

EFFECT OF DESULFURIZATION GYPSUM ON SALINE-ALKALI SOIL IN NINGXIA UNDER RIDGE CULTIVATION AND DRIP IRRIGATION

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Abstract: Addressing the actual issues of severe soil salinity and exchangeable sodium percentage (ESP), and water shortage in the Yellow River irrigation area of Ningxia. With the goal of controlling soil salinity and reducing ESP, ridge cultivation and drip irrigation technology were adopted. Through field positioning experiments, three desulfurization gypsum (DG) application rates of 12 t/hm² (T1), 15 t/hm² (T2), and 18 t/hm² (T3) were set up in the ridge planting area, with a control treatment without desulfurization gypsum (CK) to explore the effect of different desulfurization gypsum application rates on saline-alkali soil in the Yellow River irrigation area of Ningxia under high ridge drip irrigation mode. The results showed that: (1) The application of desulfurization gypsum was beneficial in reducing soil ESP and pH, with the T3 treatment showing the most significant reduction effect; (2) Drip irrigation was conducive to creating a suitable water-salt environment for the ridge planting area. The soil salinity in the 0-20 cm layer of the T1 treatment was 22.5% and 32.2% lower than those of the T2 and T3 treatments, respectively, with soil salinity accumulating in the ridge furrows; (3) Under ridge cultivation and drip irrigation mode, the application of desulfurization gypsum promoted the growth of sweet sorghum, but the higher the application rate of desulfurization gypsum, the better the effect was not necessarily observed. The growth indicators of sweet sorghum in the T2 treatment were the highest. Under the ridge cultivation and drip irrigation mode, the application of 15 t/hm² desulfurization gypsum had the best effect on controlling soil salinity and reducing ESP. The research results can provide theoretical basis and technical support for the improvement and utilization of moderately to severely saline-alkali land in the arid areas of Northwest China.

Keywords: Ridge cultivation; drip irrigation; saline-alkali soil; exchangeable sodium percentage (ESP); soil salinity

1. INTRODUCTION

Soil salinization and alkalization are key factors causing soil degradation, reduced grain yield, and affecting agroforestry ecological health (Tarolli et al., 2024), seriously restricting sustainable agricultural development in arid and semi-arid regions. The Yellow River irrigation area of Ningxia has a thousand-year irrigation history, flat terrain, and a well-established agricultural industry system. However, due to the influence of topography, climate, and unreasonable irrigation practices, a large area of saline-alkali soil has formed, covering 148000 hectares, accounting for one-third of the total area of the Yellow River irrigation area in Ningxia (Wang et al., 2024; Jia et al., 2023). Proper utilization of saline-alkali soil can effectively alleviate the shortage of arable land (Gu et al., 2022; Lu et al.,

2022), and is of great significance for maintaining the 1.2 billion hectares red line of arable land.

Salts migrate with water as the medium and carrier. The core of comprehensive utilization of saline-alkali soil lies in controlling salt with water. Measures such as surface irrigation (Minhas et al., 2020), irrigation and drainage coordination (Yang et al., 2022), water-saving salt control (Li et al., 2021), evaporation prevention cover (Zang et al., 2023), and biological improvement (Wang et al., 2024) can effectively regulate soil salinity and achieve the improvement and utilization of saline-alkali soil. However, the rigid constraint of water resource shortage in the arid areas of Northwest China makes large-scale irrigation and salt leaching difficult (Liu et al., 2023; Tao et al., 2023), and the traditional method of large-scale salt leaching is no longer suitable for the current trend of efficient water-

saving agriculture. Drip irrigation has the characteristics of high-frequency water output and point source diffusion (He et al., 2019; Mattar et al., 2021). Drip irrigation water drives the salts to the vicinity of the wetting front, creating a suitable water-salt environment for plant root growth and achieving water-saving salt control (Karimi & Appels, 2021; Friedman & Gamliel, 2021). Changing the micro-topography of the soil surface through agronomic tillage measures helps regulate the distribution of soil profile salinity. Ridge cultivation can improve soil light and heat conditions, increase soil permeability, provide a suitable growth environment for crop roots, and alleviate stress faced by crop growth (Li & Kang, 2019). Hydraulic measures can effectively reduce soil salinity, but the neutralization of exchangeable sodium percentage (ESP) can only be achieved through chemical improvement by applying amendments (Li et al., 2022). The main component of desulfurization gypsum (DG) is $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. Application on saline-alkali soil can reduce soil ESP, improve soil porosity, promote leaching of soluble salts, and increase crop yield (James, 2021). In recent years, Ningxia has vigorously developed characteristic animal husbandry such as beef cattle and Tan sheep. High-quality forage is crucial for ensuring the healthy development of animal husbandry. Sweet sorghum is a high-quality forage with characteristics of drought resistance, salinity and ESP resistance, and barrenness tolerance (Ren et al., 2021). If it can be planted on a large scale on saline-alkali soil, it can not only utilize the resources of saline-alkali land but also provide forage security for the sustainable development of animal husbandry.

