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Decision of Straw Deep Burial and Aluminum Sulfate Drip Irrigation in Soda Saline Soil Based on Grey Relation Analysis and TOPSIS Coupling

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Abstract: To investigate the impact of combining aluminum sulfate with straw and irrigation water to enhance soil quality in soda saline–alkali soil, in this study a field experiment was conducted in Tongliao City, Inner Mongolia Autonomous Region, China. With beet IM1162 as the indicator crop, four levels of aluminum sulfate dosage (30, 60, 90, 120 g m^{-2}) and four levels of drip irrigation water quota (225, 270, 315, 360 m^3 ha^{-1}) were set. The study examined the impact of varying levels of aluminum sulfate and irrigation water on soil water salt and crop yield. Next, using a comprehensive evaluation method, the optimal quantities of aluminum sulfate and irrigation water needed for effective soil improvement were determined. The research findings indicate that the most effective treatment (W2S3) involved an aluminum sulfate dosage of 90 g m^{-2} and an irrigation quota of 270 m^3 ha^{-1}. This treatment resulted in significant improvements compared to the control (CK) group. Specifically, in the 0–50 cm soil layer, the following improvements were observed: the water storage capacity (SWS) increased by 51.7%; evapotranspiration (ET) increased by 16.2%; water use efficiency (WUE) increased by 55.0%; and irrigation water use efficiency (IWUE) increased by 98.1% ($p < 0.05$). These results emphasize the importance of optimizing the combination of aluminum sulfate dosage and irrigation water quota to improve soil conditions and crop performance. It is worth nothing that this study highlights the potential for enhancing water use efficiency and crop yield in agricultural practices, which can contribute to sustainable and efficient farming practices. The study results revealed significant improvements in soil quality and crop yield when compared to the control group (CK). Specifically, in the 0–50 cm soil layer: the soil salt content decreased by 19.8%, soil pH increased by 8.7%, and exchangeable sodium percentage (ESP) decreased by 34.0%. Moreover, the crop yield in the treatment group increased significantly, by 32.1%. These findings indicate the positive impact of the intervention on soil health and agricultural productivity. The study employed the game theory combination weighting method to comprehensively evaluate soil water, salt, and various yield indicators. The results showed that the sustainability weight for crop yield reached 0.116, emphasizing the aim of soil improvement: the sustainable enhancement of crop yield. This approach underscores the importance of balanced soil management practices to ensure long-term agricultural productivity and environmental sustainability. The comprehensive evaluation results of grey relation analysis and the TOPSIS coupling model showed that the soil improvement effect score was the highest when the dosage of aluminum sulfate was 61.7–120.0 g m^{-2}, and the irrigation quota was 250.4–319.4 m^3 ha^{-1}, which was the recommended range for the local area. The research findings discussed in the provided sources contribute to the theoretical basis for soil improvement in soda–saline–alkali land.

Keywords: aluminum sulfate; soil improvement; TOPSIS; grey relation analysis

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1. Introduction

China's Songnen Plain is one of the world's three significant saline–alkali soil concentrated areas, with a salinized area of 3.73 million hm^2 [1]. Soil saline–alkali stress destroys ecological balance and reduces arable productivity, which in turn restricts the development of the local agricultural economy [2]. How to effectively improve soda salt land has become an important issue that urgently needs to be solved [3]. Relevant scholars [4,5] have extensively explored the causes of saline-alkali land formation and its challenges to agricultural productivity, delving deeply into integrated strategies for effective farmland management. Among them, aluminum sulfate, a chemical modifier, has been widely used in research concerning saline–alkali soil due to its characteristics of rapidly improving soil physicochemical properties and providing an excellent external environment for crop growth [6]. It has also been reported that the application of aluminum sulfate can significantly reduce soil pH [7], alleviate soil alkalinity [8], increase soil infiltration rate [9], and increase crop yield [10]. O'Kelly et al. [11] proposed that H^+ released by hydrolysis of aluminum sulfate reacts with deposited calcium in the soil, which can alleviate soil salt surface polymerization and improve soil physical and chemical properties. Zhou et al. [12] compared the improvement effects of organic fertilizer, bioinorganic fertilizer, organic–inorganic compound fertilizer, and different concentrations of aluminum sulfate, and further elaborated that aluminum sulfate can rapidly optimize soil structure. However, the effect of a single improvement measure takes place slowly, it has a short duration, and cannot easily form stable production [13]. In addition, saline–alkali soil is mainly distributed in arid and semiarid areas, and agricultural production is often accompanied by water stress and other problems [14]. Some studies [15] have found that a small amount of multiple irrigation can make soil water movement mainly unsaturated and maintain the total soil water potential at a high level to compensate for the decreased osmotic potential due to the presence of salt. This is conducive to improving the crop root environment, promoting the water absorption of crop roots, and realizing the sustainability of crop yield. Benson D. A. et al. [16] found that controlled drip irrigation could realize the redistribution of soil salt, thus promoting the expected growth of crops through leaching, in turn improving the economic benefits of farmland. Therefore, realizing the rational application of aluminum sulfate–irrigation and changing the current situation of "a mess when wet and a knife when dry" in saline–alkali land has become the critical problem in solving the sustainable development of farmland.

Many scholars [17,18] have used advanced evaluation methods and established a multi-index evaluation model to determine the best treatment scheme. Among them, the analytic hierarchy process, CRITIC, grey relation analysis, and TOPSIS methods show good adaptability and rationality in multi-index evaluation. However, due to the different angles and bias points of information acquisition, these studies based on a single evaluation method have the drawbacks of considerable data variation, difficult-to-find typical distribution rules, and uneven results of rights confirmation, which seriously affect the accuracy of evaluation results. The coupling model of TOPSIS and grey relation analysis takes the comprehensive relative proximity as the distance measure and uses multiple index factors to rank the proximity between the evaluation object and the idealized target, thereby further improving the accuracy and reliability of the evaluation results. For example, the GRA-TOPSIS coupling model proposed by Liu Dong et al. [19] effectively identified the main controlling factors of irrigation water efficiency in various irrigation districts, and comprehensively evaluated irrigation water efficiency indicators. In the present study, the TOPSIS method was optimized by grey relation analysis. Next, three significant indexes were used to evaluate the soil improvement effect, which characterized soil moisture, soil salinization degree, and crop growth. We developed an optimal sulfate–irrigation scheme for soil improvement in the experimental area based on a comprehensive evaluation. This scheme is a scientific foundation for the rational utilization and development of saline–alkali land resources in this region.

2. Materials and Methods

2.1. Overview of the Test Area

Field trials were conducted from May to October 2021 and from May to October 2022 in Horqin Left Wing Middle Banner, Tongliao City, Inner Mongolia Autonomous Region, China (121°08′ to 123°32′ E longitude, 43°32′ to 44°32′ N latitude). The location of the test area is shown in Figure 1. The region has a temperate continental monsoon climate, with an annual average rainfall of 336.6 mm, average temperature of 7.41 °C, annual evaporation of 1817.4 mm, and annual groundwater depth of 7.33 m. The monthly climate and underground water depth during the two-year growth period of sugar beet are shown in Figure 2. The soils in the test area are mainly soda–saline–alkali soil and sodium–alkali soil. The soil pH was 8.02–10.07, and the total water-soluble salt was 1.0–8.7 g kg^{-1}.

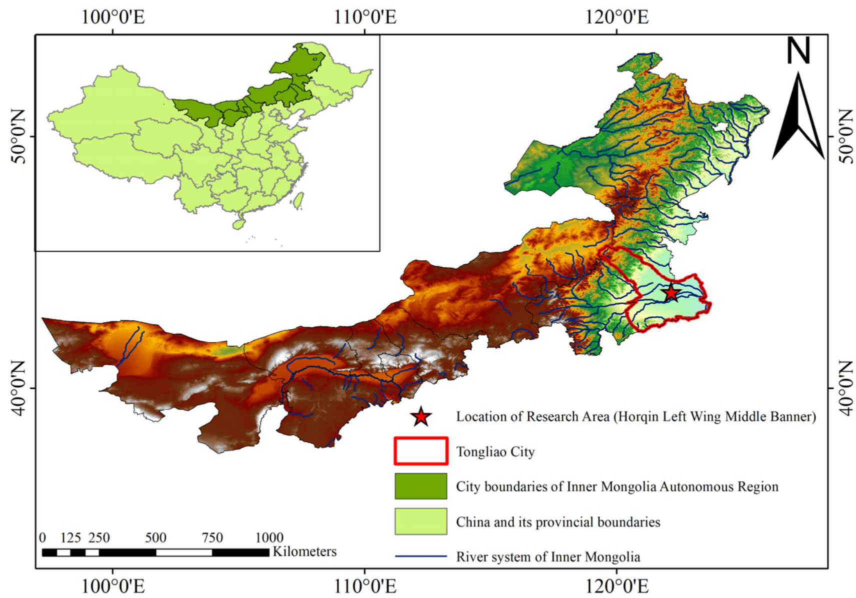


Figure 1. Geographical location of the test area.

