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Effect of magnetic water irrigation on the improvement of salinized soil and cotton growth in Xinjiang

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ABSTRACT

To study the effect of magnetic water irrigation on the improvement of different salinized soils and the growth of cotton in Xinjiang, field experiments were conducted in three salinity soils (slight, medium, and heavy salinity soils), with five intensities of magnetized irrigation water (0 GS (CK,G0), 1000 GS (G1), 3000 GS (G3), 4000 GS (G4), and 5000 GS (G5)). Magnetized irrigation water can change the distribution of water and salt in all salinized soils, increase the water holding capacity and salt leaching of soil, and reduce the soil salt contents in the soil profile. It is better for the improvement on slight saline soil was better than on medium and heavy saline soils; the G3 treatment had the strongest effect by increasing soil water content by 33.2%−56.2% and improving the desalination rate by 29.2%−50.4%, compared to the control. Magnetic water irrigation significantly increased cotton growth. A negative relationship was found between soil salt content and plant growth characteristics (plant height, stem diameter, leaf number, leaf area index, and chlorophyll SPAD). Under the different intensities of magnetic water treatment, cotton growth indexes showed the same trends: CK < G1 < G5 < G4 < G3 in all three salinized soils. (3) Compared with the control treatment, magnetic water treatment can increase cotton yield and water use efficiently. Maximum water use efficiency and yields were obtained when the magnetization was 3000GS, in which the water use efficiency was increased by 27.4–42.8%, and the yield was increased by 28.8–31.69% compared with control. In this region, irrigating with magnetized water with 3000GS could improve saline soil quality and cotton growth, especially in slight salinity soil.

1. Introduction

In arid and semi-arid regions, sustainable agricultural development is significantly influenced by water resources. In China, the agricultural water consumption is 376.64 billion m^3, accounting for more than 60% of the total human water consumption (Li et al., 2016). Due to high evaporation and low precipitation in the arid and semi-arid areas of China, especially in Xinjiang, water resource shortages restrict local agriculture development. Saline-alkali soil is widespread which seriously influences plant growth and yield due to its physical and chemical properties. In addition to improper field management and irrigation, soil secondary salinization is also a big problem. In order to address these problems in Xinjiang, film-mulched drip irrigation methods are widely used to effectively moderate soil evaporation, prevent the risk of soil degradation, and increase water-use efficiency (WUE) and crop yields (Tan and Wang, 2017).

In order to reduce the water and salt stress, research on magnetized water and magnetization started in the 1960s, which there has been paid increased attention as an efficient and sustainable utilization method (Kney and Parsons, 2006; Mostafazadeh et al., 2011). Up to now, kinds of devices have been produced, but the performing mechanism is almost the same. When water passes through the magnetized field, its structure and physical characteristic such as density, salt solution capacity, and deposition ratio of solid particles will be changed which has great beneficial for soil improvement and plant growth (Ahmed and Bassem, 2013; Higashitani et al., 1993; Liu et al., 2019).

Thereafter, magnetized water has been widely used for agricultural irrigation. It has been found that magnetized water treatment can promote seed germination, crop growth, increase yield, and improve fruit quality (Jia et al., 2019; H.B. Wang et al., 2018; Y. Wang et al., 2018). Haq et al. (2016) studied the effect of magnetized water treatment on the germination of radish seeds, and found that the germination rate, emergence rate index, vigor index I, and vigor index II were all increased by 28.33%, 11.54%, 57.59% and 32.26%, respectively. Magnetization

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treatment also promoted the growth of corn, rape, and other crops (Anand et al., 2012; Pietruszewski and Kania, 2010; Belyavskaya, 2004). Hozayn et al. (2016) evaluated the effect of magnetized water on the growth, yield, and WUE of rape Which showed that magnetized water irrigation significantly improved the plant growth parameters, such as plant height, fresh and dry weight, as well as soil water content. Patil (2014) treated different types of irrigation water with magnetic treatments, and the results indicated that the magnetic water could significantly improve plant yield and water productivity. In addition, magnetized water has a positive effect on crop root development, photosynthesis, and enzyme activity (Sayed, 2014; Turker et al., 2007; Liu et al., 2019).

Furthermore, magnetized water can indirectly improve the soil environment. Hachicha et al. (2016) found that the content of salt, Na^+ and Cl^- in the soil irrigated by electromagnetic salt water was significantly lower than that irrigated by non-electromagnetic salt water. With a field experiment, Constable (2006) found that the desalination rate under magnetized water irrigation was higher than that of ordinary water irrigation in a field experiment, and Hilal et al. (2013) reported a similar conclusion. Khoshravesh and Kiani (2014) studied the permeability of magnetized water into soil, and found that the cumulative infiltration rate and final infiltration rate of magnetized water were much higher than those of non-magnetized water, and magnetized irrigation water had the greatest impact on the infiltration capacity in clay soil.

However, most of previous researches focus on how magnetized water promote crop growth, yield, and soil properties in unsaline soil. Little literature concerns about the magnetized intensity and soil salt contents. Based on the above problems, this study explores the influence of magnetized water on the distribution of soil water and salt in different degrees of salinized soil, analyzes the influence of different magnetized density water on the growth characteristics and yield of cotton. This study will provide a method for using magnetized technology to improve saline-alkali land quality, and provide a theoretical guide for land use efficiency and WUE.

2. Materials and methods

2.1. Experimental site description

The experimental site was located at the Bazhou Irrigation Experimental Station (41°33′N , 86°12′E) in the suburbs of Korla in southern Xinjiang, an autonomous region in north-western China. The area has a continental desert climate, with an annual precipitation and maximum potential evaporation (20 cm diameter evaporation pan) of approximate 58 mm and 2788.2 mm, respectively. The long-term seasonal (April to October) reference evapotranspiration (ET_0) and rainfall are 950 and 47 mm, respectively. The average maximum and minimum temperatures during the cotton growing season are 29.1 ℃ and 15.8 ℃, respectively (Tan et al., 2018). The buried depth of groundwater is below 5.1–7.8 m, and the salinity of groundwater is 1.87–2.001 $g \cdot L^{-1}$.

2.2. Experimental design

The experiments were performed at the late seedling stage (16 June 2017 and 14 June 2018) to ensure good seeding emergence for all plots. Three levels of salinized soil (slight salinized soil, medium salinized soil, and heavy salinized soil) and five intensities of magnetized irrigation water [CK 0gs (G0), 1000gs (G1), 3000gs (G3), 4000gs (G4) and 5000gs (G5)] were established as treatments in a randomized block designed with three replicates, and the total number of the plots was 45. In order to obtain five intensities of magnetized irrigation water, the tap water were subjected to the five different magnetic field (established by constant magnetic field, CK 0gs (G0), 1000gs (G1), 3000gs (G3), 4000gs (G4) and 5000gs (G5)). Each block was 5 m × 5 m and adjacent plots were separated by a partition (buried depth of 1.7 m) to eliminate lateral movement of soil water between plots.

