methods of Zhang et al. (2017) on drilling and sand irrigation, Gong et al. (2022) on sand-ridge deep tillage combined with ditching and drainage, Yin et al. (2021) on sand covering and Zhang et al. (2019) on sand mixing. Among these measures, drilling and sand irrigation not only promoted water infiltration but also improved the desalting rate of soil. By breaking the interlayer through drilling, the ditch drilling and sand irrigation (G6) method, for example, fills the entire hole with salt-free coarse sand. The presence of numerous large pores between the sand and the

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original soil, as well as between the sand grains, along with the uniform turning layer formed at a depth of 2 m after ditching, enables the permeation of soil water and salt to the deep layers through these pores. This process results in effective desalination, which is evident at all depths. The average desalting rate over two years was 19.2%, with the highest desalting rate (21.7%) observed at a depth of 80–100 cm. The G3 treatment exhibited the second highest desalting rate, after the G6 treatment. The average desalting rate over two winter irrigations was 17.1%. The desalting rate was highest (17.2%) at the 0–20 cm soil surface depth, after which the rate decreased and subsequently increased with depth, with desalting rates of 12.6%–17.1% observed. At the 20–40 cm depth, the desalting rate peaked at 18.3%, with an average desalting rate of 17.0%. The G1 treatment outperformed all other treatments in terms of desalination at all depths, with the highest desalting rate (25.8%) observed at 40–60 cm, followed by the 0–20 cm surface layer (26.4%), and an average desalting rate of 23.6%. In each treatment, the desalting rate at the interlayer position was relatively low, ranging from 3.7% to 23.5%. In contrast, the CK treatment exhibited salt accumulation after three winter irrigations, with an average salt accumulation of 2.7% over three years. These results indicate that the inclusion of interlayer treatments can significantly improve the desalination effect.

Notably, the improvement measures showed more pronounced effects after multiple winter irrigation cycles. For example, in the surface layer at 0–20 cm, the salt content decreased from 9.64 $g \cdot kg^{-1}$ before winter irrigation in 2020 to 2.0 $g \cdot kg^{-1}$ after winter irrigation in 2022, indicating an improvement from heavily saline soil to lightly saline soil. Similarly, the G2 treatment exhibited a decrease from 11.51 $g \cdot kg^{-1}$ before 2020 winter irrigation to 5.4 $g \cdot kg^{-1}$ after 2022 winter irrigation, achieving a desalting rate of 53.1%. The G6 and G3 treatments, which underwent only two winter irrigation cycles, exhibited desalination rates of 55.8% and 53.1% in the surface layer at 0–20 cm, respectively. Overall, these findings highlight the significant contribution of interlayer improvement measures in promoting soil desalination.

To summarise, although pipe-drainage (Dou et al., 2020; Wang et al., 2022), deep tillage (Ma et al., 2020; Cao et al., 2022), amendment application (Yao et al., 2020; Wang et al., 2020) and ditching drainage (Gong et al., 2022) are effective in improving saline–alkali soil, they are accompanied by high engineering costs. Owing to water resource limitations and economic considerations, low-cost, large-scale approaches are favoured in southern Xinjiang. Building upon previous research, this study explored the effectiveness of drilling and sand irrigation measures. The results revealed that deep-turning and ditching measures, after two winter irrigation cycles, effectively washed away salt and prevented its return to the soil surface. This study aimed to determine whether drilling and sand irrigation could provide a practical alternative to large-scale deep-turning and ditching in combating salt accumulation. The results indicate that drilling sand irrigation can serve as a simple and practical method for enhancing salt washing and inhibiting salt accumulation in saline–alkali soil. However, the complete desalting effect on heavily saline–alkali soil was not fully demonstrated, warranting future systematic studies on the influence of sand density, hole spacing, soil water and salt movement, and water and salt migration characteristics in interlayer soil.

Conclusions

This study focused on the heavy saline–alkali interlayer soil discovered in the Weigan River irrigation area after large-scale efficient water-saving construction. Field

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experiments were conducted to investigate the desalination effects of different improvement measures on this soil.

Regarding soil moisture content, all treatments, except for deep-turning, exhibited an initial increase followed by a decrease with increasing soil depth. After irrigation in 2020, the average water content was 3.9%–4.8% higher compared with that before irrigation. In 2021, after irrigation, the average water content was 23.0%–26.0%. In 2022, the average water content after irrigation was 20.9%–24.2%, which was 2.3%–13.6% lower compared with the CK treatment. The soil moisture content at the 60–80 cm interlayer was higher than that at other depths. The interlayer soil in the CK treatment exhibited 1.4%–16.2% higher moisture content after three winter irrigations, indicating reduced water infiltration. Thus, the improvement measures enhanced water infiltration rates in the interlayer soil. Among the improvement measures, deep-turning showed the most effective results, followed by ditching, drilling and sand irrigation. Given that drilling and sand irrigation exhibited intermediate effectiveness, the results emphasise the benefits of combining various improvement measures to enhance interlayer soil moisture content.

Regarding soil desalination, G1 showed the highest desalting rate of 75.9% after three irrigations, followed by G6 (51.5%), G3 (39.4%), G2 (38.2%) and G5 (37.4%), with the CK treatment exhibiting the lowest desalting rate (36.7%). The highest salt content for each treatment was found in the 60–80 cm interlayer. Comparing salt content before irrigation in 2020 with after irrigation in 2022, the desalting rate of interlayer soil was 14.9%–74.5%. The average desalting rate of each treatment was aligned with the interlayer soil results, with the order of effectiveness being G1 > G6 > G3 > G2 > G5 > CK > G4. The increase in salt content was inversely proportional to the increase in water content, highlighting the impact of clay interlayers on water and salt migration.

In conclusion, the desalination effect improved with an increased number of winter irrigation cycles over three years. After two years of winter irrigation, the desalination effect of drilling irrigation and ditching irrigation was lower than that of deep-turning irrigation but higher than that of three-time winter irrigation. Furthermore, drilling and sand irrigation offer advantages and feasibility in terms of economic input compared with deep-turning irrigation. Therefore, when attempting to improve interlayer soil in heavy saline–alkali soil, it is important to consider engineering quantity, economic cost and application feasibility when selecting appropriate improvement measures.

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