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Magnetized Water Irrigation Alleviates Emitter Clogging of a Drip Fertigation System

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Abstract: Drip fertigation systems are a new technology to alleviate water shortages and improve fertilizer use efficiency. Emitter clogging is the main obstacle to their application. However, few efficient, safe, and environmentally friendly methods are available to alleviate clogging. In this study, we explored the effects of magnetized water irrigation on emitter clogging at different fertilization levels. Field experiments were conducted to study the patterns and clogging characteristics of drip irrigation systems during two planting seasons. The results showed that with an increase in fertilizer application, clogging of the emitter was aggravated. Magnetization treatment effectively relieved emitter clogging, which increased the average discharge variation rate (Dra) by 4.1–29.0% and 2.6–64.4%, respectively, and decreased the dry weight (DW) of the clogging substance by 14.0–64.6% and 15.0–75%, respectively, in the two planting seasons, compared with that of the non-magnetization treatment. The composition of the main clogging substances was estimated using X-rays; the results showed that quartz, silicate, and carbonate were the dominant substances that induced emitter clogging. Magnetization treatment can reduce the content of clogging substances and is thus a possible mechanism to alleviate clogging. Our study demonstrated that water magnetization treatment is an effective, chemical-free treatment method with great potential for clogging control in drip fertigation systems.

Keywords: magnetization; emitter; clogging substance; mineral composition; drip fertigation

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1. Introduction

The drip fertigation system is a new technology that is recognized to efficiently save water and fertilizer resources. It can supply water and nutrients to crops uniformly, accurately, and in a timely manner according to soil characteristics and crop growth laws [1]. Many studies have shown that drip fertigation technology can improve water and fertilizer utilization efficiency and promote crop growth and yield increase [2–5]. The emitter is the key component of drip irrigation systems; it dissipates the energy of pressurized water flow by means of the complex and narrow channels inside it so that the water flow drops into the soil stably and evenly [6]. However, owing to the small, narrow flow path (0.5–1.2 mm) of the emitter, it is easily clogged by solid particles, chemical precipitation, microorganisms, and other substances in irrigation water [7,8]. In particular, the use of fertilizers contributes to the formation and development of clogging substances in drip fertigation systems [9]. This, in turn, reduces the service life of the system and causes uneven fertilization, eventually resulting in a decrease in economic benefits [10]. Emitter clogging has become a major obstacle to the development and application of drip irrigation technology.

Recently, numerous studies have been conducted on the effects of fertigation on emitter clogging when using irrigation water with complex water quality and various types of fertilizers. Tang [9] stated that the fertilizer solution concentration is one of the factors affecting fertilization uniformity, with poor fertilization uniformity leading to the clogging of drip irrigation systems. Li [11] and Tayel [12] inferred that the clogging effect of emitters is more obvious at higher fertilizer concentrations than at lower fertilizer concentrations. Muhammad [13] conducted field experiments to investigate the influence of water irrigation salinity and fertilizer type on emitter clogging, and the results indicated that P fertilizer application aggravated the emitter clogging process and that water salinity had a larger impact on the emitter clogging process than fertilizer type. Xiao [14] stated that emitter clogging was aggravated after the application of potassium phosphate monobasic, urea phosphate (UP), and ammonium polyphosphate (APP). Under the same amount of fertilizer, low concentration and long-term fertilization effectively relieved the clogging issue, and this study suggested to choose UP as the fertilizer type and adopt low concentration and long-term fertilization modes in phosphorus fertigation using a drip irrigation system. However, Ma [15] reported that UP effectively alleviated emitter clogging under high-salinity water, mainly because it lowered the water pH and inhibited the formation of carbonate. Wang [16] evaluated the clogging process and mechanisms in drip emitters during the application of saline water with combined P and N fertigation and suggested that phosphorus-coupled nitrogen drip fertigation should be applied with caution when applying saline water with electrical conductivity higher than 4 dS m^{-1}. The operation patterns of drip irrigation fertigation systems have a significant impact on emitter clogging. Zhou [17] stated that shortening drip system running intervals could alleviate emitter clogging. Besides the macro-element above, Wang [18] stated that chelated trace-element ethylenediaminetetraacetic acid (EDTA)–Cu effectively alleviated the emitter fouling due to its strong adsorption ability for Ca^{2+} and Mg^{2+}, whereas EDTA–Mn significantly aggravated the emitter fouling. These studies provide good references for understanding the mechanism of emitter clogging under drip fertigation when applying saline water or Yellow River water. However, farmers still prefer to use traditional fertilizer than the new type of UP fertilizer because of the high price, strong acid of urea phosphate, and improper use resulting in soil acidification [14]. Because irrigation water quality is the key factor that leads to emitter clogging [19], the injection of acidic chemical reagents into the drip irrigation system to reduce the pH of irrigation water can significantly prevent the production and accumulation of chemical precipitation, which is a common method for controlling the clogging of drip irrigation systems. However, the injection of acidic chemicals poses the risks of soil acidification, erosion, and crop damage [20]. Therefore, a more effective, safe, and environmentally friendly technology for emitter clogging control is urgently required.