There have been reports on agronomic water-saving salt control (He et al., 2019) and desulfurization gypsum (Li et al., 2022) improvement of saline-alkali soil, but there are few reports on the effects of different desulfurization gypsum application rates on soil salinity and ESP distribution and sweet sorghum in the Yellow River irrigation area of Ningxia under the high ridge drip irrigation mode. Therefore, with the goal of controlling soil salinity and reducing ESP, this study conducted a field positioning experiment in Yongxing Village, Ligang Town, Helan County, Ningxia ($38^\circ 34' \text{ N}$, $106^\circ 32' \text{ E}$).

On the basis of uniform ridge cultivation and drip irrigation, different desulfurization gypsum application rates were set in the ridge planting area to study the effects of different desulfurization gypsum application rates on soil salinity and ESP properties, salinity distribution patterns, and sweet sorghum in the Yellow River irrigation area of Ningxia. The research results can provide theoretical basis and technical support for the comprehensive utilization of saline-alkali soil in the Yellow River irrigation area.

2. MATERIALS AND METHODS

2.1 Overview of the test area

The experiment area is located in Yongxing Village, Ligang Town, Helan County, Ningxia ($38^\circ 34' \text{ N}$, $106^\circ 32' \text{ E}$), in the northern Yellow River irrigation area of Ningxia (Figure 1). This region has a temperate continental climate with large temperature differences between day and night. The annual average temperature is 9.2° C , rainfall is scarce and unevenly distributed throughout the year, with an annual average precipitation of 138.8 mm and an annual average evaporation of 1744 mm. The evaporation was measured by Class A Pan method. The soil in the experiment area consists of 17.5% clay particles ($<0.002 \text{ mm}$), 46.9% silt particles ($0.002\text{--}0.02 \text{ mm}$), and 35.6% sand particles ($0.02\text{--}2.0 \text{ mm}$), making the soil texture silty clay loam (Bao, 2018). The electric conductivity (EC) of soil in the 0-100 cm layer ranges from 1.96 to 3.32 mS/cm, with a pH of 8.73 to 9.79, and an ESP of 19.66%–27.94% (Table 1), showing a "surface accumulation" characteristic of soil salinity. The main cation in the 0-100 cm soil layer is Na^+ , and the main anion is SO_4^{2-} , with K^+ distributed evenly. The sodium adsorption ratio (SAR) is above 14 ($\text{mmol}\cdot\text{L}^{-1})^{1/2}$; the high content of SO_4^{2-} and Cl^- indicates significant soil salinization, and the high Na^+ content leads to high soil ESP, causing soil colloid dispersion. The soil profile forms a dense barrier layer, easily causing water retention and salt accumulation. This area is in the Yellow River irrigation zone, where long-term furrow irrigation has resulted in a high groundwater level of 0.8–1.5 m, causing severe secondary soil salinization and frequent spring salt return.

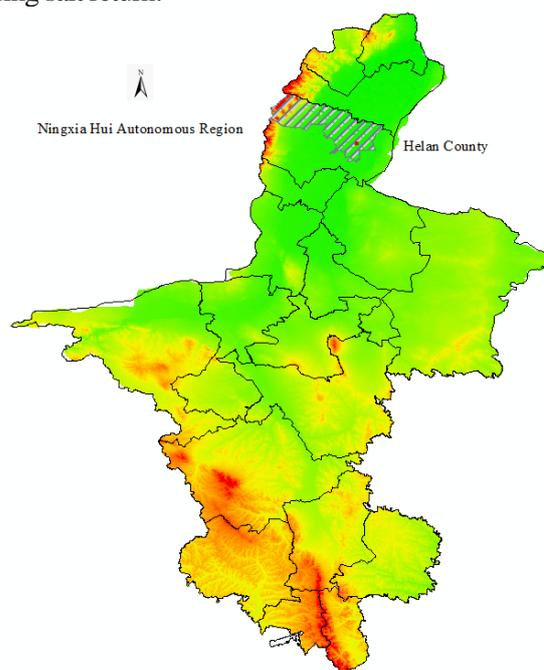


Figure 1. Geographical position of study area

Table 1. Main physical and chemical properties of soil

Soil depth (cm)	pH	EC(mS·cm ⁻¹)	ESP /%	Salt ions (cmol·kg ⁻¹)								SAR (mmol·L ⁻¹) ^{1/2}
				Na ⁺	Ca ²⁺	K ⁺	Mg ²⁺	CO ₃ ²⁻	HCO ₃ ⁻	Cl ⁻	SO ₄ ²⁻	
0–20	8.73	3.32	19.66	8.65	0.23	0.32	0.47	0.00	0.55	1.32	1.73	14.62
20–40	8.94	2.62	22.62	9.43	0.27	0.34	0.52	0.00	0.62	1.41	1.82	15.00
40–60	9.27	2.07	27.09	10.87	0.32	0.31	0.49	0.54	0.87	1.37	2.03	17.08
60–80	9.67	1.96	27.94	11.21	0.38	0.35	0.53	0.76	0.95	1.40	2.15	17.39
80–100	9.79	2.03	27.90	11.47	0.38	0.37	0.49	0.75	1.12	1.63	2.17	17.62

Note: EC: Electric conductivity. ESP: Exchangeable sodium percentage. SAR: Sodium adsorption ratio.

