water

Article

Effects of Drip Irrigation Models on Chemical Clogging under Saline Water Use in Hetao District, China

Lili Zhangzhong [1,2], Peiling Yang [1,*], Wengang Zheng [2], Caiyuan Wang [1], Chong Zhang [1] and Minglei Niu [3]

1 National Engineering Research Center for Intelligent Equipment in Agriculture, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China; lilizhangzhong@163.com (L.Z.); wangcaiyuan555@163.com (C.W.); zhangchong@cau.edu.cn (C.Z.)

2 College of Water Resources and Civil Engineering, China Agricultural University, Beijing 100083, China; zhengwg@nercita.org.cn

3 China Agricultural Engineering Construction Center, Beijing 100081, China; nmlbox@163.com

* Correspondence: yangpeiling@126.com

Received: 26 January 2018; Accepted: 16 March 2018; Published: 20 March 2018

Abstract: Saline water is a major resource for agricultural irrigation in arid-semi arid regions, especially when it is combined with drip irrigation. However, highly saline water can easily cause clogging of the emitters in drip irrigation systems, adversely affecting crop growth. Hence, a 2a processing tomatoes drip irrigation study was conducted in Hetao irrigation district. The chemical clogging of the emitters was analyzed using four drip irrigation models: RI1 (all fresh water irrigation), RI2 (saline water use in the flowering stage, fresh water in the fruiting stage), RI3 (fresh water use in the flowering stage, saline water in the fruiting stage), and RI4 (all saline water irrigation). The results revealed that the discharge ratio variation (Dra) and the Christiansen uniformity coefficient (CU) of RI4 decreased to 74.0% and 70.9%, respectively, which is considered as a clogged condition with poor irrigation uniformity. When compared to the all saline water irrigation model, the Dra and CU of fresh-saline alternating irrigation models (RI2 and RI3) were higher by 12.16% and 18.05%, respectively. Additionally, the dry weight (DW) of emitters fouling was less than that of RI4 by 16.30%. The Dra and CU showed linear relationships ($R^2 > 0.79$) for the different irrigation models. However, as the Dra declined, the more adverse influence on maintaining the high CU was found in RI4. Using irrigation models with alternating fresh-saline water were recommended to control chemical clogging in drip irrigation systems. Calcium carbonate ($CaCO_3$) was the dominant scale formed, which caused the emitters to clog when processing tomatoes were grown using a drip irrigation system with saline water.

Keywords: saline water; processing tomato; emitter clogging; drip irrigation; alternating irrigation models

1. Introduction

Population growth and rapid urbanization have led to increasing demand for fresh water resources over the past few decades [1]. Agriculture, which is considered as the major consumer of water supplies, accounts for over 70% of freshwater use globally [2]. In this context, finding a balance between the available water resources and the rising water demands for agricultural production is critical, especially in arid and semi-arid regions. Exploring alternative water resources for irrigation has already become one of the important ways to address water shortage and achieve sustainable agricultural development. Saline water has been widely used for irrigation in many countries [3,4]. Drip irrigation is the most efficient irrigation application for saline water [5]. When compared to flood and furrow irrigations, drip irrigation is advantageous, as it increase the water use efficiency (WUE). Moreover, in sprinkler irrigation, the phenomenon of excessive leaf burn due to salt water is observed, which is completely avoided in drip irrigation. Owing to the patterns of soil water movement that was observed under drip irrigation, the accumulated salt contents move toward the regions of moist peaks, which is beneficial for plant growth. Long-term practices indicated that using drip irrigation with saline water could maintain high matric potential and low salt accumulation in the wetting zone, thus maintaining a low salinity level in the root zone [6,7]. In South Africa, low-cost drip irrigation was successfully used in combination with saline water for garden crop irrigation, and a higher yield than the average marketable yield was achieved [8]. In India, higher cotton yields and water productivity were obtained when drip irrigation with saline water was used when compared with furrow irrigation. In Israel, reasonable potato yield could be obtained by drip irrigation with saline water (salinity < 7 dS/m) on deep sandy soils without extreme weather conditions [9]. In China, the WUE and quality of watermelons improved when drip irrigation with saline water was used in Hetao District [10]. The soil matric potential at 0.2 m depth was recommended to be kept above −20 kPa when drip irrigation with saline water was used in Northwest China to help alleviate the dangerous increase in the water table, while increasing the cotton seed yield [11]. Irrigation emitters should be placed on the northern side of the plants when constructing shelterbelts for water conservation and soil salt reduction under saline drip irrigation in the Taklimakan Desert [12]. In Caofeidian District, the drip irrigation with saline water was beneficial for salt leaching, and the highly saline soil became mildly saline after reclamation by leaching salts from the root zone of soil profiles irrigated with water of salinity level up to 7.8 dS/m [13]. It is a common observation that using saline water for drip irrigation is a feasible solution in areas that lack freshwater resources. However, emitter clogging was indicated as a critical issue that was affecting the performance of drip irrigation with saline water in long-term practices, which need to be further evaluated for the sustainability of such a system [14]. Highly saline water can easily form precipitates, resulting in chemical clogging. This enhances the potential for clogging, and the clogging mechanism becomes more complex [15]. The emitter is the key part of a drip irrigation system, which irrigates the root zone of plants with small water droplets by dissipating the water energy through the internal flow path. The flow path of emitters is complex and narrow (with a size of 0.5 to 1.5 mm), which can easily be clogged. For the saline water drip irrigation system, the emitter clogging degrades irrigation uniformity obviously. The poor irrigation uniformity impacts the water availability and soil salinity. Finally, the crop growth was limited directly by the variable water stress and indirectly by the impaired salinity management. It restricts the advancement of saline water drip irrigation technology [16]. Nonetheless, the current research in this field mainly focuses on the suitable mode of saline water drip irrigation by considering the effects of saline water on the soil environment, crops production, and WUE, while neglecting the issues that are related to emitter clogging that is caused by saline water.

