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Effect of Magnetized Brackish Water Drip Irrigation on Water and Salt Transport Characteristics of Sandy Soil in Southern Xinjiang, China

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Abstract: Xinjiang is short on freshwater resources and rich in ones. The unregulated use of brackish water for agriculture leads to the aggravation of secondary salinization in soil; however, magnetization can improve the quality of brackish water. To evaluate the effects of magnetized brackish water drip irrigation on the water and salt transport characteristics of sandy soil in southern Xinjiang, China, a field plot experiment was carried out in which irrigation water was treated using one or two water magnetization events at different magnetization intensities. Water was treated at five magnetization intensities: 1000, 2000, 3000, 4000, or 5000 Gs, while unmagnetized water was used as the control. The results showed that the magnetization of brackish water used in drip irrigation decreased the water transport rate and increased the water holding capacity of the root layer soil. Magnetized irrigation water enhanced the leaching of soil salt and reduced the rate of salt accumulation. Compared with the control, the salt content of the magnetized water-irrigated soil decreased by 15.0%~33.7%, and the salt storage in the magnetized water-irrigated soil decreased by 44.99%~86.78%. The lowest rate of salt accumulation (4.96%) was observed at a magnetization intensity of 3000 Gs. Magnetized water irrigation changed the composition and proportions of soil ions, and Na^+, Cl^-, and $SO_4{}^{2-}$ leaching from the soil increased. The effect of magnetizing the irrigation water twice was greater than that of one magnetization event. Magnetizing the water twice at an intensity of 3000 Gs led to the largest decrease in the relative percentage contents of Na^+ and Cl^-, which were 80.90% and 82.36%, respectively. The magnetization intensity had a significant effect on the soil carbon and nitrogen contents, which showed a trend of first increasing and then decreasing as the magnetization intensity rose. The total carbon content after irrigation with magnetized water increased by 13.48%~63.35%, and the total nitrogen content increased by 11.73%~147.96%. The magnetization treatment of irrigation water can therefore reduce the risk of soil salinization and reduce salinity stress on crops in arid regions, providing a new method for alleviating the shortage of freshwater resources in Xinjiang and a means to use brackish water safely while improving salinized soil.

Keywords: magnetized brackish water; water salt distribution; salt accumulation; salt ions; soil carbon and nitrogen

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1. Introduction

The shortage of freshwater resources and soil salinization are the main limiting factors for agricultural development in China [1]. Xinjiang, located in the northwest of the country, has one of the widest distributions of saline-alkali land in China. The region extends over about 20 million ha, is mainly distributed in the south of Xinjiang, and accounts for about 1/8 of the land area of Xinjiang and 1/4 of the plain area. It is internationally known as the "World Museum of Saline-Alkali Land" [2]. The southern Xinjiang oasis agricultural area is mostly distributed on the edge of the Taklimakan Desert, located in an arid inland region with little rainfall and strong evaporation, and forms a typical "desert oasis, irrigated agriculture" area. The agricultural land is affected by factors such as the salt content of the soil parent material, the unregulated use of brackish water irrigation, the high salinity of the groundwater, and a large evaporation rate. Long-term drip irrigation has gradually increased the soil salt content, aggravating the risk of secondary soil salinization and seriously restricting the sustainable development of agriculture [3]. Therefore, seeking to alleviate the shortage of freshwater resources and improve soil salinization has become an important proposition for the sustainable development of agriculture.

As a new technology for use in agricultural irrigation, magnetized water irrigation shows great potential for application in agriculture and forestry [4,5]. Magnetized water mainly refers to water standing in or passing through a magnetic field of a certain intensity, vertically or horizontally, at a certain velocity. The former is called static magnetized water, and the latter is known as dynamic magnetized water [6]. After magnetization, the physical and chemical properties of irrigation water change considerably [7], such that the hydrogen bonds of the water molecules become weak, the surface tension of the water decreases, the infiltration increases at the soil surface but decreases from the top layer to the deeper layers [8], the viscosity of the water molecules decreases [9], the association coefficient decreases [10], the conductivity and pH value increase, the dissolved oxygen content increases [11], and the original macromolecular group becomes a single and active small molecular group [12]. Changes in the physical and chemical properties of magnetized water cause the water molecules to be more permeable and soluble during migration, which can promote the dissolution of minerals in the soil and improve the availability of soil nutrients [12].

Previous studies have shown that magnetized water irrigation can effectively promote the leaching of salt from soil, which provides a new idea for improving soil in saline-alkali areas. Magnetized water irrigation can effectively promote salt leaching in cotton growing regions; when the magnetization intensity is at 4000 Gauss (Gs), the soil desalination rate, cotton yield, and water productivity are at the highest [1]. Magnetized water irrigation can promote the downward movement of soil water and salt, increase soil leakage, and increase the leaching of chloride and sodium ions [3]. Magnetized brackish water irrigation increased the absorption and utilization of soil nutrients by crops [13]. Magnetized water irrigation can leach more base ions than ordinary water [14]. The contents of Cl^- and SO_4^{2-}, in the 0–60 cm soil under drip irrigation with magnetized water, decreased significantly [15]. Magnetized water irrigation improved the activities of catalase, amylase, and other enzymes in the soil [16]. Magnetized water irrigation treatment can effectively promote the growth of jujube trees, increase the contents of macroelements and microelements in leaves, and improve the availability of soil nutrients [17]. Compared with unmagnetized treatment, magnetized water irrigation significantly increases the soil desalting rate and cotton yield [18]. Magnetized water irrigation reduced the solubility of soil-soluble salts, and soil salt content decreased with the increase in the number of times the water was magnetized [19].

In general, magnetized water irrigation can, to a certain extent, promote the leaching of soil salts and reduce salt stress in crop roots, which is of great significance to the improvement of saline-alkali land. However, the mechanism of soil desalination under magnetized water irrigation is still unclear. The movement and distribution of soil water and salt, the amount of soil salt leaching, and changes to the levels of base ions in soil solution under different magnetization intensities and magnetization times are still unclear. To address this issue, we investigated the influence of magnetized brackish water drip irrigation on the water and salt transport characteristics of soil in a sandy area of Xinjiang, analyzed the water and salt transport distribution and desalination characteristics of soil under magnetized brackish water irrigation, and explored the best use of magnetized water technology for brackish water and saline-alkali land improvement. The findings provide information for promoting saline-alkali land improvement and ecological recovery in the oasis irrigation area.