Cotton (*Gossypium hirsutum* L.), the variety called No.55 Xinzhong Road, was sown after plowing on 26 April 2018 and 3 May 2018 at a density of 22 seeds m^{-2}. The planting pattern and drip line arrangements in the field followed the local practice of “one film, two drip lines and four rows” (Fig. 1).

The field was flooded irrigated in mid-April each year, two weeks before sowing, to provide sufficient water and to leach salt from the soil for cotton emergence and seedling growth. The total amount of flood irrigation was about 300 mm for each year, and the water was derived from the Kongque River with a salinity of 0.8 $dS \cdot m^{-1}$. The irrigation mainly concentrated at squaring, flowering and early boll stages (55–115 DAS). The experiment ended in late August in the four experimental years. Four rows of cotton were covered by one white plastic film 110 cm in width and irrigated with two drip lines with emitter intervals of 30 cm and a discharge rate of 2.0 L h^{-1}. The width of the bare strip between a pair of mulches was 30 cm. The irrigation schemes during both growing seasons are illustrated in Fig. 2 (Tan et al., 2018). Table 1.

2.3. Data collection and calculation

2.3.1. Crop index measurement

In all treatments, the number of cotton seeds planted in each plot was recorded, and the number of cotton emergence was recorded every day until all seedlings emerged. The ratio of the total number of seedlings to the seeds planted in cotton was calculated.

In each plot, 6 cotton plants (3 in the inner group and 3 in the outer group) were selected and marked. After that, plant height, stem diameter, leaf number, leaf area, as well as chlorophyll of cotton were measured every 15 days. Four cotton plants were randomly selected from each plot during each growth period and measured using drying method. The number of harvested plants, effective bell and weight of single bell were also measured in each plot.

2.3.2. Soil water content and salinity

Soil samples under the mulch were collected to determine the soil water content and salinity simultaneously at a 10-cm interval from 0 to 40 cm and at a 20-cm interval from 40 to 100 cm by using an auger with 5-cm diameter. The soil samples were collected at the main cotton growth stages (seedling, squaring, flowering, initial boll-opening, and full boll-opening stage). All auger holes were refilled with soil to minimize the experimental error after each sampling. The soil samples were weighed, dried in a oven at 105 ± 2 °C for 24 h, and reweighed to determine the gravimetric SWC (soil water content). Volumetric SWC was then obtained by multiplying the gravimetric SWC with certain soil bulk density which was measured every 10 cm of the whole soil profile. A DDS-307A conductivity meter (Shanghai Precision &Scientific Instrument Inc., Shanghai, China) was used to measure the electrical conductivity in a 1:5 soil:water extract at 25 °C.

2.4. Calculation and analysis methods

2.4.1. Salt accumulation calculation

To study the effect of magnetized water irrigation on soil salt accumulation during cotton growth, soil salt accumulation amount from later seedling stage to harvest during the both seasons was obtained according to the salt balance formula, which was as follows:

$$\Delta S = S2 - S1 = S_R + S_I + S_G + S_S + S_F - S_C - S_P - S_D \quad (1)$$

Where ΔS is the change of soil salt before and after irrigation in growth period (g); S1 is the soil salt storage at the beginning of period (g); S2 is the soil salt storage at the end of period, S_I is the increase of irrigation salt (g); S_F is the increase of fertilization salt (g); S_R is the increase of rainfall salt (g); S_G is the increase of groundwater supply salt (g); S_C is

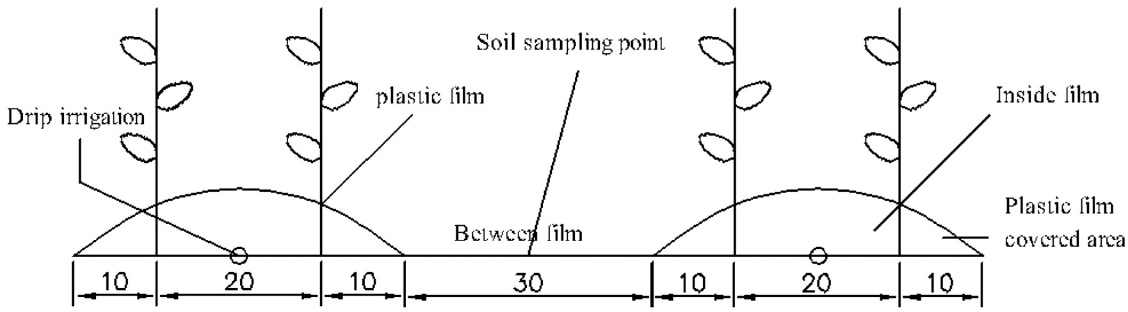

Fig. 1. Planting and drip-line arrangement in the experimental plots.

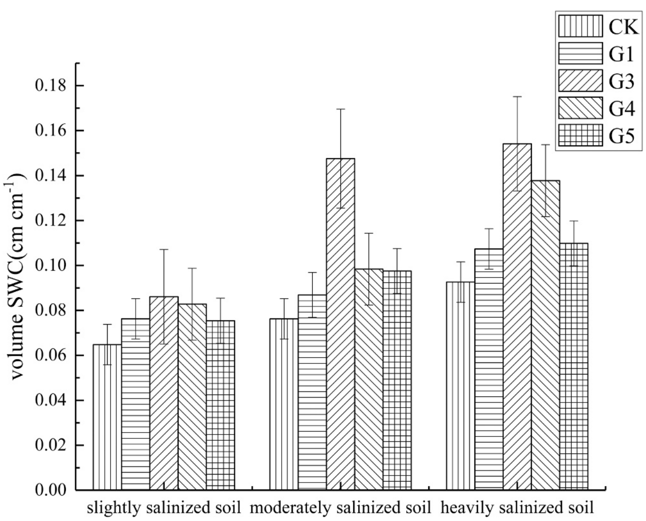

Fig. 2. Effects of magnetized water on the average water content in 0–100 cm soil depth at different saline-alkali soils Re: SWC means the soil water content; G0, G1, G3, G4, G5 represent five intensities of magnetized irrigation water of 0gs (CK), 1000gs, 3000gs, 4000gs and 5000gs.

the salt absorption consumption of crops (g); S_P is the salt precipitation, S_D is the salt loss of drainage leakage (g).

