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Assessment of water quality ions in brackish water on drip irrigation system performance applied in saline areas

Yayu Wang [a,b], Yang Xiao [a], Jaume Puig-Bargués [d], Bo Zhou [a,c,*], Zeyuan Liu [a], Tahir Muhammad [a], Hongbang Liang [b], Memetmin Maitusong [e], Zhenhua Wang [b], Yunkai Li [a,c]

[a] College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China
[b] College of Water Conservancy & Architectural Engineering, Shihezi University, Shihezi 832000, Xinjiang, China
[c] Engineering Research Center for Agricultural Water-Saving and Water Resources, Ministry of Education, Beijing 100083, China
[d] Department of Chemical and Agricultural Engineering and Technology, University of Girona, Girona 17003, Spain
[e] Xinjiang Kashgar River Basin Authority, Kashgar 844000, Xinjiang, China

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ABSTRACT

Utilizing brackish water with drip irrigation technology, due to its precise water control alleviates the secondary soil salinization, and improves crop yield and quality, which offers sustainable agricultural development opportunities in saline areas. However, the complex characteristics of brackish water increase the risk of drip irrigation emitter clogging, which inhibit its promotion and adoption. It is necessary to find out the dominant water quality ions that lead to emitter clogging under multiple ion interactions when using brackish water under multiple ion coexistence conditions. Thus, the in-situ pilot research was conducted to study the emitter clogging mechanism using brackish water collected from 16 different salt-alkaline regions. A comprehensive evaluation with the consideration of 11 water quality ions on emitter clogging were conducted. Results showed that the degree of emitter clogging gradually increased in the first 40 days of irrigation, hereafter started an accelerated reduction until the days 64 of brackish water application. Spearman correlation and structural equation modelling were used to identify the main factors contribute to emitter clogging. And results indicated that calcium fouling (CF) and silica fouling (SF) were the major fouling minerals in the emitter flow channels. Ca^{2+}, CO_3^{2-}+HCO_3^-, pH, total hardness (TH), and zeta potential (ZP) were the key water characteristics leading to emitter clogging. These factors directly affected CF and SF, while also affecting the Mg^{2+}, Mn^{2+}, Cu^{2+}, and other water quality factors which indirectly enhanced the CF and SF. Thereafter a few water quality control strategies were proposed based on emitter clogging and soil salinization mitigation. This study identified the key water quality ions that induce drip irrigation emitter clogging when using brackish water, provided solid support for solving the clogging issue, and promoted the high-efficient utilization of brackish water in saline areas.

1. Introduction

Sustainable agriculture is highly dependent on soil and water resources (Ondrasek and Rengel, 2021; Bagheri and Teymouri, 2022; Masud et al., 2019). However, in recent decades, decreasing of arable land per capita and the shortage of freshwater resources have become major obstacles to sustainable agricultural development (Dinar et al., 2019; Viana et al., 2022). Besides, saline soils are widely distributed, estimated as 1 billion hm^2 globally (Wang et al., 2018), and still growing with annual rate of 10%. As a result, saline area has become an extremely important strategic resource of reserve arable land and a potential grain-producing area. Meanwhile, shallow brackish water is a major source for agriculture irrigation water in saline soil areas (Zhang et al., 2022). Brackish water irrigation would help alleviating the drought associated issues and freshwater scarcity. However, the improper and intense saline irrigation patterns may lead to exacerbation of secondary salinization and long-term damage to soil ecosystem (Singh, 2009; Haj-Amor et al., 2022). Therefore, brackish water cannot be directly irrigated, usually pre-treated using methods such as filtration and desalination (Guo et al., 2021). In addition, its application for agricultural irrigation is limited by the huge infrastructure and cost (Slater et al., 2020). Therefore, an effective strategy for brackish water

* Corresponding author at: College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China.
E-mail address: zhoubo89@cau.edu.cn (B. Zhou).

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irrigation is urgently needed. Drip irrigation can be more widely applied to brackish water because of its fine volume control and its ability to reduce salt accumulation in the soil root zone (Li and Kang, 2020), drip irrigation was considered the most suitable technique for using brackish water irrigation in saline soils. Action as a salt drench, drip irrigation will effectively alleviate salt stress in crop root zone, minimize the hazards of secondary salinization, protect the soil environment (Wang et al., 2019b) and improve saline crop yield and quality (Liang and Shi, 2021; Zhao et al., 2021).

Drip irrigation with saline or brackish water in drought areas has been widely used (e.g., Israel, Egypt, Spain, etc.) (Sun et al., 2017; Dagar et al., 2019). However, the brackish water contains large amounts of Ca^{2+}, Mg^{2+}, CO_3^{2-}, HCO_3^- ions and suspended particles (Generous et al., 2020), and drip irrigation emitter flow paths are very narrow (usually 0.5–1.2 mm), being easy for suspended particles to accumulate and result in emitters clogging(Shen et al., 2022). Consequently, the use of brackish water affects the management of the drip irrigation systems. Therefore, the quality of brackish water is a key factor for emitter clogging in saline or brackish water utilization with drip irrigation. Previous studies suggested that Ca^{2+} and Mg^{2+} were likely to precipitate as calcium carbonate ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), which were major clogging compounds when using brackish water in drip irrigation emitters (Wang et al., 2019a; Wang et al., 2022a). Some studies also suggested that PO_4^{3-} and SO_4^{2-} in brackish water were prone to forming phosphate and sulfate precipitates (Wang et al., 2021b). Barzegari et al. (2020) reported that particulate content in brackish water was the key factor to emitter clogging. Zhangzhong et al. (2019) highlighted that electrical conductivity (EC) of irrigation water determined the intensity of emitter clogging of brackish water in drip irrigation, and severe clogging was found when EC exceeded 4 ds/m. In comparison, Liu et al. (2022) reported that clogging increased significantly when brackish water total dissolved salts exceeded 5.0 g/L. So far, previous studies analyzed the emitter clogging from the perspective of the single brackish water quality parameter. However, the potential interaction of water quality ions may lead to a more complex clogging (Xiao et al., 2023). For instance, Ca^{2+} content directly affected the formation of calcium carbonate fouling, while Mg^{2+}, Mn^{2+}, K^+ content and pH had a noticeable influence on formation of calcium carbonate fouling (Rahardianto et al., 2007; Gräber et al., 2021). Thus, the co-existence of multiple water quality ions of the brackish water may intensify the process and mechanism of drip irrigation emitter clogging, which was unknown yet.

Therefore, the main study aims to: (1) identify how brackish water of different quality affects emitter clogging; (2) specify the key brackish water quality ions and the mechanism of emitter clogging; and (3) propose possible water quality control strategy for mitigating emitter clogging using saline brackish water.

2. Materials and methods

2.1. Experimental basic information

This study was conducted in the Irrigation Test Station of the First Division Water Resources Management Center of Xinjiang Production and Construction Corps (81°2′E, 40°6′N). Fig. 1 shows the drip irrigation system testing system. During the test period, the brackish water was temporarily stored in the water tank, filtered in a screen filter (length × width × height: 290 ×260 ×150 mm, filtration level: 120 μm), and then conveyed to the drip irrigation system. 16 different brackish water sources collected from different areas at Alar, Xinjiang, were utilized. Detailed location information about the water sources collected are shown in Table S1. The experiment operated continuously 10 h per day, with a total operation of 64 days. Three types of the non-pressure compensated emitters (with rated outflow of 1.0 L/h, 1.6 L/h and 2.0 L/h, respectively) were applied as three replications those under the same working conditions, and their structural parameters are shown in Table 1. During the test period, the measured outflow was corrected to eliminate the influence of water temperature on emitter clogging. Table 2 summarizes the major water quality characteristics for the different treatments.