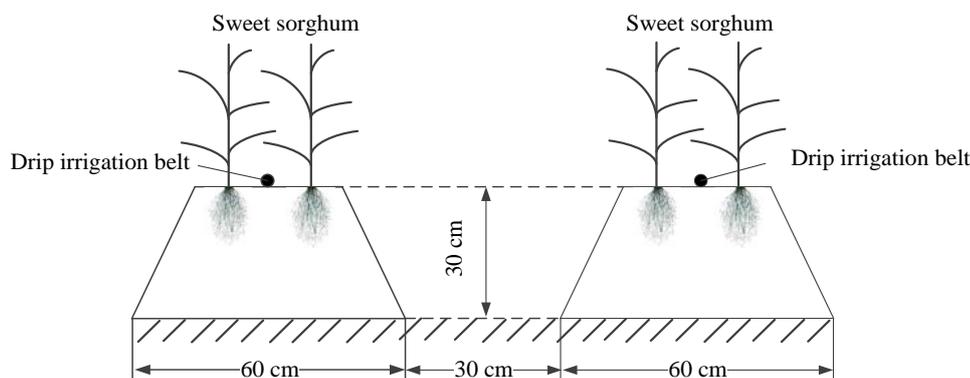


Figure 2. The diagram of planting

2.2 Experiment Design and Process

The experiment uniformly adopted a ridge cultivation and drip irrigation mode. In the autumn of 2022, the original soil was ridged (ridge height 0.3 m, ridge width 0.6 m). Three desulfurization gypsum application rates were set in the ridge planting area: 12 t/hm² (T1), 15 t/hm² (T2), and 18 t/hm² (T3), with a control treatment without desulfurization gypsum (CK). Each treatment was repeated three times in a randomized block design.

In October 2022, 30 t/hm² of organic fertilizer was uniformly applied to all treatments. The desulfurization gypsum was mixed with the organic fertilizer, evenly spread on the ridge back, and rototilled to mix it with the surface soil. Sweet sorghum was sown on May 15, 2023, with two rows of sweet sorghum per drip irrigation tape (Figure 2). The row spacing of sweet sorghum was 20 cm, and the planting specifications were consistent across all treatments. The first irrigation on May 30, 2023, included an additional application of 120 kg/hm² of urea. In early August, 105 kg/hm² of nitrogen fertilizer was applied. After the emergence of sweet sorghum, irrigation was performed every 15 days, with an irrigation quota of 180 m³/hm² each time, totaling six times of irrigation during the sweet sorghum growth period.

2.3 Measurement and Methods

In April 2023, before planting, three days after each irrigation, and after the autumn harvest, soil

samples were collected from each experimental plot using the "five-point sampling method." Soil samples were taken from the top of the ridge and the bottom of the furrow at 0–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, and 80–100 cm soil layers. Five soil samples were taken from each plot each time, with gravel, residual roots, and other debris removed. The samples were air-dried in a cool place, crushed, and passed through a 2 mm sieve. Soil bulk density was determined using the ring knife method; soil moisture content was determined by the drying method; soil pH was measured using a pH meter; soil salinity was measured using the electrical conductivity method; cation exchange capacity (CEC) was determined using the ammonium chloride-acetate exchange method; K⁺ and Na⁺ contents were determined using the flame photometer method; ESP was calculated as the percentage of Na⁺ in the cation exchange capacity; Ca²⁺ and Mg²⁺ contents were determined using the EDTA titration method; Cl⁻ content was determined using the AgNO₃ titration method; SO₄²⁻ content was determined using the EDTA back-titration method; CO₃²⁻ and HCO₃⁻ contents were determined using the double indicator titration method, as described in the literature (Bao, 2018).

The sodium adsorption ratio (SAR) was calculated using the following formula:

$$SAR = \frac{[Na^+]}{\sqrt{[Ca^{2+}] + [Mg^{2+}]}} \quad (1)$$

Where SAR is the sodium adsorption ratio (mmol·L⁻¹)^{1/2}; [Na⁺] is the concentration of Na⁺ in

mmol·L⁻¹; [Ca²⁺] is the concentration of Ca²⁺ in mmol·L⁻¹; [Mg²⁺] is the concentration of Mg²⁺ in mmol·L⁻¹.

The exchangeable sodium percentage (ESP) was calculated using the following formula:

$$ESP = \frac{[Na^+]}{CEC} \times 100\% \quad (2)$$

Where ESP is the exchangeable sodium percentage (%); [Na⁺] is the concentration of Na⁺ in mmol·L⁻¹; CEC is the cation exchange capacity in mmol·L⁻¹.

The emergence rate of sweet sorghum was calculated using statistical methods, and plant height was measured using a tape measure. After harvesting sweet sorghum on September 25, 2023, the fresh grass yield of the experimental plots was weighed and recorded.

2.4 Data Processing and Analysis

Data were processed using Microsoft Excel 2010. The significance of differences between the experimental results of different treatments was compared using one-way ANOVA with Duncan's method in SPSS 19.0. Surfer 10.0 was used to create 3D Wireframe diagrams based on the nearest neighbor method and Contour Map diagrams based on the Kriging interpolation method to analyze soil water and salt distribution differences between different treatments.