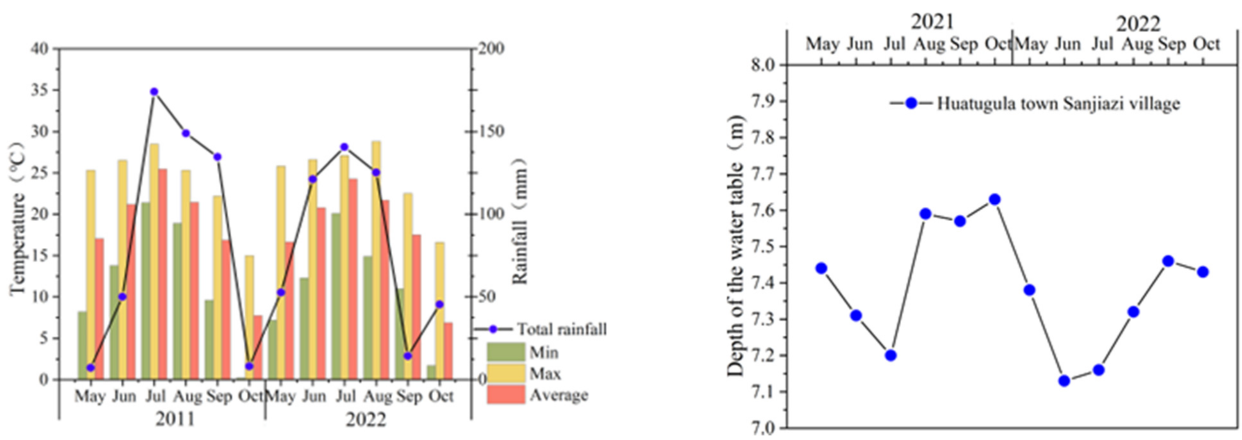


Figure 2. Temperature, rainfall, and groundwater depth in the test area during 2021 and 2022. The purple dot plot represents the total rainfall, the bar chart shows the monthly minimum temperature in green, the monthly maximum temperature in yellow, and the monthly average temperature in red. The blue dot plot shows two-year groundwater depths.

2.2. Experimental Design

Deep plowing to 30 cm was performed in early May every year to level the site. In addition, a layer of 9000 kg hm^{-2} corn stalk was mechanically buried at 30 cm. Beet variety IM1162 was selected as the test object, and the crop was covered by film drip irrigation with one film and one tube in two rows. Two-factor tests were set for four horizontal irrigation quotas (W1: 225 m^3 ha^{-1}, W2: 270 m^3 ha^{-1}, W3: 315 m^3 ha^{-1}, W4: 360 m^3 ha^{-1}) and four horizontal aluminum sulfate dosages (S1: 30 g m^{-2}, S2: 60 g m^{-2}, S3: 90 g m^{-2}, S4: 120 g m^{-2}). After applying aluminum sulfate to each treatment, it was mixed with a rotary tiller (20–30 cm) and the site was leveled. Each treatment was separated with a plastic plate buried 1.2 m deep to prevent the water and fertilizer from channeling into each other. The beet was irrigated seven times during the growth period (17 May, 15 June, 10 July, 22 July, 15 August, 30 August, and 20 September). No straw layer was set for CK treatment, and other field management systems were consistent with the local area (irrigation quota 405 m^3 ha^{-1}). All processes, including CK, are performed. The base fertilizer was 262 kg ha^{-1} beet compound fertilizer, which was applied into the soil with seeding. Urea was applied at 675 kg ha^{-1} in early June and at 450 kg ha^{-1} before ridging. Other field management measures were consistent with local traditional planting. The specific test scheme and layout are shown in Table 1 and Figure 3.

Table 1. Field trial design. Establish four levels of aluminum sulfate dosage (30, 60, 90, 120 g m^{-2}), four levels of irrigation quota (225, 270, 315, 360 m^3 ha^{-1}), and set CK treatment (irrigation quota 405 m^3 ha^{-1}, aluminum sulfate dosage 0 g m^{-2}).

$Al_2(SO_4)_3$ (g m^{-2})	Irrigation Quota (m^3 ha^{-1})				
	225	270	315	360	405
0	-	-	-	-	CK
30	W1S1	W2S1	W3S1	W4S1	-
60	W1S2	W2S2	W3S2	W4S2	-
90	W1S3	W2S3	W3S3	W4S3	-
120	W1S4	W2S4	W3S4	W4S4	-

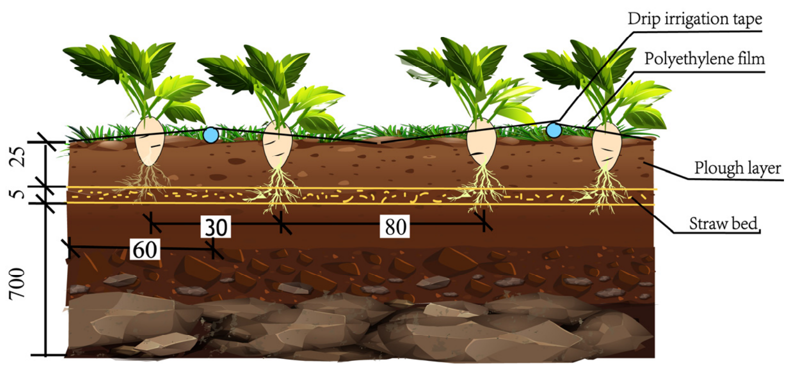


Figure 3. Test layout. Plant spacing 30 cm, row spacing 80 cm, polyethylene film width 60 cm, underground ±30 cm buried corn stalks; mulching drip irrigation technology used to control irrigation.

2.3. Measurement Items and Methods

According to the length of beetroot (±30 cm), soil samples were taken from 0–10, 10–20, 20–30, 30–40 and 40–50 cm, respectively, at the seedling, foliage luxuriant, root tuber growth, and sugar accumulation stages, to determine the soil water and salt levels.

2.3.1. Soil Moisture

(1) Soil water storage (SWS) [20]:

$$\mathrm{SWS} = C \times \rho \times H \times 10 \tag{1}$$

where SWS is the soil water storage (mm); C is the soil volumetric moisture content (SMC) (%); ρ is the soil bulk density (g cm^{-3}); and H is the soil layer thickness (cm).

(2) Evapotranspiration (ET) [21]:

$$\text{ET} = P + I + C + (\Delta W) - D - R \tag{2}$$

where ET is evapotranspiration (mm); P is precipitation (mm); I is the irrigation amount (mm); C is the upward traffic through the root zone; ΔW is the change in soil water storage from 0 to 50 cm between sowing and harvesting; D is the deep leakage; and R is the surface runoff. The terrain of the test area is flat, and no runoff occurred, thus $R = 0$. Because the irrigation method was shallow buried drip irrigation, the irrigation water quota was small, and evaporation occurred easily, so deep leakage was ignored. The groundwater in the test area was kept 7 m below the surface throughout the year, thus the upward flow in the root was not considered.

(3) Water use Efficiency (WUE) [22]:

$$\text{WUE} = GY/ET \tag{3}$$

where WUE is the water use efficiency kg (ha·mm)$^{-1}$; GY is the sugar beet yield (kg ha^{-1}); and ET is the crop water use (mm).

(4) Irrigation water efficiency (IWUE):

$$\text{IWUE} = GY/I \tag{4}$$

where IWUE is the efficient rate of irrigation water kg (ha·mm)$^{-1}$; GY is the sugar beet yield (kg ha^{-1}); and I is the total irrigation amount (mm).