To analyze the desalination effect of different treatments for the whole growth period, the desalination rate was calculated as follows (Lu et al., 2017),

$$P = \frac{S1 - S2}{S1} \times 100\% \quad (2)$$

Where, P is the desalination rate, and $p > 0$, it means soil desalination, $p < 0$ means soil salt accumulation, and $p = 0$ means salt balance.

2.4.2. WUE calculation

Water consumption of cotton was calculated by the water balance method (Thevs, 2014):

$$ET_a = P_r + I + \Delta W - R - D + K \quad (3)$$

Where ET_a is the actual crop water consumption of crops, P_r is the rainfall during the growth period, I is the amount of irrigation, and ΔW is the change of soil water storage in the soil layer. R is the surface runoff, D is the amount of leakage, K is the amount of groundwater recharge, and all quantities are in mm. The influence of precipitation in the whole growth period (21.1 mm) and groundwater depth (>5 m) is small, which can be ignored. The irrigation mode is drip irrigation under the film, which does not produce surface runoff and deep leakage, and therefore, R and D can be ignored.

Water use efficiency is calculated based on cotton yield and crop water consumption (Lu et al., 2017):

$$\mathrm{WUE} = \frac{\mathrm{Y}}{\mathrm{ET_a}} \quad (4)$$

Where WUE is water use efficiency, kg/(hm^2 mm), and Y is cotton yield (kg/hm^2).

2.4.3. Statistical methods

SPSS (Statistical Product and Service Solutions) software (version 21.0, IBM Corporation, USA) was used to conduct statistical analyses. The soil water amount was analyzed for average and standard deviation for each treatment ($n = 3$). The analysis of one-way variance was used to determine if there were differences between treatments.

3. Results and discussion

3.1. Effect of magnetized irrigation water on soil water content and salt distribution

3.1.1. Effect of magnetized irrigation water on soil water content

The average volumetric water contents in 0–100 cm soil layer of

Table 1
Soil physical properties in experimental field, sowing date and basic irrigation practices.

soil	Soil particle size composition/%		Soil type	Bulk density (g/cm^3)	Initial salt content (g/kg)	Sowing date	Irrigation start date	Irrigation end date	Number of irrigations	Total irrigation amount (mm)
	Clay ≤ 0.002 mm	Silt> 0.002 ~ 0.05 mm								
Slightly salinized soil	3.65	29.97	Sandy loam	1.67	3.27	22 April	27 June	5 Sept.	15	487.5
Medium salinized soil	3.1	18.8	Loam sandy soil	1.61	7.23					
Heavily salinized soil	2.64	13.79	sand	1.56	10.4					

salinized soil with different magnetization intensities are shown in Fig. 2. Fig. 2 shows that the average volumetric soil water content irrigated with different magnetized intensities in light salinized soil is less than that in medium and heavy salinized soil. The total average moisture content of light, medium, and heavy salinized soil was 0.077, 0.101 and 0.12 cm^3 cm^{-3}, respectively. The reason for this result may be that the higher the soil salinity, the lower the osmotic pressure of soil water, which will inhibit the effectiveness of soil water, and reduce the water absorption by cotton roots (Guo et al., 2013). In addition, the magnetization has an effect on the volumetric water content when applied to soil with the same degree of salinization. When the magnetization intensity was 3000GS, the soil moisture content was significantly higher than in other treatments. For slight salinized soil, the volumetric moisture content of each magnetization treatment (G1,G3,G4,G5) increased by 18.5%, 34%, 29%, and 16.6%, compared to the CK treatment, respectively. For medium salinized soil, the volumetric moisture content of each treatment increased by 14.2%, 92.5%, 28.6%, 27.1% compared to the CK treatment(G0), respectively. For heavy salinized soil, the volume moisture content of each treatment increased by 15.4%, 65.2%, 47.8%, 17.8% compared to the CK treatment, respectively. When average over all soil salinities, the soil volumetric water content of different magnetization intensities were G0 < G1 < G5 < G4 < G3. This is due to the fact that after the irrigation water was magnetized, the macromolecules decomposed into smaller molecules, which increased the mobility of water, allowing the water to enter into smaller soil pores, and then improved the water retention and the soil water content in soil profile (Hachicha et al., 2016). After magnetization, the physical and chemical properties of water molecules change (H.B. Wang et al., 2018; Y. Wang et al., 2018), and when applied to soil, magnetized water will alter soil water movement, affecting irrigation water infiltration as well as soil water storage. For this reason, irrigating with 3000GS magnetized water resulted in the greatest soil water holding capacity.

Fig. 3 shows the volumetric water content changed with different growing periods in the 0–100 cm soil layer under the magnetized water irrigation of different intensities. It can be seen in Fig. 3 that the volumetric water content of 0–100 cm soil layer in different degrees of salinized soil decreased with the changing of time after sowing, and the volumetric water content increased between treatments in the initial boll-opening stage.

This is because cotton was in the initial boll-opening stage, and with increased vegetative growth with an increase in irrigation frequency. As a result, the water absorption and consumption capacity of the root system increased as well as soil water holding capacity and the relative volumetric water content. Compared with saline-alkali soil with the same magnetization intensity, the volumetric water content first decreased and then increased with increased salinization in the seedling stage, and increased with an increasing degree of salinization after the squaring stage. The main reason may be that with the increase of salt ions in the soil, the salinity in soil water increased, and as a result, the available water that can be absorbed by crops decreased, leaving relatively more water in the soil.

3.1.2. Effect of magnetized irrigation water on soil salinity

The distribution of salt content of 0–100 cm soil layer in the whole growth period under irrigation with different intensities of magnetized water is shown in the Fig. 4. The soil salt content of each treatment decreased first and then increased with changes in the growing period. At the early stage of cotton growth, the evapotranspiration is lower and the magnetized irrigation water will improve salt leaching, which will reduce the salinity of the soil solution, and reduce the salt content of the soil. After the squaring stage, the temperature increased and the irrigation frequency increased, which made the evapotranspiration increase. Evapotranspiration brought salt from the deep soil layers to the soil surface, which resulted in salt accumulation. When soil is irrigated with the same intensity of magnetized water treatment, the average soil salt content in the whole growth period from A, B and C treatments were 2.26, 6.09, and 8.08 g kg^{-1}, respectively. Compared with the initial salt content, the salt content of the three salinized soils decreased by 30.9%, 15.8%, and 22.3% respectively.