3. RESULTS

3.1 Effects of Different Treatments on pH and ESP

To analyze the effects of different treatments on soil pH and ESP, data collected after the autumn harvest in October were used to examine the effects of different treatments on soil pH and ESP in the ridge and furrow (Table 2). The application of desulfurization gypsum under the high ridge drip irrigation mode helped reduce soil pH and ESP. In the 0-20 cm soil layer, the soil pH and ESP of the T1, T2, and T3 treatments were reduced by 2.8%, 3.8%, 4.5%, and 40.0%, 49.7%, 54.5%, respectively, compared to the control. In the 20-40 cm soil layer, the soil pH and ESP of the T1, T2, and T3 treatments were reduced by 0.8%, 1.3%, 1.8%, and 33.0%, 39.8%, 43.7%, respectively, compared to the control. The reduction in soil ESP was significant in the 0-40 cm soil layer in the ridge ($P < 0.05$), while the reduction in soil pH was not significant ($P > 0.05$). In the furrow, where no desulfurization gypsum was applied, there were no significant differences in soil pH and ESP compared to the control ($P > 0.05$), and there were no

significant differences in soil pH and ESP among the three treatments ($P > 0.05$). Within the same treatment area, in the 0-20 cm soil layer, the soil pH and ESP in the ridge were reduced by 3.9%, 5.2%, 6.7%, and 38.9%, 48.3%, 52.6%, respectively, compared to the furrow. In the 20-40 cm soil layer, the soil pH and ESP in the ridge were reduced by 3.8%, 4.9%, 5.9%, and 42.8%, 47.2%, 49.9%, respectively, compared to the furrow. The application of desulfurization gypsum in the ridge significantly reduced soil ESP, but had no significant effect on reducing soil pH. The effect of reducing soil ESP became more apparent with increasing desulfurization gypsum application rates. In the furrow, where no desulfurization gypsum was applied, there was no significant effect on reducing soil pH and ESP.

3.2. Effects of Different Treatments on Soil Profile Moisture

In spring, the surface evaporation is strong due to high wind speeds, resulting in significantly lower surface moisture compared to deeper soil layers. Soil moisture increased with soil depth, and soil moisture in the ridge was significantly higher than in the furrow (Figure 3). With drip irrigation tapes laid on the ridge, benefiting from the characteristics of high-frequency water output, soil moisture in the ridge planting area was higher than in the non-planting area of the furrow. Soil profile moisture in the ridge increased with increasing desulfurization gypsum application rates among the three treatments, but the differences were not significant ($P > 0.05$). There were no differences in soil profile moisture between the control and the three treatments in the furrow ($P > 0.05$). The combination of high ridge drip irrigation and the application of desulfurization gypsum had the most significant impact on surface soil moisture and salinity. Soil moisture in the 0-20 cm layer of the ridge was 10.4%, 12.2%, and 14.8% higher than CK, respectively, and 11.4%, 14.2%, and 14.8% higher than in the 0-20 cm layer of the furrow. The high ridge drip irrigation mode influenced moisture movement through vertical and horizontal infiltration, causing part of the soil moisture in the ridge to accumulate in the furrow. Soil moisture in the furrow was higher than before planting. Soil profile moisture in the ridge for the three treatments was higher than CK, with no significant differences in soil profile moisture between the control and the three treatments in the furrow, indicating that the application of desulfurization gypsum improved soil structure and promoted soil movement. Combined with high ridge drip irrigation technology, it created a suitable water-salt environment for the ridge planting area.

Table 2. Effect of different treatments on pH and ESP of 0-100 cm soil layers

Position	Index	Soil depth (cm)	Treatment			
			CK	T1	T2	T3
Furrow ridge	pH	0~20	8.65±0.13a	8.41±0.21a	8.32±0.17a	8.26±0.23a
		20~40	8.79±0.12a	8.58±0.17a	8.54±0.23a	8.49±0.15a
		40~60	9.14±0.17a	8.97±0.23a	8.94±0.15a	8.96±0.12a
		60~80	9.55±0.23a	9.48±0.15a	9.45±0.12a	9.42±0.23a
		80~100	9.58±0.17a	9.52±0.22a	9.48±0.17a	9.50±0.15a
	ESP (%)	0~20	18.57±0.23a	11.14±0.23b	9.34±0.19bc	8.45±0.05c
		20~40	21.87±0.15a	12.45±0.32b	11.17±0.23bc	10.45±0.27c
		40~60	25.56±0.21a	18.87±0.43b	17.96±0.35b	17.26±0.23b
		60~80	26.92±0.27a	23.24±0.34b	22.87±0.25b	22.35±0.34b
		80~100	25.55±0.33a	24.25±0.23a	25.14±0.13a	24.67±0.24a
Furrow bottom	pH	0~20	8.68±0.02a	8.75±0.03a	8.78±0.04a	8.85±0.03a
		20~40	8.75±0.04a	8.92±0.03a	8.98±0.02a	9.02±0.03a
		40~60	9.18±0.03a	9.29±0.04a	9.32±0.04a	9.37±0.03a
		60~80	9.55±0.05a	9.64±0.03a	9.68±0.04a	9.71±0.04a
		80~100	9.81±0.04a	9.77±0.05a	9.83±0.03a	9.82±0.04a
	ESP (%)	0~20	19.42±0.22a	18.23±0.13a	18.08±0.16a	17.82±0.24a
		20~40	22.45±0.24a	21.76±0.25a	21.17±0.18a	20.84±0.23a
		40~60	26.94±0.23a	26.73±0.32a	26.25±0.21a	26.13±0.27a
		60~80	27.15±0.34a	26.75±0.27a	26.34±0.32a	26.62±0.29a
		80~100	26.35±0.42a	26.34±0.32a	25.51±0.27a	25.95±0.32a

Note: Different letters indicate significant difference among treatments in the same soil depth at 0.05 level.