Magnetization technology was first developed for the industrial descaling of heat exchangers and boilers [21]. When water passes through a magnetic field, the larger cluster structure of water molecules becomes smaller, which changes the physical and chemical properties of water, such as permeability, ionic hydration reaction, and solubility enhancement [22], which improves the solubility of the solution to scale substances to achieve physical descaling [23]. Magnetization technology has been gradually extended to many fields, including agricultural production. Studies have shown that magnetized water irrigation can promote seed germination [24–26], increase yield [27–29], maintain soil moisture [30], and improve saline land [31]. In recent years, some scholars have innovatively introduced magnetization into brackish water drip irrigation systems, aiming to solve the problem of chemical clogging of emitters. Aali [21] and Sahin [32] found that magnetization treatment can alleviate the clogging problem of brackish water drip irrigation systems and that the magnetization effect is affected by irrigation water quality.

At present, research on emitter clogging in drip fertigation is mainly focused on simulation conditions; however, the results remain at the theoretical level. Studies under actual field production conditions have rarely been reported. Moreover, the common method of adding acid chemical reagents to control clogging is risky for soil, drip irrigation systems, and crops; therefore, it is urgent to find an efficient, safe, and environmentally friendly technology to control emitter clogging. In addition, research on magnetization technology for controlling clogging has mainly focused on brackish water and remains to be proven in drip fertigation systems. In this study, we explored the effect of magnetization on emitter clogging under different fertilizer application levels and the main components of the materials causing emitter clogging were investigated. We hypothesized that magnetization treatment could alleviate emitter clogging in drip fertigation systems and that this effect is relevant to the decrease in specific components.

2. Materials and Methods

2.1. Experimental Setup

The experiment was conducted in the national precision agriculture demonstration base in Xiaotangshan Town, Changping District Beijing, China. Tomatoes were planted in a sunlight greenhouse, two rows of tomatoes were planted in each ridge and one drip irrigation tape was arranged in each row of tomatoes. The experiment was conducted for two consecutive seasons. The drip irrigation emitter was a no-pressure-compensating type with a spacing of 30 cm, rated working pressure of 0.1 MPa, and rated flow rate of 0.95 L/H (produced by Netafim Company, Hatzerim, Israel). The drip irrigation system consists of a water bucket, check valve, gate valve, and metering equipment such as a water meter and pressure gauge. The whole drip irrigation system installed a proportional fertilization pump for fertilization followed by two-stage filtration (screen filter and laminated filter). The operating pressure of the drip irrigation system was 0.1 MPa.

The experiment was divided into magnetized water irrigation areas (labeled M1) and non-magnetized areas (labeled M0). The magnetized water was generated using a magnetizer (manufacture: Yishui, China) with coils twined around branch pipes. Three fertilization levels were both set in the magnetized water irrigation area and non-magnetization treatment. The total fertilization rates (N-P_2O_5-K_2O) were 275 kg/hm^2 (F1), 412.5 kg/hm^2 (F2), and 550 kg/hm^2 (F3), respectively. Urea, diammonium phosphate, and potassium chloride were used in the experiment. The details of treatments were shown in Table 1.