Compared with control treatment, the salt content in slight salinized soils irrigated with different magnetization treatments (G1,G3,G4,G5) decreased by 8.1%, 27%, 17.8%, and 17.5%, respectively. For moderate salinized soil, the salt content decreased by 5%, 18.5%, 7.9%, 10.1%, and 2.3%, respectively, while in heavy salinized soil, the soil salinity decreased by 19.7%, 14.9%, and 12.5%. When averaged over all soil salinities, the salt content of G3 was the lowest in the whole growth period. The salt content of G3 was the lowest in the whole growth period. In general, the salt content of soil irrigated different magnetization treatments was CK > G1 > G5 > G4 > G3. After magnetization, the physical and chemical properties of water, such as surface tension, contact Angle, and viscosity coefficient were changed, so that water molecules can enter smaller pores in the soil and then can remove salt from those pores easily, thus increase salinity leaching efficiency. However, once the magnetization was too high, the ions in water and soluble salt ions in soil will gather to form large grain precipitate, which reduced the solubility of salt in soil, as well as water association degree

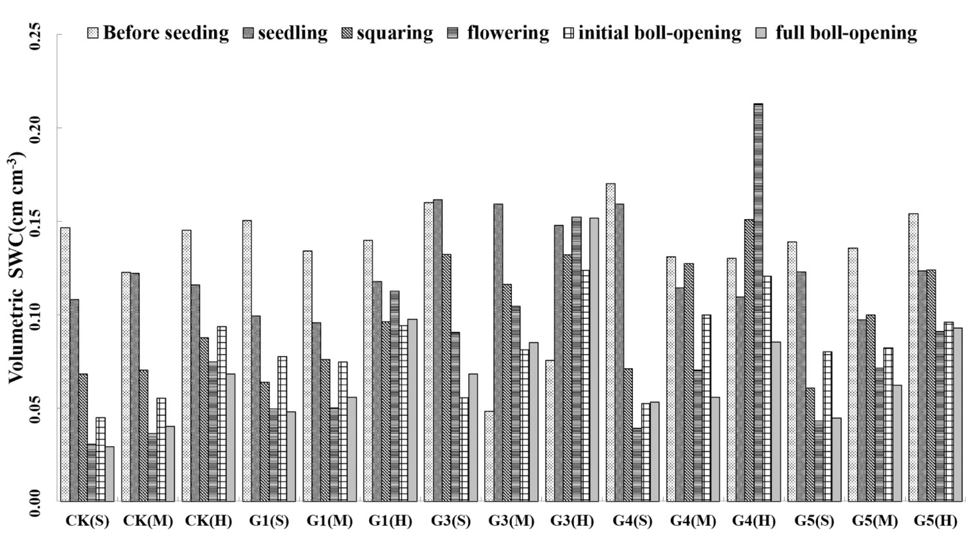

Fig. 3. Effects of magnetized water on dynamic changing of water content in the 0–100 cm soil layer at different saline-alkali soils Re: G0, G1, G3, G4, G5 represent five intensities of magnetized irrigation water of 0gs (CK), 1000gs, 3000gs, 4000gs and 5000gs; S,M,H represent slight, moderate, heavy salt contents.

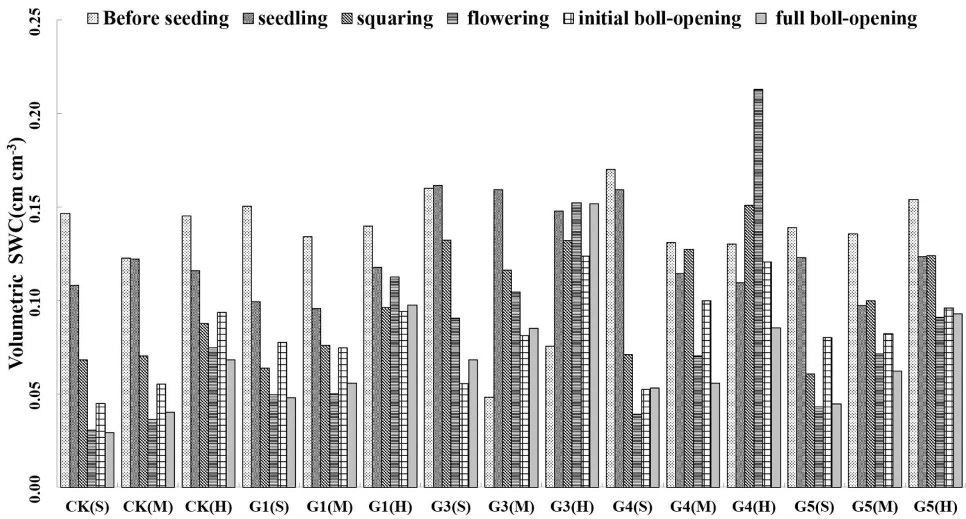

Fig. 4. Effects of magnetized water on changes in salt content in the 0–100 cm soil layer at different saline-alkali soils Re: G0, G1, G3, G4, G5 represent five intensities of magnetized irrigation water of 0gs (CK), 1000gs, 3000gs, 4000gs and 5000gs; S,M,H represent slight, moderate, heavy salt contents.

and viscosity of magnetized water, which impeded salt leaching (Pietruszewski and Kania, 2010). The G3 treatment magnetized water has the most significant effect on soil desalination.

3.1.3. Effect of magnetized irrigation water on desalination rate of soil

To study the effect of magnetized water on soil salt desalination during the whole growth period, the salt accumulation characteristics of the 0–100 cm soil layer during the whole growth period of cotton were analyzed according to the formula of soil salt balance (Table 2). Table 2 showed that all the treatments have a desalting trend in the 0–100 cm soil layer with irrigation. With further comparison of the desalination in three levels of salinized soils, it can be seen that the average amount of desalination in heavy salinized soil is greater than that in medium and slight salinized soil. The average desalination rate of slight salinized soil was greater than that of heavy salinized soil, and the lowest desalination rate was obtained in medium salinized soil. Further analysis showed that magnetization greatly influenced the desalination in all three levels of salinized soils. The desalination rate of slight salinized soil was 26.1%, 25.9%, 50.4%, 45.4%, and 29.7% under each magnetization treatment (G1,G3,G4,G5). The desalination rate of medium salinized soil was 12.9%, 11%, 29.2%, 18.5%, and 13.2%. The desalination rate of heavy salinized soil was 21.6%, 24.8%, 48.5%, 36%, and 16.6%. When averaged over all soils, the desalination effect was as follows: CK < G1 < G5 < G4 < G3, of which G3 also had the greatest positive effect on salt desalination. Similarly, according to the findings, when the magnetization is G3, the desalination effect and leaching water efficiency reached their maximum, indicating that magnetized was easily leached reducing soil salination. Ghauri et al. have found that a relatively weak magnetic influence (field) can increase the viscosity of water and consequently caused the stronger hydrogen bonds under the magnetic field which will keep more water around the soil particles and good for salt desalination (Hilal et al., 2013). But once the magnetic influence was too high, the calcium and carbonate ions tend to collide due to opposite directions because of their opposite charges, which will prevent salt desalination (Wang et al., 2020).