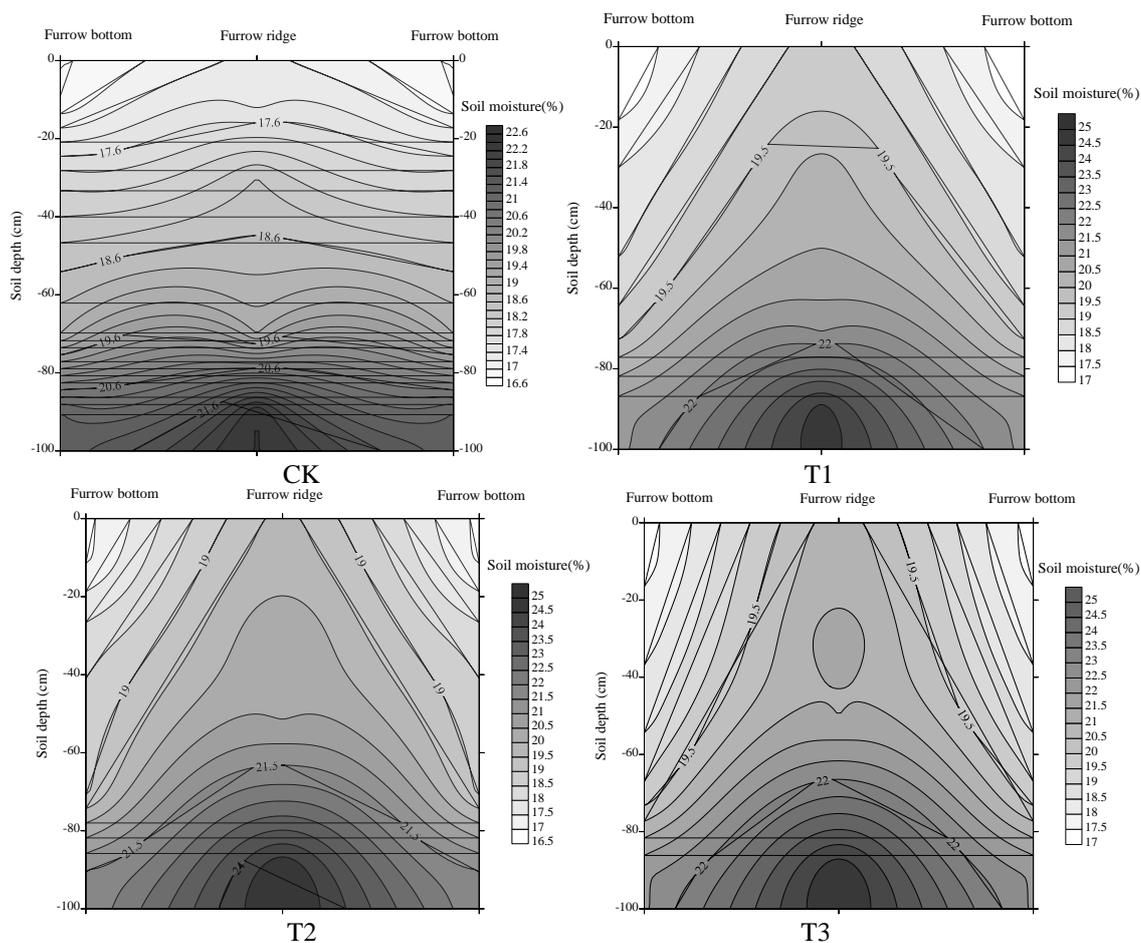
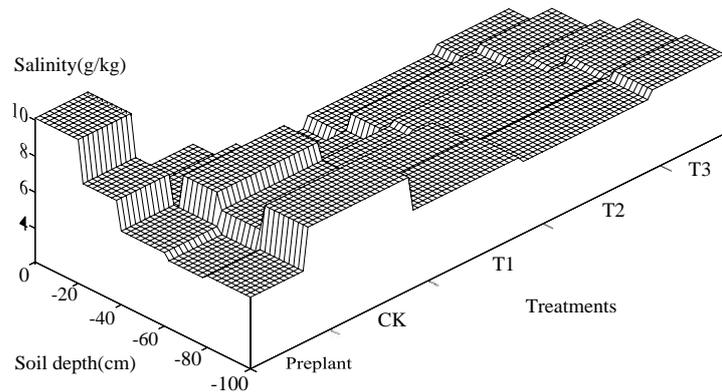


Figure 3. Effects of different treatments on moisture of 0-100 cm soil layers, Note: Soil moisture content is the mass moisture content, % (g/g).