2. Materials and Methods

2.1. Experimental Site

The experiment was conducted at the Irrigation Test Station of Pimo Reclamation Area, Kunyu City (37°12′ N, 79°17′ E, altitude 1458 m, average ground slope 5.4%), from April to November 2021 in Xinjiang, China (Figure 1). The experimental site is in an arid inland area, typically known as a desert oasis or irrigated agriculture region. The area has an annual average rainfall of 61.5 mm, an annual average evaporation of 2487 mm, an evaporation-rainfall ratio of more than 30, an active accumulated temperature above 10 °C of 4208.1 °C, an annual average atmospheric temperature of 12.2 °C, and 2769.5 h of sunshine annually. The frost-free period lasts for 244 days. The annual average number of dusty days is about 220 days. Air temperature, precipitation, wind speed, and other meteorological data were recorded by an automatic weather station located 100 m from the study site.

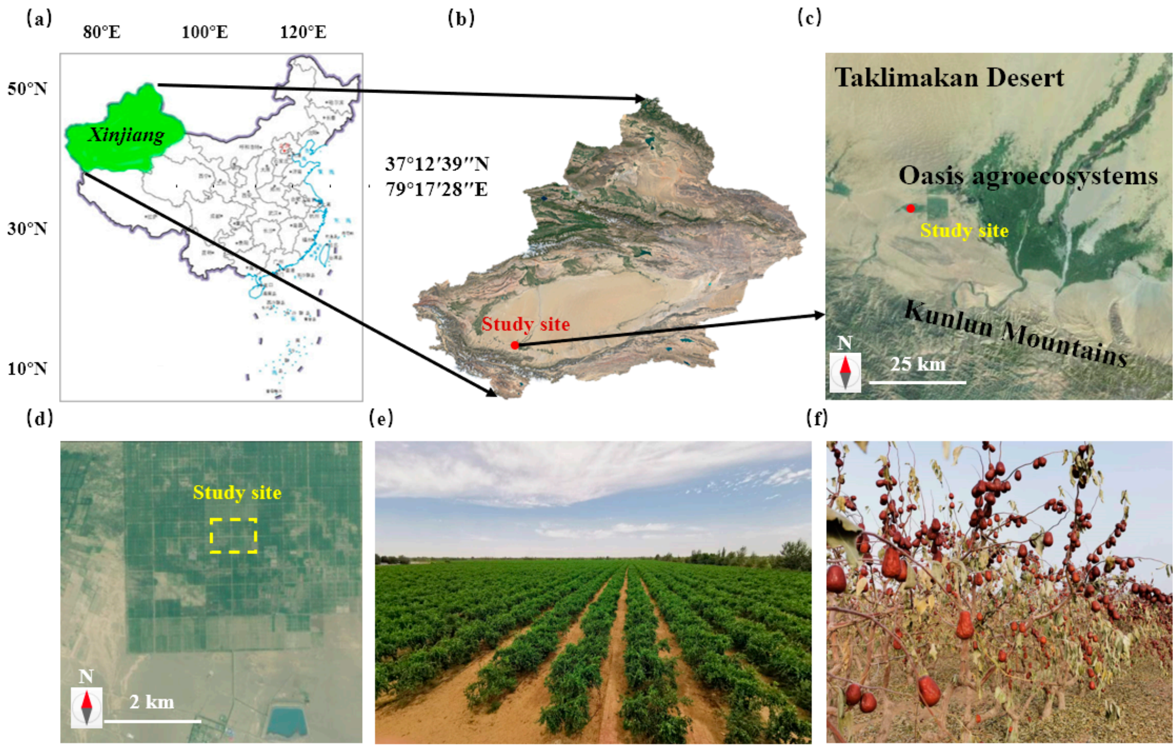

Figure 1. Maps and imagery of the study site. Xinjiang is located in the northwest of China (**a**) and is characterized by an extremely arid desert climate (**b**). High levels of agricultural irrigation are required for the oasis agroecosystems in Xinjiang (**c**). Field experiments were conducted at the Irrigation Test Station of Pimo Reclamation Area (37°12′ N, 79°17′ E) in Kunyu City, Xinjiang (**d**–**f**).

The soil at this site is sandy loam with a pH of 7.88. The depth of groundwater is about 3.0 m, and the maximum depth of frozen soil is 0.67 m. Due to strong evaporation, the problem of soil salinization in this area is serious. The meteorological data during the growth period of jujube is shown in Figure 2. Within the 0–40 cm topsoil, the organic matter, total N, and available P and K are 4.23 g kg^{-1}, 4.82 mg kg^{-1}, 17.61 mg kg^{-1}, and 84.52 mg kg^{-1}, respectively. The physical characteristics of the soil (dry bulk density and field water holding capacity) in different soil layers (0–140 cm) are shown in Table 1.

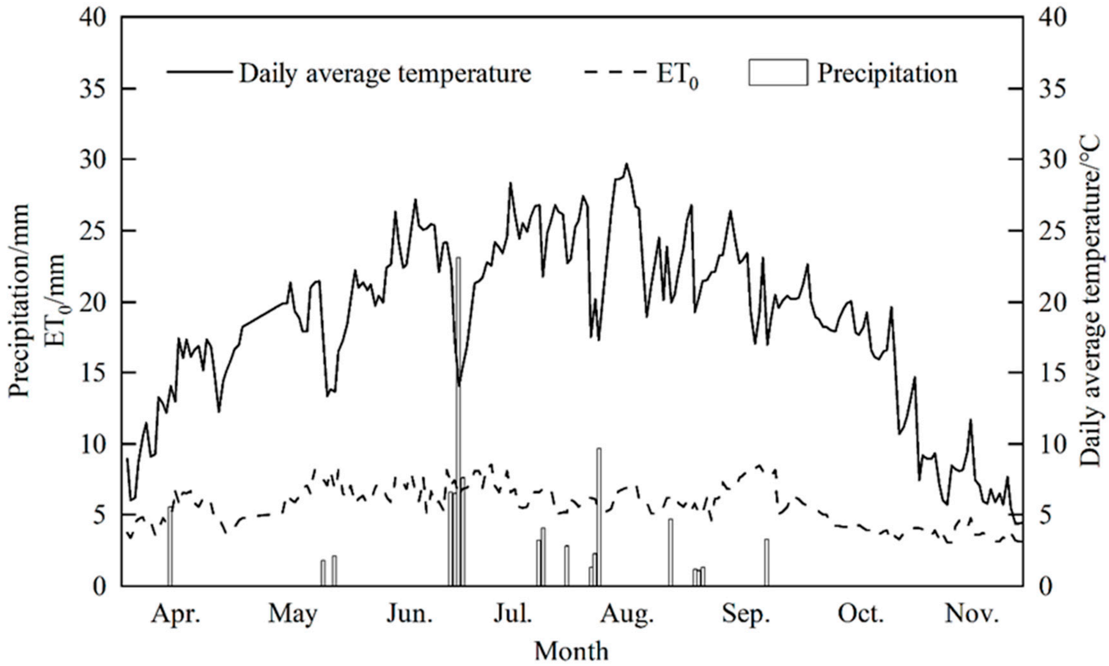

Figure 2. Daily average temperature (indicated by the curves), daily precipitation (indicated by the bars), and ET_0 (reference crop evapotranspiration, indicated by the dashed curve) during the jujube tree growing season at the experimental site in 2021.