Table 1. Experiment treatments.

Treatment	Fertilization Amount/(kg·hm^{-2})			
	N	P_2O_5	K_2O	Total
M0F1	110	75	90	275
M0F2	165	112.5	135	412.5
M0F3	220	150	180	550
M1F1	110	75	90	275
M1F2	165	112.5	135	412.5
M1F3	220	150	180	550

2.2. Evaluation Parameters of Emitter Performance

The outflow of each emitter was collected for 5 min at the end of each planting seasons with 3 replicates per treatment. Based on the weight of collected water, the emitters' average discharge variation rate (Dra) was calculated as follows.

$$\mathrm{Dra} = \frac{\sum_{i=1}^{n} q_i}{nq} \times 100\%$$

where q_i is the flow rate of emitter i, in L/h; q is initial flow rate of the emitter, in L/h; and n is the total number of emitters installed along the lateral.

The outflow uniformity of the drip irrigation emitters can be represented by the Christiansen of uniformity (CU); CU was calculated as follows [33].

$$\mathrm{CU} = 100\left(1 - \frac{\sum_{i=1}^{n}|q_i - \overline{q}|}{n\overline{q}}\right)$$

where q_i is the flow rate of the emitter i, in L/h; $\overline{q}$ is average flow of each emitter along the lateral, in L/h; and n is the total number of emitters installed along the lateral.

2.3. Extraction and Evaluation of Clogging Substances in Emitters

2.3.1. Dry Weight of Clogging Substances

The sampling of the emitters was conducted at the end of each planting season, when 6-drip irrigation emitters were intercepted at the head, middle, and tail of a lateral, respectively. A high-precision electronic weight balance (accuracy 10^{-4} g) was used to weigh the emitter samples and then placed in the zip-lock bags. Thereafter, 20 mL deionized water was added to remove the clogging substances using an ultrasonic cleaner. Weighing the clean samples, the average dry weight of clogging substances in the emitters was obtained based on the weight difference.

2.3.2. Mineral Composition of Clogging Substances

The emitters' dry clogging substances were then analyzed by the X-ray diffractometer (manufacture: Bruker, Karlsruhe, Germany; type: D8-Advance) to obtain the polycrystalline diffraction image. Then, the patterns were analyzed by TOPAS (Bruker, Karlsruhe, Germany) software to obtain the mineral contents and components of the clogging substances.

2.3.3. Surface Morphology of the Fouling

After the end of planting season, two emitters were selected from the head, middle, and tail, respectively, and were carefully peeled off with a knife. The surface morphology of the fouling in the emitters was observed using a scanning electron microscope (SEM). The specific operation steps are as follows: the sample is fixed on the sample stage by a conductive tape and is placed in a vacuum chamber to spray the conductive gold film before scanning. Machine conditions were: acceleration voltage 30 kV and magnification 3000×.

2.4. Statistical Analysis

Data were subjected to statistical analysis using SPSS (ver. 22.0 IBM, Chicago, IL, USA). Paired *t*-tests were used to determine significant differences among treatments. Analysis of variance (ANOVA) was applied to determine the effects of magnetization, fertilizer concentration, and their interactions on Dra, CU, and DW. Pearson correlation analysis was used to study the correlation between Dra, CU, and DW.

3. Results

3.1. Effect of Fertilizer Application and Magnetization on Emitter Performance

The average discharge variation rate (Dra) and Christiansen of uniformity (CU) values of emitters with different treatments after the end of each of the two planting seasons are shown in Figure 1. The results show that Dra decreased gradually with operation time and the maximum decrease was 68.5%, which was observed after the second season compared with that after the first season. In both seasons, the Dra of the non-magnetization treatment decreased significantly with an increase in fertilizer application. The Dra values for M0F1, M0F2, and M0F3 were 87.8%, 87.7%, and 57.5%, respectively, at the end of the first season. At the end of the second season, the Dra of M0F1 and M0F2 decreased sharply from 84.6% and 81.1% to 18.1% of M0F3, respectively. Compared with that of M0F1 and M0F2, the Dra of M0F3 was reduced by 30.3–66.5% and 30.2–63%, respectively. Moreover, under the same fertilizer application level, the Dra of the magnetized treatment was significantly higher than that of the non-magnetized treatment in both seasons and the Dra increased by 4.1–29.0% and 2.6–64.4%, respectively. The CU of the non-magnetized treatment in F3 in the two seasons decreased sharply to 45.8% and −39.4%, respectively, whereas that of the magnetized treatment increased to 99.4% and 98.9%, respectively, which significantly improved the irrigation non-uniformity caused by high fertilizer application.