2.3.2. Soil Salinity

$$\text{S}_\text{a} = \sum (S_t \times D_i \times H_i/10) \tag{5}$$

where S_a is the salt reserve of a soil layer; S_t is the salt content of the soil; D_i is the soil bulk density of the soil layer; and H_i is the thickness of the soil layer.

$$\text{N} = (S_1 - S_2)/S_1 \times 100\% \tag{6}$$

where N is the soil salt accumulation rate; S_1 is the soil salt storage before sowing; and S_2 is the soil salt storage after autumn harvest.

(1) Alkalization degree (ESP): Na^+ was determined by flame spectrophotometry, and the cation exchange capacity by sodium acetate flame spectrophotometry.

$$\text{ESP (\%)} = \frac{\text{Exchangeable sodium Na}^+ (\text{cmol kg}^{-1})}{\text{Cation exchange capacity (cmol kg}^{-1})} \times 100 \tag{7}$$

(2) Soil pH value was measured with a THUNDER magnetic portable pH meter.

2.3.3. Stability and Sustainability of Crop Yield

(1) Yield stability: During the harvest period, the average representative yield measured in the middle two lines of each plot was selected to calculate the total yield of corn, and the coefficient of variation (CV) was used to represent the yield stability of sugar beet:

$$\text{CV} = \sigma/\overline{\text{Y}} \tag{8}$$

where σ is the standard deviation of sugar beet yield (t ha^{-1}) of a particular treatment in both years, and $\overline{\text{Y}}$ is the average annual yield of sugar beet of a particular treatment in both years (t ha^{-1}).

(2) Sustainability (SYI):

$$\text{SYI} = (\overline{\text{Y}} - \sigma)/Y_{max} \tag{9}$$

where Y_{max} is the highest yield (t ha^{-1}) at the test site.

2.4. GRA-TOPSIS Comprehensive Evaluation

The conventional TOPSIS approach focuses solely on the relative positioning of each alternative's positive and negative ideals, overlooking the dynamic trends of individual projects [23]. Conversely, the grey relational analysis (GRA) primarily examines the pattern of variation within the data curve [24]. To better account for the data series' position and shape characteristics and achieve more precise decision-making outcomes, this paper introduces the integration of grey analysis and TOPSIS models. Initially, the Euclidean distance between each evaluation object and the positive and negative ideals, as determined by TOPSIS, along with the grey correlation degree between each object and the positive and negative ideals, as calculated by GRA, were normalized. These were then integrated into a singular comprehensive index. Subsequently, the overall closeness is computed based on this comprehensive index. The evaluation objects are then ranked and assessed according to the derived outcomes [25].

The comprehensive correlation degree is characterized by combining the grey attribute of grey relational analysis (GRA) with the Euclidean distance measure inherent to the technique for order of preference by similarity to ideal solution (TOPSIS). This approach effectively ranks the distance between the ideal target and the evaluation object across multiple indicators, enhancing the reliability and validity of the evaluation outcomes [26]. Consequently, the integrated GRA-TOPSIS methodology was employed to assess and analyze the amelioration effects on saline–alkali land.

2.5. Data Processing Methods

Office Excel 2003 was used for preliminary data processing and analysis; SPSS22.0 was used for variance analysis and correlation analysis; and Origin2021, MATLAB R2019b and R4.3.0, and Adobe Illustrator 2021 were used to complete the drawing.

3. Results and Analysis

3.1. Impact on Soil Moisture

Soil Storage Capacity (SWS), Evapotranspiration (ET), Water Use Efficiency (WUE), and Irrigation Water Use Efficiency (IWUE)

As illustrated in Table 2, the soil water storage (SWS) in soil increased proportionally with the irrigation volume in 2021 when the concentration of aluminum sulfate remained constant. This growth initially showed an increasing trend, which subsequently decreased. Across the four aluminum sulfate concentration levels S1 (W1S1, W2S1, W3S1, W4S1), S2 (W1S2, W2S2, W3S2, W4S2), S3 (W1S3, W2S3, W3S3, W4S3), and S4 (W1S4, W2S4, W3S4, W4S4), the increase in SWS varied in the ranges 2.9–20.8%, 8.7–32.4%, 19.4–47.0%, and 19.4–38.7%, respectively, compared to the control treatment (CK). Notably, the S3 treatment, which involved applying aluminum sulfate at 90 g m^{-2}, was the most effective. When the aluminum sulfate concentration exceeded 90 g m^{-2}, the growth rate for soil water storage (SWS) in the 0–50 cm soil layer under the S4 treatment was 4.1% lower than that under the S3 treatment ($p < 0.05$). Additionally, when the irrigation quota surpassed 270 m^3 ha^{-1}, the growth rate for W3S3 significantly decreased by 15.7% compared to W2S3, attributable to the impact of the irrigation volume ($p < 0.05$). The SWS of 0–50 cm soil treated with W2S3 had the same trend for two consecutive years. In 2022, the soil storage effect was the best under the aluminum sulfate dosage of 90 g m^{-2} and the irrigation quota of 270 m^3 ha^{-1}. In addition, the SWS of the 0–50 cm soil mass treated by W2S3 in 2022 increased by 8.9% compared with that treated by W2S3 in 2021.

Table 2. Soil water changes during 2021 and 2022 under each treatment and the coupling effect of irrigation quota (225, 270, 315, 360 m^3 ha^{-1}) and aluminum sulfate dosage (30, 60, 90, 120 g m^{-2}). CK treatment was used as the comparison group, and a W × S four-level test was carried out by two-way ANOVA. Different lowercase letters signify significant differences among various concentrations of aluminum sulfate under the same irrigation quota. In contrast, different uppercase letters denote significant differences between distinct irrigation quotas with a specific aluminum sulfate amount ($p < 0.05$). In the analysis of variance, * and ** indicate that the variable effect reached 0.05 and 0.01 significance levels, respectively.