3.2. Effect of magnetized irrigation water on emergence rate and growth characteristics of cotton in different levels of salinized soil

3.2.1. Effect of magnetized irrigation water on emergence rate

Soil salinization in Xinjiang is serious, and salt stress easily causes a degree of damage to cotton seeds. Table 3 showed the emergence of seedlings in slight, medium, and heavy salinized soil under different magnetized irrigation water treatments. From Table 3 it could be seen that the emergence rate of slight salinized soil was 15% higher than that of medium salinized soil, and the emergence rate of medium salinized soil was 15.7% higher than that in heavy salinized soil. Higher soil salinity lowers soil fertility and the quality of soil nutrients, which will damage the soil environment. As a result, greater salt stress has a more serious toxic effect on cotton seeds, which caused the emergence rate decrease. In addition, different magnetization intensities had significant influence on the emergence rate of cotton. For slight salinized soil, the

Table 2
Effects of magnetized water on salt accumulation characteristics of different treatments at 0–100 cm depth.

Soil	Soil depth/cm	Treatment	Initial soil salt storage/g	Final soil salt storage/g	Desalination capacity/g	Desalination rate/%
Slightly salinized soil	0–100	G0(CK)	5293.9	3912.5	1381.4	26.10%
		G1	5644.6	4184.3	1460.3	25.90%
		G3	5811.6	2882.9	2928.7	50.40%
		G4	5210.4	2846.2	2364.2	45.40%
		G5	5377.4	3780.7	1596.7	29.70%
Medium salinized soil	0–100	CK	11,270	9816.2	1453.8	12.90%
		G1	12,091.1	10,763.9	1327.2	11.00%
		G3	11,302.2	8004.4	3297.8	29.20%
		G4	11,479.3	9358.4	2120.9	18.50%
		G5	11,994.5	10,416.3	1578.2	13.20%
Heavily salinized soil	0–100	CK	15,646.8	12,274.3	3372.5	21.60%
		G1	17,191.2	12,926.4	4264.8	24.80%
		G3	15,615.6	8048.2	7567.4	48.50%
		G4	15,631.2	10,010.3	5620.9	36.00%
		G5	17,222.4	14,361.4	2861.0	16.60%

Table 3
Effects of magnetized water on emergence rate of seedlings in different salinized soil.

Emergence rate/%	CK	G1	G3	G4	G5
Slightly salinized soil	0.705 ± 0.023c	0.73 ± 0.023 BCE	0.841 ± 0.022a	0.798 ± 0.024b	0.773 ± 0.024b
Medium salinized soil	0.636 ± 0.018d	0.636 ± 0.018 cd	0.727 ± 0.016a	0.682 ± 0.016b	0.659 ± 0.015 BCE
Heavily salinized soil	0.5 ± 0.023c	0.568 ± 0.023b	0.636 ± 0.023a	0.614 ± 0.023a	0.568 ± 0.023b

emergence rate of cotton treated with different magnetization intensity increased by 3.2%, 19.3%, 12.9%, and 9.6% compared with the control treatment, respectively. For medium salinized soil, the emergence rate increased by 0%, 14.3%, 7.1%, and 3.6% compared with the control treatment, respectively. The heavy salinized soil showed the greatest effect that the emergence rate increased by 13.6%, 27.3%,22.7%, and 13.6% compared with the control treatment, respectively. Therefore, the effect of magnetization treatment on seedling emergence of heavy salinized soil is more prominent compared to the other levels of soil salinity. When averaged over all levels of soil salinity, the overall seedling emergence rate of each magnetization treatment was CK < G1 < G5 < G4 < G3, and the effect of G3 magnetized water irrigation on seedling emergence of salinized soil was the best. This is similar to the experimental results of Zia et al. who showed that magnetized treated water has potential to improve turnip germination seeding growth (Haq et al., 2016). The main reason was that magnetized water can promote the activity of enzymes in seed cells, affect cell division and differentiation, as well as improving seed vigor and salt tolerance of crops, and then promote cotton emergence (Shine et al., 2011; Pietruszewski and Kania, 2010).

3.2.2. *Effect of magnetized irrigation water on plant height and stem diameter*

Plant height and stem diameter are important cotton growth indexes. The effect of magnetized irrigation water on the plant height and stem diameter of cotton in different salinized soil is shown in Table 4. The plant height of cotton increased slowly in the seedling stage, and increased greatly in the squaring and flowering stages. At the initial boll-opening stage, because of topping, the plant height of cotton decreased slightly, and the plant height no longer increased in the boll stage. Compared with the growth trend of plant height under different salinized soil irrigated by magnetized water, the average maximum plant height of cotton in slight, medium, and heavy salinized soil was 77.7, 62.24, and 58.68 cm, respectively. Salinization greatly influenced cotton height though cotton is generally tolerant to salinity. The plant height of cotton in slight, medium, and heavy salinized soil treated with magnetized water of different intensities were also significantly different. In slight salinized soil, the maximum plant height of the magnetized treatments (G1, G3, G4, G5) was 1.8%, 19.7%, 15.8%, and 13.4% higher than that in CK treatment, respectively. In medium salinized soil, The maximum plant height under the magnetized treatments were 5%, 23%, 16%, and 6.2% higher than that of CK treatment, respectively. While for heavy salinized soil, the maximum plant height under the magnetic treatments were 14.1%, 42.5%, 33.8%, and 24.9% higher than under the CK treatment, respectively.

Table 4 also showed that the cotton stem diameter increased faster before the flowering stage, and the growth in initial boll-opening and full boll-opening stages were slower and became stable. The average maximum stem diameter of cotton in slight, medium, and heavy salinized soil were 10.13 mm, 8.243 mm, and 7.226 mm, respectively, which showed a negative correlation between cotton stem diameter and soil salt content. Under different magnetized water treatments, cotton stem diameter varied significantly in slight, medium and heavy salinized soil. The maximum stem diameter were 3.4%, 19.7%, 12.9%, and 8.6% higher than that of CK treatment, respectively, in slight salinized soil. The maximum stem diameter under the magnetic treatments increased by 7.5%, 40.7%, 27.3%, and 14% compared to CK, respectively, in medium salinized soil. The maximum stem diameter under the magnetic treatments was 7.3%, 28.6%, 18.7%, and 13.4% higher than that under the treatment of CK, respectively, in heavy salinized soil. 3000 GS also had the most obvious effect on cotton height and stem diameter.