Table 1. Particle composition and physical properties of soil layers in the test area (soil dry bulk density and field water holding capacity).

Soil Depth (cm)	Soil Texture	Percentage of Sand (2–0.02 mm)/%	Percentage of Silt (0.02–0.002 mm)/%	Percentage of Clay (<0.002 mm)/%	Dry Bulk Density/(g·cm^{-3})	Field Water Holding Capacity/%	pH
0–20	Sand	89.58	4.69	5.73	1.58	31.28	7.76
20–40	Sand	74.66	13.00	12.35	1.61	30.91	7.72
40–60	Sand	69.58	16.83	13.59	1.61	39.22	7.69
60–80	Sand	63.66	31.73	4.61	1.60	45.57	7.56
80–100	Clay	44.37	4.21	51.42	1.54	31.37	8.15
100–120	Sand	68.92	26.76	4.32	1.77	52.96	7.46
120–140	Sand	73.09	23.47	3.44	1.80	54.22	7.45
Average value	/	69.12	17.24	13.64	1.64	40.79	7.68

2.2. Experimental Design

The random block design was used based on the number of magnetization events and magnetization intensity. The research objects were 12 dwarf, densely-planted jujube trees. The number of times water could be magnetized was set to two, and the magnetization intensity was set to five levels: 1000, 2000, 3000, 4000, and 5000 Gs. The unmagnetized treatment was set as the control (CK). There were 11 treatments (Table 2), with three replicates for each treatment and a protection row between each treatment. There were 33 experimental plots in total, each with a length of 38 m, a width of 4 m, and an area of 152 m^2 (with an area >130 m^2 meeting the requirements of the specification).

Table 2. Combination design of experimental scheme.

Level Factor	Experimental Factors		Experimental Treatment
	Magnetization Frequency (M)	Magnetization Intensity (G/GS)	
0	0	0	CK
1		1000	M1G1 (T1)
2		2000	M1G2 (T2)
3	1	3000	M1G3 (T3)
4		4000	M1G4 (T4)
5		5000	M1G5 (T5)
1		1000	M2G1 (T6)
2		2000	M2G2 (T7)
3	2	3000	M2G3 (T8)
4		4000	M2G4 (T9)
5		5000	M2G5 (T10)

The experimental magnetizer was a permanent agricultural magnet produced by the Inner Mongolia Baotou Magnetic Materials Factory. The permanent magnet was made of sintered Ru iron boron. Magnetizers of different magnetization intensities were fixed to the water supply pipe, vertically to the flow, from pole N to pole S. When the irrigation water flowed through the magnetizer, magnetized water with different magnetic intensities was obtained. A Gauss meter was installed at the end of the pipe to monitor the magnetization of the irrigation water. A schematic diagram of the magnetization system installation in the field plots can be seen in Figure 3.

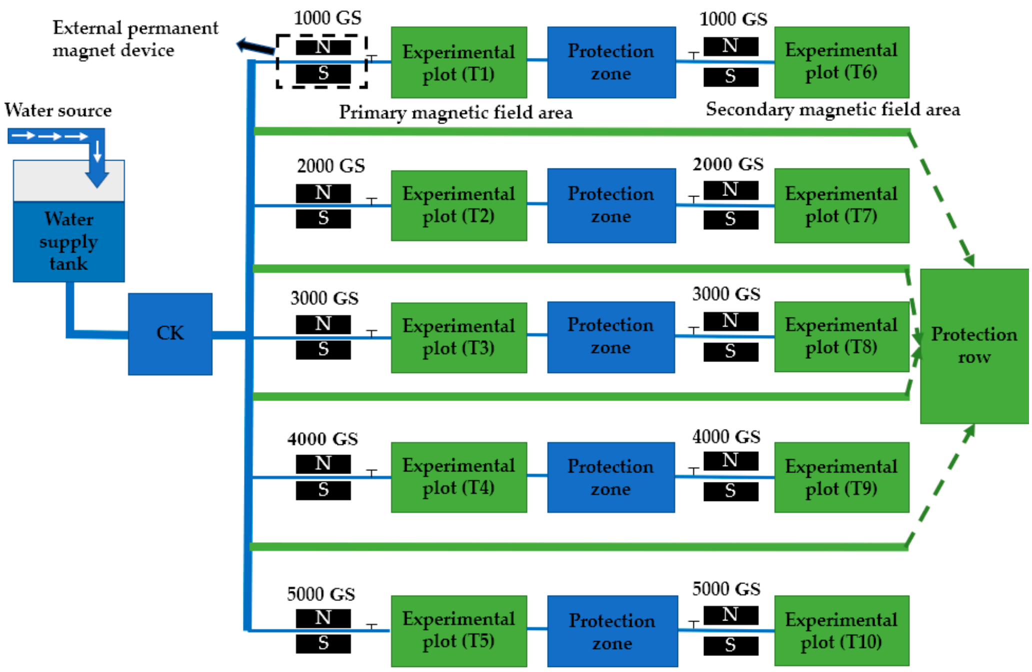

Figure 3. Schematic diagram of magnetization installation and layout in field plots.

The dwarf dense planting mode was adopted for the jujube trees (Figure 4). The row spacing was 4 m, and the plant spacing was 1 m. The plant height was about 2.4 m, and the theoretical planting density was 2500 ha^{-1}. The arrangement of drip tapes was one row of jujube trees to two drip tapes, which were located 20 cm to each side of the trees. The drip irrigation capillary was a single-wing labyrinth of thin-walled drip tape. The distance between the drippers was 30 cm, and the emitter flow rate was 2.6 L h^{-1}. The water supply system in the study area was mainly formed by self-pressure irrigation, with the pressure and regulating valve installed at the head of the system. The amount of irrigation, irrigation dates and frequencies, and fertigation frequencies for all treatments were the same throughout the experiment. The irrigation quota was 6750 m^3 ha^{-1}, and the salinity of irrigation water was generally between 1.6 and 3.0 g L^{-1}. The jujube trees were irrigated 11 times during the whole growth period. The irrigation interval was about 14 days: twice during the budding and new shoot stages, three times during the flowering period, three times during the fruit expansion stage, twice during the white ripening stage, and once during the mature stage. According to local fertilization experience, N fertilizer was applied at 342 kg ha^{-1}, P_2O_5 fertilizer at 171 kg ha^{-1}, and K_2O fertilizer at 257 kg ha^{-1} during the whole growth period. The fertilizer was dissolved in the water used for irrigation. The details of irrigation and fertilization management during the growth period are shown in Table 3. The jujube planting mode is shown in Figure 4.