Handle	2021				2022			
	SWS (mm)	ET (mm)	WUE (kg $ha^{-1}mm^{-1}$)	IWUE (kg $ha^{-1}mm^{-1}$)	SWS (mm)	ET (mm)	WUE (kg $ha^{-1}mm^{-1}$)	IWUE (kg $ha^{-1}mm^{-1}$)
W1S1	33.1 ± 0.7 Cd	585.6 ± 12.5 Da	88.6 ± 1.9 Cb	329.3 ± 7.0 Bb	35.4 ± 0.8 Bd	541.4 ± 11.6 Da	109.0 ± 2.3 Ca	384.4 ± 8.2 Ab
W1S2	36.4 ± 0.8 Bc	584.1 ± 12.5 Da	88.5 ± 1.9 Cb	329.1 ± 7.0 Bb	41.3 ± 0.9 Bc	539.8 ± 11.5 Da	113.5 ± 2.4 Bb	400.2 ± 8.5 Aa
W1S3	40.3 ± 0.9 Ba	584.1 ± 12.5 Da	93.4 ± 2.0 Ca	347.1 ± 7.4 Aa	44.4 ± 0.9 Ba	540.1 ± 11.5 Da	114.5 ± 2.4 Bb	403.5 ± 8.6 Aa
W1S4	38.4 ± 0.8 Cb	585.8 ± 12.5 Da	94.0 ± 2.0 Ca	348.5 ± 7.4 Aa	42.8 ± 0.9 Bb	541.6 ± 11.6 Da	114.2 ± 2.4 BCb	401.3 ± 8.6 Aa
W2S1	38.4 ± 0.8 Ad	616.2 ± 13.2 Ca	112.3 ± 2.4 Aa	346.6 ± 7.4 Aa	40.7 ± 0.9 Ad	571.8 ± 12.2 Ca	133.4 ± 2.9 Ab	390.4 ± 8.3 Ab
W2S2	41.1 ± 0.9 Ac	621.0 ± 13.3 Ca	114.1 ± 2.4 Aa	352.7 ± 7.5 Aa	45.9 ± 1.0 Ac	576.6 ± 12.3 Ca	136.5 ± 2.9 Aab	399.8 ± 8.5 Aab
W2S3	46.2 ± 1.0 Aa	621.7 ± 13.3 Ca	114.3 ± 2.4 Aa	353.7 ± 7.6 Aa	50.2 ± 1.1 Aa	577.4 ± 12.3 Ca	139.7 ± 3.0 Aa	410.1 ± 8.8 Aa
W2S4	43.5 ± 0.9 Ab	622.3 ± 13.3 Ca	113.4 ± 2.4 Aa	350.9 ± 7.5 Aa	47.4 ± 1.0 Ab	578.1 ± 12.3 Ca	137.9 ± 2.9 Aab	404.7 ± 8.6 Aa
W3S1	34.3 ± 0.7 Bc	650.2 ± 13.9 Ba	101.1 ± 2.2 Bb	267.5 ± 5.7 Cb	36.6 ± 0.8 Bc	606.0 ± 12.9 Ba	113.5 ± 2.4 Ba	284.7 ± 6.1 Ba
W3S2	37.2 ± 0.8 Bb	649.6 ± 13.9 Ba	103.1 ± 2.2 Bab	273.2 ± 5.8 Cab	42.0 ± 0.9 Bb	605.3 ± 12.9 Ba	115.5 ± 2.5 Ba	290.4 ± 6.2 Ba
W3S3	41.0 ± 0.9 Ba	648.6 ± 13.9 Ba	105.8 ± 2.3 Ba	280.3 ± 6.0 Ba	45.2 ± 1.0 Ba	604.5 ± 12.9 Ba	116.2 ± 2.5 Ba	291.8 ± 6.2 Ba
W3S4	40.0 ± 0.9 Bb	647 ± 13.8 Ba	103.7 ± 2.2 Bab	274.3 ± 5.9 Bab	44.4 ± 0.9 Ba	602.7 ± 12.9 Ba	116.6 ± 2.5 Ba	292.5 ± 6.2 Ba
W4S1	32.0 ± 0.7 Dc	677.7 ± 14.5 Aa	88.3 ± 1.9 Cb	204.1 ± 4.4 Db	34.3 ± 0.7 Cc	633.5 ± 13.5 Aa	107.8 ± 2.3 Cb	236.2 ± 5.0 Cb
W4S2	33.3 ± 0.7 Cb	679.5 ± 14.5 Aa	88.2 ± 1.9 Cb	204.3 ± 4.4 Db	38.2 ± 0.8 Cb	635.3 ± 13.6 Aa	112.7 ± 2.4 Ba	247.3 ± 5.3 Ca
W4S3	37.1 ± 0.8 Ca	682.8 ± 14.6 Aa	93.4 ± 2.0 Ca	215.9 ± 4.6 Ca	41.3 ± 0.9 Ca	638.6 ± 13.6 Aa	113.9 ± 2.4 Ba	249.6 ± 5.3 Ca
W4S4	37.0 ± 0.8 Db	681.4 ± 14.6 Aa	94.4 ± 2.0 Ca	219.5 ± 4.7 Ca	41.4 ± 0.9 Ca	637.2 ± 13.6 Aa	112.4 ± 2.4 Ba	247.8 ± 5.3 Ca
CK	31.0 ± 0.7	715.5 ± 15.3	81.9 ± 1.8	173.4 ± 3.7	35.3 ± 0.8	671.2 ± 14.3	103.7 ± 2.2	208.4 ± 4.5
				Source of difference				
S	**	—	**	**	**	—	**	**
W	**	**	**	**	**	**	**	**
S × W	*	—	*	*	*	—	—	—

Table 2 reveals that, in 2021, with a constant irrigation amount, evapotranspiration (ET) was inversely correlated with the concentration of aluminum sulfate, displaying a diminishing rate of change as the aluminum sulfate quantity increased. The ET reductions for treatments W1 (W1S1, W1S2, W1S3, W1S4), W2 (W2S1, W2S2, W2S3, W2S4), W3 (W3S1, W3S2, W3S3, W3S4), and W4 (W4S1, W4S2, W4S3, W4S4) were found to be 18.7–19.0%, 13.4–14.4%, 9.4–9.9%, and 4.7–5.4% lower, respectively, compared to the control treatment (CK). Notably, the most significant change in ET was observed in the W2 treatment at an irrigation level of 270 m^3 ha^{-1}. Affected by the concentration of aluminum sulfate, the evapotranspiration (ET) growth rate in the W2 treatment exhibited a significant reduction of 1.3% and 1.1% compared to the W3 and W4 treatments, respectively ($p < 0.05$). Compared with W2S1, W2S2, and W2S3, the W2S4 treatment, respectively, increased by 1.1%, 0.2%, and 0.1%, but there was no significant difference level ($p > 0.05$). Finally, there was a negative correlation between ET and planting years, and the ET of W2S4 treatment in 2022 was reduced by 7.1% compared with 2021.

Compared with CK, the W1, W2, W3, and W4 treatment WUE, respectively, increased by 6.6–12.4%, 32.9–37.1%, 16.4–20.6%, and 5.8–11.9%. As influenced by the concentration of aluminum sulfate, the water use efficiency (WUE) in the W2 treatment was notably higher compared to the other treatments, showing a statistically significant difference ($p < 0.05$). With the increase in aluminum sulfate, the WUE of each treatment gradually increased. The WUE of W2S1, W2S2, W2S3, and W2S4 were, respectively, 50.0%, 52.9%, 55.0%, and 53.3% higher than those of CK. When the amount of aluminum sulfate exceeded 90 g m^{-2}, the increasing trend of WUE began to decline, and the WUE growth rate for the W2S4 treatment was 1.6% lower than that for W2S3. With the increase in planting years, the WUE of each treatment gradually increased, and that of the W2S3 treatment in 2022 was 22.3% higher than that in 2021. The change trend in IWUE was consistent with that for WUE. Compared with the CK treatment, the W2S1, W2S2, W2S3, and W2S4 treatment, respectively, increased the IWUE by 82.4%, 88.2%, 98.1%, and 96.1%. The increase in irrigation water use efficiency (IWUE) for the W2S3 treatment was observed to be 2.0% higher compared to the W2S4 treatment. However, this difference was not statistically significant ($p > 0.05$). Finally, the 2022 W2S3 processing IWUE increased by 0.6% compared to 2021.

3.2. Influence on Soil Salinity

Soil Salt Content (SSC), Desalting Rate, Alkalinity (ESP), and pH

Soil salinity changes under the coupling of aluminum sulfate in straw and irrigation for the two consecutive years are shown in Table 3. As the volume of irrigation increased, the soil salinity in all treatments was lower than the control (CK) treatment. When the irrigation amount remained constant, soil salinity under the W2 treatment showed significant reductions of 1.5–7.5%, 1.0–3.1%, and 3.9–6.5% compared to the W1, W3, and W4 treatments, respectively ($p < 0.05$). When aluminum sulfate was 90 g m^{-2}, the soil salt content of W2S3 treatment was significantly reduced by 5.6%, 5.1%, and 2.4% compared with W2S1, W2S2 and W2S4 treatments, respectively ($p < 0.05$). In 2022, the 0–50 cm soil salt content treated by W2S3 was 6.9% lower than that in 2021.

Table 3. Under the coupling effect of irrigation quota (225, 270, 315, 360 m^3 ha^{-1}) and aluminum sulfate dosage (30, 60, 90, 120 g m^{-2}), soil salinity, and alkalinity of each treatment showed a decreasing trend in 2021 and 2022. CK treatment was used as the comparison group, and W × S four-level test was carried out by two-way ANOVA. Different lowercase letters signify significant differences among various concentrations of aluminum sulfate under the same irrigation quota. In contrast, different uppercase letters denote significant differences between distinct irrigation quotas with a specific aluminum sulfate amount ($p < 0.05$). In the analysis of variance, * and ** indicate that the variable effect reached 0.05 and 0.01 significance levels, respectively.

