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Magnetized Saline Water Irrigation Enhances Soil Chemical and Physical Properties

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Abstract: Due to rapid population growth and pressure on water resources, it is necessary to use economic and non-traditional techniques for irrigation. One of these techniques is the use of salt water after treatment with a magnetic force. A simulation experiment was conducted with soil columns using three quantities of saline water: 0, 3, and 6 g L^{-1} (S_0, S_3, and S_6). Magnetic forces of 0, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 gauss were used to study the effects of magnetic forces on leachate and soil physicochemical properties at different depths. The results at all soil depths showed that the pH decreased with increasing salinity from S_0 to S3 and S_6 by an average of 8.44, 8.28, and 8.27%, respectively. Soil EC decreased significantly with depth by 10–35%. The maximum *SAR*, *SSP*, and *CROSS* values (16.3, 51.1, and 17.6, respectively) were reported when no magnetic force was used, while the lowest values (13.9, 49.9, and 15.3) were recorded when using 3000 gauss under S_6 within the soil profile. Magnetizing the water halved the EC of the leachate under S_0, while it decreased the EC by 12.4% under S3. Increasing the magnetic force enhanced the leachate *SAR*, *SSP*, and *CROSS* values by 4.9–20.4% on average under S_3 and S_6. Magnetic forces augmented the hydraulic conductivity at the same salinity level and with increasing salinity, resulting in an increment of 50% at S_3 and S_6 compared with S_0. After nine hours, the maximum cumulative infiltration rate was under 1000 and 4000 gauss. Our results demonstrated the important effects of magnetically treated irrigation water and could therefore support its application in agriculture under conditions of low water resources and quality.

Keywords: magnetic force; saline water irrigation; soil leachate; soil sector

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1. Introduction

Globally, major arid and semi-arid regions are more likely to experience higher temperatures, lower precipitation, and reduced snowmelt due to climate change [1,2]. A particular concern expressed in the Intergovernmental Panel on Climate Change (IPCC) report was that these impacts would lead to more volatile water supplies and more droughts around the world [1]. In China, for example, high evaporation and low rainfall in arid and semi-arid regions have led to a shortage of water resources, which in turn has hampered local agricultural development [3]. Hence, the use of alternative water sources for irrigation could help to significantly reduce the pressure on limited freshwater resources, especially in arid and semi-arid regions. Saline water is an alternative option for irrigation purposes [4]. Nevertheless, the use of highly saline water has implications for soil properties, plant growth, and productivity. Currently, the use of magnetized water (MW) for agricultural irrigation is gaining more attention as an effective strategy to reduce water and salt stress on agricultural soils, especially in arid and semi-arid regions [4,5]. Water magnetization technology is a promising approach in agriculture that offers numerous benefits, including soil desalination and improved crop growth and production [6]. The magnetization of water occurs as it passes through a magnetic field, which converts the present salts into an inactive state [7,8], reducing the negative effects of salinity on plant growth [9].

Exposing water to a magnetic field changes its properties, including its electromagnetism, thermodynamics, dielectric constant, mechanics, freezing and boiling points, surface tension, electrical conductivity (EC), and viscosity [10,11]. Since water molecules are linked via hydrogen bonds to form multiple clusters, magnetic field waves lead to water clusters with smaller structures by affecting the bonds among them. Thus, the physicochemical properties of water can be manipulated in response to magnetic fields [12,13]. Numerous agricultural applications of MW, including irrigation, soil salinity remediation, and soil fertility maintenance, have been studied [14]. MW has been shown to improve soil properties by leaching salts from the soil rhizosphere [8]. Zhang et al. [15] showed that MW could accelerate the downward migration of water from the soil rhizosphere in saline soils, and that soil water content and salt leaching reached their maximum values at a magnetic field strength of 3000 gausses. MW also affects soil nutrient availability [8]; plays a central role in cation uptake capacity; and promotes the uptake of immobile nutrients by plants [16]. Previous studies have reported the effects of MW on reducing soil alkalinity and salinity [6,17]; dissolving poorly soluble salts (carbonates, sulfates, and phosphates); increasing soil water uptake; and improving nutrient availability [18]. The use of MW also increases the physiological production potential of irrigation water and thus improves the overall efficiency of irrigation water use in agricultural soils [5,19]. Compared to soils irrigated with non-magnetized water, soils irrigated with MW had lower salinity levels [14]. The magnetic treatment of irrigation water also affects the soil moisture content [6] and improves the soil pore structure [20]. Khoshravesh et al. [21] showed that MW can effectively improve the infiltration performance and soil moisture distribution of clay soils. Wang et al. [22–24] proposed using the relative reduction in surface tension as a quantitative evaluation standard for the magnetization effect of brackish water; they found that the magnetization effect was linked with the magnetic field strength and salinity, and the soil irrigated with magnetized brackish water also had obvious effects. Desalination can effectively increase soil organic carbon and nitrogen content [20,25], improve soil salt ion exchange characteristics and ion composition, increase soil mineral content [26], and increase the soil nutrient fixation capacity. However, the mechanism of magnetization is not yet fully understood scientifically. In addition, the effects of MW on soil salinity and alkalinity are unclear.

Although several field-scale and laboratory experiments have been conducted to investigate how MW improves plant growth and yield; soil nutrient availability; and even soil properties (e.g., soil pH and EC), there are still some gaps in our knowledge, such as: (1) no attempts have been made so far to investigate salt accumulation and soil infiltration in soils treated with MW when the soil has a lower salinity than the irrigation water; (2) no evidence has been provided for the effect of MW on other important chemical properties, e.g., the sodium adsorption ratio (*SAR*), the cation ratio of structuration stability (*CROSS*), and the soluble sodium percentage (*SSP*), in soil and leachates; and (3) little is known about the effects of MW on soil infiltration properties. Therefore, the present study aimed to fill the gaps mentioned above and contribute to an adequate discussion of the effects of magnetic water treatment on the behavior of water and salts in soil by simulating the soil sector through experiments with soil columns.