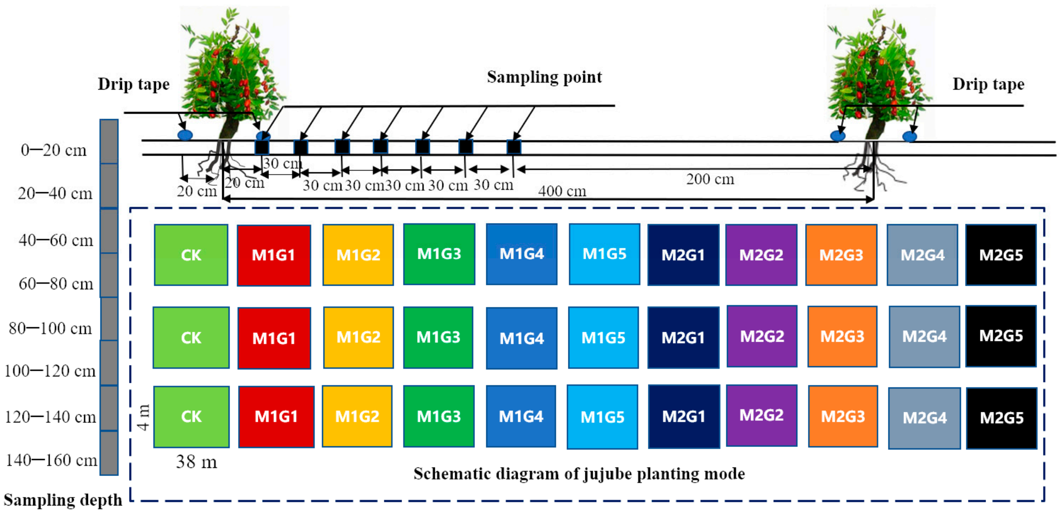

Figure 4. Schematic diagram of jujube planting mode.

Table 3. Irrigation schedule during the jujube growing season in 2021.

Growth Stage	Irrigation Date	Irrigation Quota (m^3/ha)
Budding and new shoot stage	25 April 2021	560
	9 May 2021	560
Flowering stage	23 May 2021	600
	6 June 2021	600
	20 June 2021	600
Fruit expansion stage	4 July 2021	650
	18 July 2021	650
	1 August 2021	650
White ripening stage	15 August 2021	630
	29 August 2021	630
Maturity stage	12 September 2021	620

2.3. Sampling and Field Measurements

2.3.1. Soil Water Content

Soil moisture was measured to a depth of 160 cm at 20 cm intervals during different jujube growth periods by drying and weighing the soil. The sampling point was between 0 and 180 cm away from the drip tape. There were seven sampling points in the vertical drip irrigation belt at intervals of 30 cm (Figure 4). The soil was removed by drilling a hole, which was then backfilled with fine soil. Soil samples were collected using a stainless-steel ring knife (100 m^3). Three replicate soil samples were taken from each sampling point, corresponding to the horizontal position. These soil samples were oven-dried to a constant weight to calculate the gravimetric soil moisture. The volumetric soil moisture content was calculated based on the measured gravimetric soil moisture and soil bulk density. Soil water storage was calculated to a depth of 0–160 cm.

Soil water storage refers to the amount of water stored in a certain area and soil layer. The water storage (C) per unit area (1 m^2) of soil mass at a certain depth was calculated as [20]:

$$C = 10\gamma_i h_i \theta_i \tag{1}$$

where, C is the soil water storage at a certain depth (mm); γ_i is the soil bulk density of layer i (g cm^{-3}); h_i is the soil thickness of layer i (cm); and θ_i is the gravimetric soil moisture of layer i (%).

2.3.2. Soil Salinity and Soil Desalination Rate

Soil samples before irrigation and at different jujube growth stages were taken to measure soil salinity. The oven-dried soil samples were pulverized and passed through a 1 mm sieve. Then, 20 g of soil powder were taken from each sample and mixed at a ratio of 1:5 with water. After being shaken evenly, the mixture was set aside for 2 h. The electrical conductivities ($EC_{1:5}$) of the mixtures were measured using a portable electrical conductivity meter (DDS11-A, manufactured by Shanghai Leichi, Shanghai, China). The residue drying mass method was used to calibrate the total amount of water-soluble salts in the soil. The calibration equation for electrical conductivity and salt content was y = 1.5984x − 0.37 (R^2 = 0.96; n = 21) (Figure 5). The salt storage (S) per unit area (1 m^2) of soil mass at a certain depth was calculated as [21]:

$$S = 10\gamma_i h_i y_i \tag{2}$$

where S is the soil salt storage (g); γ_i is the soil bulk density of layer i (g cm^{-3}); h_i is the thickness of layer i (cm); y_i is the soil salt content of layer i (g kg^{-1}).

Soil desalination rate:

$$P = \frac{S1 - S2}{S1} \times 100\% \tag{3}$$

where P is the desalination rate (%); $S1$ is the initial salt content of the soil before irrigation (g kg^{-1}); $S2$ is the soil salt content at the end of the jujube growth period. $P > 0$ represents soil desalination; $P < 0$ indicates salt accumulation in soil; and $P = 0$ means the amount of soil desalination is equal to the amount of accumulated salt, and the salt content is in equilibrium.

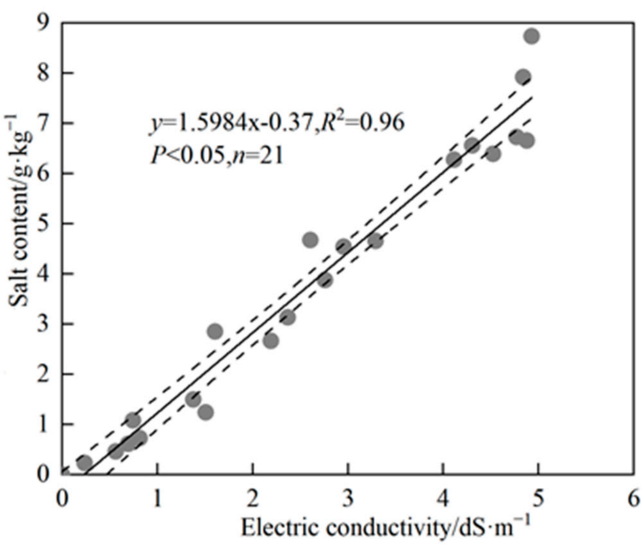

Figure 5. Relationship between soil salt content and conductivity ($EC_{1:5}$).

2.3.3. Soil Salt Base Ions

The sampling time and location were the same as those used for testing soil moisture. The method for determining sample ions is from Li et al. [22]. The Ca^{2+} and Mg^{2+} concentrations were determined by EDTA titration, Na^+ and K^+ by flame photometry, $CO_3{}^{2-}$ and $HCO_3{}^-$ by double indicator-neutralization titration, Cl^- by silver nitrate titration, and $SO_4{}^{2-}$ by EDTA indirect complexometric titration. The results were converted to the same unit (g kg^{-1}). The above measurements were repeated three times for each treatment, and the average value was taken.