	2021			2022		
Handle	**SSA**	**ESP**	**pH**	**SSA**	**ESP**	**pH**
W1S1	1.53 ± 0.03 Aa	0.31 ± 0.01 ABa	7.76 ± 0.16 ABa	1.45 ± 0.03 Aa	0.3 ± 0.01 Ba	7.62 ± 0.16 ABa
W1S2	1.49 ± 0.03 Aa	0.3 ± 0.01 ABb	7.75 ± 0.17 Aa	1.34 ± 0.03 Bb	0.29 ± 0.01 Bb	7.6 ± 0.16 Aa
W1S3	1.41 ± 0.03 ABb	0.28 ± 0.01 Bd	7.64 ± 0.16 Aa	1.27 ± 0.03 Bc	0.26 ± 0.01 Bd	7.49 ± 0.16 Aa
W1S4	1.43 ± 0.03 Ab	0.28 ± 0.01 Bc	7.66 ± 0.16 Aa	1.28 ± 0.03 Bc	0.27 ± 0.01 Bc	7.52 ± 0.16 Aa
W2S1	1.45 ± 0.03 Ba	0.28 ± 0.01 Ca	7.61 ± 0.16 Ba	1.31 ± 0.03 Ca	0.27 ± 0.01 Da	7.46 ± 0.16 Ba
W2S2	1.41 ± 0.03 BAb	0.28 ± 0.01 Ca	7.57 ± 0.16 Aa	1.33 ± 0.03 Ca	0.27 ± 0.01 Ca	7.43 ± 0.16 Aa
W2S3	1.35 ± 0.03 Cc	0.26 ± 0.01 Cd	7.51 ± 0.16 Ab	1.25 ± 0.03 Cb	0.25 ± 0.01 Cc	7.37 ± 0.16 Ab
W2S4	1.38 ± 0.03 Bb	0.27 ± 0.01 Bc	7.52 ± 0.16 Aa	1.29 ± 0.03 Ca	0.26 ± 0.01 Cb	7.38 ± 0.16 Aa
W3S1	1.45 ± 0.03 Aa	0.3 ± 0.01 Ba	7.68 ± 0.16 ABa	1.36 ± 0.03 Ba	0.29 ± 0.01 Ca	7.53 ± 0.16 ABa
W3S2	1.43 ± 0.03 AAb	0.29 ± 0.01 BCb	7.64 ± 0.16 Aa	1.34 ± 0.03 Ba	0.28 ± 0.01 Bb	7.5 ± 0.16 Aa
W3S3	1.39 ± 0.03 Bb	0.27 ± 0.01 Bd	7.59 ± 0.16 Aa	1.3 ± 0.03 Bb	0.26 ± 0.01 Cd	7.44 ± 0.16 Aa
W3S4	1.42 ± 0.03 AAb	0.28 ± 0.01 Bc	7.61 ± 0.16 Aa	1.33 ± 0.03 BAb	0.27 ± 0.01 Bc	7.46 ± 0.16 Aa
W4S1	1.54 ± 0.03 Aa	0.32 ± 0.01 Aa	7.88 ± 0.17 Aa	1.46 ± 0.03 Aa	0.31 ± 0.01 Aa	7.74 ± 0.17 Aa
W4S2	1.52 ± 0.03 Aa	0.31 ± 0.01 AAb	7.82 ± 0.17 Aa	1.44 ± 0.03 Aa	0.3 ± 0.01 Ab	7.67 ± 0.16 Aa
W4S3	1.46 ± 0.03 Ab	0.29 ± 0.01 Ac	7.74 ± 0.17 Aa	1.38 ± 0.03 Ab	0.28 ± 0.01 Ab	7.6 ± 0.16 Aa
W4S4	1.47 ± 0.03 Ab	0.3 ± 0.01 ABc	7.79 ± 0.17 Aa	1.39 ± 0.03 Ab	0.28 ± 0.01 Ab	7.65 ± 0.16 Aa
CK	1.67 ± 0.04	0.39 ± 0.01	8.15 ± 0.17	1.57 ± 0.03	0.38 ± 0.01	8 ± 0.17
			Source of difference			
S	**	—	—	**	**	—
W	**	**	**	**	**	**
S × W	—	—	—	**	*	—

As shown in Table 3, for the two consecutive years, the coupling of straw deep-buried aluminum sulfate and irrigation had the same change trend of ESP and pH in the soda saline–alkali soil. With the increased irrigation amount, ESP and pH of the 0–50 cm soil mass first decreased and then increased. With a constant amount of aluminum sulfate, the W2 treatment ESP at 26.5%, which is attributed to the variance in irrigation volume. Compared to the W1, W3, and W4 treatments, the pH reduction in the W2 treatment was 1.7–2.3%, 0.9–1.1%, and 3.1–3.5%, respectively. However, these differences were not statistically significant ($p > 0.05$). When the amount of irrigation was constant, the soil

ESP was negatively correlated with the amount of aluminum sulfate. When the aluminum sulfate was greater than 90 g m^{-2}, the downward trend in soil ESP was slow. The ESP of the 0–50 cm soil mass treated by W2S3, respectively, decreased by 32.3% and 2.9% compared with CK and W2S4. Moreover, the pH of the 0–50 cm soil treated by W2S3 decreased to the lowest value, 7.44, which was 0.2% significantly lower than that treated by W2S4 ($p < 0.05$). Soil ESP and pH were negatively correlated with planting years, and the ESP and pH of the 0–50 cm soil treated by W2S3, respectively, decreased by 5.2% and 1.9%, compared with 2021.

3.3. Impact on Crops

Yield and Sugar Content (SP)

The sugar beet yields of each treatment for the two consecutive years are shown in Table 4. When the amount of aluminum sulfate remains constant, there is a positive correlation between sugar beet yield and irrigation quantity. However, the growth rate initially rises and then declines. Under varying irrigation amounts, the yield of the W2 treatment saw a significant increase, ranging from 20.6% to 21.5%, compared to treatments W1, W3, and W4, with increases of 4.3% to 8.0% and 20.5% to 22.4%, respectively ($p < 0.05$). Conversely, the sugar beet yield gradually rises with increased aluminum sulfate quantity when the irrigation amount is constant. Here, too, the growth rate exhibits an initial increase followed by a decrease. When the irrigation amount is 270 m^3 ha^{-1}, the yield of beet treated with W2S3 reached a maximum of 67 (t ha^{-1}), which was, respectively, 8.6%, 5.3%, and 1.0% higher than that treated with W2S1, W2S2, and W2S4, and the growth rate was 1.3% higher than that treated with W2S4. Moreover, the W2S3 processing output in 2022 increased by 0.6% compared with 2021. According to Formulas (8) and (9), the variation trend in output is closely related to its stability and sustainability (Figure 4). With the combined application of irrigation and aluminum sulfate, the yield variation coefficient (CV) for the W2S3 treatment was the lowest, at 0.06, and the stability was the highest. The sustainability index (SYI) reached a maximum of 0.91.

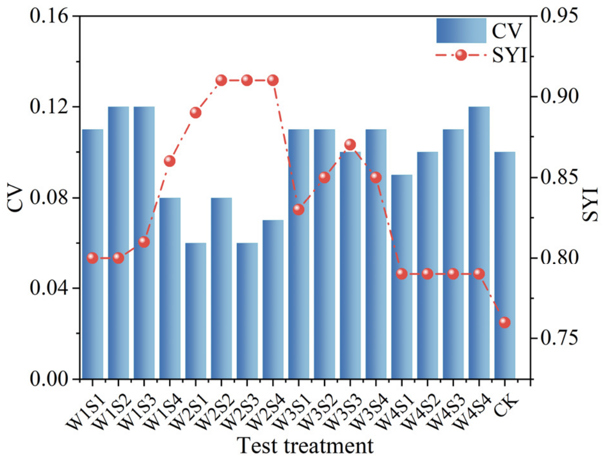


Figure 4. Stability and sustainability of sugar beet yield under the coupling effect of irrigation quota (225, 270, 315, 360 m^3 ha^{-1}) and aluminum sulfate dosage (30, 60, 90, 120 g m^{-2}). Blue bars indicate yield stability (CV); the yellow dot plot shows yield sustainability (SYI).

The coupling of aluminum sulfate with straw buried deep and irrigation achieved the expected increase in sugar yield and high sugar content of sugar beet (Table 4). The sugar yield of all treated beets was higher than that of CK. Among them, the maximum sugar yield of beet treated with W2 was 8.5 (t ha^{-1}), which was significantly increased by 33.3–41.0%, 8.7–17.5%, and 36.7–54.3% compared with W1, W3, and W4S1 ($p < 0.05$). When the irrigation quota was 270 m^3 ha^{-1}, the variation trend in sugar production was W2S3 > W2S4 > W2S2 > W2S1 > CK. Among them, the sugar production growth rate for sugar beet treated with W2S3 was 11.9% higher than that for W2S4. Finally, in 2022, the sugar production of beets treated by W2S3 increased by 1.9% compared with 2021.