2.2. Evaluation of emitters' performance

The system consisted of three layers those 15 m in length, and each layer installed one type of drip irrigation lateral mentioned above. The emitters were evenly installed along drip laterals with 30 cm interval. A total of 50 emitters were involved in each drip irrigation lateral and the rated outflows were performed at the beginning of system operation. The emitter outflow was tested every 8 days (day 8, day 16, day 24, day 32, day 40, day 48, day 56 and day 64, respectively), involving all the emitters on the drip irrigation lateral. The system head pressure was adjusted to 0.1 MPa before conducting the test. Then, the emitter discharge was collected and weighed using a high-precision electronic balance (accuracy of 10^{-4} g). After correcting the measured discharge regarding the temperature according to the method proposed by Pei et al. (2013) and Liu et al. (2019), the average relative flow rate was calculated as average discharge variation rate (Dra) to determine the

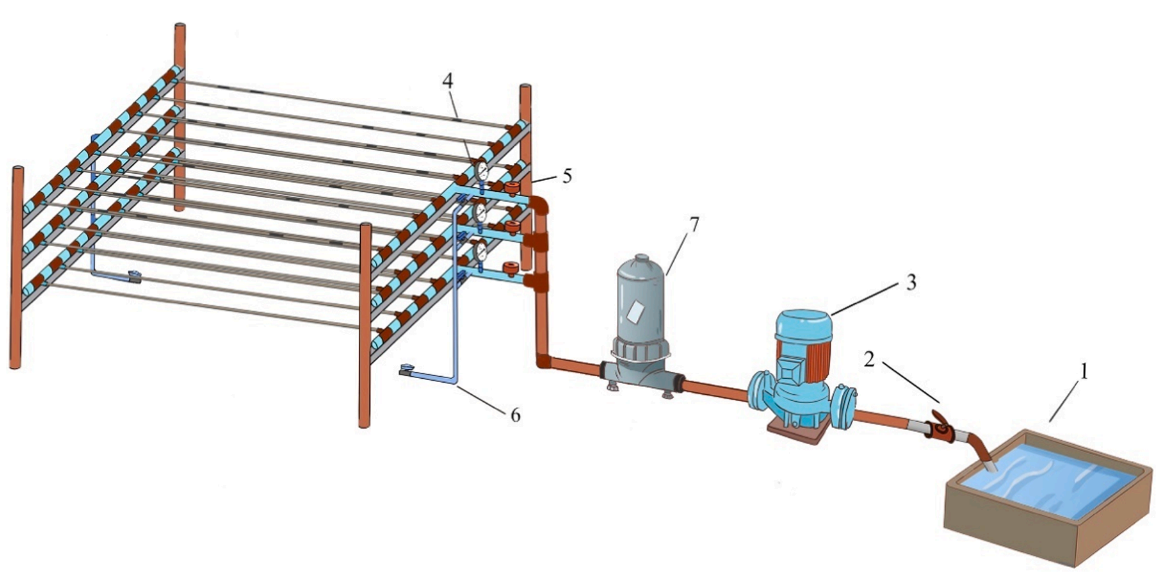

Fig. 1. Test set-up diagram. 1- water tank, 2-water inlet, 3-water pump, 4-emitters, 5-precise adjusting valve, 6-exhaust device, 7-screen filter.

Table 1
Structure parameters of emitters.

Emitter	Rated discharge q (L/h)	Flow path dimensions (mm)			Discharge coefficient k_d	Flow index x	Emitter flow channel structure
		Length	Width	Depth			
E1	1.00	34.41	0.85	0.72	3.61	0.53	
E2	1.60	27.48	1.07	1.14	5.40	0.52	
E3	2.00	25.29	0.87	1.04	6.50	0.61	

Note: The size of the flow channel was measured by electron microscope, and the rated flow rate, flow coefficient and flow index were tested according to the standard (GB/T17188-1997).

Table 2
Water quality characteristics for the different treatments.

Types	pH	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Mn^{2+} (mg/L)	Cu^{2+} (mg/L)	K^{+} (mg/L)	Na^{+} (mg/L)	CO_3^{2-} + HCO_3^{-} (mg/L)	SO_4^{2-} (mg/L)	TH (mg/L)	ZP (mV)
WQ1	7.75 ± 0.02b	423.83 ± 6.05ef	287.33 ± 7.34i	185.67 ± 5.46b	1.33 ± 0.24c	32.25 ± 2.11de	43.69 ± 2.13 f	134.0 ± 4.05 h	2938.67 ± 75.98 cd	1033.33 ± 50.52def	-2.81 ± 1.15cde
WQ2	7.69 ± 0.02e	334.00 ± 7.04i	345.67 ± 13.99 f	98.25 ± 3.13 f	1.07 ± 0.15c	51.85 ± 1.79a	68.32 ± 1.46a	118.83 ± 3.49fg	2246.33 ± 75.72 g	973.33 ± 56.04fg	-5.97 ± 1.81gh
WQ3	8.05 ± 0.09 f	453.00 ± 11.09d	401.00 ± 6.54d	85.50 ± 1.87 g	2.45 ± 0.16b	34.08 ± 1.88d	46.16 ± 1.42e	141.5 ± 3.45b	1599.00 ± 142.84jk	1107.33 ± 49.11bc	-2.45 ± 0.68bcd
WQ4	8.20 ± 0.05 g	570.83 ± 10.44a	459.83 ± 13.21b	62.50 ± 1.87k	2.59 ± 0.14a	41.85 ± 2.10c	55.33 ± 1.46d	159.83 ± 2.56c	3532.00 ± 152.95b	1203.0 ± 80.7a	-0.96 ± 1.93ab
WQ5	7.67 ± 0.04a	332.00 ± 8.60i	325.98 ± 7.18 g	105.08 ± 2.29e	1.37 ± 0.14c	53.47 ± 2.10a	69.41 ± 1.55a	107.5 ± 3.08i	1964.33 ± 73.95 h	927.00 ± 39.57gh	-6.67 ± 0.89 h
WQ6	7.68 ± 0.04b	332.50 ± 9.10i	211.00 ± 7.15 l	176.33 ± 4.97c	1.72 ± 0.15b	41.73 ± 2.56c	55.39 ± 1.48d	111.67 ± 2.65j	2303.33 ± 64.84fg	960.33 ± 55.39 g	-6.60 ± 0.85 h
WQ7	7.75 ± 0.02ef	419.83 ± 8.35 f	271.00 ± 7.15j	106.32 ± 12.58e	1.15 ± 0.17c	20.70 ± 1.94 h	29.49 ± 1.60i	128.16 ± 2.99ef	1714.66 ± 85.57ij	1054.00 ± 59.27cde	-2.86 ± 1.30def
WQ8	7.72 ± 0.04ef	383.50 ± 10.33 g	215.17 ± 6.21 l	194.67 ± 6.22a	1.26 ± 0.16c	23.80 ± 1.80 g	32.09 ± 1.42 h	131.83 ± 4.3de	4669.67 ± 130.44a	938.00 ± 53.45gh	-3.32 ± 0.92cdef
WQ9	7.71 ± 0.02e	362.08 ± 11.62 h	383.00 ± 8.07e	82.50 ± 2.74gh	2.15 ± 0.16b	30.68 ± 2.93ef	42.41 ± 1.45 f	125.67 ± 3.20j	1834.67 ± 107.46hi	988.66 ± 68.62efg	-4.23 ± 1.29efg
WQ10	8.10 ± 0.04 f	522.50 ± 9.95c	412.00 ± 7.15c	73.50 ± 1.87ij	2.08 ± 0.14b	43.07 ± 2.05bc	57.05 ± 1.41 cd	144.80 ± 3.48de	2698.67 ± 133.61e	1140.67 ± 72.76ab	-1.89 ± 1.35bc
WQ11	7.73 ± 0.02c	361.00 ± 13.88 h	305.66 ± 7.74 h	69.50 ± 1.87j	2.03 ± 0.20b	28.90 ± 2.04 f	40.20 ± 1.42 g	127.83 ± 4.12 g	1476.00 ± 241.91k	957.66 ± 36.27fg	-3.43 ± 1.33cdef
WQ12	7.99 ± 0.06ef	451.17 ± 15.38d	354.67 ± 8.98 f	83.00 ± 2.61gh	2.07 ± 0.11b	22.15 ± 1.42gh	30.32 ± 1.43i	137.33 ± 2.94d	1682.00 ± 145.88ij	1090.67 ± 58.07bcd	-2.47 ± 0.87cdef
WQ13	7.56 ± 0.07a	310.17 ± 7.93j	206.00 ± 7.15 l	183.17 ± 3.4b	1.15 ± 0.15c	45.02 ± 2.73b	59.28 ± 1.44b	105.50 ± 2.81fg	2841.33 ± 66.67de	871.00 ± 51.39 h	-7.26 ± 0.79i
WQ14	8.17 ± 0.02ef	534.33 ± 8.48b	497.17 ± 13.69a	75.50 ± 1.87i	2.35 ± 0.16b	31.75 ± 2.81de	43.36 ± 1.47 f	146.16 ± 5.15a	2453.00 ± 187.09 f	1155.67 ± 68.2ab	-1.61 ± 1.34a
WQ15	7.81 ± 0.03ef	433.83 ± 8.95e	406.00 ± 5.93 cd	77.50 ± 1.87hi	1.97 ± 0.15b	42.77 ± 1.75bc	56.42 ± 1.49 cd	135.50 ± 3.08bc	2365.67 ± 122.11fg	1020.30 ± 70.07def	-2.62 ± 1.64bc
WQ16	7.70 ± 0.02d	342.33 ± 11.86i	255.17 ± 7.49k	113.75 ± 8.51d	1.22 ± 0.14c	43.13 ± 2.36bc	58.07 ± 1.42bc	124.33 ± 2.80 g	3060.67 ± 98.48c	984.67 ± 44.76efg	-5.08 ± 1.02fgh

Note: TH, Total hardness. ZP, Zeta potential. Different letters for a given quality ions mean that there were significant differences ($p < 0.05$) between treatments.

degree of emitter clogging (Li et al., 2019). The Christiansen coefficient of uniformity (CU) was used to evaluate the emitter's outflow uniformity (Christiansen, 1942), and the detailed calculation process is shown in the supplementary material (Section 1.2).