2.3.4. Soil Total Carbon and Nitrogen Contents

The total C and N contents of the soil were measured to a depth of 160 cm at 20 cm intervals during different jujube growth periods. The air-dried soil sample was ground through a 0.1 mm sieve, and then a 100 mg soil sample was wrapped in tin foil and weighed using a balance with 1/10,000 accuracy. The total N and C contents of the soil were determined using a CN-802 system (VELP, Monza, Italy). The total C was determined by the nondispersive infrared method, and the total N was determined by the Dumas combustion method.

2.4. Statistics and Analysis

The experimental data were graphed and processed using Origin 9.0 and SPSS 20.0. The SAS package (SAS Institute Inc., Cary, NC, USA) was used to conduct the analysis of variance (ANOVA). Differences were considered statistically significant when $p \leq 0.05$.

3. Results

3.1. Soil Volumetric Water Content

Soil water content during crop growth significantly affected cotton's final crop yield [18]. The effects of different magnetized water treatments on soil volumetric water content during the growth period of jujube are shown in Figure 6. The change trend of average soil volumetric water content in the 0–160 cm soil layer, irrigated with once magnetized and twice magnetized water during the growth period of jujube, was the same, which was to increase first and then decrease over the growth period. The water requirement of jujube at the germination and new shoot stages was small, and the irrigation amount and frequency were low, so the soil water content at the germination and new shoot stages was low. Over the course of the growth period, the water requirement, irrigation frequency, and irrigation amount increased, and the soil water content gradually increased to reach a maximum at the fruit expansion stage. During the maturity stage of jujube, sugars began to accumulate, and the water demand decreased. With the decrease in irrigation water, the soil water content gradually decreased.

Comparing and analyzing the soil water content following one (M1) or two (M2) magnetization events, the average soil volumetric water contents following irrigation with once magnetized and twice magnetized water were 20.2%, 20.8%, 24.7%, 23.4%, 21.3%, and 21.4%, 21.9%, 25.5%, 24.5%, and 22.6%, respectively. The average volumetric water content of soil following M2 was greater than that following M1 under the same magnetization intensity, while under magnetized water irrigation it was greater than under the non-magnetized treatment. The average soil volumetric water content under each magnetization intensity was in the following order: 3000 Gs $\approx$ 4000 Gs > 5000 Gs > 2000 Gs > 1000 Gs > 0. When the magnetization intensity was 3000 Gs, the soil volumetric water content was at its maximum, and when the intensity was 0 Gs, the average soil volumetric water content was at its minimum. Compared with the unmagnetized treatment, the average volumetric water content of soil treated with 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs under M1 and M2 conditions increased by 9.8%, 13.0%, 34.2%, 27.2%, 15.8%, and 16.3%, 19.0%, 38.6%, 33.2%, and 22.8%, respectively.

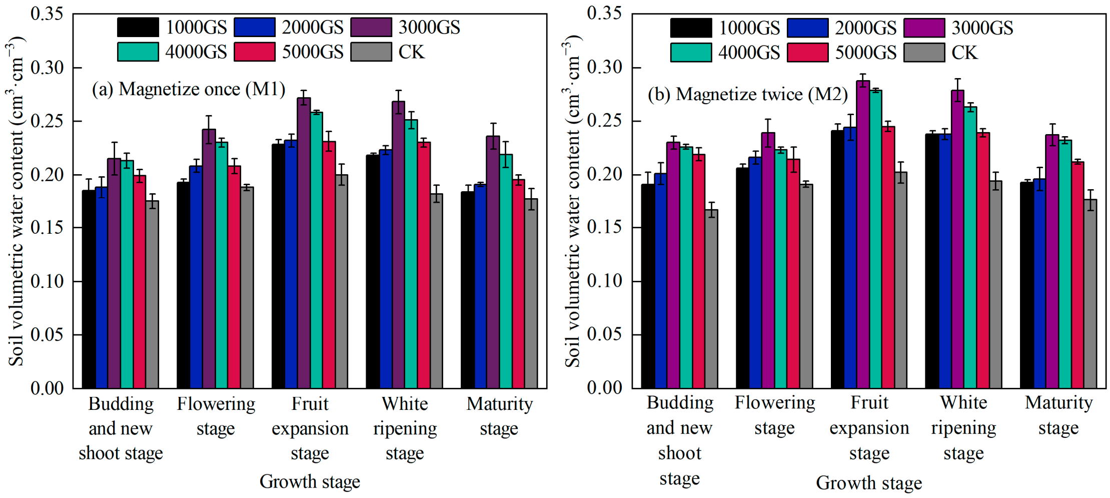

Figure 6. Changes in soil volumetric water content during the growth period of jujube treated with magnetized water drip irrigation. M1 and M2 represent once magnetized and twice magnetized water, respectively.

3.2. Cumulative Change in Soil Water Storage before and after Drip Irrigation with Magnetized Water

The cumulative change in the average capacity to store water in different soil layers was measured 48 h after irrigation with water following different magnetization treatments during the fruit expansion stage (Table 4). Table 4 shows that the cumulative change in soil water storage capacity in different soil layers under magnetized water irrigation was greater than that under unmagnetized water irrigation. The average water storage capacity in the 0–80 cm and 0–120 cm layers of soil irrigated with magnetized water was significantly higher than that of soil treated with unmagnetized water, and the difference between the 0–160 cm soil treatments was small. The amount of infiltration and the downward movement rate were reduced when the soil was irrigated with magnetically treated brackish water.

Table 4. Cumulative change in average soil water storage capacity in different soil layers under magnetized water irrigation treatment.

Treatment	Magnetization Frequency	Magnetization Intensity/Gs	Change of Average Soil Water Storage Δ*C*/(mm)			Ratio of 0–80 cm Soil Water Storage and 0–160 cm Soil Water Storage (Δ*R*)
			0–80 cm	0–120 cm	0–160 cm	
CK	0	0	56.99 d	66.26 d	149.08 b	38.22%
M1G1 (T1)	1	1000	62.20 c	74.56 c	151.91 b	40.95%
M1G2 (T2)		2000	63.31 c	76.95 c	151.34 b	41.83%
M1G3 (T3)		3000	79.35 b	95.90 a	154.71 b	51.29%
M1G4 (T4)		4000	79.53 b	97.38 a	154.11 b	51.61%
M1G5 (T5)		5000	64.33 c	83.86 b	152.08 b	42.30%
M2G1 (T6)	2	1000	66.62 c	79.74 c	153.25 b	43.47%
M2G2 (T7)		2000	69.91 c	81.58 b c	154.08 b	45.37%
M2G3 (T8)		3000	85.07 a	100.62 a	161.98 a	52.52%
M2G4 (T9)		4000	86.51 a	97.49 a	161.39 a	53.60%
M2G5 (T10)		5000	70.52 b	88.69 b	152.34 b	46.29%

Note: The irrigation date is 31 July 2021. The lower case letters within columns indicate significant differences at the 0.05 level.