Table 4. Changes in yield (t ha^{-1}) and sugar content (t ha^{-1}) for each treated beet in 2021 and 2022 under the coupling effect of irrigation quota (225, 270, 315, 360 m^3 ha^{-1}) and aluminum sulfate dosage (30, 60, 90, 120 g m^{-2}). CK treatment was used as the comparison group, and W × S four-level test was carried out by two-way ANOVA. Different lowercase letters signify significant differences among various concentrations of aluminum sulfate under the same irrigation quota. In contrast, different uppercase letters denote significant differences between distinct irrigation quotas with a specific aluminum sulfate amount ($p < 0.05$). In the analysis of variance, * and ** indicate that the variable effect reached 0.05 and 0.01 significance levels, respectively.

	2021		**2022**	
Handle	**Yield**	**Sugar Production**	**Yield**	**Sugar Production**
	(t ha^{-1})		**(t ha^{-1})**	
W1S1	51.9 ± 0.11 Cb	5.1 ± 0.01 Cc	60.5 ± 0.13 Cb	6.1 ± 0.01 Cc
W1S2	51.8 ± 0.11 Cb	5.4 ± 0.01 Cb	63.1 ± 0.13 Ba	6.6 ± 0.01 Cb
W1S3	54.7 ± 0.12 Ca	5.9 ± 0.01 Ca	63.5 ± 0.14 Ba	7.1 ± 0.02 Ca
W1S4	54.9 ± 0.12 Ca	5.8 ± 0.01 Ca	63.2 ± 0.13 Ba	6.7 ± 0.01 Cb
W2S1	65.5 ± 0.14 Aa	7.2 ± 0.02 Ac	73.8 ± 0.16 Ab	8.1 ± 0.02 Ac
W2S2	66.7 ± 0.14 Aa	7.8 ± 0.02 Ab	75.6 ± 0.16 Aab	9.0 ± 0.02 Ab
W2S3	66.9 ± 0.14 Aa	8.5 ± 0.02 Aa	77.5 ± 0.17 Aa	9.9 ± 0.02 Aa
W2S4	66.3 ± 0.14 Aa	7.9 ± 0.02 Ab	76.5 ± 0.16 Aa	9.2 ± 0.02 Ab
W3S1	59.1 ± 0.13 Bb	6.1 ± 0.01 Bc	62.8 ± 0.13 Ba	6.7 ± 0.01 Bc
W3S2	60.2 ± 0.13 Bab	6.7 ± 0.01 Bb	64.2 ± 0.14 Ba	7.1 ± 0.02 Bb
W3S3	61.8 ± 0.13 Ba	7.2 ± 0.02 Ba	64.3 ± 0.14 Ba	7.5 ± 0.02 Ba
W3S4	6.05 ± 0.13 Bab	0.66 ± 0.01 Bb	6.45 ± 0.14 Ba	0.72 ± 0.02 Bb
W4S1	51.4 ± 0.11 Cb	4.9 ± 0.01 Db	59.5 ± 0.13 Cb	5.9 ± 0.01 Cb
W4S2	51.5 ± 0.11 Cb	4.9 ± 0.01 Db	62.3 ± 0.13 Ba	6.1 ± 0.01 Da
W4S3	54.4 ± 0.12 Ca	5.5 ± 0.01 Da	62.9 ± 0.13 Ba	6.4 ± 0.01 Da
W4S4	55.3 ± 0.12 Ca	5.5 ± 0.01 Da	62.4 ± 0.13 Ba	6.3 ± 0.01 Da
CK	49.1 ± 0.1	4.7 ± 0.01	59.1 ± 0.13	5.7 ± 0.01
		Source of difference		
S	**	**	**	**
W	**	**	**	**
S × W	*	**	—	**

3.4. Integrated Evaluation of TOPSIS and Grey Correlation

3.4.1. Correlation Analysis of a Single Indicator

To establish a reasonable evaluation system, Spearman correlation analysis was conducted on various indexes of soil improvement in saline–alkali soda land (Figure 5). The results showed a significant positive correlation between soil water index and crop index ($p < 0.01$). There was also a significant positive correlation between SWS and SP, and the correlation coefficient was 0.81. The soil salinity indexes were negatively correlated with crop indexes ($p < 0.01$), and SSC, ESP, pH, and SP were negatively correlated, with respective correlation coefficients of −0.67, −0.83, and −0.82. The soil salinity and moisture indexes were negatively correlated ($p < 0.01$), and SWS was negatively correlated with SSC, ESP, and pH, with respective correlation coefficients of −0.89, −0.94, and −0.89.

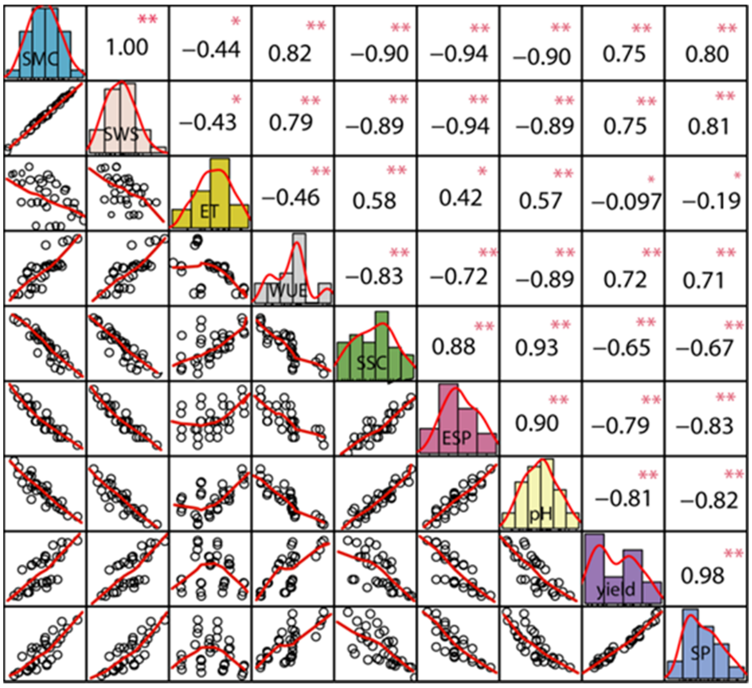


Figure 5. Spearman correlation coefficient (a nonparametric indicator used to measure the relationship between two variables in statistics) among single indicators of saline–alkali land improvement. In correlation analysis, * and ** indicated that $p < 0.05$ was a significant level, and $p < 0.01$ was a very significant level, respectively.

3.4.2. Determining the Weights of Indicators at All Levels

Due to the inevitable overlap between information for each index when a single index is used to reflect the soil improvement, each index plays an indispensable role in reflecting the soil improvement. Therefore, considering the conditions of soil, ecology, and crop growth, the criterion layer of the comprehensive evaluation system for soil improvement, shown in Figure 6, was constructed by dividing the three indexes of water, crop, and salt.

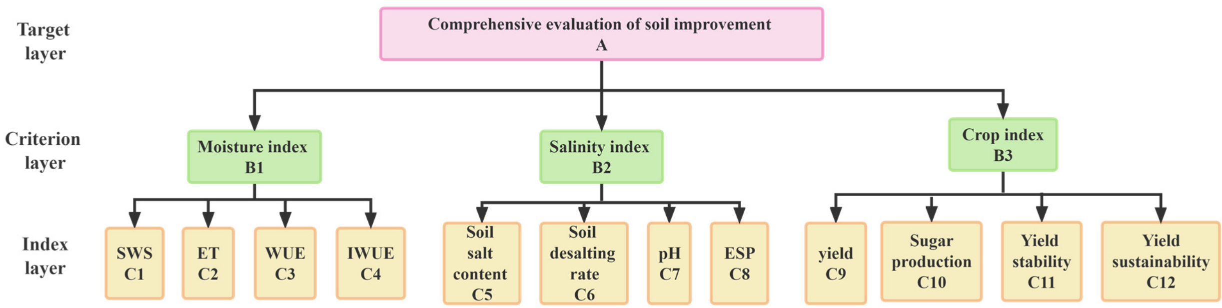


Figure 6. The comprehensive evaluation of soil improvement was carried out according to three categories: moisture index (B1), crop index (B2), and salt index (B3).