2.3. Clogged material sampling and analysis

The fouling produced in the emitter labyrinth channel was assessed in 50 emitters of the dripline whose discharges were close to average. Sampling was performed on days 16 and 64 days of system operation. Carefully stripped emitter samples were cleaned for 20 min using an ultrasonic cleaner (Manufacturer: Hangzhou Farent Ultrasonic Cleaning Co., Ltd, China; Model: GVS-10 L). Sample drying in the oven for 48 h (70 °C) (Jiangsu Aobo Technology Co., Ltd, China; Model: DER-232). After that, the final dry weight (DW) were obtained by weighing using an electronic balance (Guangdong Juheng Precision Measurement & Control Co., Ltd., China; model: ERT, accuracy: 10^{-4} g). The dried samples were ground and analyzed by X-ray diffractometer (Bruker, Germany;. Model: D8-advance) to get the polycrystalline diffraction pattern, which in turn yielded the compositions and contents of the mineral fractions, such as carbonate fouling (CF) and silicate fouling (SF). Surface morphology of clogged material was analyzed by SEM (manufacturer: TESCAN, Czech Republic; Model: VEGA COMPACT, Voltage: 25 kV, amplification ratio: 400–15000).

2.4. Statistical analysis

The underlying data were calculated using Microsoft Excel and analyzed using SPSS. Analysis of variance was performed between different treatments (ANOVA). Duncan's method was used to perform the mean separation test. Correlation analysis was performed using Spearman. Structural equation modeling analysis (SEM) was used for further evaluation.

3. Results

3.1. Clogging characteristics under different brackish water drip irrigation systems

Each type of brackish water noticeable Dra along with system operation. The Dra showed a gradual and decrease during 0–40 days, and then accelerated the decreasing rate during 40–64 days (Fig. 2a, c and e). By the end of the system operation time (Fig. 2b, d), compared to the local water source (WQ1), for the 3 types of emitters as a whole, the

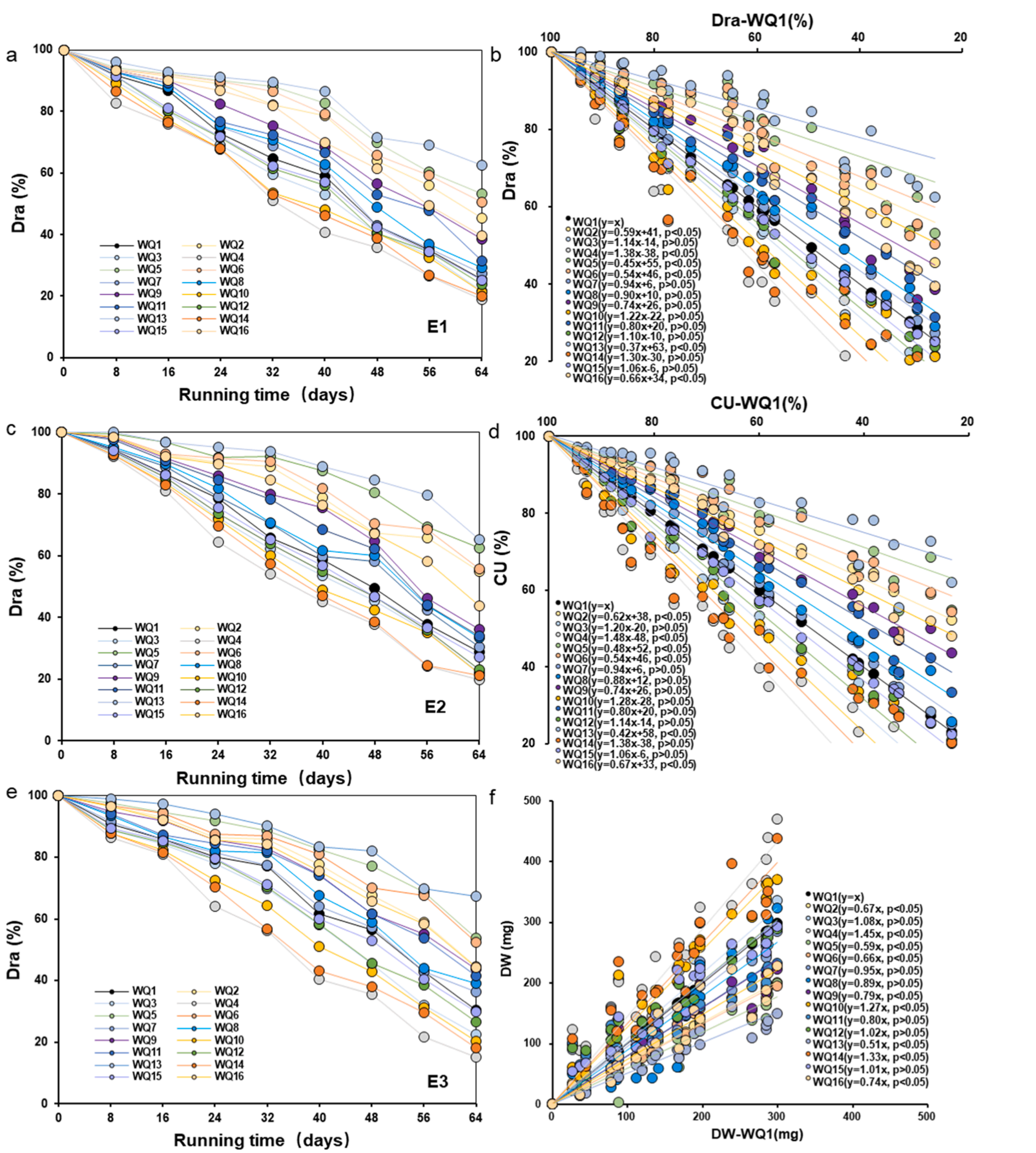

Fig. 2. Effects of different brackish water sources on emitter clogging, a, c, and e show the dynamic changes of different emitter types (E1、E2 and E3) on Dra, and b, d, and f show the correlations of different brackish water treatments on Dra (discharge average ratio), CU (Christiansen coefficient of uniformity), and DW (dry weight of the fouling substances) of drip irrigation system, respectively.

water quality 4 (WQ4) resulted in smaller Dra and CU (decreased by 16.2%–23.8% and 19.1%–21.1%, respectively). While WQ13 treatment most significant, which indicated mitigated emitter clogging.

Moreover, each type of brackish water greatly affected the clogging substances in drip irrigation systems (Fig. 2f). As it may be anticipated, the total fouling substances' DW showed a similar decreasing trend compared with Dra and CU (Fig. S1 of supplementary materials). At the end of system operation, WQ4, WQ10, and WQ14 had a significant increase in clogged material compared to the WQ1. Of these, WQ4 was the most heavily clogged (51.7%–58.7% increase in DW) and W13 was the least clogged (40.5%–53.4% decrease in DW).

3.2. Drip irrigation emitter fouling substances using different brackish water

The XRD diffraction results showed that the fouling mineral components in the emitters using different brackish waters (Fig. 3a) were quartz [SiO_2], calcite [$CaCO_3$], muscovite [$(K,Na)(Al,Mg,Fe)_2(Si_{3.1}Al_{0.9})O_{10}(OH)_2$], clinochlore [$(Mg,Fe)_6(Si,Al)_4O_{10}(OH)_8$] and albite [$Na(AlSi_3O_8)$]. Quartz and calcite accounted for 47.1%– 68.2% and 15.9%– 31.4%, muscovite and clinochlore ranged between 4.0%– 8.6% and 3.2%– 7.1%, and albite accounted for 6.9%– 22.9%, respectively. The fouling mineral fraction were divided in two subgroups according to their chemical composition as CF (calcite) and SF (quartz, muscovite, clinochlore and albite) (Fig. 3b). CF and SF ranged 16.0%– 31.4% and 68.6%– 84.0%, respectively. Moreover, SEM