2. Materials and Methods

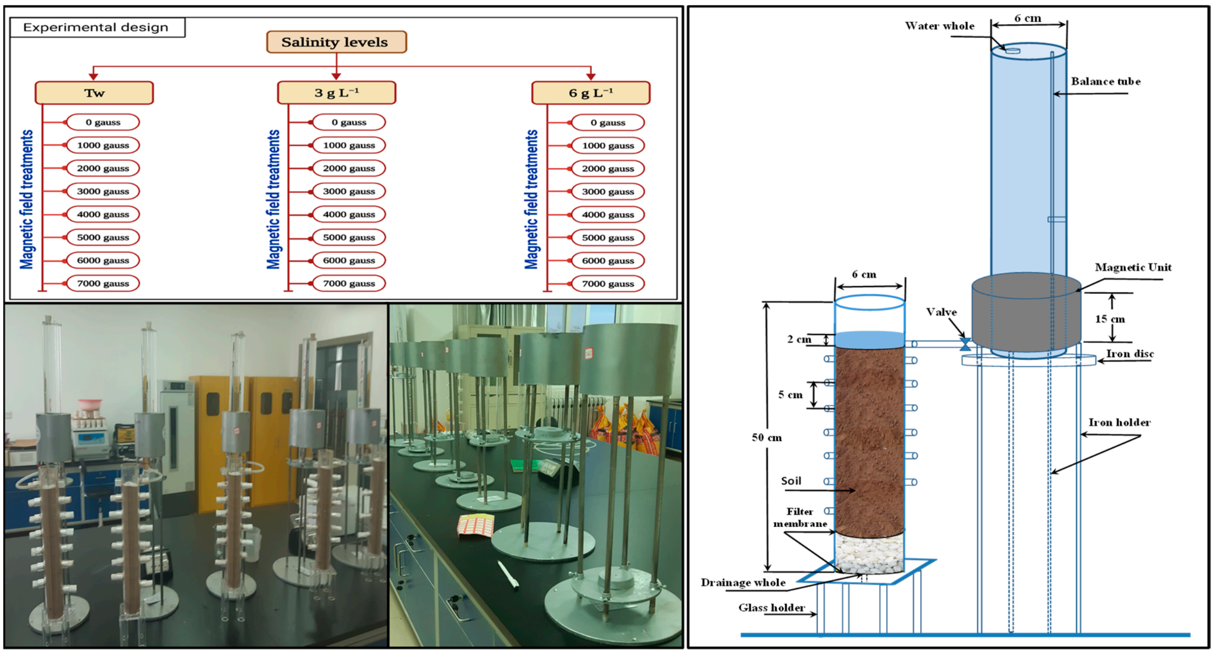
2.1. Soil Sampling

The soil used in this study was collected in June 2020 from a field irrigation station (34°20′ N, 108°24′ E; 521 m above sea level (a.s.l)) at the Northwest Agriculture and Forestry University, Yangling, Shaanxi Province, China. The climate in this region is semi-humid. The average annual precipitation, temperature, and evapotranspiration are 632 mm, 13 °C, and 1500 mm, respectively. The work was carried out in the Agriculture and Water Engineering Laboratory at the Institute of Water Saving Technology and the irrigation station affiliated with the university, which was the nearest place for soil sampling.

Soil samples (0–50 cm) were collected from three typical sites (three replicates) in the field. At each site, 10 kg of topsoil (50 cm) was randomly collected from 10 locations using the S-shaped sampling method [23,27] and then mixed well to obtain a representative sample. The collected soil was air-dried at 20 ± 3 °C, sieved through a 2 mm nylon sieve to remove stones and plant residues, and then stored at room temperature for further use. The investigated soil was silty clay loam with 8.0%, 75%, and 17% sand, silt, and clay content, respectively. The field capacity (FC), permanent wilting point (PWP), and bulk density (BD) averaged 24.0% (0.268 cm^3 cm^{-3}), 8.5% (0.138 cm^3 cm^{-3}), and 1.35 g cm^{-3}, respectively [28]. The physical and chemical properties of the soil were: pH, 8.14; total available nitrogen, 45.3 mg kg^{-1}; total phosphorus, 18.5 mg kg^{-1}; total potassium, 102 mg kg^{-1}; and organic matter, 11.9 g kg^{-1}.

2.2. Experimental Layout

A laboratory experiment was conducted in the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semi-arid areas of the Ministry of Education at the Northwest Agriculture and Forestry University. The temperature in the laboratory was controlled at about 23 ± 2 °C. The experiment was configured to follow a split-plot design with triplicate treatments (Figure 1). The main plots represented three salinity levels (0, 3, and 6 g L^{-1}) of NaCl dissolved in freshwater (tap water) (i.e., S_0, S_3, and S_6), which were then divided into subplots subjected to different magnetic field treatments (0, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 gauss).



Experiment view **Magnetic units** **Experiment scheme**

Figure 1. Experimental design, photos of the experiments, and a schematic representation of the experimental system.

2.3. Material Preparation

To perform this experiment, soil columns (6 cm inner diameter, 50 cm height) were custom-made with a base of four 10 cm high Perspex cylinder stands (Figure 1). Each column had 14 opposing holes, with inner diameters of 2 cm and a vertical distance of 5 cm between the holes, at depths of 1, 2, 3, 4, 5, 6, and 7, i.e., 0:5, 5:10, 10:15, 15:20, 20:25, 25:30, and 30:37 cm of the soil surface. The holes were sealed with foam from the outside. A filter membrane was attached to the bottom of each soil column. To avoid the possible penetration of the membrane by soil sediments, a 2 cm layer of fine gravel in combination with 1 cm of coarse gravel was placed over the membrane [29]. A total of 1374.12 g of soil was added to each column in 12 batches (i.e., 114.51 g of soil per batch). To maintain a uniform bulk density (1.53 g cm^{-3}) across all soil columns, the soil was continuously knocked and compacted in each batch (i.e., every 3 cm in height) until reaching the final height of 37 cm. After filling the soil column, another filter membrane was placed over the upper soil layers to prevent it from being stirred up by the water currents. The bottom of each soil column was provided with holes for drainage and the collection of the drainage water in a glass canister.