The effect of magnetized water in heavy salinized soil on cotton plant height and stem diameter was better than medium salinized soil. The main reason is that soil salt stress could inhibit the activities of various enzymes on the root system, and further inhibit the absorption and utilization of water and nutrients by the roots. Once the salt content is too high, the original ion balance in the cotton plant will be destroyed, which will increase the concentration of Na^{+}, Cl^{-}, and Mg^{2+}, but decrease the concentration of K^{+} and Ca^{2+}. As a result, salt tolerance and the ability of cotton to absorb nutrients decreases (An et al., 2014; Zhang et al., 2010). The decrease of dry matter accumulation in cotton stems resulted in the thinning of cotton stems and the low growth of cotton plants. Magnetized water increased salt leaching and provided a good soil environment for crop growth. Sheng and Zhang (2019) found that the plant height increased the most in the treatment of G5 magnetized water at the seedling stage of cotton. The results in this study further

Table 4
Effect of magnetized water on plant height and stem diameter of cotton in different salinized soil.

Soil	Treatment	Plant height (cm)					Stem diameter (mm)				
		Seedling	Squaring	Flowering	Initial boll-opening	Full boll-opening	Seedling	Squaring	Flowering	Initial boll-opening	Full boll-opening
Slightly salinized soil	G0(CK)	20.41	49.54	69.95	71.1	70.18	3.33	6.05	8.65	9.25	9.3
	G1	25.69	58.03	72.25	72.25	72.25	4.15	8.05	9.22	9.35	9.6
	G3	27.75	58.03	83.95	85.09	84.17	4.42	9.76	10.25	10.96	11.1
	G4	22.71	55.5	82.34	82.11	82.11	3.49	9.19	9.85	10.06	10.47
	G5	24.54	58.03	79.13	80.5	80.05	4.96	8.86	9.05	9.71	10.09
Medium salinized soil	CK	20.92	36.88	59.63	50.83	49.17	3.4	6.34	6.61	6.83	6.99
	G1	22.02	46.97	62.57	60.37	61.1	3.65	6.59	6.75	7.21	7.51
	G3	24.04	50.09	73.21	73.39	71.56	4.05	8.03	9.33	9.5	9.82
	G4	22.02	44.77	69.36	66.06	66.24	4.24	6.97	8.35	8.65	8.9
	G5	19.27	44.77	63.49	62.2	63.3	4.14	6.45	7.02	7.51	7.97
Heavily salinized soil	CK	15.2	31.57	45.6	46.26	48.27	2.16	4.19	5.7	6.24	6.35
	G1	15.2	38.25	52.28	53.61	55.11	2.74	5.37	6.48	6.61	6.82
	G3	16.7	43.76	68.64	66.3	65.47	3.2	5.87	7.29	7.86	8.18
	G4	17.54	44.93	63.3	64.3	64.47	2.57	5.25	7.12	7.45	7.55
	G5	17.54	30.9	58.12	58.62	60.29	3.19	5.27	6.86	6.99	7.21

proved that magnetized water has a significant role in promoting crop growth.

3.2.3. Effect of magnetized irrigation water on leaf number and leaf area index

Leaf is the main organ for photosynthesis. The number and growth of leaves can affect the utilization and transformation efficiency of light energy, and then affect the formation of organic matter in cotton and cotton yield. Table 5 showed the effect of magnetized irrigation water on cotton leaves in slight, medium and heavy salinized soils. From the Table 5, it can be seen that, with the increase of cotton growth, the number of leaves increased, which reached the maximum value at the flowering and initial boll-opening stages, and decreased again at the full boll-opening stage. In different salinized soil, the number of cotton leaves of the control treatment was less than that with magnetized irrigation water treatment. In slight salinized soil, the number of leaves treated with different intensities of magnetized water treatments (G1, G3,G4,G5) increased by 33.3%, 61.1%, 44.4% and 36.1% compared with control treatment, respectively. In medium salinized soil, the number of leaves increased by 5.9%, 55.9%, 29.4%, and 14.7% compared with the control treatment, respectively. In heavy salinized soil, the number of leaves increased by 20%, 36.7%, 26.7%, and 26.7%, compared with control treatment, respectively.

From Table 5, we could also find that during the cotton growth periods, the leaf area index in different levels of salinized soil and under different intensities of magnetization treatments was much similar. During the growth period, the leaf area index first increased and then decreased, then reach to the maximum value at the flowering stage, which was due to an accumulation of dry matter in cotton from the sowing to the flowering stages. With the increase of leaf area, the leaf area index also increased gradually. In initial boll-opening and full boll-opening stages, cotton is mainly showing reproductive growth. The old leaves began to fall off, and the number and area of leaves decreased, and as result, the leaf area index decreased. The average maximum leaf area index of cotton in slight, medium, and heavy salinized soils were 7.79, 6.08, and 3.94, respectively, which showed the largest value in light salinized soil, and the smallest value was obtained in heavy salinized soil. The leaf area index of the magnetized water irrigation treatments was significantly higher than that in the control treatment. Compared with the CK treatment, the leaf area index in G1, G3, G4, and G5 treatments increased by 11.4%, 63.3%, 40.4%, and 13.8% in slight salinized soil, respectively. In medium salinized soil, the value increased by 11.3%, 64%, 37%, and 33.3%, respectively, compared to the CK treatment. In the heavy salinized soil, the effect was more obvious, and the leaf area index increased by 16.3%, 36.7%, 32.1%, and 23.3%, respectively, compared to the CK treatment.

The improvement of leaf growth may be attributed to the stimulatory effect of magnetic water on photosynthetic pigments and protein biosynthesis. The mode of action of magnetic water is through its partially broken hydrogen bonds. Moreover, some water molecules become like free monomer molecules that can easily penetrate the biological cell walls, thus promoting leaf growth (Toledo et al., 2008). Selim et al. (2009) stated that the increased cell division and enlargement may be attributed to the increment in enzyme activities, gibberellic acid (GA 3), indole acetic acid (IAA) and cytokinin synthesis and reduced abscisic acid (ABA). Thus, magnetized water treatments can promote the growth of cotton leaf numbers and leaf area index, which further promotes photosynthesis and increases cotton yields. The effect of magnetic irrigation water on slight salinized soil is better than the other two salinized soil, and with the G3 treatment, the effects were most significant.