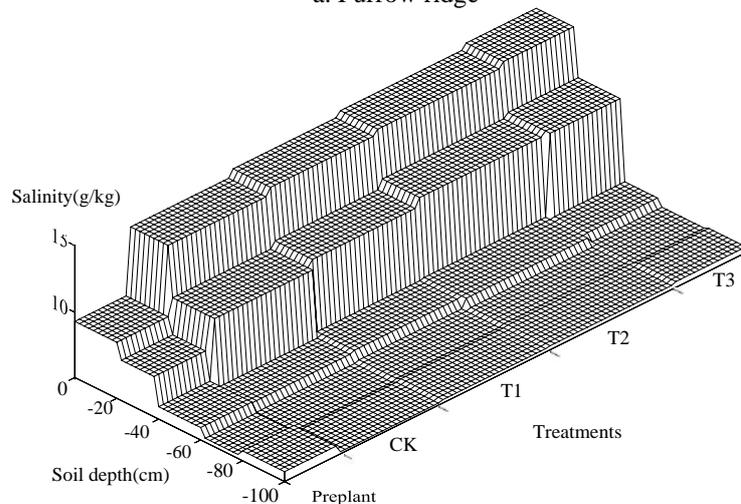
3.3 Effects of Different Treatments on Soil Profile Salinity

Before planting, soil salinity decreased with increasing soil depth, showing a "surface accumulation" characteristic in the 0-100 cm profile. In April, before planting, soil salinity in the ridge was significantly higher than in the furrow (Figure 4). In spring, due to the influence of arid climate, surface evaporation was strong, causing moisture to move upwards along the ridge and salt to accumulate in the ridge after evaporation, resulting in significantly higher soil salinity in the ridge than in the furrow. Soil salinity in the ridge planting area increased with soil depth among the treatments. Due to the use of drip irrigation technology, soil salinity decreased significantly in the 0-40 cm soil layer. In the 0-20 cm soil layer, soil salinity in CK, T1, T2, and T3 treatments decreased by 57.3%, 78.9%, 72.8%, and 68.9%, respectively, compared to before planting. The decrease in soil salinity was significant in the 0-20 cm soil layer for all treatments, with the smallest decrease in CK. Soil salinity in T1 was 22.5%

and 32.2% lower than in T2 and T3, respectively. The decrease in soil salinity in the 0-20 cm layer became more apparent with increasing desulfurization gypsum application rates. Soil salinity in the 0-40 cm soil layer in the furrow was significantly higher than in other soil layers and higher than before planting, especially in the 0-20 cm soil layer, where soil salinity exceeded 14 g/kg in all treatments. Due to the salt-driving effect of drip irrigation, salt accumulated in the furrow through lateral infiltration, with soil salinity in the 0-20 cm layer of CK, T1, T2, and T3 treatments increasing by 34.9%, 37.3%, 38.8%, and 40.3%, respectively, compared to before planting, indicating significant salt accumulation in the furrow for all treatments. The high ridge drip irrigation mode affected moisture movement, thereby influencing salt distribution. Moisture moved from areas of high water potential to areas of low water potential through vertical and horizontal infiltration, causing more moisture to accumulate in the furrow, leaching soil salinity from the ridge planting area while accumulating salt in the furrow.



a. Furrow ridge



b. Furrow bottom

Figure 4. Effects of different treatments on salinity of 0-100 cm soil layers

3.4 Effects of Different Treatments on Soil SAR

Under different treatment conditions, the soil SAR in the ridge increased with soil depth (Figure 5). In the ridge area, the T3 treatment had the lowest soil SAR in the 0-20 cm and 20-40 cm soil layers, with values of $5.96 \text{ (mmol}\cdot\text{L}^{-1})^{1/2}$ and $7.04 \text{ (mmol}\cdot\text{L}^{-1})^{1/2}$, respectively. In the 0-100 cm profile, the SAR of CK was higher than other treatments, with significant differences in the 0-60 cm soil layer compared to the T1, T2, and T3 treatments ($P<0.05$). In the 0-60 cm profile, there were no significant differences in SAR among T1, T2, and T3 treatments ($P>0.05$). In the 0-20 cm and 20-40 cm soil layers, the SAR of T1, T2, and T3 treatments was reduced by 54.3%, 55.5%, 56.8%, and 49.9%, 50.1%, 51.0%, respectively, compared to CK. In the furrow area, the SAR of the 0-20 cm soil layer in T1, T2, and T3 treatments was reduced by 11.4%, 12.7%, and 13.4%, respectively, compared to CK, with SAR values significantly lower than CK ($P<0.05$). Below the 20 cm soil layer, there were no significant differences among treatments ($P>0.05$). According to the calculation formula of SAR, changes in soil Na^+ , Ca^{2+} , and Mg^{2+} ion contents can affect soil SAR. In this experiment, the

addition of desulfurization gypsum in the ridge affected the soil Na^+ and Ca^{2+} contents, significantly impacting soil SAR in the ridge, while the ion content changes in the furrow, where no desulfurization gypsum was applied, were minimal. Therefore, the three treatments significantly improved soil SAR in the ridge but had no significant effect on soil SAR in the furrow.