Analyzing the change in the average soil water storage capacity in the 0–80 cm soil layer under M1 and M2 treatments showed that magnetization of water at 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs increased the soil water capacity by 9.14%, 11.09%, 39.24%, 39.55%, 12.88%, and 16.90%, 22.67%, 49.27%, 51.80%, and 23.74%, respectively, compared with the unmagnetized treatment. Compared with the unmagnetized treatment, the average soil water storage in the 0–120 cm layer increased by 12.53%~51.86% when irrigated with magnetized water, and the average soil water storage in the 0–160 cm soil layer changed only slightly. Under the same number of magnetization treatments, the soil water storage capacity in the 0–80 cm and 0–120 cm layers was in the following order: 4000 Gs > 3000 Gs > 5000 Gs > 2000 Gs > 1000 Gs. Notably, there was no significant difference between the 3000 Gs and 4000 Gs treatments, but capacity was significantly higher than that under the other treatments.

The ratio (ΔR) of 0–80 cm soil water storage and 0–160 cm soil water storage was significantly higher under the magnetized treatment than that under the unmagnetized treatment (Table 4). Under the same magnetization frequency, ΔR was higher under M2 than M1, and the ΔR values were in the following order: 4000 Gs > 3000 Gs > 5000 Gs > 2000 Gs > 1000 Gs. Therefore, magnetized water irrigation increased the water holding capacity of the upper middle layer of the soil.

3.3. Soil Salinity

The distribution of salt in different soil layers during the growth of jujube is shown in Figure 7. The salt distribution under different treatments in the 0–160 cm soil layer was consistent, and the salt content showed the phenomenon of surface concentration. The soil salt content of the 0–60 cm soil layer showed a decreasing trend, and the soil salt content was concentrated in the 80 cm soil layer. The soil salt content of the 100–160 cm soil layer showed a gradually increasing trend, and the average salt content of the 100–160 cm soil layer was greater than the average salt content of the 0–60 cm soil layer. During the fruit expansion stage, water and salt moved to the 100–160 cm soil layer with an increase in irrigation water.

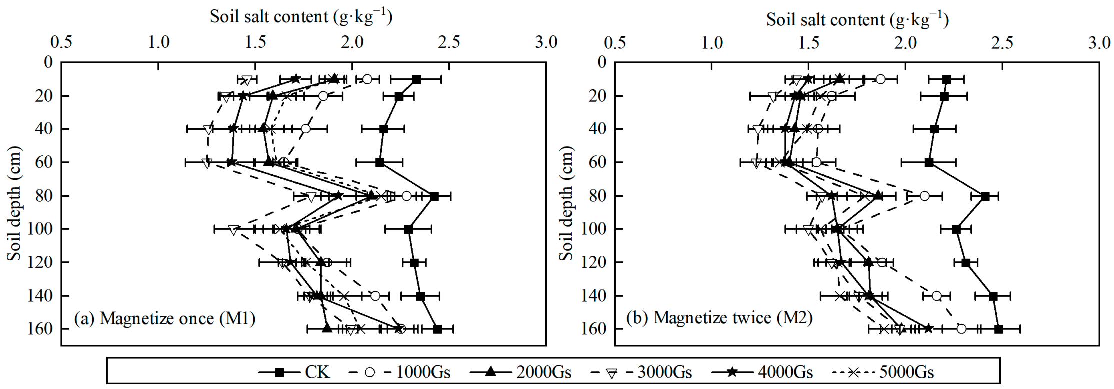

Figure 7. Vertical distribution of salinity content in jujube growth period under magnetized water irrigation.

Under the same number of magnetization events, compared with the CK treatment, the soil salt content under magnetized water irrigation decreased significantly, and the average salt content of the soil under different magnetization intensities was in the following order: 3000 Gs < 4000 Gs < 2000 Gs < 5000 Gs < 1000 Gs < CK. Compared with the CK treatment, the average soil salt content under the 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs treatments following M1 and M2 decreased by 15.0%, 22.8%, 32.8%, 26.3%, 21.3%, and 19.0%, 26.8%, 33.7%, 29.3%, and 29.0%, respectively. Following magnetization at 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs, the average soil salt content under M2 decreased by 5.2%, 5.6%, 1.8%, 4.5%, and 3.3% compared with M1, respectively. When the magnetic intensity was 3000 Gs, the salt content of the 0–80 cm soil in the root layer of jujube was relatively low, and the desalting effect of two magnetization events was better than that of one magnetization event.

3.4. Effect of Magnetized Brackish Water Irrigation on the Salt Balance of Jujube before and after Its Growth Period

The change in soil salt storage in the 0–160 cm soil layer before and after the growth period of jujube under magnetized brackish water irrigation is presented in Table 5. The 0–160 cm soil layer treated with magnetized brackish water showed salt accumulation. Under the same number of magnetization events, the change in salt storage for each treatment was in the following order: 3000 Gs < 4000 Gs < 5000 Gs < 2000 Gs < 1000 Gs < 0 s, and the change in salt storage in the M2 treatment was significantly lower than that in the M1 treatment. Under the M1 and M2 treatments, the salt accumulation rates following magnetization at 0 Gs, 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs before and after the growth period of jujube were 39.37%, 22.44%, 18.69%, 9.96%, 16.42%, 16.05%, and 16.35%, 9.58%, 4.96%, 8.27%, and 12.59%, respectively. The soil salt accumulation rate following M2 and 3000 Gs treatments was the lowest, while that in the unmagnetized treatment was the highest.

Table 5. Changes to salt storage in the 0–160 cm soil layer before and after the growth period of jujube under magnetized brackish water irrigation.

Treatment	Magnetization Frequency (M)	Magnetization Intensity (Gs)	Average Initial Salt Storage of Soil before Irrigation (g)	Soil Salt Storage after Harvest (g)	Change in Salt Storage (ΔS g^{-1})	Desalination Rate (%)
M1G1 (T1)		1000	4265.10	5222.10	−957.00	22.44
M1G2 (T2)		2000	4836.21	5740.06	−903.85	18.69
M1G3 (T3)	1	3000	5411.99	5950.9	−538.91	9.96
M1G4 (T4)		4000	3887.56	4525.82	−638.26	16.42
M1G5 (T5)		5000	4521.32	5247.18	−725.86	16.05
M2G1 (T6)		1000	4864.26	5659.66	−795.40	16.35
M2G2 (T7)		2000	4952.13	5426.31	−474.18	9.58
M2G3 (T8)	2	3000	4652.89	4882.97	−230.08	4.96
M2G4 (T9)		4000	5012.64	5427.26	−414.62	8.27
M2G5 (T10)		5000	3987.46	4489.31	−501.85	12.59
CK	0	0	4419.58	6159.4	−1739.8	39.37

Compared with the CK treatment, the change in soil salt storage before and after the growth period of jujube under treatments 1–10 (see Table 5) decreased by 44.99%, 48.05%, 69.02%, 63.31%, 58.28%, 54.28%, 72.75%, 86.78%, 76.17%, and 71.16%, respectively. Compared with the unmagnetized treatment, magnetized water irrigation significantly reduced the soil salt content.