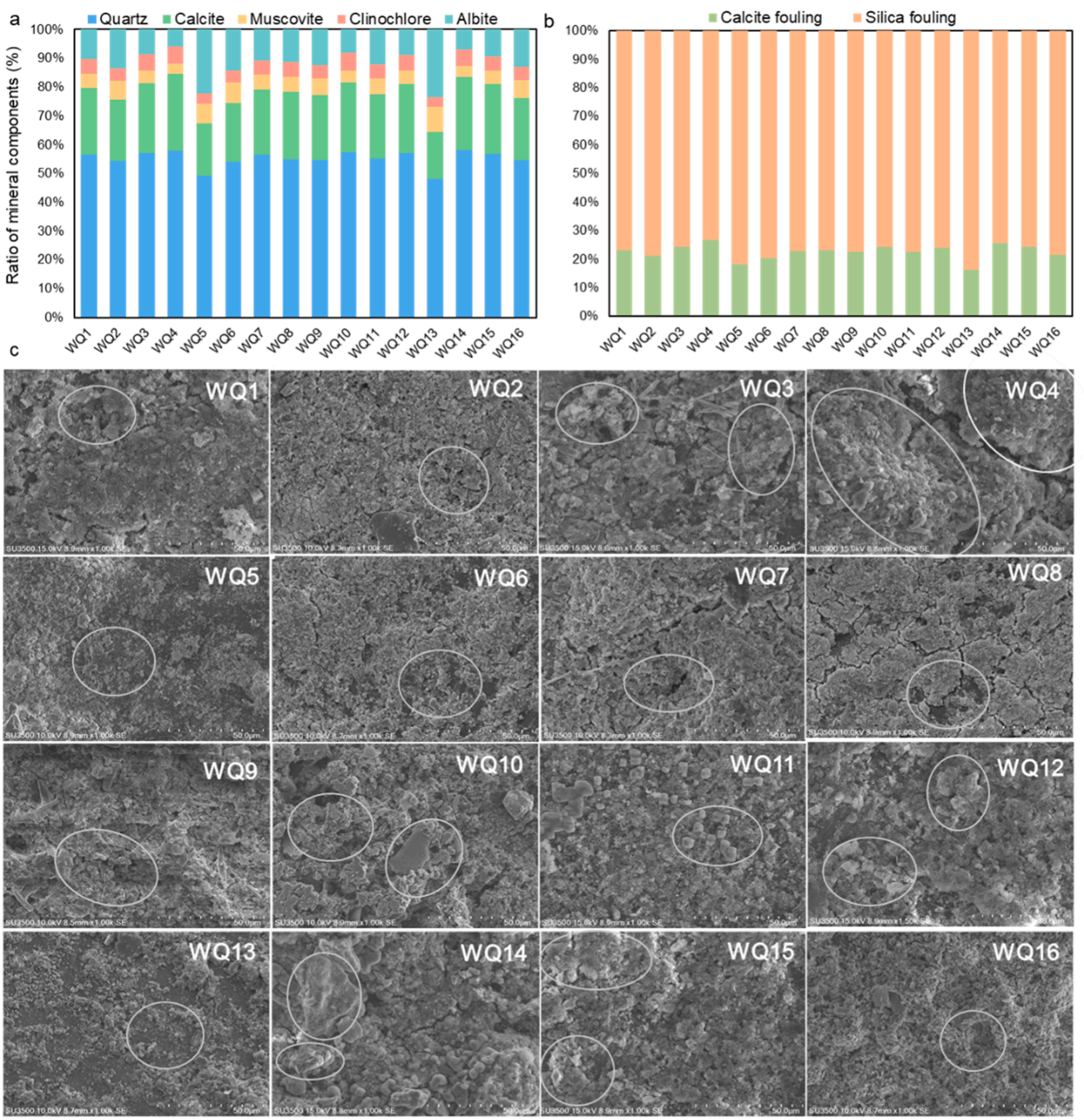

Fig. 3. Clogging substance distribution in different brackish water sources, a and b show the percentages of fouling of different clogging substances, c shows the scanning electron microscope for the clogging substance fouling with the different water qualities (E2 for example, flow path length × width × depth: 27.48 mm × 1.07 mm×1.14 mm).

images further confirmed the differences between the fouling substances using different brackish water (Fig. 3c). Compared with WQ1, WQ2, WQ5, WQ6, WQ7, WQ8, WQ9, WQ11 and WQ16, fouling particles of WQ13 were smaller and relatively loose, the roughness between the fouling was reduced, and the fouling was distributed sporadically in the flow channels, which was easier to take place. Fouling particles of WQ3, WQ4, WQ10, WQ12, WQ14, WQ15 were large and thick and tightly bonded together. The fouling surface was not only rough, but also covered the entire surface of the drip irrigation system flow channels. Among them, fouling particles of WQ4 were the most and the largest, and that of WQ13 were the smallest and the least.

3.3. CF and SF under different drip irrigation systems

The content of CF and SF at end of test varied significantly considering the brackish water quality. Fig. 4a shows that WQ4 had the significantly ($p < 0.05$) highest CF (62.6 mg/cm^2) and WQ13 had the lowest CF (25.7 mg/cm^2) in average. The WQ4 showed significantly higher CF than WQ3, WQ10 and WQ14. SF had a similar pattern to CF (Fig. 4f): SF was maximum (213.0 mg/cm^2) for WQ4, and minimum (102.1 mg/cm^2) for WQ13, although the latter was not significantly different than WQ5 and WQ6. The SF of WQ4 was significantly higher than those of WQ1. And SF found in the emitter labyrinth for WQ13 was significantly lower than with WQ8, WQ9, WQ11, and WQ16. Fig. 4b shows that the content of quartz in WQ4 was significantly higher than that in WQ1. WQ13 were significantly lower than that in WQ8 and WQ9. The highest quartz fouling content (182.8 mg/cm^2) was observed in WQ4, while the lowest (53.8 mg/cm^2) was in WQ13, which was not significantly different from WQ5. The clinochlore fouling content was consistent with the variation of quartz fouling (Fig. 4d). The highest clinochlore content (14.2 mg/cm^2) in WQ4 was not statistically different than WQ14, while the lowest clinochlore fouling content (4.8 mg/cm^2) in WQ13 was not significantly different than WQ2, WQ5, WQ6 and WQ16. For muscovite fouling (Fig. 4c), the highest muscovite fouling content was found in WQ13 treatment (13.5 mg/cm^2), but there was no difference with WQ5. The lowest muscovite fouling content

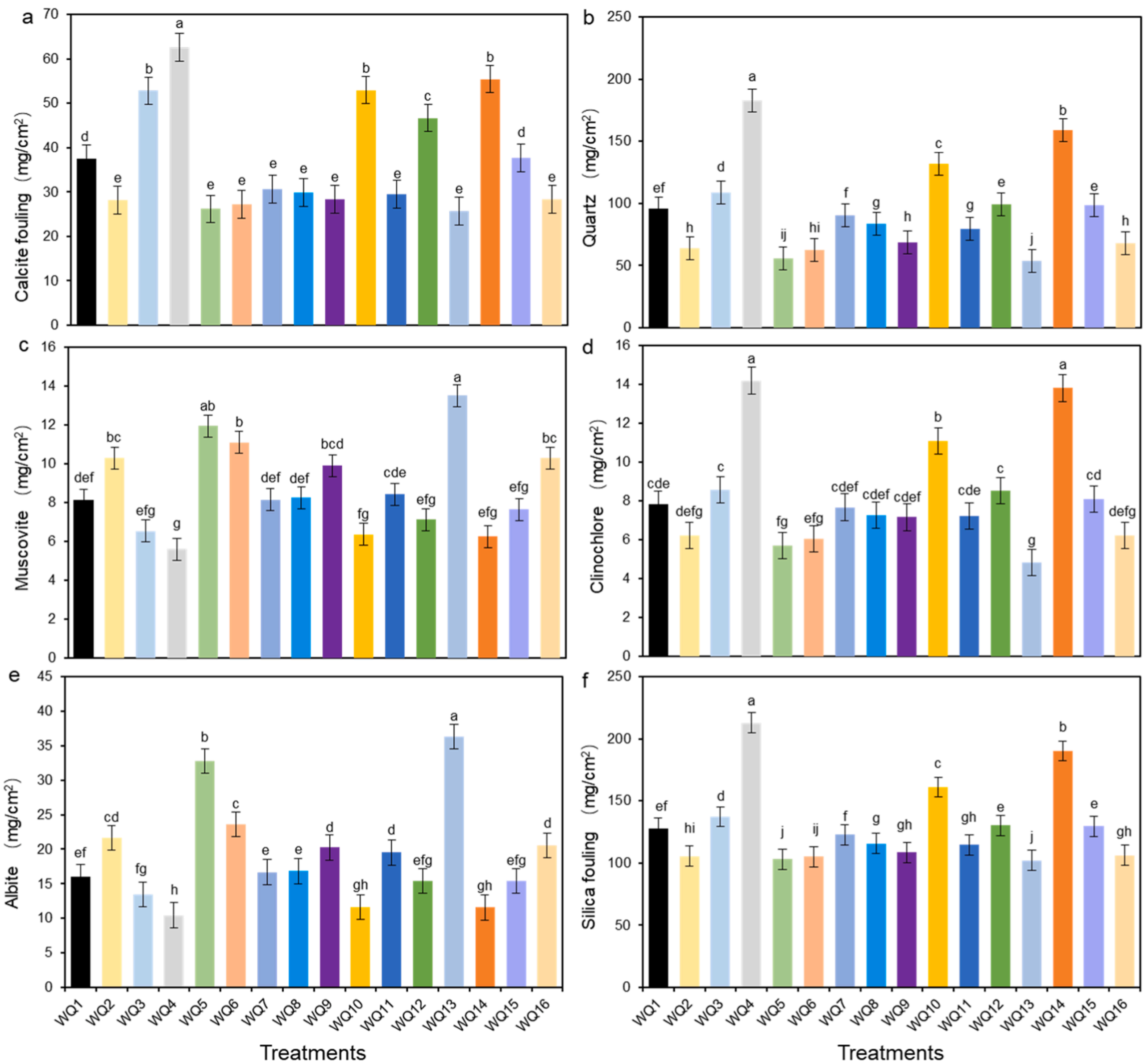

Fig. 4. Effect of different brackish waters on the average (± standard error) emitter mineral fraction at the end of system operation (64 days). a, b, c, d, e and f are the contents of calcium fouling (CF), quartz, muscovite, clinochlore, albite and silica fouling (SF) in mineral fraction fouling, respectively. Different letters between water quality treatments mean significant differences ($p < 0.05$).