3.5 Effects of Different Treatments on Sweet Sorghum

The three treatments with desulfurization gypsum significantly improved the emergence rate, plant height, and yield indicators of sweet sorghum ($P<0.05$). There were no significant differences in the growth indicators of sweet sorghum among the three treatments ($P>0.05$). The emergence rate of sweet sorghum in the CK treatment, without desulfurization gypsum, was only 32.4%, while the emergence rates in the three treatments with desulfurization gypsum were all above 89% (Table 3). The emergence rates and fresh grass yields of sweet sorghum in the T1, T2, and T3 treatments were higher than CK by 63.7%, 64.6%, 64.0%, and 73.6%, 75.1%, 74.8%, respectively. The growth indicators of sweet sorghum did not increase

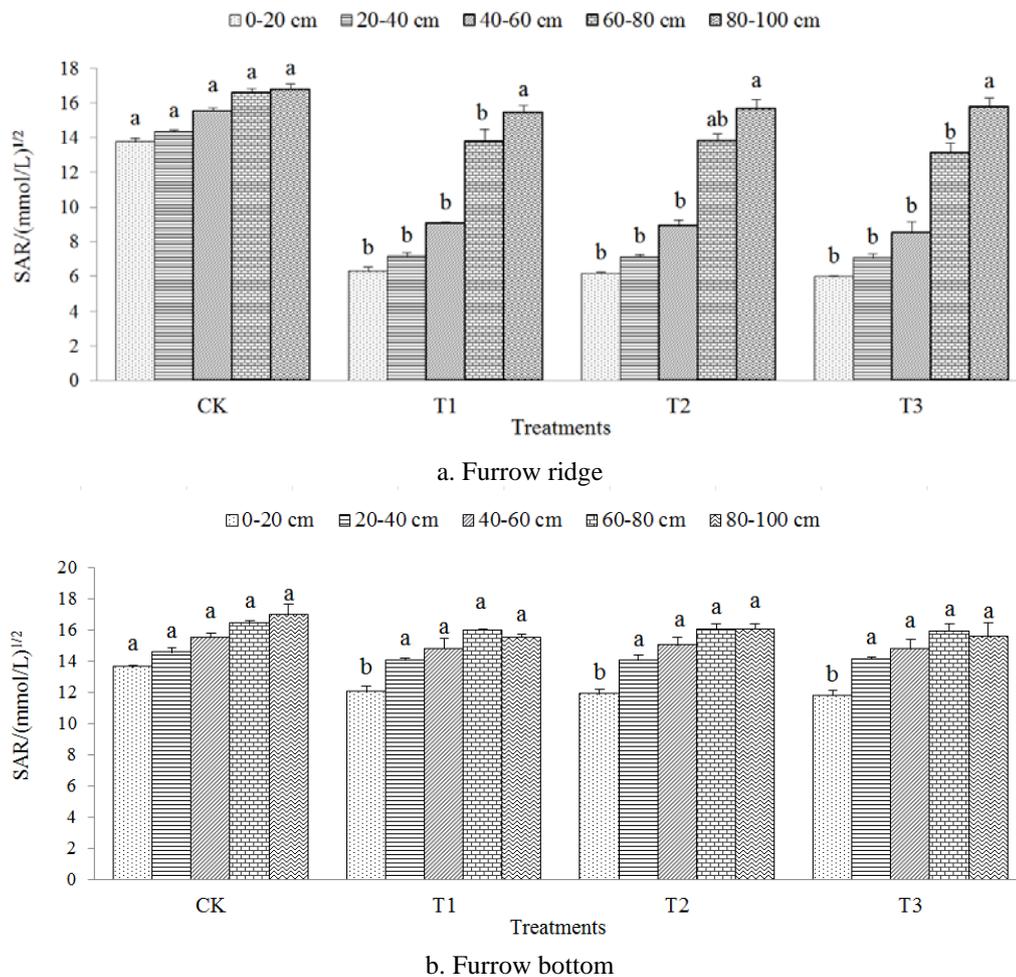


Figure 5. Effects of all treatments on SAR of soil

Table 3 Effects of different treatments on growth of sweet sorghum

Treatment	Emergence rate (%)	Height (cm)	Single plant fresh heavy (kg)	Fresh grass yield (t·hm ⁻²)
CK	32.4±1.23b	90.3±3.34b	0.12±0.02b	12.3±1.12b
T1	89.3±1.65a	198.4±6.26a	0.27±0.03a	46.6±9.20a
T2	91.4±1.89a	203.3±8.96a	0.32±0.08a	49.3±10.9a
T3	90.1±1.73a	201.9±9.17a	0.30±0.05a	48.8±11.7a

Note: Different letters indicate significant difference among treatments at 0.05 level.

with higher desulfurization gypsum application rates, with the highest indicators observed in the T2 treatment. The application of desulfurization gypsum to saline-alkali soil, combined with drip irrigation technology, helped reduce soil salinity and ESP, significantly promoting the growth of sweet sorghum. However, higher desulfurization gypsum application rates did not necessarily yield better results.