3.5. Soil Salt Base Ions

The effect of magnetized water irrigation treatment on the percentage of anion and cation groups in the 0–100 cm soil solution can be seen in Figure 8a,b. Before magnetized water irrigation, the relative percentages of Na^+, Ca^{2+} + K^+, Cl^-, and $SO_4{}^{2-}$ were high in the initial soil ion composition. The relative percentage of the cation Na^+ was 40%–70%, and the relative percentages of anions Cl^- and $SO_4{}^{2-}$ were 75%–95% (Figure 8a). The percentages of the anion and cation groups in the soil solution changed significantly at the end of the growth period after irrigation with magnetized water. The percentages of Ca^{2+} + K^+ and Mg^{2+} among the cations in the 0–100 cm soil solution increased, while the percentage of Na^+ decreased significantly. The relative percentages of Cl^- and $SO_4{}^{2-}$ decreased significantly, while the relative percentages of $CO_3{}^{2-}$ and $HCO_3{}^-$ increased, indicating that the composition and proportion of soil salt base ions were changed by magnetized water irrigation and that the leaching effect of magnetized water irrigation on Na^+, Cl^-, and $SO_4{}^{2-}$ was more obvious.

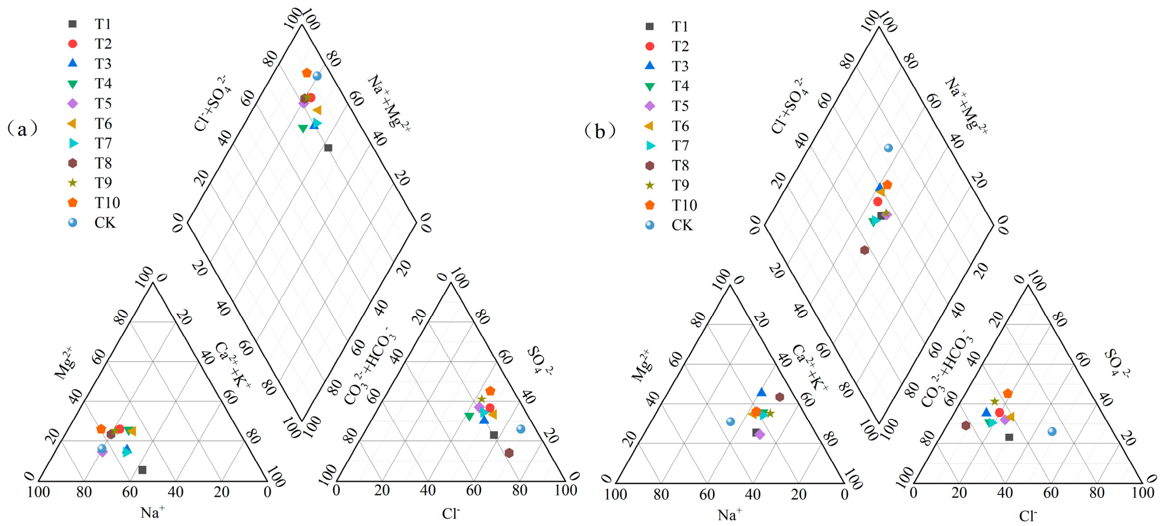

Figure 8. Piper plots of soil salt ions under different magnetized water irrigation treatments. The Piper diagram shows the composition and evolution characteristics of the main ions in the soil solution irrigated with different magnetized water treatments [23–25]. (**a**) the initial percentage ratio of soil salt ion groups under different treatments before magnetized water irrigation; (**b**) the percentage ratio of soil salt ion groups at the end of the growth period of jujube under different magnetized water irrigation treatments.

Under the same magnetization intensity, the leaching effect of twice magnetized water on the concentrations of Na^+, Cl^-, and $SO_4{}^{2-}$ in soil was more significant than that of once magnetized water. Compared with the CK treatment, the relative percentage content of Na^+ and Cl^- in each treatment decreased by 24.67%~82.36%, and the relative percentage content of Na^+ and Cl^- decreased by 80.90% and 82.36%, respectively, under the M2 treatment at 3000 Gs. Cl^- and Na^+ are the main salt ions that cause soil salinization [3]. Magnetized water irrigation can leach more Na^+ and Cl^- out of the soil, thereby reducing the harm caused by soil salinization, which is of great significance to the improvement of saline soil.

3.6. Soil Total Carbon and Nitrogen Contents

The total C content of 0~100 cm soil irrigated with magnetized water was 59.02–84.96 $mg \cdot g^{-1}$, and the total N content of the soil was 2.19–4.86 $mg \cdot g^{-1}$. The total C and N contents of soil irrigated with unmagnetized water were 52.01 $mg \cdot g^{-1}$ and 1.96 $mg \cdot g^{-1}$, respectively (Figure 9). Compared with the unmagnetized water irrigation treatment, the total C content when magnetized water was used for irrigation increased by 13.48%–63.35%, and the total N content increased by 11.73%–147.96%. Under magnetization intensities of 1000 Gs, 2000 Gs, 3000 Gs, 4000 Gs, and 5000 Gs, the total C content of soil under the M2 treatment increased by 12.03%, 8.92%, 6.9%, 11.42%, and 9.39%, and the total N content increased by 28.02%, 57.53%, 11.88%, 26.23%, and 10.91%, respectively, compared with the M1 treatment. Magnetization intensity increased the soil C and N contents, which increased further with the magnetization intensity. Under M1 and M2, when the magnetization intensity was 3000 Gs and 4000 Gs, the soil total C and N content was relatively high, and there was no significant difference between the 3000 Gs and 4000 Gs treatments.