A CHQ-type magnetic device with permanent magnets, manufactured by Baotou Xinda Magnetic Material Factory, located seven kilometers from Baobai Road, Jiuyuan District, Baotou City, Inner Mongolia Autonomous Region, China, was used to treat the water with different magnetic strengths ranging from zero to 7000 G. The magnetic unit was cylindrical, with outer diameters of 139.13, 139.33, 139.33, 139.2, 142.22, 183.15, and 183.15 cm corresponding to 1000, 2000, 3000, 4000, 5000, 6000, and 7000 G, respectively; the inner diameter was 71.85 mm and the length was 15 cm. The magnetic field strength was measured using a Gauss meter (Model HT20 Yu Yao Key Li Magnetics Co., Ltd., Ningbo, China). A glass Markov tube column, 65 cm high, was stood on an iron disk that was moved up and down on 4 iron rods to control the column height and balance and stabilize the height of the water head above the soil (Figure 1). To ensure adequate exposure to the magnetic field, the water column was located at the center of the magnetic field. Each water column was filled with irrigation water solutions and placed in the center of the magnetic unit. The water in the Markov tube column was exposed to the magnetic field for one hour before the start of the experiment to ensure that the time of irrigation water exposure to the magnetic field was fixed for all treatments. A 15 cm pipe was placed directly below the magnetic unit to direct the water from the water column to the surface of the soil column, and a valve was added to control the start of irrigation and end it when the experiment was completed.

2.4. Sample Collection and Calculations

To measure the velocity of water seepage through the soil sector and the velocity of soil water wetting, we recorded the decrease in water height in the water column and the depth of wetness reached by the water through the soil sector over time. The velocity of water permeability through the soil sector was determined by recording a reasonable volume of drainage water over time. The hydraulic conductivity (k_s mm h^{-1}) of the infiltrated solutions through the soil columns was determined using Equation (1) following Bardhan et al. [30].

$$k_s = \frac{V \times L}{A \times t \times \Delta H} \quad (1)$$

where V is the volume of water collected under the soil column (cm^3); L is the length of the soil column (37 cm); A is the internal diameter of the soil column (28.2743 cm^2); t is the water collection time (min); and ΔH is the difference in water head (cm, i.e., 2 cm).

After the water was collected, the connections between the water column and the soil column were removed. Then, the foam material was removed from the lateral openings, and two soil samples were taken from these openings, representing the depths of the soil in the soil column. The first set of soil samples was dried in an oven at 105 °C for at least 24 h to calculate the percentage of moisture. The second set of soil samples was air-dried at room temperature for two weeks and stored until analysis. The physicochemical characteristics were analyzed by standard methods according to Sparks et al. [31], as follows: the soil electrical conductivity (EC) was tested in a 1:5 soil: water extract using an EC meter (DDS-11A, Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China), while the pH was measured in a 1:2.5 soil: water suspension by a pH meter (PHS-3C, Shanghai Precision & Scientific Instrument Co., Ltd., Shanghai, China). Soluble cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) were measured by a Flame Atomic Absorption Spectrometer (pinAAcle900F; PerkinElmer, Waltham, MA, USA) as described by Bao [32]. The sodium adsorption ratio (*SAR*), cation ratio of structuration stability (*CROSS*), and soluble sodium percentage (*SSP*) were calculated by molar concentration (Equations (2)–(4)) [33]:

$$SAR = \frac{Na^+}{\left(\frac{Ca^{++}+Mg^{++}}{2}\right)^{0.5}} \quad (2)$$

$$CROSS = \frac{Na^+ + 0.33K^+}{\left(\frac{Ca^{++}+0.0758Mg^{++}}{2}\right)^{0.5}} \quad (3)$$

$$SSP = \frac{Na^+}{Na^+ + Ca^{++} + Mg^{++} + K^+} \quad (4)$$

where Na^+, Ca^{2+}, and Mg^{2+} are the concentrations in mill equivalents per liter (meq L^{-1}) in the soil paste extract. The characteristics (pH; EC; and Na, Ca, Mg, and K concentrations) of the infiltrated solutions in the bottom of the soil columns were analyzed, and the *SAR*, *SSP*, and *CROSS* of the infiltrated solutions were calculated. All soil and water measurements were performed in triplicate (n = 3).

2.5. Statistical Analysis

Data were compiled and processed using Microsoft Excel 2016 (Microsoft Corporation, Albuquerque, NM, USA). Linear regression modeling was used to predict the effects of the different irrigation water salinities and magnetic forces on the infiltrated water volume and time using Microsoft Excel 2016. One-way analysis of variance (ANOVA) was used to evaluate significant differences in the independent variables between treatments using COASTAT software (Sun Microsystems, Inc., Santa Clara, CA, USA). The means of the treatments were compared using Duncan's multiple-range test. The differences were considered significant at $p \leq 0.05$. Origin 2021b was used for visualization.

3. Results

3.1. Effects of Magnetized Saline Water Irrigation on Chemical Properties of Soil

Our results showed slight differences in the soil pH within the soil profile as the salinity increased, with S_0, S_3, and S_6 presenting values of 8.44, 8.28, and 8.27, respectively (Figure 2A–C). Increasing the magnetic force from 1000 to 7000 at the same depth decreased the pH by 1.4% under S_0, while it increased the pH by 2.6% under S_3 and had no effect under S_6. It is worth noting that the pH at depth 7 was decreased by 3.6% compared to depth 1, and this reduction increased with an increase in the magnetic force. The lowest pH (7.9) was recorded at the 30–37 cm depth under salinity level S_6 and a magnetic force of 7000 gauss. On the other hand, the highest pH values (8.8–8.9) resulted from the application of magnetic forces of 6000–7000 gauss to water at salinity level S_6 and a depth of 0–5 cm. The results showed that the soil EC decreased significantly with depth under S_0, demonstrating a 10–35% reduction between depths 1 and 7, while it increased notably with depth under S_3 and S_6 (Figure 2D–F). The use of water magnetized at any force reduced the increase in the soil EC with depth from 10% at 0 gauss to 35% at 7000 gauss for S_0. Contrarily, increasing the magnetic force from 0 to 1000–7000 gauss improved the increase in the soil EC with depth by 2–6 folds under S_3 (Figure 2E). On the other hand, increasing the magnetic force decreased the increase in the soil EC with soil depth, with a reduction recorded for

7000 gauss under S_6 (Figure 2F). The minimum EC values (132, 442, and 737 ds m^{-1}) were recorded at different depths under the magnetic forces of 4000, 4000, and 7000 gauss for salinity levels S_0, S_3, and S_6, respectively.