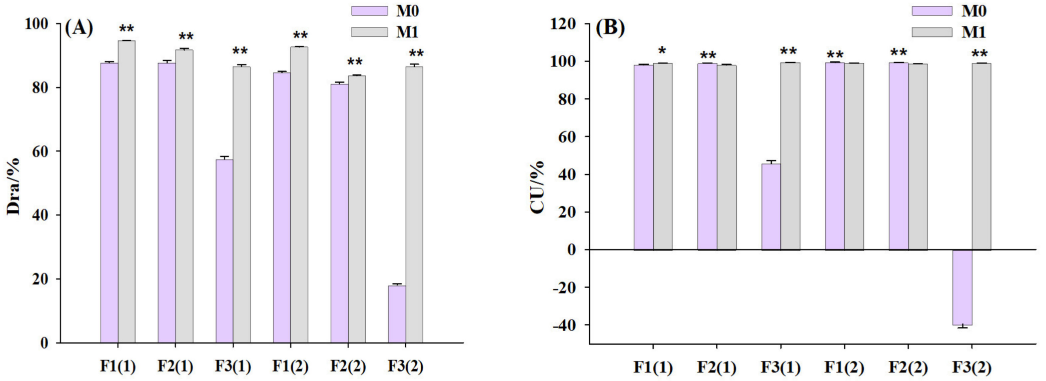


Figure 1. Dra (**A**) and CU (**B**) of magnetization treatments and under three fertilization levels of two planting seasons. (1) Means the first season, (2) means the second season; * indicates $p < 0.05$, ** indicates $p < 0.01$.

The results of the analysis (Table 2) showed that fertilizer application, magnetization, and their interaction had significant effects on Dra and CU ($p < 0.01$). The effect of magnetization on the Dra was greater than that of fertilization. In the first season, the effect of magnetization treatment on CU was greater than that of fertilization; however, in the second season, the effect of magnetization treatment on CU was less than that of fertilization.

Table 2. The effects of fertilizer application and magnetization on the Dra and CU under different seasons.

Treatment	The First Season		The Second Season	
	Dra	CU	Dra	CU
Fertilizer application (F)	2025.297 **	2969.601 **	12,494.782 **	12,490.952 **
Magnetization (M)	2358.173 **	3172.257 **	17,180.818 **	12,214.173 **
Fertilizer application × magnetization (F × M)	822.341 **	3154.981 **	11,016.973 **	12,523.260 **

** indicates $p < 0.01$.

3.2. Clogging Substance and Surface Morphology Characteristics

The dry weight (DW) of the clogging substances in each treatment gradually increased over time (Figure 2). Compared with that of the first season, the DW of the second season increased by 5.4–67.6%. In addition, the magnetization and fertilization rates directly affected the accumulation of DW. In both planting seasons, an increase in fertilizer promoted DW accumulation. Compared with that of M0F1 and M0F2, the DW of M0F3 was increased by 203.5–321.3% and 133.0–155.1%, respectively. Under the same fertilization level, compared with the non-magnetization treatment, the magnetization treatment significantly reduced DW, with decreases of 14.0–64.6% in the first season and 15.0–75% in the second season. The results of the variance analysis show that fertilizer application, magnetization treatment, and their interaction had significant effects on DW ($p < 0.01$) and the effect of magnetization was stronger than that of fertilization in both seasons (Table 3).