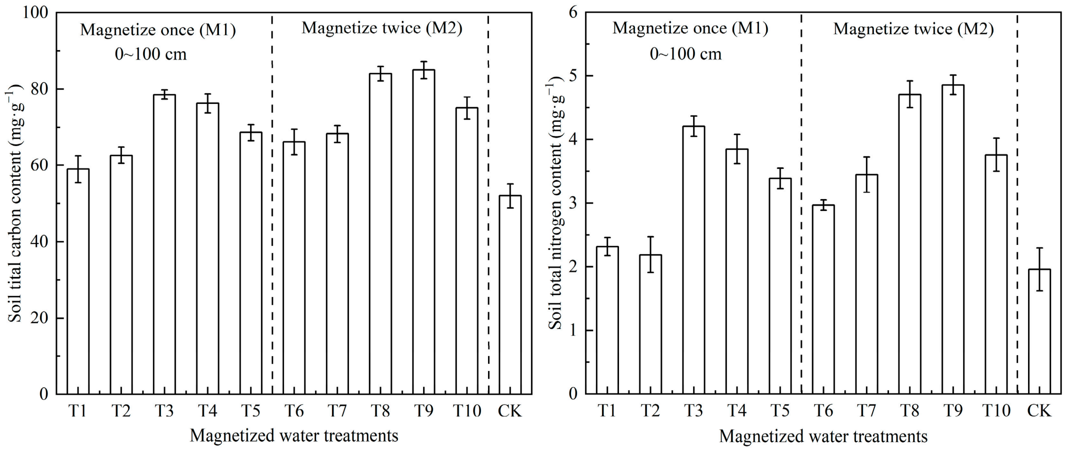

Figure 9. Effects of magnetized water irrigation treatment on total carbon and total nitrogen content in the soil root layer of jujube.

4. Discussion

The results revealed that drip irrigation with magnetically treated brackish water could reduce the water transport rate and improve the soil's water holding capacity. After being treated at different magnetization intensities, the average soil water content was greater than that under the unmagnetized treatment (Figure 6), which was consistent with the results obtained by Peng et al., who found that magnetized water drip irrigation enhances soil water retention and effectively improves soil water content [18]. Magnetized irrigation water can change the distribution of water and salt in salinized soil and improve soil water holding capacity and salt leaching capacity. [26,27]. This finding was consistent with our study. The properties and functions of the irrigation water following magnetization changed significantly, which promoted the infiltration of water through the soil surface [28]. Cai et al. [29] concluded that as the surface tension of brackish water decreases, the viscosity increases, and the activation energy of water molecules increases after being magnetized at a constant velocity in the magnetic field. In addition, water molecules form new hydrogen bonds during the magnetic treatment process. Magnetized water irrigation increases the water content of the upper soil layer and reduces water infiltration into the deep soil [4], which is consistent with our findings. The results also show that magnetization of brackish water at low concentration penetrated the upper soil profile more slowly, thus reducing deep seepage and retaining more water in the upper layers, in agreement with Guo et al. [30]. Our results also confirm this conclusion. In our study, after being magnetically treated at different intensities, the average water content of soil increased by 9.8%~38.6%. The reason for this increase is likely related to the fact that the original structure of the water molecular group changes [31,32] after magnetization treatment and the osmotic pressure increases [33], which causes more water to enter soil pores, thus increasing soil water content.

According to the soil salt distribution and leaching effect under magnetic brackish water drip irrigation, magnetic water irrigation reduced the soil salt content of the 0–80 cm soil layer, which corresponded to the soil layer around the roots of the jujube trees. Magnetized water irrigation enhanced the leaching of soil salt and reduced the soil salt accumulation rate. The composition and proportion of soil salt base ions were changed by magnetized water irrigation, and the leaching effect of magnetized water irrigation on Na^+, Cl^-, and SO_4^{2-} was more obvious. The salt leaching effect was most significant under the M2 treatment at 3000 Gs. These findings were consistent with previous studies. A relatively low magnetization can increase the viscosity of water, resulting in stronger hydrogen bonds under the magnetic field, which will make more water surround the soil particles, which is conducive to salt desalination [34]. However, once the magnetic field was too large, calcium ions and carbonate ions were prone to collide in opposite directions due to their opposite charges, thus hindering the desalination of salt [4]. Magnetized water irrigation can promote soil desalination, significantly reduce the contents of exchangeable and total sodium in soil, and be conducive to improving the soil salinization environment [12]. Magnetized water irrigation can promote the downward movement of soil salt and enhance the leaching of soil salt ions Cl^- and Na^+ but has little impact on HCO_3^-, and the effect of secondary magnetization is greater than that of primary magnetization [35]. Magnetized water irrigation not only leached Cl^- significantly but leached HCO_3^- and Na^+ more than unmagnetized water [14]. The contents of Cl^- and SO_4^{2-} in the 0~60 cm soil layer decreased significantly under mulched drip irrigation with magnetized water [15]. Magnetized water improves the solubility of various minerals [36]. The activity of magnetized water is enhanced, and the ability to dissolve salt is improved. The salt leaching efficiency increases first and then decreases with magnetization [4]. This finding was consistent with our study. In our study, magnetized water irrigation enhanced the leaching of soil salt and reduced the soil salt accumulation rate. The reason may be that the structure of the water molecule changes after magnetization, the viscosity and association degree of water decrease, the solubility of soluble salt increases, and the salt leaches into the deep soil [37].

Compared with the unmagnetized treatment, the total C content increased by 13.48%–63.35% and the total N content increased by 11.73%–147.96% when irrigated with magnetically treated brackish water, and showed a trend of first increasing and then decreasing with magnetization. In general, the use of magnetized water irrigation in saline-alkali land can increase the leaching effect of soil salt, reduce the percentage contents of Na^+ and Cl^- in soil, improve the soil microenvironment, reduce the harm caused by salt to crops, and help improve the physiological activity of crop roots. These findings provide theoretical support for the application of magnetized water irrigation technology in agriculture.

5. Conclusions

Soil salinization is an important factor affecting agricultural development in arid oasis regions. A field experiment was carried out to study the mechanism behind the influence of magnetized brackish water drip irrigation on soil water and salt transport in a typical dryland area of southern Xinjiang, China. The results revealed that drip irrigation with magnetically treated brackish water could reduce the water transport rate and improve the soil's water holding capacity. Magnetized water irrigation enhanced the leaching of soil salt and reduced the soil salt accumulation rate. The lowest soil salt accumulation rate was 4.96% under treatment with water twice magnetized at 3000 Gs. The composition and proportion of soil salt base ions were changed by magnetized water irrigation, and the leaching effect of magnetized water irrigation on Na^+, Cl^-, and SO_4^{2-} was more obvious. Moreover, the effect of the twice magnetized water was greater than that of the once magnetized water. The relative percentage contents of Na^+ and Cl^- decreased the most, to 80.90% and 82.36%, respectively, under treatment with water twice magnetized at 3000 Gs. Magnetization intensity had a significant increasing effect on soil C and N contents, which first increased and then decreased with the magnetization intensity. Magnetized water irrigation can reduce the risk of soil salinization, reduce the salt stress of crops in arid areas, and provide a theoretical basis for the use of magnetized water technology to alleviate the shortage of freshwater resources and safely use brackish water.

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