4. DISCUSSION

Soil salinity can be leached using hydraulic measures, but soil ESP can only be neutralized through chemical amendments (Li et al., 2022). The experimental area faces both salinity and ESP challenges and water shortages; thus, combining agronomic water-saving measures with chemical amendments is necessary to achieve the goals of controlling salinity and reducing ESP. Excess salt ions in the soil affect soil structure. High Na⁺ content in saline-alkali soil increases the electrokinetic potential of soil colloids, causing soil to disperse when encountering water, leading to the dispersion of soil aggregates, reduced permeability, and smaller or completely blocked soil pores, hindering soil moisture movement. On the other hand, Ca²⁺ can cause flocculation of soil colloids, forming water-stable granular structures and improving soil structure (Sakai et al., 2022). In this experiment, the high Na⁺ content in the soil before the experiment (Table 1) led to a significant reduction in soil ESP in the three treatments because the applied desulfurization gypsum increased the Ca²⁺ and SO₄²⁻ content. The divalent cation Ca²⁺ has a stronger adsorption capacity for soil colloids than Na⁺. Ca²⁺ replaces the Na⁺ attached to the soil colloids, forming neutral salt Na₂SO₄ with SO₄²⁻, effectively reducing soil ESP (Zhao et al., 2022). Meanwhile, SO₄²⁻, a strong acid radical, has a certain neutralizing effect. The reduced soil SAR in the ridge of the three treatments is due to the addition of desulfurization gypsum, which increased the Ca²⁺ content and reduced the Na⁺ content.

Soil moisture movement in the vertical direction is evident due to irrigation and evaporation, and soil salinity migrates with moisture as a medium and carrier, leading to significant fluctuations in surface salinity. The ridging in the experimental area changed the microtopography of the surface, artificially interfering with

the distribution of soil profile salinity. Drip irrigation, characterized by high-frequency water output and point source diffusion, causes soil salinity to migrate downward as moisture infiltrates. Soil salinity in the ridge was effectively leached, with some salt accumulating below the 40 cm depth in the vertical direction and some accumulating on the surface in the furrow (Figure 2). Different irrigation methods affect the redistribution of salinity under ridging. In the ridge-furrow planting mode, salt easily accumulates on the ridge with furrow irrigation (Wang et al., 2017a), while in the high-ridge drip irrigation mode, salt easily accumulates in the furrow through lateral infiltration, as confirmed by Cui Tingting's ridge drip irrigation experiment (Cui et al., 2017). The effectiveness of salinity leaching is related to the initial salinity before planting; the higher the initial salinity, the higher the desalination rate. In the high-ridge drip irrigation mode, a large amount of soil salinity in the ridge was leached into the furrow. Although the application of desulfurization gypsum can reduce soil ESP, promote soil colloid flocculation, improve soil structure, and facilitate moisture movement for salinity leaching, some scholars pointed out that desulfurization gypsum contains some salt, and excessive application can add extra salt to the soil (Zhao et al., 2022). This experiment also showed that higher application rates of desulfurization gypsum did not necessarily result in greater salinity reduction or better growth of sweet sorghum. Therefore, desulfurization gypsum should be applied in moderation; excessive application can increase soil salinity. Additionally, studies have shown that excessive application of desulfurization gypsum can lead to an increase in powder, blocking soil pores locally and affecting salinity leaching (Zhao et al., 2022). In this experiment, the 0-40 cm soil layer in the T2 treatment had the lowest soil salinity in the ridge, and most crops and shallow-rooted plants mainly distribute their roots in the 0-40 cm soil layer. Thus, the appropriate application rate of desulfurization gypsum in this experimental area is 15 t/hm².

DG was used to amelioration saline-alkali soil, the soil texture and method of irrigation will affect nutrient loss (Paltineanu et al., 2021; Paltineanu et al., 2022). In order to minimize nutrient leaching losses some measures should be recommended, such as water-saving irrigation technology. The research has shown

that drip irrigation or spray irrigation can reduce nitrate leaching effectively (Domnariu et al., 2020). The research has shown that oil leakage, coal combustion and external addition of PAHs will lead to soil pollution (Ihenetu et al., 2024). DG contains small amount of heavy metals, mainly from the heavy metals adsorbed by fly ash during coal combustion, although some studies have shown that the application of DG will not lead to excessive heavy metals in soil (Wang et al., 2017b), however whether long-term excessive application will produce potential risks needs to be further verified.

It is worth noting that the drip irrigation mode can reduce deep leakage and prevent salt return caused by high groundwater levels. High-ridge drip irrigation can manage salinity, but the salt is not leached out of the soil, posing a risk of concentrated salt return over time. Therefore, when water resources are sufficient, surface irrigation with large amounts of water is recommended to leach salt and maintain salinity balance.

5. CONCLUSIONS

The application of desulfurization gypsum under the high-ridge drip irrigation mode can significantly reduce soil pH, ESP, and salinity. Drip irrigation creates a suitable water-salt environment for the ridge planting area, but salinity tends to laterally accumulate in the furrow. Long-term application can lead to continuous salinity accumulation. The application of desulfurization gypsum under the ridge drip irrigation mode helps reduce soil salinity and ESP and significantly promotes the growth of sweet sorghum. However, higher application rates of desulfurization gypsum do not necessarily yield better results. Desulfurization gypsum contains some salt, and excessive application can add extra salt to the soil. The optimal application rate of desulfurization gypsum under the high-ridge drip irrigation mode is 15 t/hm², suitable for improving and planting in heavily saline-alkali soils in the Yellow River irrigation area of Ningxia.

Author Contributions

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Data Availability Statement

Data are contained within the article.

Conflicts of Interest

The authors declare no conflict of interest.

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