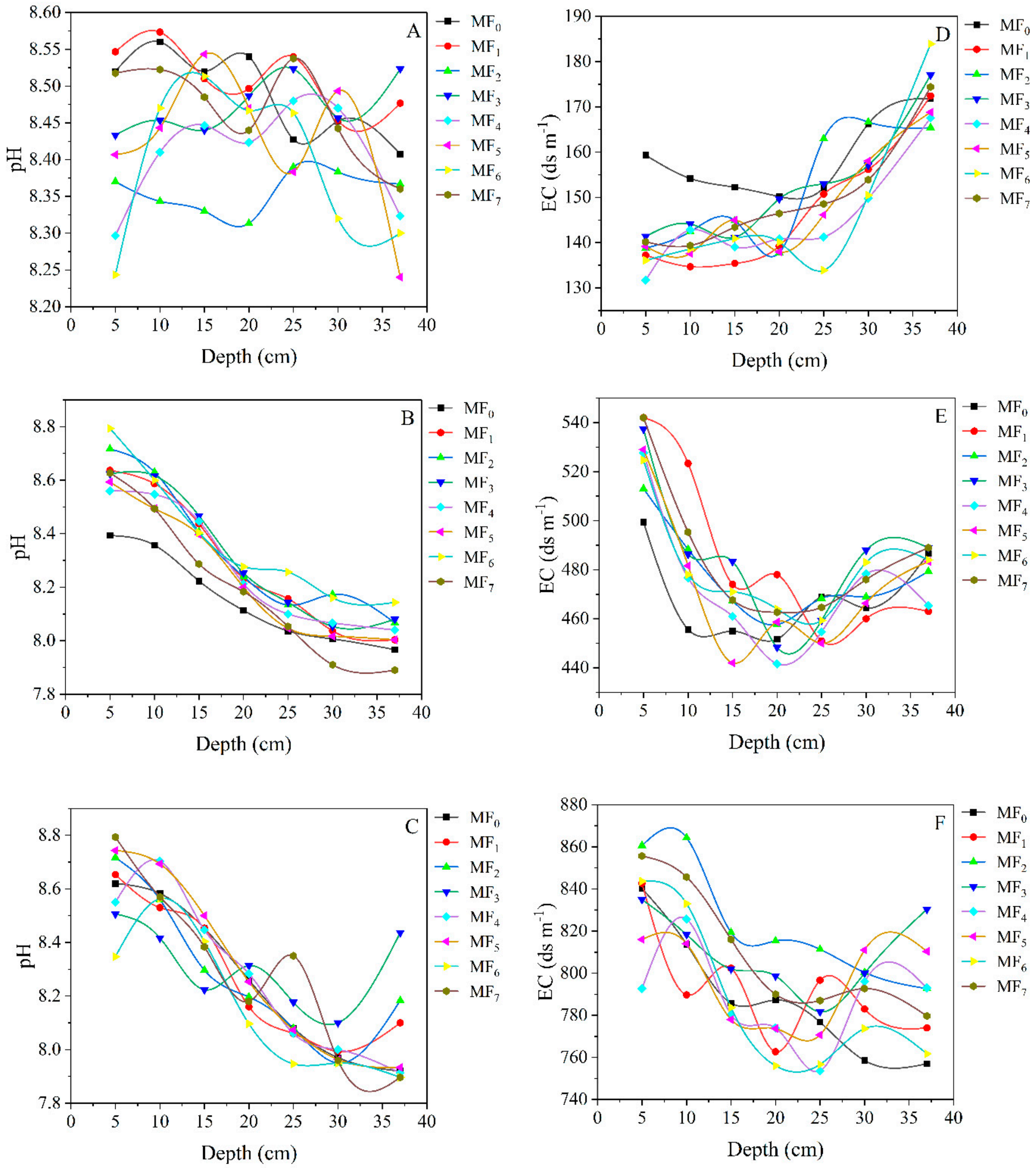


Figure 2. Effect of magnetic force on soil pH (**A**–**C**) Salinity levels: S_0 (control, 0 g L^{-1}); S_3 (3 g L^{-1}); and S_6 (6 g L^{-1}), respectively. and soil electrical conductivity (EC) (**D**−**F**) Salinity levels: S_0 (control, 0 g L^{-1}); S_3 (3 g L^{-1}); and S_6 (6 g L^{-1}), respectively, changes with depth at different levels of irrigation water salinity. MF_0, MF_1, MF_2, MF_3, MF_4, MF_5, MF_6, and MF_7 are the magnetic forces of 0, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 gauss, respectively.

The soil *SAR*, *SSP*, and *CROSS* values were highest at depths 2, 3, and 4 under all magnetic forces except 3000 and 4000 gauss, which displayed maximum values at depths 3, 4, and 5 (Figure 3). Neglecting the effect of salinity, soil *SAR*, *SSP*, and *CROSS* decreased with depth (from depths 1 to 7) by 54.2, 25.7, and 53.2% under water with zero magnetization. However, using magnetized water disturbed this reduction trend, decreasing the reduction in *SAR* and *CROSS* with depth under 1000 and 5000 gauss and augmenting the decrease in these parameters with depth under 2000 and 7000 gauss. Contrastingly, soil *SAR* increased with depth to a greater extent under 3000, 4000, and 6000 gauss compared to the control (Figure 3A–C), and so did *SSP* (Figure 3D–F) under 6000 gauss and *CROSS* (Figure 2G–I) under 4000 and 6000 gauss. Moreover, magnetized water decreased soil *SAR*, *SSP*, and *CROSS* compared to water with no magnetic force under S_0 (Figure 3A,D,G), while it had no effect on these parameters under S_3 (Figure 3B,E,H). It is worth mentioning that the magnetic force of 3000 gauss caused the minimum *SAR*, *SSP*, and *CROSS* values under S_6 (13.9, 49.9, and 15.3, respectively—the values for 0 gauss were 16.3, 51.1, and 17.6; Figure 3C,F,I). At salinity levels S_0, S_3, and S_6, the magnetic forces of 6000, 0, and 3000 gauss resulted in the lowest *SAR* (1.3, 8.2, and 13.9, respectively); *SSP* (14.6, 38.6, and 49.9, respectively); and *CROSS* values (1.6, 8.9, and 15.3, respectively).