Now, the two basic approaches for controlling emitter clogging have evolved. One is removing the potential source of clogging from the water before it enters the irrigation system, such as with filters [17]. However, the screen/disc filter has good effects on the physical clogging caused by sands, and the media filter has good effects on the biological clogging caused by colloidal and organic materials. The chemical clogging that is caused by the salts cannot be well controlled by the filter system. Hence, we seek another approach for control chemical clogging that is to prevent or control chemical processes from occurring. The clogging process is affected by irrigation water quality [18], emitter type [19], irrigation model [20], etc. Particularly, the irrigation model could influence the internal medium of drip irrigation systems, thus changing the formation and growth of clogging substances within the emitters, leading to different levels of emitter clogging. The main approaches currently considered to utilize saline water are all saline water irrigation, saline-fresh water mixture irrigation, and saline-fresh water alternating irrigation. The saline-fresh water alternating irrigation model is widely used worldwide, as it could save the fresh water resources when compared to all fresh water irrigation methods, and prevent the damage to crops and soils caused by salt when compared to all of the saline water irrigation models [21]. The alternating irrigation model could improve crop growth by changing the water-salt distribution in soils. Moreover, it could influence the anti-clogging performance of drip irrigation system by changing clogging substances formation inside the emitters. The existing literature mainly analyzed the impacts of alternating irrigation on the yield and quality of tomatoes, cottons, and lemons, and examined the water-salt movement and distribution in soil under different alternating irrigation models, neglecting its effects on the clogging substances formation inside the emitters and irrigation capacity of drip irrigation systems. The current studies conducted on emitter clogging under saline water drip irrigation focused on investigating the means to control clogging such as adding acids or applying magnetic fields to irrigation water. The relevant experiments usually conducted on bare land with continuous irrigation for a short period, without considering the real irrigation demands of crops. Very limited research has been conducted to examine the effects of saline-fresh alternating irrigation model on emitter clogging. The application of saline water irrigation models to effectively control emitter clogging is a rich study subject. Hence, processing tomato as a high value crop was selected for this research. Processing tomatoes, which grow in areas that receive direct sun and exhibit tolerance to semi-drought and salinity, are widely grown in the arid and semi-arid regions of China. A 2a study of growing processing tomatoes using drip irrigation saline water in the Hetao irrigation district was conducted. The objectives of this study are: (1) to examine the emitter clogging behaviors and clogging substances composition under different fresh-saline alternating irrigation models; and, (2) to evaluate the feasibility of using alternating irrigation models for drip irrigation systems. The results could provide the theoretical basis for agricultural water management using saline water.