3.2.4. Effect of magnetized irrigation water on chlorophyll

Chlorophyll contributes to light energy absorption, utilization, and transformation in cotton, and is an important factor affecting photosynthesis (Fan et al., 2013). Table 6 shows the effect of magnetized irrigation water on the SPAD value of cotton chlorophyll in slight, medium, and heavy salinized soil. From Table 6, it could be seen that the overall SPAD value of each treatment showed a downward trend from flowering to the full boll-opening stage. Salt stress has a significant effect on the SPAD value of cotton. Compared with different levels of salinized soil, the average SPAD value in slight salinized soil was the largest, followed by the medium salinized soil, and the SPAD value in the heavy salinized soil was the smallest. The results showed that salt stress could inhibit the production of chlorophyll in cotton. Related researches have showed that mild salt stress could improve the salinity of leaf liquid solution, activate the activity of chlorophyll enzymes, promote the decomposition of chlorophyll, and reduce the SPAD value of chlorophyll. In the same salinized soil, there were significant differences in the chlorophyll SPAD values of cotton with different magnetization intensity, and all salinity levels were CK < G1 < G5 < G4 < G3. When cotton was in the flowering stage, the chlorophyll content of magnetization treatments G1, G3, G4 and G5 in slightly salinized soil increased by 4.14%, 12.41%, 6.76%, and 5.89%, respectively, compared with the CK treatment. The chlorophyll content of magnetization of G1, G3, G4 and G5 in medium salinized soil increased by 6.22%, 16.6%, 11.04% and 9.29%, respectively, compared with CK. The chlorophyll content of the magnetization treatments G1, G3, G4 and G5 in heavily salinized soil increased by 1.36%, 12.48%, 7.23%, and 6.24%, respectively. Under the G3 treatment in slightly salinized soil, the chlorophyll SPAD of cotton

Table 5
Effect of magnetized water on leaf number and leaf area index of cotton in different salinized soil.

Soil	Treatment	Leaf number					LAI				
		seedling stage	Bud stage	Florescence	Boll stage	Opening period	Seedling stage	Bud stage	Florescence	Boll stage	Opening period
Slightly salinized soil	G0(CK)	6	10	18	17	15	0.69	2.41	6.19	4.84	4.56
	G1	7	14	24	21	20	0.61	2.52	6.88	5.7	4.81
	G3	8	18	25	29	28	0.94	3.73	9.9	10.12	8.96
	G4	6	15	23	26	25	0.75	3.29	8.68	7.66	7.38
	G5	6	13	25	22	20	0.83	2.96	7.05	6.44	5.89
Medium salinized soil	CK	5	10	17	13	12	0.41	1.45	4.71	2.97	2.82
	G1	7	14	18	15	13	0.97	2.53	5.25	4.25	4.04
	G3	6	16	24	27	22	0.31	2.24	7.71	7.59	5
	G4	6	13	22	20	17	0.75	2.9	6.45	6.03	4.5
	G5	5	11	19	16	15	0.5	2.34	6.28	4.42	4.11
Heavily salinized soil	CK	6	7	13	15	14	0.14	0.86	3.24	3.08	2.58
	G1	5	9	17	18	15	0.36	1.26	3.76	3.36	3.13
	G3	5	10	20	21	17	0.52	1.13	4.41	4.14	3.94
	G4	6	9	18	19	17	0.12	1.21	4.27	3.96	3.58
	G5	5	9	19	18	16	0.23	1.31	3.99	3.74	3.4

Re:LAI means leaf area index.

Table 6
Effect of magnetized water on cotton chlorophyll in different salinized soil.

Soil	Treatment	Chlorophyll SPAD		
		Flowering stage	Full boll stage	Boll opening stage
Slightly salinized soil	G0(CK)	41.9048	38.5714	34.6032
	G1	43.6508	39.8413	36.1905
	G3	46.9841	44.7619	38.0952
	G4	44.7619	40.1587	37.3016
	G5	44.2857	39.3651	35.873
Medium salinized soil	0GS	40	36.6667	33.0159
	G1	42.5397	38.4127	33.1746
	G3	46.8254	43.8095	37.9365
	G4	44.6032	40.9524	36.6667
	G5	43.8095	40.6349	36.0317
Heavily salinized soil	0GS	36.7184	33.5255	31.3969
	G1	37.3836	36.1863	32.3282
	G3	41.5078	37.7827	33.6585
	G4	39.5122	37.1175	33.3925
	G5	39.2461	36.5854	32.5942

reached the maximum value of 47.1, which showed that irrigating with magnetized water can promote the increase of chlorophyll content, and the effect was greatest with the G3 magnetization.

3.3. Effect of magnetized water irrigation on cotton yield and water use efficiency

Table 7 shows the effect of magnetized irrigation water on cotton yield and water consumption in different salinized soils. From Table 7, it can be seen that under different levels of salinized soil, the effect of magnetization treatments on the effective boll number, boll weight, and seed cotton yield per plant is significant and consistent. All the results showed that with the increase of magnetization, the effective boll number per plant, boll weight and seed cotton yield increased gradually at first, then decreased again, and reached the maximum value when the magnetic field intensity was G3. The cotton yield with G1, G3, G4, and G5 treatments in slight salinized soil increased by 7.54%, 28.81%, 21.08%, and 15.85%, respectively, compared with CK. The cotton yield of G1, G3, G4, and G5 treatments in medium salinized soil increased by 9.92%, 31.03%, 29.68%, and 18.31%, respectively. The yield of cotton treatments in heavy salinized soil with G1, G3, G4, and G5 increased by 1.71%, 31.69%, 24.21%, and 17.41%, respectively. The results showed that magnetized water treatment could promote the growth and development of cotton, which can increase the effective boll number and boll weight per plant and increase cotton yields. Under different salinized soil treatments, the effective boll number per plant, boll weight per plant, and seed cotton yield were different. Compared with medium salinized soil, the yield in slight salinized soil is higher than that in medium salinized soil, but the difference is not statistically significant. The yield of heavy salinized soil is much lower than that of slight and medium salinized soil. This indicates that the salt stress in a certain range had little effect on cotton yield. When the soil had heavy salinity, the cotton yield was inhibited. In addition, by comparing the effect of magnetization treatments on cotton yield in three salinized soils, it could find that the increase of cotton yield when medium salinized soils were irrigated with magnetized water was much higher than that in light and heavy salinized soils, which indicates that irrigating with magnetized water has a greater effect on increasing cotton yield in medium salinized soils. The yield improvement of cotton irrigated with magnetic water may be due to changes in the transport of assimilates, enzyme activity, growth regulators, ions and water uptake (Leelapriya et al., 2003), and/or to an energetic excitement of one or more parameters of the cellular substratum such as proteins and carbohydrates.