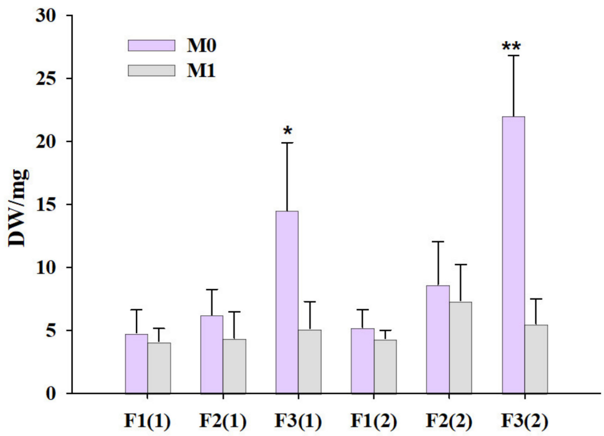


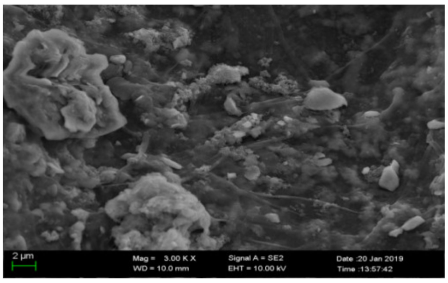
Figure 2. Dry weight of clogging substances in the emitter under different treatments in the first season (1) and the second season (2). * indicates $p < 0.05$, ** indicates $p < 0.01$.

Table 3. The effects of fertilizer application and magnetization on the DW under different seasons.

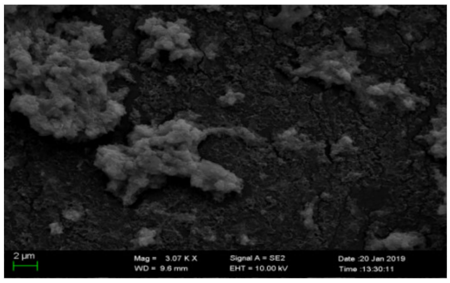
Treatment	The First Season	The Second Season
Fertilizer application (F)	6.240 **	15.139 **
Magnetization (M)	9.490 **	22.072 **
Fertilizer application × magnetization (F × M)	5.023 **	13.813 **

** indicates $p < 0.01$.

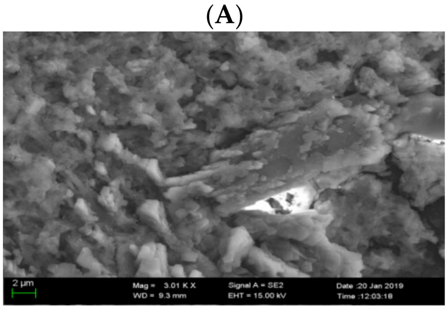
Figure 3 shows the change in surface topography of the fouling in the emitter flow channel at the end of the second season (taking F1 and F3 emitters as an example). The results show that in the non-magnetized treatment, the dirt particles of different sizes were tightly combined and the dirt size was larger (Figure 3A,C). In contrast, the magnetization treatment reduced the dirt content and changed the crystal morphology; the dirt size was smaller, more widely distributed, and more dispersed than that in the non-magnetization treatment (Figure 3B,D).



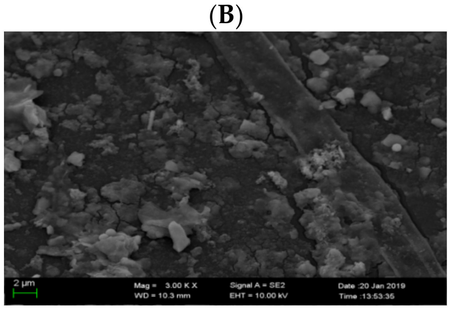
(**A**)



(**B**)



(**C**)



(**D**)

Figure 3. The appearance of scaling ((**A**) M0F1, (**B**) M1F1, (**C**) M0F3, (**D**) M1F3).