2. Materials and Methods

2.1. Experiment Design

The experiment was conducted at the Shuguang experiment station (40°46′ N, 107°24′ E) in Hetao irrigation district, Inner Mongolia. It has a temperate continental climate with four distinctive seasons, which are characterized by hot, dry summers and cold, long winters. The average temperature is 6.8 °C. The annual sunshine hours are 3180 h per year, with average frost-free period of 160 days. The annual evaporation is 2306.5 mm, and the annual average rainfall ranges between 130 and 215 mm, which mostly occur in July and August. The soil used in the experiment is sandy loam soil with bulk density of 1.58 g/cm^3 and field capacity of 0.22 m^3/m^3. No. 2 Shitun processing tomato, which belongs to the early-maturing variety, was used for the experiment. A high-ridge and wide-row planting model was adopted, with ridge width of 0.9 m, ridge height of 0.3 m, and ridge length of 20 m. Two rows of processing tomatoes were planted in each ridge, with a row spacing of 0.4 m and planting distance of 0.3 m. The tested plot comprised of a ridge of processing tomatoes with an area of 30 m^2 (Length $\times$ width: 20 m $\times$ 1.5 m), each with three replications. The drip irrigation tapes were laid near the crops root zone; each tape controlled a row of processing tomatoes. The drip irrigation tapes were used during 2013 and again in 2014. Hence, the two seasons were cumulative with respect to clogging and its effect on crop performance. The operation pressure of the drip irrigation system was 0.1 MPa. The time of any irrigation was set by the system timer, but the duration of the irrigation event was controlled by water meter to ensure that known volumes of irrigation were applied. The drip irrigation emitter was no-pressure-compensating type (Lin16, Metzerplas Co. Ltd., Tel Aviv, Israel). The spacing between emitters along the laterals was 0.30m. The emitters work pressure ranged from 0.04 MPa to 0.25 MPa, the rated work pressure was 0.1 MPa, and the flow rate was 1.2 L/h, the detail technical data references to https://www.metzer-group.com/products/lin/ and the three-dimensional (3D) structure of the emitter is shown in Figure 1.

During the seeding stage (from the field transplantation stage until 50% of plants grew their first flower), the tomatoes were irrigated with fresh water in order to ensure proper germination. The flowering stage (from 50% of plants grew their first flower until 50% of plants grew their first fruit) and during the fruiting stage (from 50% of plants grew their first fruit until 50% of plants grew their first fruit with the fruit width is more than 1 cm) they were irrigated with fresh and saline water, alternatively. The ripening stage (from 50% of plants grew their first fruit with the fruit width is more than 1 cm until all plants were harvested) irrigation was stopped to prevent the fruits from rotting. The four fresh-saline water alternating irrigation models (IR1, IR2, IR3, and IR4) that were considered in this experiment are listed in Table 1. When saline water was applied, surplus water was added to provide a leaching fraction, which was calculated according to Natural Resources Conservation Service (NRCS) National Engineering Handbook [22]. In order to maintain the total amount of irrigation water for the different treatments was equal, the irrigation practices were according the local irrigation experiences, and the leaching requirement ratio also was added to IR1. The irrigation water quota during flowering and fruiting stage were 8 mm and 12 mm, respectively, which included 1.2 or 1.7 mm, respectively, leaching fraction. The irrigation frequency was four days per irrigation.

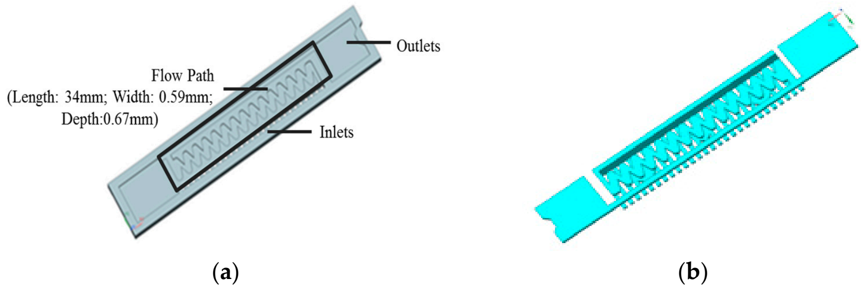


Figure 1. Three-dimensional (3D) structure (**a**) and inner flow field (**b**) of the drip irrigation emitter.