(5.6 mg/cm^2) was found in WQ4, but there was no significant difference with WQ3, WQ10, WQ12, WQ14 and WQ15. The content of albite's fouling (Fig. 4e) at the end of the experiment was the highest with WQ13 (36.3 mg/cm^2) and the lowest with WQ4 (10.4 mg/cm^2), which was not statistically different from WQ10 and WQ14.

3.4. Influence path way of different brackish water on drip irrigation emitter clogging

The influence of the different water quality ions in emitter clogging was assessed using Spearman correlation and SEM analysis (Fig. 5). Results showed that Ca^{2+} had a direct effect on CF and SF ($p < 0.01$) (Fig. 5a). Mg^{2+}, Mn^{2+} and Cu^{2+} had no direct effect on CF and SF ($p > 0.01$), but indirectly affected CF and SF by directly influencing Ca^{2+} content (Fig. 5b). $CO_3^{2-}+HCO_3^-$ had a negative effect on CF and SF ($p < 0.01$). The pH, TH and ZP had also a direct effect on CF and SF ($p < 0.01$). In conclusion, the water quality ions Ca^{2+}, Mg^{2+}, Mn^{2+}, Cu^{2+}, $CO_3^{2-}+HCO_3^-$, pH, TH and ZP had significant effects ($p < 0.01$) on DW and Dra (Fig. 5a). Based on SEM results (Fig. 5c), it suggested that Ca^{2+}, $CO_3^{2-}+HCO_3^-$, pH, TH and ZP of brackish waters directly affected the CF and SF content. Mg^{2+}, Mn^{2+}, and Cu^{2+} indirectly affected the CF and SF content by directly influencing the Ca^{2+} content, which in turn

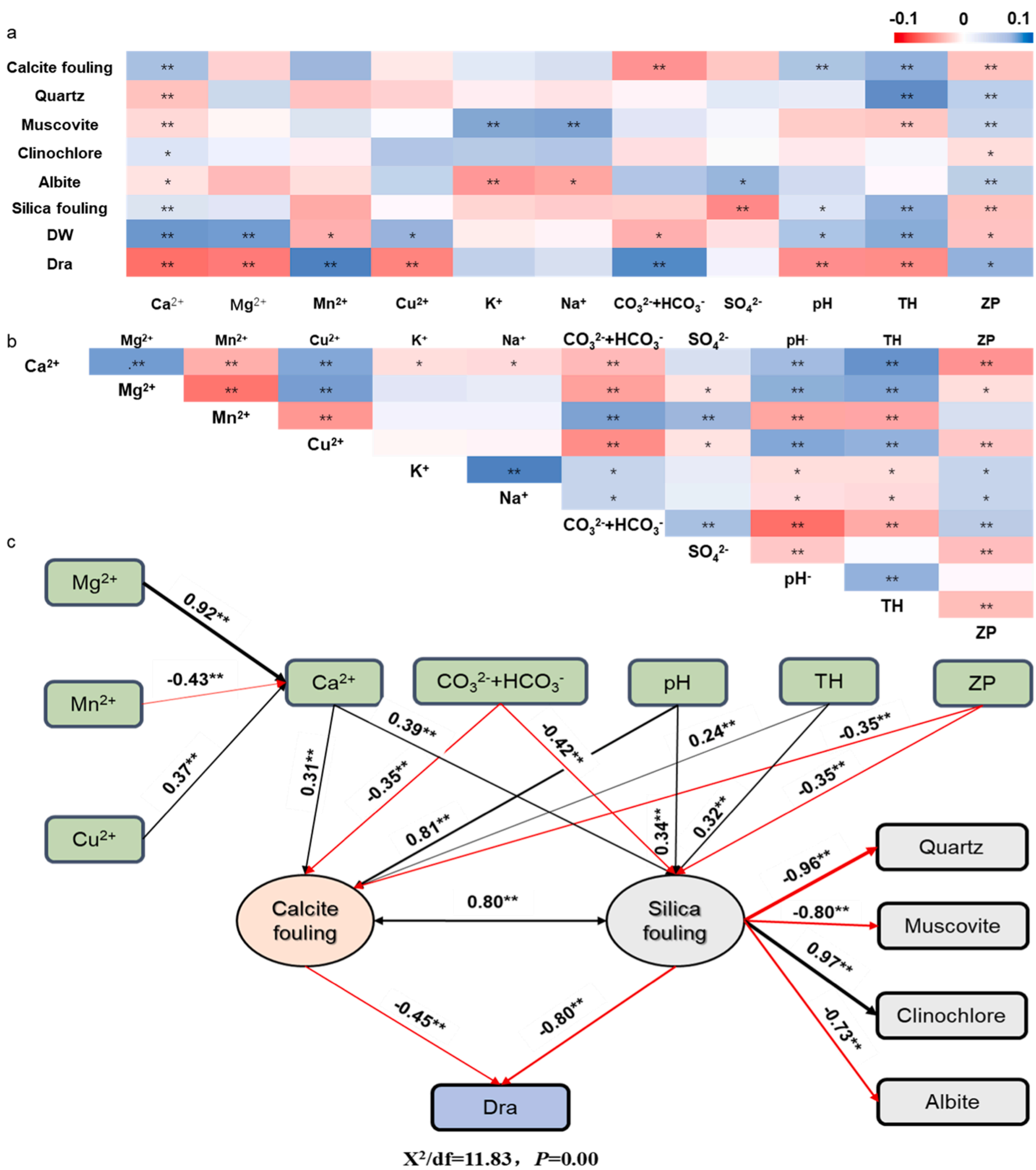

Fig. 5. Influence path analysis of different brackish water on drip irrigation system. a, Spearman correlation analysis; b, Spearman correlation between water quality ions; c, the structural equation modelling. Figures near the path arrows indicate the standard path coefficients (β), and the width of the arrows is proportional to the degree of the path coefficients. Positive and negative correlations are indicated by black and red arrows, respectively; significant levels are indicated using * for $p < 0.05$ and * * for $p < 0.01$. Also shown are calcium fouling (CF) and silica fouling (SF).

negatively affected the Dra of the drip irrigation system.

4. Discussion

4.1. Effect of brackish water quality on drip irrigation emitter fouling

Applying different sources of brackish water primarily affects brackish water quality, which in turn affects drip irrigation system fouling in both direct and indirect ways. By affecting the content of Ca^{2+}, CO_3^{2-}+HCO_3^-, pH, TH and ZP, the fouling content was directly shadowed. While Mg^{2+}, Mn^{2+}, and Cu^{2+} indirectly affect the fouling content by directly affecting the Ca^{2+} content. This study found that CF and SF were the main substances affecting the performance of brackish water drip irrigation systems and soil environment in different saline areas, which included calcite, quartz, muscovite, clinochlore, and albite. Zhangzhong et al. (2019) found that calcium carbonate was key in emitter fouling using brackish water. Liu et al. (2022) reported considerable quantity of SF and CF with brackish water in drip irrigation emitters. In brackish water the coexistence of multiple ions (Ca^{2+}, CO_3^{2-}+HCO_3^-) will directly influence the emitter fouling, owing to the changes in solubility of carbonate (Al-Agha, 2005), which decreased the content of CO_3^{2-}+HCO_3^- and made it harder for Ca^{2+} to combine with CO_3^{2-}+HCO_3^- to form calcium carbonate (Ma et al., 2020). In addition, Ca^{2+} directly promoted the polymerization of quartz and form quartz fouling in the form of silicates (Sheikholeslami et al., 2002). Besides, pH directly affected the content of $CaCO_3$ in CF, and $CaCO_3$ fouling was easily formed in the presence of Ca^{2+} at higher pH (Sheng and Zhang, 2012). The increase in Ca^{2+} content led to higher saturation of calcium carbonate and other fouling since Ca^{2+} played a dominant role in the formation of SF and CF (Zhang et al., 2012). At the meantime, high pH changed the silicate ionization and hindered the silicates polymerization (Sheikholeslami et al., 2002). Consequently, silicate and other fouling were more likely to form through adsorption and ion exchange (Mahmoud and Ghaly, 2005). The brackish water TH had also a direct impact on emitter fouling, due to high concentrations of Ca^{2+}, Mg^{2+}, sulfate, chloride, and other inorganic ions (Li et al., 2016a; Li et al., 2021). Higher TH, which changed the particle size of flocculants and growth rate of fouling, increased the denseness of CF and SF (Zhao et al., 2014), and there was a electrostatic adsorption, which created a ZP difference (Liu et al., 2021a). This directly affected the ZP of brackish water, leading to the break of $CaCO_3$ molecular structure and making it less likely to react with fouling deposit like quartz, muscovite, clinochlore, and albite. Therefore, the flocculation strength of fouling deposits reduced.