The results of determining the objective weight (w_{2j}) based on the entropy weight method are shown in Table 5. The yield stability (C11) weight is 0.109, yield sustainability (C12) weight is 0.103, and minimum pH (C7) weight is 0.036. To improve the rationality and scientificity of weight allocation and further consider both subjective and objective needs, the comprehensive weight for soil improvement indicators (W^*_j) was determined by the combination weighting method of game theory (Table 6). The comprehensive weight of yield sustainability (C12) was 0.116. This was followed by water use efficiency (WUE) (C3), with a comprehensive weight of 0.115, and the comprehensive weight of soil salt content (C5) had a minimum of 0.047.

Table 5. In the comprehensive evaluation process of soil improvement, the score for the single influence index was obtained based on the entropy weight and combined weight methods.

Method	Index C	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Entropy weight method	weight w_{2j}	0.052	0.077	0.084	0.057	0.044	0.052	0.036	0.037	0.075	0.073	0.109	0.103
Combinatorial weighting	weight W_j^*	0.056	0.077	0.115	0.067	0.047	0.060	0.060	0.053	0.077	0.101	0.106	0.116

Table 6. Comparison of soil improvement comprehensive evaluation scores for each treatment measure traditional TOPSIS and coupling of GRA-TOPSIS.

Handle	TOPSIS		GRA-TOPSIS		Handle	TOPSIS		GRA-TOPSIS	
	Score	Sort	Score	Sort		Score	Sort	Score	Sort
W1S1	0.445	15	0.054	16	W3S1	0.583	8	0.060	8
W1S2	0.493	13	0.056	13	W3S2	0.627	5	0.062	5
W1S3	0.548	10	0.059	10	W3S3	0.664	2	0.063	2
W1S4	0.527	12	0.058	12	W3S4	0.646	4	0.063	4
W2S1	0.588	7	0.061	7	W4S1	0.435	16	0.054	15
W2S2	0.615	6	0.062	6	W4S2	0.476	14	0.056	14
W2S3	0.684	1	0.065	1	W4S3	0.554	9	0.059	9
W2S4	0.649	3	0.063	3	W4S4	0.546	11	0.059	11
					CK	0.374	17	0.046	17

3.4.3. Comprehensive Evaluation

First, based on TOPSIS, the Euclidean distance D_i^+ and D_i^- under the coupling mode of aluminum sulfate–irrigation for each treatment was calculated, and the results are shown below:

$$D_i^+ = \{0.621, 0.615, 0.567, 0.566, 0.490, 0.474, 0.391, 0.430, 0.439, 0.389, 0.353, 0.374, 0.653, 0.572, 0.501, 0.514, 0.838\};$$

$$D_i^- = \{0.479, 0.598, 0.687, 0.631, 0.700, 0.756, 0.848, 0.796, 0.613, 0.656, 0.699, 0.683, 0.523, 0.520, 0.622, 0.618, 0.501\}.$$

Second, based on GRA calculation, the grey correlation degrees Y_i^+ and Y_i^- under the irrigation mode of aluminum sulfate for each treatment are shown as follows:

$$Y_i^+ = \{0.991, 0.993, 0.995, 0.994, 0.995, 0.997, 0.998, 0.997, 0.993, 0.995, 0.997, 0.995, 0.992, 0.991, 0.992, 0.992, 0.833\};$$

$$Y_i^- = \{0.834, 0.834, 0.833, 0.834, 0.833, 0.833, 0.832, 0.832, 0.834, 0.833, 0.833, 0.833, 0.834, 0.834, 0.834, 0.834, 0.984\}.$$

Based on the above, the CRA TOPSIS coupling was carried out, and the composite proximity degree is constructed by weighted processing, as shown below:

$$S_i^+ = \{0.735, 0.796, 0.841, 0.813, 0.847, 0.877, 0.924, 0.897, 0.803, 0.825, 0.848, 0.839, 0.758, 0.755, 0.807, 0.805, 0.667\};$$

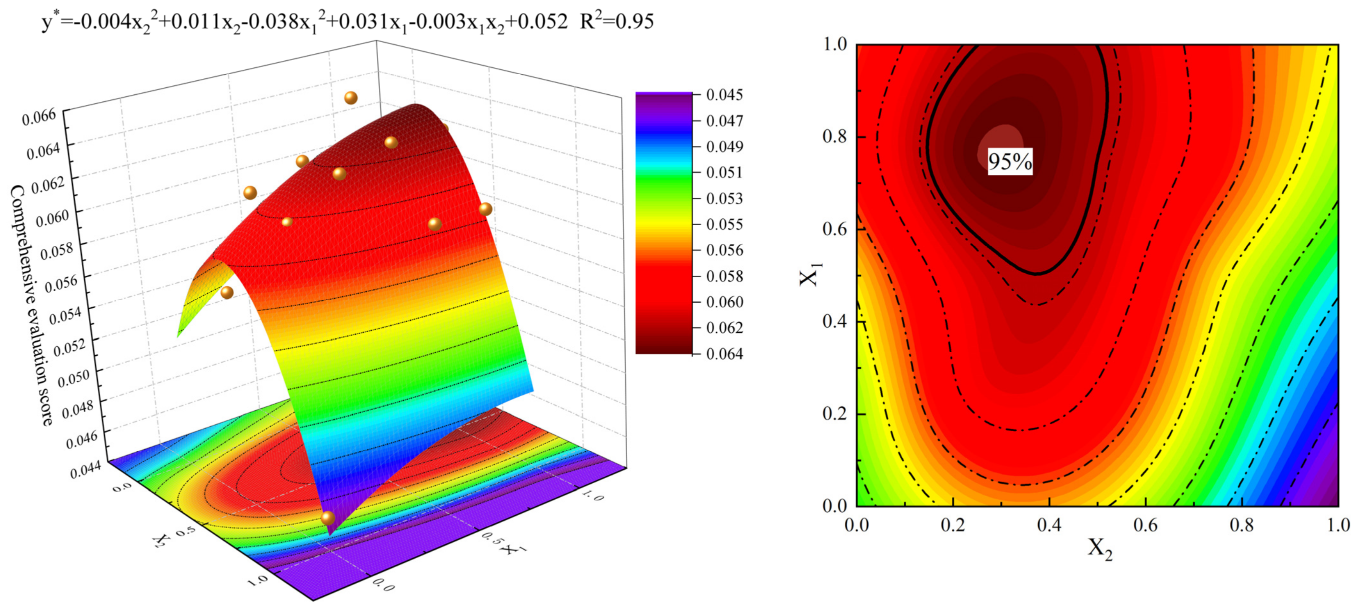
$$S_i^- = \{0.727, 0.725, 0.700, 0.700, 0.662, 0.654, 0.612, 0.631, 0.636, 0.611, 0.593, 0.603, 0.744, 0.703, 0.668, 0.674, 0.911\}.$$

The normalized score table of comprehensive proximity of aluminum sulphate-irrigation coupling treatment was obtained by calculation (Table 6). The W2S3 treatment ranked first in evaluating both the traditional TOPSIS and CRA-TOPSIS methods. The overall ranking difference between the two evaluation methods was only 1, and the Spearman correlation coefficient was 0.969 ($p < 0.01$). Under these two methods, the ranges in soil improvement evaluation were 0.310 and 0.019, and the coefficients of variation were 0.160 and 0.079.

3.5. The Optimal Range for Aluminum Sulfate-Irrigation Strategies Was Determined Based on Comprehensive Evaluation Scores

To further explore the relationship between aluminum sulfate–irrigation and the comprehensive evaluation index of soda saline–alkali land improvement, the aluminum sulfate–irrigation amount was normalized and fitted, and a regression model was established (Figure 7a):

$$y^* = -0.004x_2^2 + 0.011x_2 - 0.038x_1^2 + 0.031x_1 - 0.003x_1x_2 + 0.052, R^2 = 0.95 \quad (10)$$



(**a**) (**b**)

Figure 7. The regulating effect of aluminum sulfate−irrigation coupling on the score for soil improvement comprehensive evaluation, where (**a**) is the model of the relationship between aluminum sulphate−irrigation water and the comprehensive evaluation index of saline−alkali land, where (**b**) is the score−effect mapping.

In the formula, x_1 and x_2 are the coded values for the aluminum sulfate dosage and irrigation quota, respectively, which are 0–1; y* is the score for comprehensive evaluation on improvement of soda–saline–alkali soil by the coupling of aluminum sulfate and irrigation.