Table 1. Experimental treatments.

	Stage	RI1	RI2	RI3	RI4	Irrigation (mm)
2013	Seeding (18 May to 7 June)	Fresh water				25.0
	Flowering (8 June to 7 July)	Fresh water	Saline water	Fresh water	Saline water	32.0
	Fruiting (8 July to 19 August)	Fresh water	Fresh water	Saline water	Saline water	108.0
	Ripening (20 August to 19 September)	-	-	-	-	-
2014	Seeding (20 May to 13 June)	Fresh water				25.0
	Flowering (14 June to 9 July)	Fresh water	Saline water	Fresh water	Saline water	40.0
	Fruiting (10 July to 14 August)	Fresh water	Fresh water	Saline water	Saline water	84.0
	Ripening (15 August to 10 September)	-	-	-	-	-

In 2013, the total rainfall was 54.8 mm and the total irrigation amount was 165mm for each treatment during whole growth season. The irrigation amounts of fresh water were 165 mm in RI1, the irrigation amounts of fresh and saline water were 133 mm and 32.0 mm in RI2, the irrigation amounts of fresh and saline water were 57 mm and 108 mm in RI3, and the irrigation amounts of fresh and saline water were 25 mm and 140 mm in RI4. The base fertilizers (organic fertilizer: 22.5 t/hm^2; diammonium phosphate: 240 kg/hm^2; and mono potassium phosphate: 150 kg/hm^2) were applied before transplanting. During the initial and middle fruiting stages, 45 kg/hm^2 and 22.5 kg/hm^2 urea were applied to the irrigation system, respectively.

In 2014, the total rainfall was 49 mm and the total irrigation amount was 149 mm for each treatment during the whole growth season. The irrigation amounts of fresh water were 149 mm in

RI1, the irrigation amounts of fresh and saline water were 109 mm and 40.0 mm in RI2, the irrigation amounts of fresh and saline water were 65 mm and 84 mm in RI3, and the irrigation amounts of fresh and saline water were 25 mm and 124.0 mm in RI4. The base fertilizers (diammonium phosphate: 240 kg/hm^2; urea: 90 kg/hm^2; and, dipotassium phosphate: 160 kg/hm^2) were applied before transplanting. During the fruiting stage, 150 kg/hm^2 urea was applied to the irrigation system.

2.2. Measurement Methods

At the end of seeding, flowering, and fruiting stages, the emitter outflow rates in each treatment were measured using catch cans for 10 min duration, with three replications. The emitter clogging characteristics were evaluated based on the discharge ratio variation (Dra) and Christiansen coefficient of uniformity (CU) [23]. The Dra presented the reduction degree of outflow rates. If the Dra is less than 75%, then the emitter is considered to be clogged [24]. The outflow uniformity of the drip irrigation emitters could be represented by uniformity coefficient CU, which reflected the randomness during emitter clogging. The irrigation capacity of emitters is considered to be excellent when CU is greater than 89%. The medium condition is achieved when CU ranges between 71% and 89%; however, when CU is lower than 71%, the emitter performance is considered to be poor [25].

After the tomatoes were harvested, for each treatment, three emitters were cut from before and after each 5 cm interval of laterals at the head, middle, and end parts, respectively. Two samplings were done, one at the end of each season. Samples were stored in Ziploc bags for later use and the collected sections of laterals were replaced with new emitters. The weight of each emitter (W1) was measured using electronic balance with an accuracy of 0.0001 g. Then, clogging substances were removed using ultrasonic oscillation machine with a frequency of 40 kHz. The weight of each emitter was measured after cleaning (W2). The difference between W1 and W2 was calculated to measure the dry weight (DW) of clogging substances. The chemical characteristics of clogging substances that were removed from emitters were tested using X-ray diffractometer (XRD, Bruker D8 Advance, Karlsruhe, Germany), and Topas software was used to analyze these characteristics.