Meanwhile, Mg^{2+}, Mn^{2+} and Cu^{2+} also presented indirect impacts on emitter fouling, mainly due to inhomogeneous distribution of Mg^{2+} on the surface of CF (Zhang and Dawe, 2000), which adsorbed the Mg^{2+}. The surface of granules like quartz, increased the flocculation and sedimentation strength of quartz and clinochlore fouling through electrostatic attraction (Ma et al., 2020), resulting in a substantial increase on fouling surface area of quartz and clinochlore, which further promoted the fouling deposition in emitter flow channels. In addition, both Mn^{2+} and Cu^{2+} changed the thermodynamic affinity of Ca^{2+}, which broke the calcite and quartz fouling morphology and made it easier for aggregation deposition in drip irrigation systems (Kent et al., 2002). Meanwhile, Ca^{2+} provided numerous binding sites in muscovite and albite (Inesi, 2008), but due to the weak bonding between ions, movements will occur through the electrostatic layer, resulting in changes in crystal structure (Li et al., 2016b). Mg^{2+}will also enter the lattice structure of $CaCO_3$ and occupy the original position of Ca^{2+} in $CaCO_3$ lattice to inhibit the continuous growth of $CaCO_3$ precipitation (Nielsen et al., 2013) and reduce the adsorption capacity of Ca^{2+} on albite fouling, leading to an increase in current density, a change the ZP and a high intensity of flocculation (Moayedi and Kazemian, 2013). With the increase of Ca^{2+} concentration, the competition between Ca^{2+} and Cu^{2+} changed to cooperation and a positive synergistic effect between the fouling would occur (Lu et al., 2012).

Moreover, the Spearman correlation and SEM analysis (Fig. 5c) showed that Ca^{2+}, CO_3^{2-}+HCO_3^-, pH, TH, and ZP of brackish water directly affected the CF and SF, and further affected the drip irrigation system's ability to prevent clogging. Mg^{2+}, Mn^{2+}, and Cu^{2+} indirectly affected the CF and SF by directly affecting Ca^{2+}. Since there were plenty of binding sites between the fouling (Heo et al., 2012), the growth of one type of fouling provided the opportunities for other fouling (Muhammad et al., 2022), which indicated the fouling growth was interdependent on each other by their own interactions (Ma et al., 2019) and can simultaneously affect the anti-clogging performance of emitter (measured as Dra and DW) when using brackish water.

4.2. Engineering applications

It was determined in this study that major water quality ions of brackish water directly affect emitter clogging. Moreover, some reports also indicated that key brackish water quality ions can also increase soil salinity and reduce the repulsion between soil particles, which in turn increase the soil salinization (Bales et al., 2021). Thus, controlling major brackish water quality ions may be an effective way to mitigate both soil salinization and emitter fouling.

Ca^{2+}, CO_3^{2-}+HCO_3^-, pH, TH, and ZP of brackish water were directly linked with emitter clogging. pH, Ca^{2+} and TH presented strong positive correlation with CF and SF, while CO_3^{2-}+HCO_3^- and ZP showed a strong negative correlation (Fig. 5c). Therefore, lowering the content of Ca^{2+}, pH, and TH, and increasing CO_3^{2-}+HCO_3^-, ZP in brackish water would significantly reduce the risk of CF and SF in emitters. Water magnetization may be used for this purpose. Firstly, magnetization will promote the Ca^{2+} and HCO_3^- quick reactions to form microcrystalline particles and will reduce the CF deposits. Secondly, magnetization will also change ZP to encourage flocculation, which will inhibit the SF formation (Liu et al., 2021b). The use of magnetized water increased the permeability coefficient of saline soils and release of soil exchange ions, which further improved the soil physicochemical properties and prevented the secondary salinization (German et al., 2019; Wang et al., 2021a). Furthermore, in order to avoid CF and SF in emitters, the application of humic acid compound fertilizer to minimize the TH in brackish water by chelating the calcium and magnesium ions was recommended (Wang et al., 2022b). The application of humic acid fertilizer could promote the formation of soil aggregates and increase the water and fertilizer retention capacity of soil, which reduce the degree of soil salinization (Liu et al., 2020; Huang, 2022).

Ca^{2+} was directly affected by Mg^{2+}, Mn^{2+}, and Cu^{2+}, which indirectly affected the CF and SF. Mg^{2+} and Cu^{2+} had a significant positive correlation to Ca^{2+}. Since the ionic radii of Cu^{2+} and Mg^{2+} were smaller compared to Ca^{2+} (Volkov et al., 1997), substitution reactions between Mg^{2+} and Cu^{2+} and Ca^{2+} would lead to distortion of crystal structure of CF (Huang et al., 2022). It has been suggested that magnesium nitrate and cupric nitrate fertilizers were capable of changing the structural morphology of calcium under thermodynamic action (Chen et al., 2022). Also, the addition of NO_3^- will reduce the Na^+ content in soil through ion exchange with Na^+ in saline soils (Kaburagi et al., 2015), which will improve the saline soil and be able to stop the increase of salinization. Therefore, this study suggested that $Mg(NO_3)_2$ and $Cu(NO_3)_2$ fertilizer application could reduce both the emitter clogging and soil salinization risks when using brackish water in drip irrigation systems. In addition, Mn^{2+} presented a significant negative correlation with Ca^{2+}. Increasing the Mn^{2+} content will directly change the adsorption capacity of Mn^{2+} on Ca^{2+} in brackish water (Wessel and Tietema, 1995), ion exchange (Novikov et al., 2014), and indirectly change CF and SF. Hence, $MnSO_4$ fertilizer was also recommended to brackish water to prevent emitter clogging (Wang et al., 2022a). SO_4^{2-} also had the dual effect of lowering pH and reducing salinization by chemical reaction with Na^+. In this case, based on the extension and application of this study, more efforts should be made to address the following two aspects in the future: (1) 16 brackish water sources from different saline soil areas were used in this study, and more brackish water from other saline regions is needed to further verify the generality of the results; (2) the effect of performance from the emitter perspective was only investigated in this study, and the actual effect on field crops for different saline water sources needs to be uncovered.

5. Conclusions

From this study, the following main points were concluded:

(1) Drip irrigation emitter clogging using different brackish water sources all increased gradually during the first 40 days (400 h), and then accelerated additional increase until the end (64 days, 640 h of operation). Differences between the different brackish water treatments were significant. When system operation ends, the average values of Dra and CU ranged from 49.8%-88.1% and 48.0%-87.9%, respectively.

(2) According to the chemical composition, CF (calcite, 15.9%-31.4%) and SF (quartz, 47.1%−68.2%; muscovite, 4.0%−8.6%; clinochlore, 3.2%−7.1%; albite, 6.9%−22.9%) were the major fouling compounds accumulated. At the end of the experiment, their contents being 25.7–62.6 mg/cm^2 (proportion of 16.0%−31.4%) and 102.1–213.0 mg/cm^2 (proportion of 68.6%−84.0%), respectively. The contents of CF and SF were significantly affected by the brackish water sources.

(3) Among different types of brackish water sources applied, Ca^{2+}, CO_3^{2-}+HCO_3^-, pH, TH, and ZP were identified as the key factors causing the emitter clogging since they directly affected the CF and SF. On the other hand, Mg^{2+}, Mn^{2+}, and Cu^{2+} indirectly affected their formation by changing Ca^{2+}. Therefore, water quality ions especially Ca^{2+}, CO_3^{2-}+HCO_3^-, pH, TH and ZP should be reasonably selected for saline areas brackish water drip irrigation.

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.

Data Availability

The data is available upon request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2023.108544.

References

Al-Agha, M., 2005. Hydrogeochemistry and carbonate saturation model of groundwater, kanyounis governorate-gaza strip, Palestine. Environ. Geol. 47, 898–906. https://doi.org/10.1007/s00254-004-1211-0.

Bagheri, A., Teymouri, A., 2022. Farmers' intended and actual adoption of soil and water conservation practices. Agric. Water Manag. 259, 107244 https://doi.org/10.1016/j.agwat.2021.107244.

Bales, C., Lian, B., Fletcher, J., Wang, Y., Waite, T., 2021. Site specific assessment of the viability of membrane capacitive deionization in desalination of brackish groundwaters for selected crop watering. Desalination 502, 114913. https://doi.org/10.1016/j.desal.2020.114913.