3.3. Proportion and Content of Mineral Components of Clogging Substances

Figure 4 shows that the main mineral components of the emitter clogging material are calcite ($CaCO_3$-Calcite), magnesium calcite ($CaMgCO_3$), quartz (SiO_2), muscovite ($K(Mg,Al)_{2.04}(Si_{3.34}Al_{0.66})O_{10}(OH)_2$), chlorite ($Mg_5Al(Si_3Al)O_{10}(OH)_8$), anorthite ($CaO{\cdot}Al_2O_3{\cdot}2SiO_2$), and calcium phosphate ($Ca_5(PO_4)_3(OH)$). According to chemical elements, mineral composition can be divided into carbonate, phosphate, silicate, and quartz. The percentage of chemical components varied with treatment and system operation time. After the end of the first season, except for M0F3, the clogging substances were mainly quartz and silicate (Figure 4A), accounting for 33.7–51.0% and 35.9–50.9%, respectively, followed by carbonate (3.4–22.9%). In addition, the magnetization treatment effectively inhibited the formation of calcite under F1 and F2. After the end of the second season, the chemical composition and content of chemical composition changed. The clogging material contained not only quartz (13.4–37.6%), carbonate (4.2–34.0%), and silicate (18.9–43.1%) but also a large amount of phosphate (14.7–62.2%) (Figure 4B). Magnetization treatment promoted the formation of phosphate and reduced the deposition of anorthite under F1 and F2, whereas the opposite trend was observed under F3.

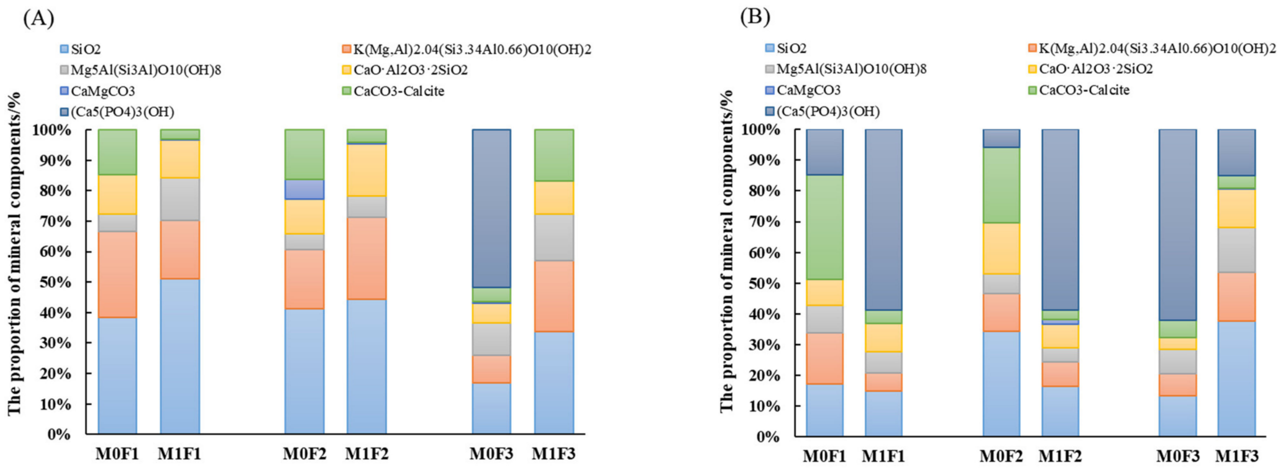


Figure 4. Proportion of mineral composition in the first season (**A**) and the second season (**B**).

As shown in Table 4, after the end of the first planting season, the muscovite content after magnetization treatment was reduced by 3.4–41.5% compared with that in non-magnetization treatment. The contents of quartz, chlorite, and magnesium calcite in the magnetized treatment increased by 14.8–114.8% under F1 and decreased by 24.2–29.7%, 3.2–49.0%, and 0–95.1% under F2 and F3. According to the chemical composition, the contents of quartz, silicate, carbonate, and phosphate were 1.73–2.56, 1.88–3.79, 0.20–1.42, and 0–7.51 mg, respectively. At the three fertilization levels, the magnetization treatment reduced the silicate content, whereas the other components showed no obvious change. At the end of the second planting season, the quartz, muscovite, chlorite, anorthite, and calcite contents in the magnetization treatment decreased by 27.8–59.1%, 44.6–70.9%, 36.2–54.3%, 9.1–60.4%, and 81.8–89.9%, respectively. Moreover, no magnesium calcite was observed in the non-magnetization treatment; however, the magnetization treatment under F2 and F3 exhibited magnesium calcite contents. According to the chemical composition, the contents of quartz, silicate, carbonate, and phosphate were 0.65–2.96, 0.95–4.16, 0.18–2.12, and 0–13.68 mg, respectively. Under the three fertilization levels, magnetization reduced their contents but increased the content of phosphate under F3.