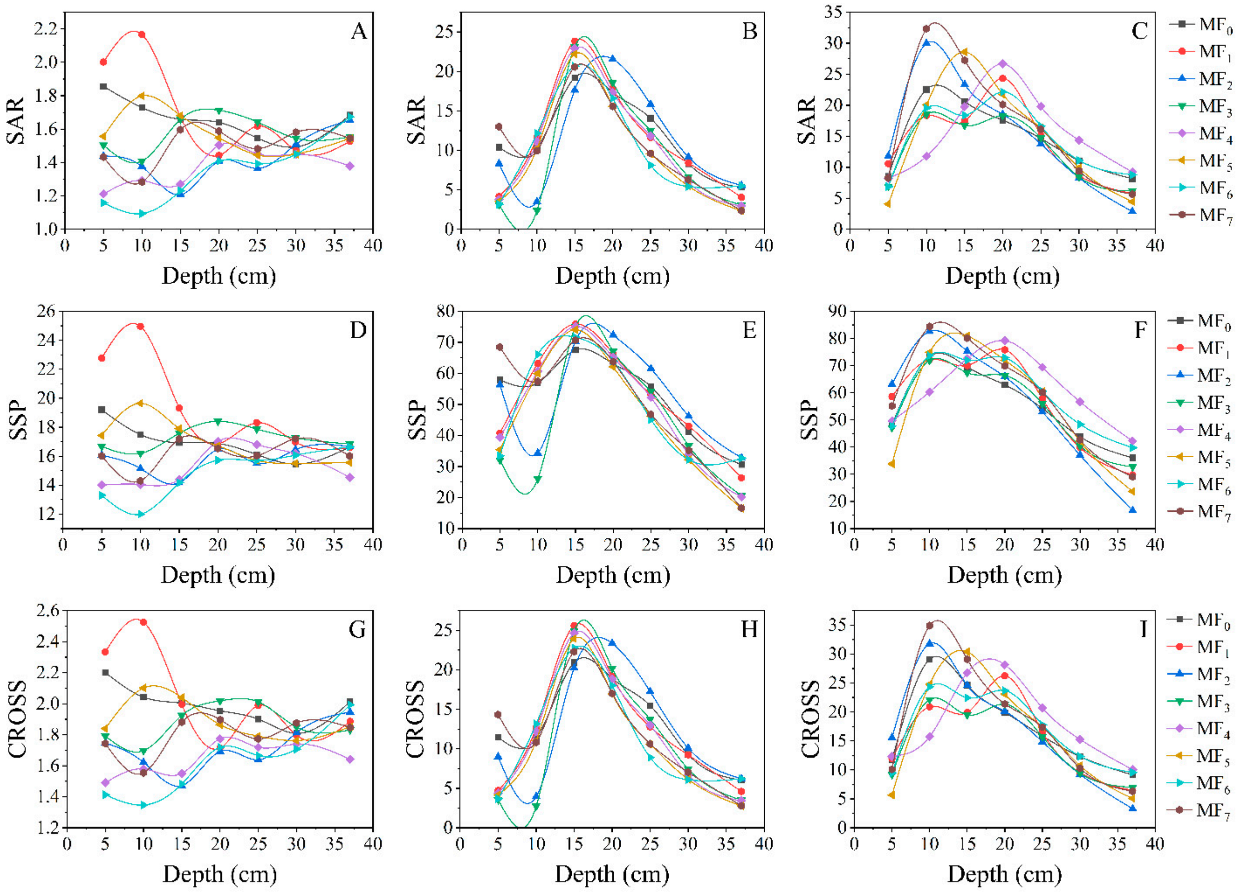


Figure 3. Effect of magnetic forces on changes in sodium adsorption ratio (*SAR*), soluble sodium percentage (*SSP*), and cation ratio of structuration stability (*CROSS*) with depth at different levels of irrigation water salinity: (**A**,**D**,**G**) 0 g L^{-1} (S_0, control); (**B**,**E**,**H**) 3 g L^{-1} (S_3); (**C**,**F**,**I**) 6 g L^{-1} (S_6). MF_0, MF_1, MF_2, MF_3, MF_4, MF_5, MF_6, and MF_7 are the magnetic forces of 0, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 gauss, respectively.

3.2. Effects of Magnetized Saline Water Irrigation on Chemical Properties of Leachate

Our results showed an overall decrease in leachate pH by 2.2% under S_3 and S_6 compared with S_0 (Figure 4C). The highest pH (6.7) was reported in the S_0 treatment under 2000 gauss, while the lowest pH (6.3) was recorded in the S_3 and S_6 treatments under 6000 and 7000 gauss. Magnetized water halved the leachate EC under S_0, decreased it by 12.4% under S_3, and increased it by 4% under S_6 (Figure 4D). None of the magnetic force levels reduced the leachate EC under saline water.