Barzegari, G., Tirkhooni, M., Khabbazi, A., 2020. Experimental assessment of clayey layers for clogging of tbm in tabriz subway lines, Iran. Tunn. Undergr. Space Technol. 105, 103560 https://doi.org/10.1016/j.tust.2020.103560.

Chen, G., Kang, S., Zhao, K., Zheng, A., Zhao, Z., 2022. Screening of potential additives for alleviating slagging and fouling during msw incineration: thermodynamic analysis and experimental evaluation. Atmosphere 13, 1163. https://doi.org/10.3390/atmos13081163.

Christiansen, J., 1942. Irrigation by sprinkling. University of California Berkeley.

Dagar, J., Yadav, R., Singh, A., Singh, N., 2019. Historical perspectives and dynamics of nature, extent, classification and management of salt-affected soils and waters. research developments in saline agriculture. Springer,, pp. 3–52. https://doi.org/10.1007/978-981-13-5832-6_1.

Dinar, A., Tieu, A., Huynh, H., 2019. Water scarcity impacts on global food production. Glob. Food Secur. 23, 212–226. https://doi.org/10.1016/j.gfs.2019.07.007.

Generous, M., Qasem, N., Zubair, S., 2020. The significance of modeling electrodialysis desalination using multi-component saline water. Desalination 496, 114347. https://doi.org/10.1016/j.desal.2020.114347.

German, M., Dong, H., Schevets, A., Smith, R., SenGupta, A., 2019. Field validation of self-regenerating reversible ion exchange-membrane process to prevent sulfate and silica fouling. Desalination 469, 114093. https://doi.org/10.1016/j.desal.2019.114093.

Gräber, Y., Nativ, P., Lahav, O., 2021. A pre-treatment concept for increasing the recovery ratio of coastline bwro plants, while providing Mg^{2+} in the product water. Desalination 515, 115202. https://doi.org/10.1016/j.desal.2021.115202.

Guo, J., Tucker, Z., Wang, Y., Ashfeld, B., Luo, T., 2021. Ionic liquid enables highly efficient low temperature desalination by directional solvent extraction. Nat. Commun. 12, 437 https://doi.org/10.1038/s41467-020-20706-y.

Haj-Amor, Z., Araya, T., Kim, D., Bouri, S., Lee, J., Ghiloufi, W., Yang, Y., Kang, H., Jhariya, M., Banerjee, A., 2022. Soil salinity and its associated effects on soil microorganisms, greenhouse gas emissions, crop yield, biodiversity and desertification: a review. Sci. Total Environ., 156946 https://doi.org/10.1016/j.scitotenv.2022.156946.

Heo, J., Kim, H., Her, N., Lee, S., Park, Y., Yoon, Y., 2012. Natural organic matter removal in single-walled carbon nanotubes-ultrafiltration membrane systems. Desalination 298, 75–84. https://doi.org/10.1016/j.desal.2012.05.003.

Huang, R., 2022. The effect of humic acid on the desalinization of coastal clayey saline soil. Water Supply 22, 7242–7255. https://doi.org/10.2166/ws.2022.311.

Huang, S., Liu, S., Chen, W., Ko, C., Shih, C., Chen, J., 2022. Morphological changes, antibacterial activity, and cytotoxicity characterization of hydrothermally synthesized metal ions-incorporated nanoapatites for biomedical application. Pharmaceuticals 15, 885. https://doi.org/10.3390/ph15070885.

Inesi, L., 2008. Specificity of ligand binding to transport sites: Ca^{2+} binding to the Ca^{2+} transport atpase and its dependence on H^+ and Mg^{2+}. Arch. Biochem. Biophys. https://doi.org/10.1016/j.abb.2008.04.035.

Kaburagi, E., Yamada, M., Fujiyama, H., 2015. Sodium, but not potassium, enhances root to leaf nitrate translocation in swiss chard (Beta vulgaris var. cicla L.). Environ. Exp. Bot. 112, 27–32. https://doi.org/10.1016/j.envexpbot.2014.11.007.

Kent, D., Davis, J., Anderson, L., Rea, B., Coston, J., 2002. Effect of adsorbed metal ions on the transport of Zn- and Ni-edta complexes in a sand and gravel aquifer. Geochim. Et. Cosmochim. Acta 66, 3017–3036. https://doi.org/10.1016/S0016-7037(02)00908-0.

Li, G., Gao, Y., Song, W., Xu, F., Wang, Y., Sun, S., Jia, R., 2021. Parameter optimization and performance analysis of nanofiltration membrane in treatment of compound-contaminated high-hardness water. aqua-Water Infrastruct., Ecosyst. Soc. 70, 1145–1158. https://doi.org/10.2166/aqua.2021.225.

Li, K., Wang, J., Liu, J., Wei, Y., Chen, M., 2016a. Advanced treatment of municipal wastewater by nanofiltration: operational optimization and membrane fouling analysis. J. Environ. Sci. 43, 106–117. https://doi.org/10.1016/j.jes.2015.09.007.

Li, X., Kang, Y., 2020. Agricultural utilization and vegetation establishment on saline-sodic soils using a water–salt regulation method for scheduled drip irrigation. Agric. Water Manag. 231, 105995 https://doi.org/10.1016/j.agwat.2019.105995.

Li, Y., Xiao, B., Gao, Y., Cheng, Y., 2016b. Theoretical study of anisotropic structural, electronic, mechanical and thermodynamic properties of rare-earth (r=y, la) oxysulfides. Comput. Mater. Sci. 125, 154–167. https://doi.org/10.1016/j.commatsci.2016.08.050.

Li, Y., Pan, J., Chen, X., Xue, S., Feng, J., Muhammad, T., Zhou, B., 2019. Dynamic effects of chemical precipitates on drip irrigation system clogging using water with high sediment and salt loads. Agric. Water Manag. 213, 833–842. https://doi.org/10.1016/j.agwat.2018.11.021.

Liang, J., Shi, W., 2021. Cotton/halophytes intercropping decreases salt accumulation and improves soil physicochemical properties and crop productivity in saline-alkali soils under mulched drip irrigation: a three-year field experiment. Field Crops Res. 262, 108027 https://doi.org/10.1016/j.fcr.2020.108027.

Liu, J., Fan, Y., Sun, Y., Wang, Z., Tang, C., 2021a. Modelling the critical roles of zeta potential and contact angle on colloidal fouling with a coupled xdlvo- collision attachment approach. J. Membr. Sci., 119048 https://doi.org/10.1016/j.memsci.2021.119048.

Liu, M., Wang, C., Liu, X., Lu, Y., Wang, Y., 2020. Saline-alkali soil applied with vermicompost and humic acid fertilizer improved macroaggregate microstructure to