Table 4. Changes of clogging substances in treatments.

Season	Category/mg	M0F1	M1F1	Tendency	M0F2	M1F2	Tendency	M0F3	M1F3	Tendency
The first season	Quartz	1.83	2.1	↑	2.56	1.94	↓	2.46	1.73	↓
	Muscovite	1.35	0.79	↓	1.22	1.17	↓	1.29	1.19	↓
	Chlorite	0.27	0.58	↑	0.31	0.3	↓	1.55	0.79	↓
	Anorthite	0.62	0.51	↓	0.71	0.75	↑	0.95	0.56	↓
	Magnesium calcite	0	0.02	↑	0.41	0.02	↓	0.09	0	↓
	Calcite	0.7	0.12	↑	1.01	0.18	↓	0.66	0.86	↑
	Calcium phosphate	0	0	—	0	0	—	7.51	0	↓
The second season	Quartz	0.90	0.65	↓	2.96	1.21	↓	2.95	2.07	↓
	Muscovite	0.86	0.25	↓	1.06	0.58	↓	1.59	0.88	↓
	Chlorite	0.47	0.30	↓	0.55	0.33	↓	1.75	0.80	↓
	Anorthite	0.44	0.40	↓	1.44	0.57	↓	0.82	0.69	↓
	Magnesium calcite	0.00	0.00	—	0.00	0.11	↑	0.00	0.02	↑
	Calcite	1.78	0.18	↓	2.12	0.22	↓	1.21	0.22	↓
	Calcium phosphate	0.77	2.55	↑	0.50	4.31	↑	13.68	0.82	↓

4. Discussion

4.1. Effect of Fertilization on the Performance of a Drip Fertigation System in the Field

Emitter clogging in drip irrigation systems directly affects irrigation uniformity, system operation benefits, and service life and even leads to crop yield reduction, which has always been one of the difficulties in drip irrigation fields [34]. The results of our study showed that in the two planting seasons, fertilizer application had a significant effect on the Dra and CU (Table 2) and the Dra in the non-magnetized treatment was significantly reduced with the increase in fertilizer application (Figure 1). This is because the nutrients in fertilizers can easily precipitate with the ions in irrigation water, which further aggravates emitter clogging [35]. Generally, according to the recommendations of the International Organization for Standardization, the standard for determining clogging is defined as the flow rate of the emitter being less than 75% of the designated value [36]. The results of our study show that the higher the fertilizer concentration, the worse the emitter clogging. Under the high fertilizer level F3, Dra values in the two seasons (indicating the clogging phenomenon) were 57.5% and 18.1%, respectively (Figure 1). This is mainly because with an increase in fertilizer concentration, the probability of forming insoluble substances between ions increases [37]. Our study results are consistent with those reported by Tayel [12]. However, studies have also shown that the application of the phosphate fertilizer APP could significantly alleviate the clogging of emitters; the higher the concentration of APP, the better the effect of relieving clogging, which may be related to the special structure of APP [15]. Yu [38] revealed that when the fertilizer concentration is lower than 0.6 g/L, increasing the fertilizer concentration accelerates emitter clogging significantly, whereas if the fertilizer concentration is greater than 0.6 g/L, the effect of accelerating the clogging by further increasing the fertilizer concentration is small. This indicates that the effect of the fertilizer concentration on emitter clogging is related to the type of fertilizer used. Verifying the material properties of the fouling composition is the key to understanding the clogging mechanism. In the two planting seasons, the components of clogging substances inside the emitters under different treatments were consistent, mainly consisting of quartz, silicate, carbonate, and phosphate, which was consistent with the research on irrigation water quality and fertilizer types [13–15], indicating that the chemical properties of the clogging component were mainly determined by the irrigation water quality and fertilizer type. As the experiments were carried out at room temperature and 100 kPa pressure, it was difficult to form SiO_2 in the emitter under these conditions. Therefore, the SiO_2 found in the clogging substances was mainly derived from irrigation water [6]. The clogging mechanism is a physical and chemical coupling process in which fertilizers are used in drip irrigation. In the first planting season, the main clogging substances were quartz and silicate, followed by carbonate. At the end of the second season, the composition and content of the composition changed and included phosphate (Figure 4B), which indicated that the clogging component contents were not only related to the type of fertilizer but also changed synchronously with the running time.