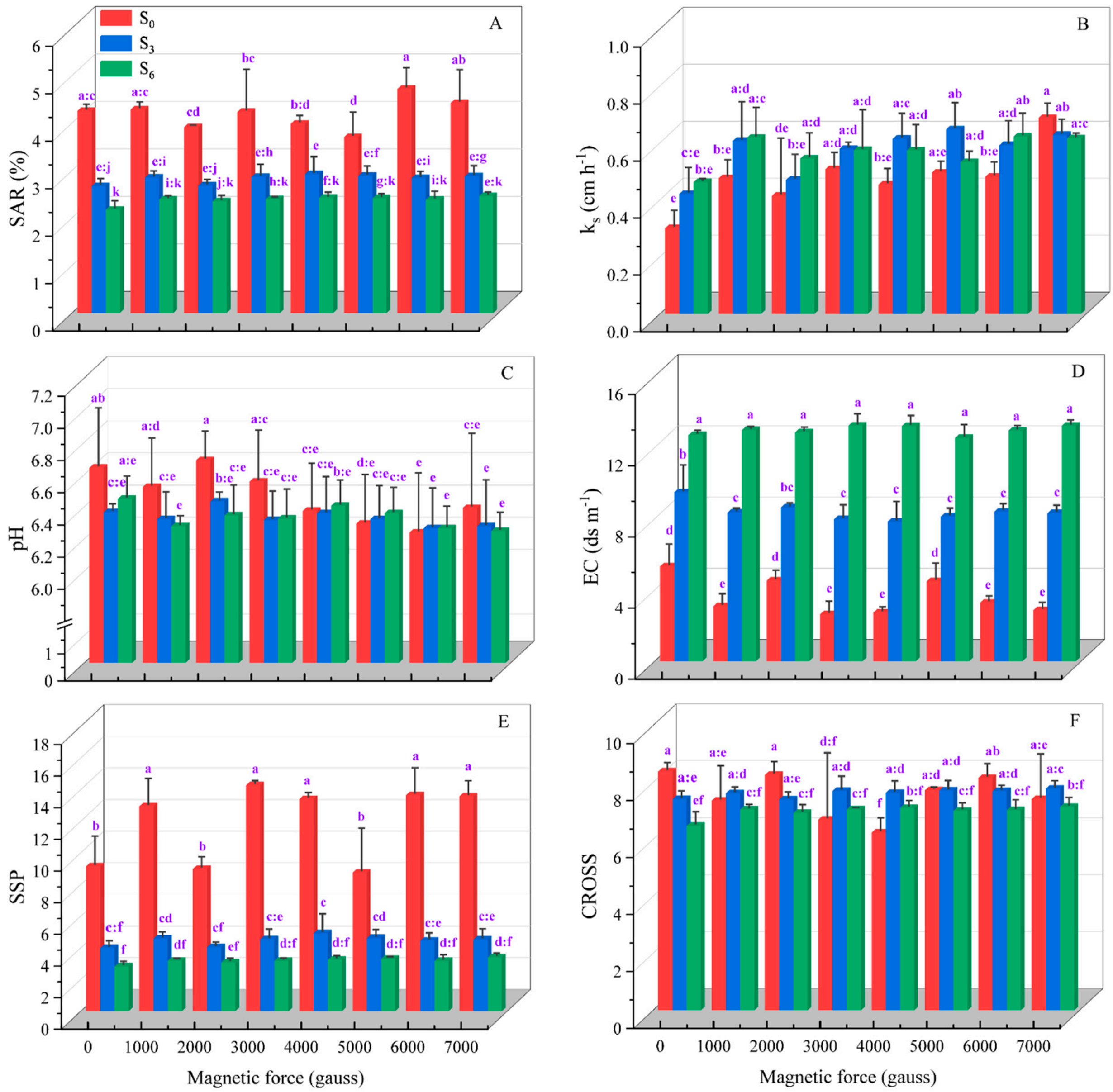


Figure 4. Effect of magnetic forces on (**A**) sodium adsorption ratio (*SAR*), (**B**) hydraulic conductivity (k_s), (**C**) soil pH, (**D**) soil electrical conductivity (EC), (**E**) soluble sodium percentage (*SSP*), and (**F**) cation ratio of structuration stability (*CROSS*) of the leachate at different levels of irrigation water salinity (S_0, 0 g L^{-1}; S_3, 3 g L^{-1}; and S_6, 3 g L^{-1}).

Increasing the magnetic force from 0 to 7000 gauss increased the leachate *SAR*, *SSP*, and *CROSS* by 7.8, 13.5, and 4.9% under S_3 and by 13.2, 20.4, and 10.2% under S_6, respectively (Figure 4A,E,F). On the other hand, the highest magnetic force (7000 gauss) increased the *SAR* and *SSP* by 3.9 and 48.2%, respectively, while the *CROSS* decreased by 11.6% as compared with 0 gauss under S_0. The highest values for *SAR*, *SSP*, and *CROSS* (4.7, 13.7, and 8.2, respectively) were recorded in S_0 under 6000 gauss, while the lowest values (2.2, 2.8, and 6.2) were reported in S_6 under 0 gauss for *SAR* and *SSP*, but in S_0 under 4000 gauss for *CROSS*.

3.3. Effects of Magnetized Saline Water Irrigation on Soil Infiltration Properties

The k_s increased as the magnetic force increased at the same salinity level, and the highest value (0.69 cm h^{-1}) was recorded for 7000 gauss under S_0 (Figure 4B). Magnetic forces higher than 5000 gauss resulted in the highest k_s for all salinity levels, with the maximum force (7000 gauss) doubling the k_s under S_0 and increasing it by 50% under S_3 and S_6. Increasing the salinity level raised the k_s by 50% under S_3 and S_6 as compared with S_0.

The infiltration curves were identical for the first two hours, especially under saline water (S_3 and S_6), as shown in Figure 5. The infiltration curves under different magnetic forces became more differentiated after two hours under S_0 and S_6, indicating larger variations in cumulative infiltration (cm^3 min^{-1}). The cumulative infiltration after nine hours increased with an increases in water salinity from 342 cm^3 min^{-1} under S_0 to 13 and 12.6 cm min^{-1} under S_3 and S_6, respectively (Figure 5). The highest magnetic forces (6000 and 7000 gauss) had insignificant effects on cumulative infiltration under S_0, while forces between 1000 and 5000 gauss had a significant effect. In contrast, magnetic forces of 6000 and 7000 gauss had a significant effect on cumulative infiltration under S_3 and S_6, while magnetic forces of 1000 and 4000 gauss exerted the strongest effect (about 14 cm min^{-1}) compared to 0 gauss (12.7 cm min^{-1} averaged over S_3 and S_6). The slope of the infiltration curve (b), which indicates the momentum of the infiltration rate (IR), followed the same trend as cumulative infiltration (Table 1).

Table 1. Parameter values of coefficient of the regression models between the infiltrated water volume and time under different irrigation water salinities and magnetic forces.