enhance salt leaching and inhibit nitrogen losses. Appl. Soil Ecol. 156, 103705 https://doi.org/10.1016/j.apsoil.2020.103705.
Liu, Z., Xiao, Y., Li, Y., Zhou, B., Feng, J., Han, S., Muhammad, T., 2019. Influence of operating pressure on emitter anti-clogging performance of drip irrigation system with high-sediment water. Agric. Water Manag. 213, 174–184. https://doi.org/10.1016/j.agwat.2018.10.017.
Liu, Z., Di Luccio, M., García, S., Puig-Bargués, J., Zhao, X., Trueba, A., Muhammad, T., Xiao, Y., Li, Y., 2021b. Effect of magnetic field on calcium-silica fouling and interactions in brackish water distribution systems. Sci. Total Environ. 798, 148900 https://doi.org/10.1016/j.scitotenv.2021.148900.
Liu, Z., Hou, P., Zha, Y., Muhammad, T., Li, Y., 2022. Salinity threshold of desalinated saline water used for drip irrigating: the perspective of emitter clogging. J. Clean. Prod. 361, 132143 https://doi.org/10.1016/j.jclepro.2022.132143.
Lu, C., Cao, L., Liu, R., Lei, Y., Ding, G., 2012. Effect of common metal ions on the rate of degradation of 4-nitrophenol by a laccase-Cu^{2+} synergistic system. J. Environ. Manag. 113, 1–6. https://doi.org/10.1016/j.jenvman.2012.08.023.
Ma, B., Wu, G., Li, W., Miao, R., Li, X., Wang, P., 2019. Roles of membrane-foulant and inter/intrafoulant species interaction forces in combined fouling of an ultrafiltration membrane. Sci. Total Environ. 652, 19–26. https://doi.org/10.1016/j.scitotenv.2018.10.229.
Ma, C., Xiao, Y., Puig-Bargues, J., Shukla, M., Tang, X., Hou, P., Li, Y., 2020. Using phosphate fertilizer to reduce emitter clogging of drip fertigation systems with high salinity water. J. Environ. Manag. 263, 110366 https://doi.org/10.1016/j.jenvman.2020.110366.
Mahmoud, N., Ghaly, A., 2005. Organic and inorganic fouling at quartz-liquid interface in ultraviolet photoreactors during on-line sterilization of cheese whey. Appl. Biochem. Biotechnol. 126, 157–175. https://doi.org/10.1385/abab:126:3:157.
Masud, M., Wada, Y., Goss, G., Faramarzi, M., 2019. Global implications of regional grain production through virtual water trade. Sci. Total Environ. 659, 807–820. https://doi.org/10.1016/j.scitotenv.2018.12.392.
Moayedi, H., Kazemian, S., 2013. Zeta potentials of suspended humus in multivalent cationic saline solution and its effect on electro-osomosis behavior. J. Dispers. Sci. Technol. 34, 283–294. https://doi.org/10.1080/01932691.2011.646601.
Muhammad, T., Li, L., Xiao, Y., Zhou, Y., Liu, Z., He, X., Bazai, N., Li, Y., 2022. Multiple fouling dynamics, interactions and synergistic effects in brackish surface water distribution systems. Chemosphere 287, 132268. https://doi.org/10.1016/j.chemosphere.2021.132268.
Nielsen, L., De Yoreo, J., DePaolo, D., 2013. General model for calcite growth kinetics in the presence of impurity ions. Geochim. Et. Cosmochim. Acta 115, 100–114. https://doi.org/10.1016/j.gca.2013.04.001.
Novikov, G., Yashina, S., Mel'nikov, M., Vikent'ev, I., Bogdanova, O., 2014. Nature of co-bearing ferromanganese crusts of the magellan seamounts (pacific ocean): communication 2. ion exchange properties of ore minerals. Lithol. Miner. Resour. 49, 138–164. https://doi.org/10.1134/S0024490214020072.
Ondrasek, G., Rengel, Z., 2021. Environmental salinization processes: detection, implications & solutions. Sci. Total Environ. 754, 142432 https://doi.org/10.1016/j.scitotenv.2020.142432.
Pei, Y., Li, Y., Liu, Y., Zhou, B., Shi, Z., Jiang, Y., 2013. Eight emitters clogging characteristics and its suitability under on-site reclaimed water drip irrigation. Irrig. Sci. 32, 141–157. https://doi.org/10.1007/s00271-013-0420-2.
Rahardianto, A., Gao, J., Gabelich, C., Williams, M., Cohen, Y., 2007. High recovery membrane desalting of low-salinity brackish water: Integration of accelerated precipitation softening with membrane ro. J. Membr. Sci. 289, 123–137. https://doi.org/10.1016/j.memsci.2006.11.043.
Sheikholeslami, R., Al-Mutaz, I., Tan, S., Tan, S., 2002. Some aspects of silica polymerization and fouling and its pretreatment by sodium aluminate, lime and soda ash. Desalination 150, 85–92. https://doi.org/10.1016/S0011-9164(02)00932-3.
Shen, Y., Puig-Bargues, J., Li, M., Xiao, Y., Li, Q., Li, Y., 2022. Physical, chemical and biological emitter clogging behaviors in drip irrigation systems using high-sediment loaded water. Agric. Water Manag. 270, 107738 https://doi.org/10.1016/j.agwat.2022.107738.
Sheng, J., Zhang, H., 2012. Precipitation characteristics of $CaCO_3$ scaling on stainless seel in cooling tower condition. Int. Conf. Vib., Struct. Eng. Meas., Shanghai, People R. China 1029–1033. https://doi.org/10.4028/www.scientific.net/amm.226-228.1029.
Singh, G., 2009. Salinity-related desertification and management strategies: Indian experience. Land Degrad. Dev. 20, 367–385. https://doi.org/10.1002/ldr.933.
Slater, Y., Finkelshtain, I., Reznik, A., Kan, I., 2020. Large-scale desalination and the external impact on irrigation-water salinity: economic analysis for the case of israel. Water Resour. Res. https://doi.org/10.1029/2019wr025657.
Sun, J., Kang, Y., Wan, S., Hu, W., 2017. Influence of drip irrigation level on salt leaching and vegetation growth during reclamation of coastal saline soil having an imbedded gravel–sand layer. Ecol. Eng. 108, 59–69. https://doi.org/10.1016/j.ecoleng.2017.08.004.
Viana, C., Freire, D., Abrantes, P., Rocha, J., Pereira, P., 2022. Agricultural land systems importance for supporting food security and sustainable development goals: a systematic review. Sci. Total Environ. 806, 150718 https://doi.org/10.1016/j.scitotenv.2021.150718.
Volkov, A., Paula, S., Deamer, D., 1997. Two mechanisms of permeation of small neutral molecules and hydrated ions across phospholipid bilayers. Bioelectrochemistry Bioenerg. 42, 153–160. https://doi.org/10.1016/s0302-4598(96)05097-0.
Wang, J., Feng, W., Zhang, H., Sun, J., Zhao, Q., 2021a. Experimental study on the effect of deep pine technology on water and salt transport in soda saline land. Arab. J. Geosci. 14, 1–10. https://doi.org/10.1007/s12517-021-06893-y.
Wang, T., Guo, Z., Kuo, C., 2019a. Effects of mixing yellow river water with brackish water on the emitter's clogging substance and solid particles in drip irrigation. SN Appl. Sci. 1 https://doi.org/10.1007/s42452-019-1287-5.
Wang, Y., Zhou, B., Zhang, J., Xu, F., Li, Y., 2021b. Effects of fertilizer types on biofilm growth in the drip irrigation system using the reclaimed water. Irrig. Sci. 39, 725–734. https://doi.org/10.1007/s00271-021-00738-y.
Wang, Y., Muhammad, T., Liu, Z., Liang, H., Wang, X., Wang, Z., Ma, C., Li, Y., 2022a. Chelated copper reduces yet manganese fertilizer increases calcium-silica fouling in brackish water drip irrigation systems. Agric. Water Manag. 269, 107655 https://doi.org/10.1016/j.agwat.2022.107655.
Wang, Y., Muhammad, T., Liu, Z., Ma, C., Zhang, C., Wang, Z., He, X., Li, Y., 2022b. Compounding with humic acid improved nutrient uniformity in drip fertigation system using brackish water: the perspective of emitter clogging. Agric. Water Manag. 269, 107670 https://doi.org/10.1016/j.agwat.2022.107670.
Wang, Z., Zhuang, J., Zhao, A., Li, X., 2018. Types, harms and improvement of saline soil in songnen plain. iop conference series: materials science and engineering. IOP Publishing, 052059. https://dx.doi.org/10.1088/1757–899x/322/5/052059.
Wang, Z., Fan, B., Guo, L., 2019b. Soil salinization after long-term mulched drip irrigation poses a potential risk to agricultural sustainability. Eur. J. Soil Sci. 70, 20–24. https://doi.org/10.1016/j.scitotenv.2022.153222.
Wessel, W., Tietema, A., 1995. Metal distribution across different pools in the organic layer of a forest under acid deposition and its consequences for the metal dynamics. Plant Soil 171, 341–350. https://doi.org/10.1007/bf00010290.
Xiao, Y., Ma, C., Li, M., Zhangzhong, L., Song, P., Li, Y., 2023. Interaction and adaptation of phosphorus fertilizer and calcium ion in drip irrigation systems: the perspective of emitter clogging. Agric. Water Manag. 282 https://doi.org/10.1016/j.agwat.2023.108269.
Zhang, Y., Dawe, R., 2000. Influence of Mg^{2+} on the kinetics of calcite precipitation and calcite crystal morphology. Chem. Geol. 163, 129–138. https://doi.org/10.1016/s0009-2541(99)00097-2.
Zhang, Y., Li, X., Šimůnek, J., Shi, H., Chen, N., Hu, Q., 2022. Optimizing drip irrigation with alternate use of fresh and brackish waters by analyzing salt stress: the experimental and simulation approaches. Soil Tillage Res. 219, 105355 https://doi.org/10.1016/j.still.2022.105355.
Zhang, Z., Li, Y., Du, X., Dong, B., Li, X., Xu, Z., 2012. Influences of water quality's effect weights and mechanisms on fouling of plate heat exchangers. Proc. Chin. Soc. Electr. Eng. 32, 69–74.
Zhangzhong, L., Yang, P., Zhen, W., Zhang, X., Wang, C., 2019. A kinetic model for the chemical clogging of drip irrigation system using saline water. Agric. Water Manag. 223, 105696 https://doi.org/10.1016/j.agwat.2019.105696.
Zhao, L., Heng, T., Yang, L., Xu, X., Feng, Y., 2021. Study on the farmland improvement effect of drainage measures under film mulch with drip irrigation in saline–alkali land in arid areas. Sustainability 13, 4159. https://doi.org/10.3390/su13084159.
Zhao, Y., Shon, H., Phuntsho, S., Gao, B., 2014. Removal of natural organic matter by titanium tetrachloride: The effect of total hardness and ionic strength. J. Environ. Manag. 134, 20–29. https://doi.org/10.1016/j.jenvman.2014.01.002.