4.2. Effect of Magnetization on Emitter Clogging of Drip Fertigation System

Magnetization has been applied to industrial-scale removal. Our study attempted to apply it to drip fertigation to explore whether magnetization can regulate emitter performance. The results showed that magnetization significantly increased the Dra and CU, especially under F3. Wang [39] and Khoshravesh [40] also found that magnetization significantly slowed the downward trend of dripper flow and irrigation uniformity. It is possible that after magnetization, the original large associated water molecular groups will be reduced, enhancing the activity of water. In addition, the solubility and permeability of minerals in solution are improved, which affects the growth and morphology of scale crystals (mainly calcium carbonate) [20], allowing them to poorly adhere to the pipe wall and be more easily washed away by water flow [41]. The Dra ($F = -0.987$, $p < 0.01$) and CU ($F = -0.969$, $p < 0.01$) were significantly negatively correlated with DW, indicating that the higher the amount of clogging materials, the more serious the clogging. Further analysis of the clogging composition revealed that magnetization reduced the silicate content after the end of the first season, and the other components showed no obvious change. At the end of the second planting season, magnetization reduced the quartz, silicate, and carbonate contents. This was consistent with the conclusion that magnetization can increase the Dra and decrease DW more significantly in the second planting season, indicating that the anti-clog effect of magnetization was better after a long operation period. The phenomenon that magnetization can inhibit carbonate formation after the end of the second planting season is consistent with that reported in previous studies [42–44]. Our study also found that magnetization could mitigate the deposition of silicates and quartz, which was consistent with the results of Liu [43] and Xiao [45]. This could be explained as follows: a lower water pH promotes silicate deposition [46]; thus, the increased water pH values due to magnetization inhibit silicate formation [43,44]. In addition, carbonate can serve as a nucleation site for silicates [47]. Consequently, magnetization effectively prevented carbonate precipitation, which in turn caused a decrease in silicate content.

Moreover, the performance of the emitter further affects crop yield. The yield of tomatoes increased with an increase in fertilizer application amount. Under the same fertilization level, compared with non-magnetized treatment, magnetized irrigation increased tomato yield by 11.2–26.3% (Table 5). This could be explained by changes in the physical and chemical properties of the irrigation water, which are conducive to the transportation and dissolution of nutrients and promote crop growth and dry matter accumulation [27]. Therefore, magnetized water irrigation can not only alleviate the clogging problem of drip irrigation but also increase the yield.

Table 5. Crop yields of different fertilizer application and magnetization.

Treatment	M0F1	M0F2	M0F3	M1F1	M1F2	M1F3
Yield (kg/ha)	95,126.85	84,848.55	75,385.05	105,771.75	99,925.95	95,242.2

5. Conclusions

Magnetization treatment is an effective, environmentally friendly, and safe method for alleviating emitter clogging in drip irrigation systems. This study revealed the significant effect of magnetization treatment on emitter clogging, and the potential mechanism was further explored by revealing the reduction in specific clogging substances. Under the same fertilizer amount, the Dra of the magnetized treatment was significantly higher than that of the non-magnetized treatment. In addition, the magnetization treatment reduced the DW of the clogging substances and the contents of the clogging components quartz, silicate, and carbonate. In addition, based on the in situ study, our results revealed that magnetization treatment has widespread value in practical production. In the future, it will be necessary to popularize magnetization treatment in other scenarios and study the effects of magnetization on other factors, such as biofouling, to understand the practical value of this method more comprehensively.

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