In order to further know the effect of magnetized water on salt distribution and cotton yield, the correlation between the test variables and cotton yield was analyzed shown in Table 8. From Table 8, it can be seen that there is a significant negative correlation between soil salt content and cotton yield ($r = -0.801$, $P < 0.01$), and a significant positive correlation between irrigation water magnetization and cotton yield was found ($r = 0.612$, $P < 0.01$), which indicated that soil salt content was an important factor restricting cotton yield in saline-alkali soil, and magnetized water irrigation could alleviate salt stress for cotton yield.

According to the simplified water balance equation, the changes of water consumption in the whole growth period of slight, medium, and heavy saline 0–100 cm soil layer under different magnetized irrigation water (CK, G1, G3, G4, and G5) were obtained, as shown in Table 3. It can be seen that under different magnetized irrigation treatments, the water consumption of the three salinized soils varies greatly in the whole growth period. Comparing the three salinized soils, the water consumption of cotton in slight salinized soil is greater than that in medium salinized soil, which is greater than in heavy salinized soil. This is because the content of soluble salt in the heavy salinized soil is higher

Table 8
Partial correlation analysis between experimental variables and cotton yield.

	Magnetized water		Soil salt content		Yield	
	r	p	r	p	r	p
Magnetized water	1	–				
Soil salt content	0.529	0.063	1	–		
Yield	0.612	0.026	-0.801	0.001	1	–

Table 7
Effect of magnetized water irrigation on cotton yield and water consumption.

Soil	Treatment	Actual irrigation capacity (mm)	Water consumption (mm)	Yield components		Yield kg/ 0.667 ha	Water use efficiency (kg/m^3)
				Effective bolls plant	Single boll weight/g		
Slightly salinized soil	G0(CK)	487	597.7	4.5	4.9	367.1	0.61
	G1	487	589.9	4.7	5.1	394.8	0.70
	G3	487	604.0	6	5.2	472.8	0.78
	G4	487	602.8	5.1	5.1	444.5	0.74
	G5	487	581.8	4.8	5.1	425.3	0.73
Medium salinized soil	G0(CK)	487	555.6	3.7	4.8	345	0.62
	G1	487	551.6	4	4.7	379.2	0.69
	G3	487	556.8	5.3	5.5	452	0.81
	G4	487	552.9	5.3	5.2	447.4	0.81
	G5	487	547.2	4.4	4.9	408.1	0.75
Heavily salinized soil	G0(CK)	487	536.8	3.3	4.6	264.5	0.49
	G1	487	503.5	3.5	4.8	269.1	0.53
	G3	487	495.0	4.9	5.1	348.4	0.70
	G4	487	505.9	4.7	5	328.6	0.65
	G5	487	521.3	4.5	4.9	310.6	0.60

than that in the slight and medium salinized soils, which leads to the increase of soil solution salinity, the increase of osmotic pressure, the inhibition of soil water availability, as well as the decrease of water absorption and consumption during the cotton growth period. In addition, with the increase of magnetization, the water consumption of slight and medium salinized soil increased first and then decreased. The water consumption of magnetization treatment is greater than that of CK treatment, and the cotton water consumption in the whole growth period is the largest under the G3 magnetization treatment. When fresh water is magnetized by magnetic poles of different intensities, the surface tension of the water decreases, which promotes the relative increase of the soil matrix potential, soil water suction is relatively weakened, and capillary force is strengthened. This promotes water absorption capacity of cotton roots in the soil, and water consumption was significantly increased compared with the CK treatment.

From Table 7, it can also found that there is a positive correlation between WUE and cotton yield, whereby cotton yield increased with the increase of WUE, and both variables showed a trend of first rising and then falling with the increase of magnetic field intensity. The overall effect of different magnetic field intensities on WUE was CK < G1 < G5 < G4 < G3. Comparing the WUE of the three salinized soils shows that the WUE of slight salinized soils is the largest, followed by the medium salinized soils, and heavy salinized soils was the lowest. Compared with the CK treatment, the WUE of G1, G3, G4, and G5 magnetized water treatment in the slight salinized soil increased by 9%, 27.4%, 20%, and 19%, respectively. Compared with the CK treatment, the WUE of G1, G3, G4, and G5 magnetized water treatment in the medium salinized soil increased by 10.7%, 30.7%, 30.3%, and 20.1%, respectively. The WUE of magnetized water treatments G1, G3, G4, and G5 in heavily salinized soil increased by 8.4%, 42.8%, 31.8%, and 20.9% respectively compared with the CK treatment. From the increasing range of magnetization treatments compared with the CK treatment, the WUE of heavy salinized soil is higher than that of medium salinized soil. This shows that salt stress has a certain inhibition effect on WUE of cotton. Magnetization treatment technology can improve water efficiency. The more serious salt stress is, the greater effect will be obtained with the treatment of magnetization on WUE.

4. Conclusions

The effects of magnetic irrigation water on soil properties and cotton growth in different degrees of salinized soil were studied with a field experiment in southern Xinjiang, northwestern China. The main conclusions are as follows.

(1) Magnetized irrigation water can optimized the water distribution and salt desalination significantly. For the same salinized soil, magnetization intensity has similar effect on soil volume water content and salt desalination in soil profile, whereby CK < G1 < G5 < G4 < G3. Irrigating with magnetized water can reduce the salt leaching and improve the desalination effect of soil, with the greatest benefits observed with the use of G3 magnetized water.
(2) Different salinized soils have great effects on cotton seedling rates, and cotton seedling rates was improved in slight salinized soil. Lowest seedling rate with medium salinized soil was found in heavy salinized soil. In the same salinized soil, different magnetization greatly influenced rates of cotton emergence. The emergence rate of cotton under CK treatment was lower than that under magnetized water treatments, the results showed that CK > G1 > G5 > G4 > G3, and irrigation with G3 magnetized water had the best cotton emergence rates.
(3) Soil salt content has a negative relationship with growth characteristics of cotton were negative. Magnetized water treatments can improve the leaf area index of cotton, promote photosynthesis and in addition, promote cotton yield and WUE. When the magnetization intensity is G3, the biomass of each salinized soil increased by 53–99.5%, the WUE increased by 27.4–42.8%, and the yield increased by 28.8–31.69%.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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