Salinity	MF	Equation	a	b	R^2
TW	0	y = 0.0198x + 2.1666	0.0198	2.1666	0.9598
	1000	y = 0.0208x + 1.9345	0.0208	1.9345	0.9632
	2000	y = 0.025x + 1.8526	0.025	1.8526	0.9515
	3000	y = 0.0222x + 1.7509	0.0222	1.7509	0.9645
	4000	y = 0.0226x + 1.7968	0.226	1.7968	0.9716
	5000	y = 0.0243x + 1.9066	0.0243	1.9066	0.9627
	6000	y = 0.0196x + 2.0982	0.0196	2.0982	0.9579
	7000	y = 0.0182x + 2.0764	0.0182	2.0764	0.955
S_3	0	y = 0.0248x + 1.9881	0.0248	1.9881	0.9611
	1000	y = 0.0254x + 2.1281	0.0257	2.1281	0.9627
	2000	y = 0.0231x + 1.7258	0.0231	1.7258	0.9595
	3000	y = 0.0238x + 1.5418	0.0238	1.5418	0.967
	4000	y = 0.0252x + 1.7493	0.0252	1.7493	0.9673
	5000	y = 0.0259x + 1.846	0.0259	1.846	0.9668
	6000	y = 0.024x + 1.6524	0.024	1.6524	0.9707
	7000	y = 0.0258x + 1.6558	0.0258	1.6558	0.9677
S_6	0	y = 0.0248x + 1.9881	0.0248	1.9881	0.9611
	1000	y = 0.0254x + 2.1281	0.0254	2.1281	0.9627
	2000	y = 0.0231x + 1.7258	0.0231	1.7258	0.9595
	3000	y = 0.0238x + 1.5418	0.0238	1.5418	0.967
	4000	y = 0.0252x + 1.7493	0.0252	1.7493	0.9673
	5000	y = 0.0259x + 1.846	0.0259	1.846	0.9668
	6000	y = 0.024x + 1.6524	0.024	1.6524	0.9707
	7000	y = 0.0258x + 1.6558	0.0258	1.6558	0.9677

S_0 (control, 0 g L^{-1}); S_3 (3 g L^{-1}); and S_6 (6 g L^{-1}) indicate the level of irrigation water salinity. MF_0, MF_1, MF_2, MF_3, MF_4, MF_5, MF_6, and MF_7 are the magnetic forces of 0, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 gauss, respectively. a is the gradient, b is the slope of the infiltration curves, and R^2 is the coefficient of determination.

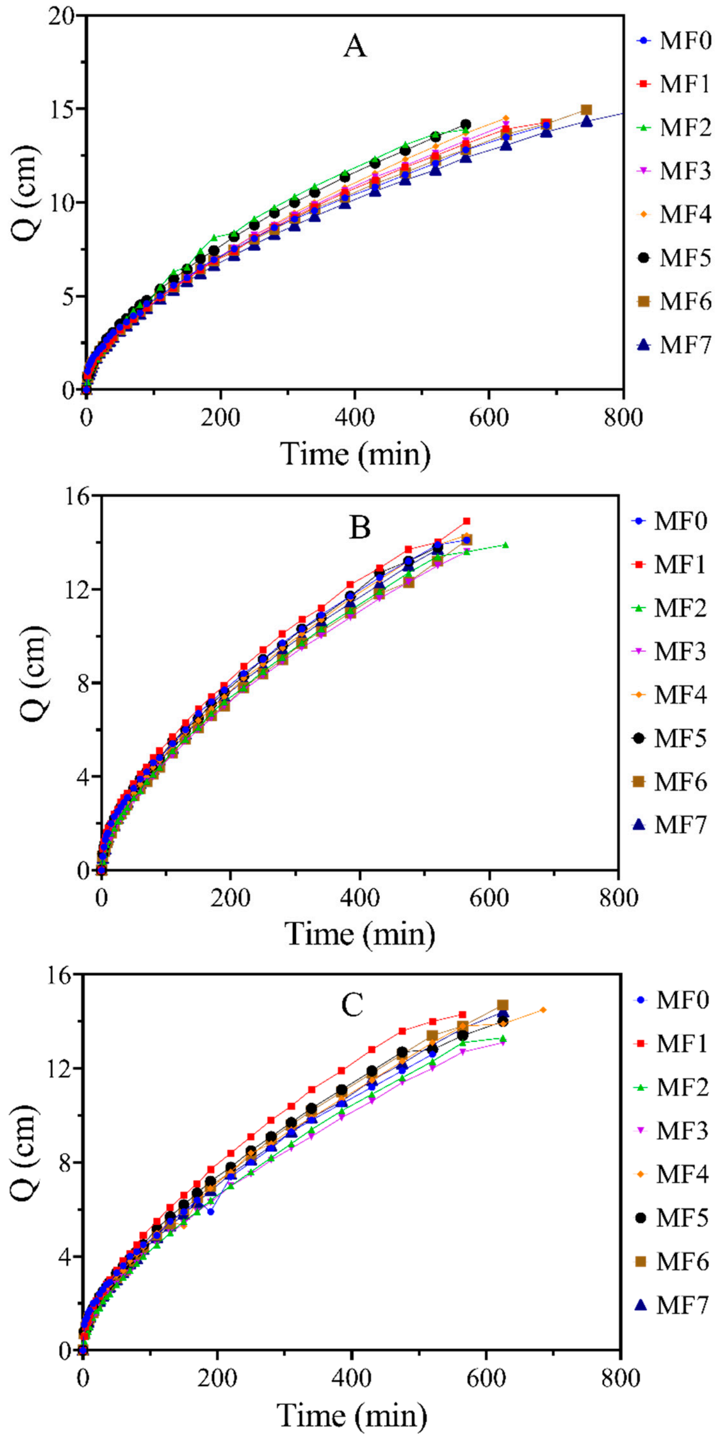


Figure 5. The effect of magnetic forces on changes in cumulative infiltration (Q; cm min^{-1}) with depth at different levels of irrigation water salinity: (**A**) 0 g L^{-1} (S_0, control); (**B**) 3 g L^{-1} (S_3); and (**C**) 6 g L^{-1} (S_6). MF_0, MF_1, MF_2, MF_3, MF_4, MF_5, MF_6, and MF_7 are the magnetic forces of 0, 1000, 2000, 3000, 4000, 5000, 6000, and 7000 gauss, respectively.