Based on Formula (10) and MATLAB simulation optimization, we established a relationship between the comprehensive evaluation index and the combination of aluminum sulfate and irrigation. This allowed us to deduce the appropriate application range for this approach. More than 95% of the highest comprehensive evaluation score was used to determine the optimal application amount of aluminum sulfate–irrigation (Figure 7b). Under the combined application of aluminum sulfate and irrigation, the optimal dosage of aluminum sulfate falls within the range of 61.7–120.0 g m^{-2}, while the ideal irrigation quota is between 250.4–319.4 m^3 ha^{-1}. This combination has yielded the most favorable results in improving saline-alkali soil conditions and enhancing crop growth. This is conducive to realizing the vision of high-efficiency soil improvement and high crop yield for soda salt land.

4. Discussion

The purpose of soda saline–alkali land improvement is efficient utilization of land resources to excellent yield of crops, by coordinating the relationship between soil amendments and irrigation amount. Therefore, exploring the irrigation amount of aluminum sulfate buried in straw is significant to achieve sustainable farmland development. A small amount of multifrequency irrigation can slow the infiltration rate of soil water, reduce the amount of water infiltration, and improve the soil's water-holding capacity [27]. In this study, it was found that SWS in 0–50 cm soil for all treatments was significantly higher than CK ($p < 0.05$), because the applied aluminum sulfate improved the soil water retention capacity [28] and reduced soil liquid loss, thereby significantly increasing the SWS. In addition, this study found that as the deep-buried straw gradually formed an impervious barrier with the evaporation of water, groundwater could only diffuse through the upper soil into the atmosphere in the form of water vapor, thus reducing the ineffective waste of groundwater [29]. The changing trend in the SWS at 20–30 cm was significantly higher than that at the 30–40 cm soil layer. ET is the main form of field water consumption, and an indispensable part of measuring water balance during crop growth. The results showed that the interaction between aluminum sulfate and irrigation could significantly reduce the ET ($p < 0.05$). This may be due to the improvement in soil physical and chemical properties, because more soil water remained in the soil, thus reducing the ineffective evapotranspiration from soil. Previous studies [30] found that soil amendments can inhibit soil evaporation and allow more soil water to be stored for later crop nutrition and reproductive growth. Moreover, combined with controlled irrigation, the volume of rainwater stored in the test field can be increased, and the ineffective evapotranspiration can be reduced [31]. Studies have also found that aluminum sulfate can increase the proportion of water-stable macroaggregates in soil, improve soil pore properties, and reduce ineffective evaporation from irrigation and rainfall [32]. In the present study, crop yield was positively correlated with WUE and IWUE ($p < 0.01$). Controlled irrigation can stimulate crop growth and production potential [33], and further promote improvement in WUE and IWUE. This study also found that a certain amount of aluminum sulfate could significantly increase crop yield and sugar yield ($p < 0.05$). The yield stability and sustainability reached the maximum when the irrigation quota was 270 m^3 ha^{-1} and combined with 90 g m^{-2} aluminum sulfate. By comparing the studies of Elbashier M. et al. [34] regarding the addition of biochar, swamp liquid, and other amendments, it was found that the amendments applied to soil could improve the physical and chemical properties of soil, increase the soil moisture content, promote the net photosynthetic rate of crops, and increase the stem diameter of crops, thus achieving high and excellent yield of crops. Controlled irrigation combined with application can effectively improve the water utilization rate, which has been confirmed in the study by Batool A. et al. [35].

The present study found that the soil salt content under each treatment presents a distribution form of "high at both ends and low in the middle", due to the high soil surface exposure, strong water consumption, and soil salt accumulation. With the irrigation water leaching, the salt in the root zone of crops migrates to the outside of the root layer with the wetting front, forming a desalination and desalination zone [36]. Feng D. et al. [37] found that the amount of irrigation affected the shape of a wetted body. With the expansion in the water-logging area, soil salt content migrated to the depth of soil along the wetted front. Previous studies have shown that because "water follows salt" [38], and that the hydrolysis of aluminum sulfate improves the characteristics of soil chemical composition [12], so that the interaction between aluminum sulfate and irrigation can significantly reduce soil salt content. Although drip irrigation can evenly retain soil water and reduce soil salinity, the results of the present study showed that when the irrigation quota exceeded 270 m^3 hm^{-2}, the soil salt content showed an upward trend, and the desalting rate gradually decreased. This was due to the high adsorption ratio of soda salt and sodium, poor soil infiltration, and excessive irrigation water, resulting in the expansion and decomposition of soil particles, the closure of soil pores, and the obstruction of salt leaching [39]. Since straw and aluminum sulfate are long-term improvement measures, it was found that the soil salt content was inversely proportional to the planting years. In addition, Hinsinger et al. [40] proposed in a study on rhizosphere that organic acids secreted by both crop roots and CO_2 produced by microbial activities could cause a decrease in soil pH and ESP. The variation trend in pH and ESP was found to be the same as that of soil salt content, and there was a significant positive correlation between the two ($p < 0.01$). This may have occurred because the downward leaching activity of base ions (K^+, Ca^{2+}, Na^+) in the soil solution was strengthened with the increase in irrigation water, and a large amount of H^+ generated by the hydrolysis of aluminum sulfate applied to the soil replaced the base ions in the soil. Consequently, the acid–base balance of the soil was broken, and the soil was gradually acidified, thereby reducing the pH and ESP of the soil.

Since straw and aluminum sulfate are long-term improvement measures, to consider the influence of different categories of indicators on soil improvement, the GRA-TOPSIS method was introduced in this study to comprehensively evaluate soil improvement in soda–saline–alkali soil, and to more accurately analyze the rule of aluminum sulfate buried under straw. Due to the overlap among soil water, salt, and crop growth indexes verified by the Spearman correlation coefficient, the correlation among all indexes should be considered in the comprehensive evaluation. To better balance subjective and objective needs, this study used the combination weighting method to assign weights to nine indicators, including SWS, ET, WUE, pH, and yield. Among them, the comprehensive weight of yield stability was the largest (0.116). This was similar to the result of the comprehensive assessment method used by Li et al. [41] in improving saline–sodic soil with flue gas desulfurization gypsum. The goal of building sustainable and cyclic high-standard farmland is finally realized based on the improvement in saline soil. In the soil improvement process, the priority is to achieve a sustainable high yield from farmland, the core goal is to improve the degree of soil salinization, and the coupling of straw–buried aluminum sulfate with irrigation and water is an effective method. The GRA-TOPSIS method results showed that the W2S3 treatment had the highest comprehensive evaluation score when the aluminum sulfate dosage was 90 g m^{-2} and the irrigation quota was 270 m^3 ha^{-1}. This is similar to the idea proposed by Zhao et al. [42], which suggested that the contents of soil organic carbon were significantly increased (13–92%) with different application amounts of rice straw and aluminum sulfate. The GRA-TOPSIS method overcomes the limitation in the accuracy of a single evaluation model, and establishes a regression analysis model based on the evaluation results. The optimal range for soil improvement is an aluminum sulfate dosage of 61.7–120.0 g m^{-2} and an irrigation quota of 250.4–319.4 m^3 ha^{-1}.

5. Conclusions

The interaction of aluminum sulfate buried in straw and irrigation water can effectively alleviate agricultural water shortage, reduce the level of soil salinization, and promote stable and sustainable high yield of field crops. This synergy not only addresses crucial environmental challenges but also bolsters agricultural productivity, ensuring a more resilient and prosperous future for farming. In this instance, the game theory combination weighting method was employed to ascertain the maximum yield sustainability weight, achieving a value of 0.116. Field experiments and a comprehensive GRA-TOPSIS evaluation demonstrated that the W2S3 treatment (aluminum sulfate dosage: 90 g m^{-2}, irrigation quota: 270 m^3 ha^{-1}) is highly effective in mitigating soil salinity. This approach significantly enhances the crop growth environment, leading to a notable increase in crop yield, thereby offering a practical solution to address agricultural challenges related to soil health. Utilizing the GRA-TOPSIS comprehensive evaluation index, a regression model was developed to analyze the interaction between aluminum sulfate and irrigation water. This model revealed that the most effective dosage of aluminum sulfate is 61.7–120.0 g m^{-2}, and the ideal irrigation quota is 250.4–319.4 m^3 ha^{-1}.

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