4. Discussion

4.1. Chemical Properties of Soil and Leachate

Magnetic treatments led to a decrease in EC in all solutions with different salinity levels except tap water, while the pH increased in all solutions. On the other hand, the effect of magnetized water was nullified after 108 h, and the pH and EC of the solutions returned to the original values. The increase in pH and decrease in EC in magnetically treated water could be due to the changes in hydrogen bonding and the increased mobility of ions. The decrease in EC could be due to the increased ability of electrolytic substances to sediment, as the magnetized water contains tiny colloidal molecules that respond to magnetic treatment. Similarly, researchers have indicated that the physicochemical properties of water, such as the hydrogen polarity, bonding, surface tension, pH, conductivity, solubility of salts, and refractive index, change due to the effect of magnetic fields [34,35]. In addition, the effects of magnetically treated water on soil properties led to a decrease in EC [36] and the sedimentation of salts [37]. However, Maheshwari and Grewal [8] reported that irrigation with magnetized water decreased soil pH. In addition to breaking hydrogen bonds, the electromagnetic fields could disrupt the gas–liquid interface, generating reactive oxygen species and affecting the hydration of carbon dioxide [38]. Our results demonstrated the inverse relationship between pH and EC [39] and that the application of magnetic force strengthened this relationship by affecting water movement in the soil profile (infiltration properties, Figure 4B and Table 1) and the distribution of salts (cations and anions) [40].

These effects impacted the soil chemistry along the column and thus influenced the chemical properties of the leachate. Our results indicated that the distribution of salts in the soil layers was changed by the application of magnetically treated water, with decreased salt content in the higher layers. The accumulation rate of soil salts decreased compared to soils irrigated with untreated saline leaching solution Zlotopolski [6]. The results of the current study are more reliable than the results of field experiments due to the controlled conditions in the laboratory. The effects of the magnetization force on the leachate were directly related to the changes in the infiltration rate and thus the leachate volume [6]. The soil columns treated with magnetized water were able to hold 25% more water compared to those treated with non-magnetized water, possibly due to the decline in surface tension. In addition, the magnetic force changed the microscopic molecular structure of the marginal irrigation water, enhancing the crystallization of cations and the viscosity, which in turn affected the chemical properties at depth and in the leachate [40]. Because salinity does not always influence the entire soil profile equally, salt profiling can be used to comprehensively represent the vertical distribution of salts in terms of composition and content [41]. The greater accumulation of salts in the soil columns in response to magnetic treatment resulted in a lower EC in the leachate and thus a higher pH. Magnetic treatment does not change the chemical parameters of water. However, it does affect the physical parameters, decreasing the viscosity, surface tension, diffusion, solubility, and zeta potential [42,43].

To consider the various impacts of cations on soil structure, *CROSS* (improved irrigation water and soil quality parameter) was introduced to replace *SAR* [44]. Under this arrangement, the detrimental effect of K^+ was one third that of Na^+, while the effect of Ca^{2+} was 13 times that of Mg^{2+}. Therefore, *CROSS* was expected to be a more representative parameter to evaluate the positive and negative impacts of cations more accurately on soil structure in various soils [45]. These changes in the soil and leachate are interrelated and could be explained by changes in the cation composition and balance. Mg^{2+} had the highest correlation with Ca^{2+}, which emphasized the similar effect of both cations on soil structure maintenance according to soil solidity and irrigation water evaluation [45]. Accordingly, more K^+ was displaced by other cations from soil particles by cation exchange [46]. The divalent cations such as Ca^{2+} and Mg^{2+} were expected to replace the adsorbed Na^+ and lead to colloidal flocculation, which would in turn improve the soil structure [47,48]. The accumulation of Ca^{2+} and Mg^{2+} indicated the lower mobility of bivalent cations with water flow, which was consistent with previous findings [49].

4.2. Soil Physical Properties

Our results indicated that applying magnetic treatments enhanced the hydraulic conductivity of the clay soil by 50%, which agreed well with the findings of Abd-Elhady and Rady [50], who reported an increment of 31% in the k_s. This effect was related to the role of the magnetic field in weakening the cohesive and adhesive forces between water molecules and soil particles [50,51]. Magnetic fields can change the surface tension of water by impacting the microscopic structure of water molecules [52]. We recorded a significant increase in k_s with increasing water salinity, which was consistent with the results of Yilmaz et al. [53] and Basile et al. [54]. However, some studies have produced contradictory results due to the fact that the matrix potential of soil increases with increasing salinity, which in turn may lead to a decrease in k_s [55].

The current study suggested that the magnetization of water could play an important role in improving the infiltration of clay soils and thus reducing waterlogging under such conditions for two main reasons. First, water molecules that are adhered by Van der Waals forces and hydrogen bonds in reactions with other ions become less cohesive and are released under magnetized conditions [56]. This also corresponds to the increased infiltration rate (curve slopes, b) with the increase in magnetic force (Table 1). Additionally, water molecules easily percolate into soil micro spaces [21,57]. Second, the magnetic treatment of water affects the physical characteristics of soil by breaking down the free gasses present in the water [57]. A decrease in contact angles results in an increase in hydrophobic materials and a decrease in their surface tension forces compared to untreated water. This increases the solubilizing power of water molecules, which easily percolate into the soil micro spaces [7].

5. Conclusions

In this study, we investigated the effect of eight magnetic forces on soil chemical and physical properties under three salinity levels (S_0, S_3, and S_6) at seven depths using soil columns in a controlled laboratory environment. The results showed that magnetic treatment decreased the soil pH and electrical conductivity and improved the hydraulic conductivity and infiltration parameters under the three salinity levels. An increase in magnetic force caused a decrease in soil pH and a decrease in soil EC with depth under salinities of S_3 and S_6 compared to S_0. The soil *SAR*, *SSP*, and *CROSS* displayed the highest values at depths 2, 3, 4, and 5 under all magnetic forces. In the leachate soil column study, the use of saline irrigation water under the same magnetic forces resulted in an increase in soil EC and a decrease in soil pH. An increase in magnetic force corresponded to an increase in k_s at the same salinity level. An increase in salinity increased k_s under S_3 and S_6 compared to S_0. As salinity increased, the cumulative infiltration increased after nine hours, and the effect of magnetic forces on the cumulative infiltration rate varied: magnetic forces of 6000 and 7000 gauss had a significant effect, while magnetic forces of 1000 and 4000 gauss had the highest effect under salinity levels S_3 and S_6. These results emphasize the importance of the magnetization of saline water for sustainably improving soil properties and avoiding soil degradation when using marginal water. Our study revealed a significant change in soil properties in response to magnetized saline water, which must be considered when planning irrigation with MW. This study served as a field simulation that allowed us to predict and understand the impact on yield. However, there is still a need to evaluate and generalize our initial results at the field level.

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