3. Results

3.1. Evaluation of Irrigation Water Quality

The fresh water used in the experiment was local underground water. The saline water was made up by adding $NaHCO_3$, KCl, and NaCl (molar ratio: 1:2.57:5.85) into the underground water, according to the saline water characteristics in Hetao Irrigation District. The water quality parameters were listed in Table 2. Higher content of Na^+, K^+, HCO_3^-, and Cl^- was detected in the saline water, and HCO_3^- was the critical ion that caused emitter clogging. The water quality evaluation revealed that based on the hazard ranking system [26], medium and severe hazard ratings were obtained for the experimental fresh water and saline water, respectively.

Table 2. Water quality analysis of experimental water.

Index	Fresh Water		Saline Water		
	Experimental Fresh Water Samples	Grade	Local Saline Water Samples	Experimental Saline Water Samples	Grade
Ca^{2+} (g·L^{-1})	0.0601	-	0.0701	0.0601	-
Mg^{2+} (g·L^{-1})	0.0911	-	0.079	0.911	-
Na^+ (g·L^{-1}) K^+ (g·L^{-1})	0.150	-	0.825	0.942	-
HCO_3^- (g·L^{-1})	0.336	-	0.519	0.526	-
CO_3^{2-} (g·L^{-1})	0.00	-	0.00	0.00	-
Cl^- (g·L^{-1})	0.160	-	0.975	1.060	-
$S0_4^{2-}$ (g·L^{-1})	0.312	-	0.312	0.337	-
Ion content (g·L^{-1})	1.108	Moderate	2.804	3.000	Severe
pH	7.50	Moderate	8.10	8.25	Severe
EC (dS/m)	1.30	Moderate	3.40	3.56	Severe

The irrigation water temperature and electrical conductivity (EC) were monitored during the experiment, as shown in Figure 2. The water temperature varied with the weather conditions. 2013 and 2014 water temperatures were similar, with the average temperature ranging between 26.1 °C and 25.4 °C. Fluctuating EC values of the tested saline water were found, with average values of 3.53 dS/m and 3.54 dS/m obtained in 2013 and 2014, respectively. The EC of fresh water was more stable, with average values of 1.27 dS/m and 1.24 dS/m in 2013 and 2014, respectively. The EC value of saline water was 2.81 times greater than that of fresh water.

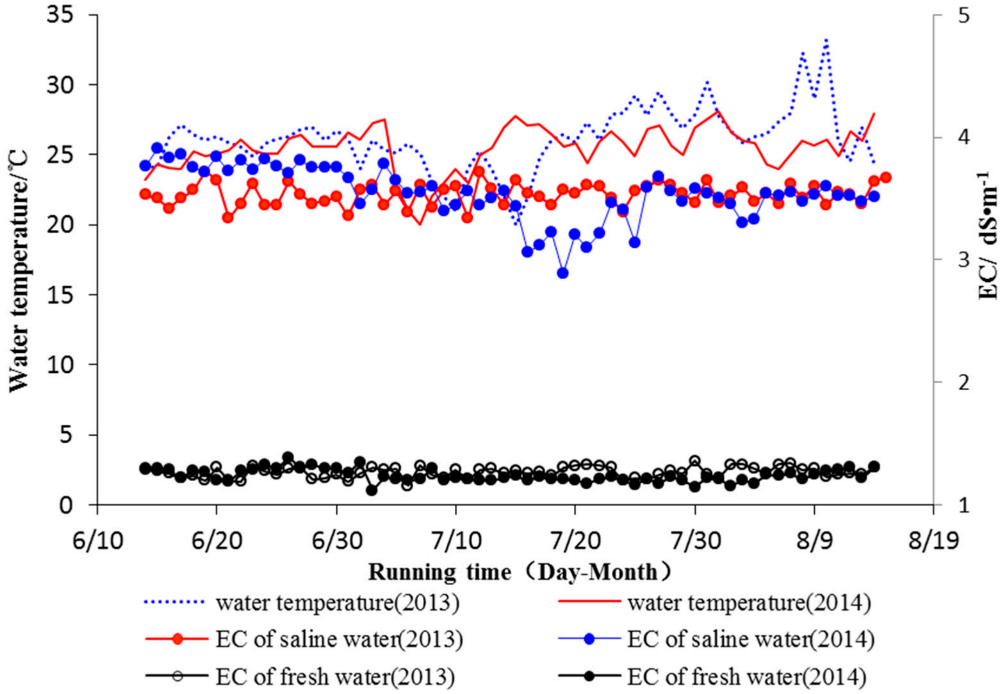
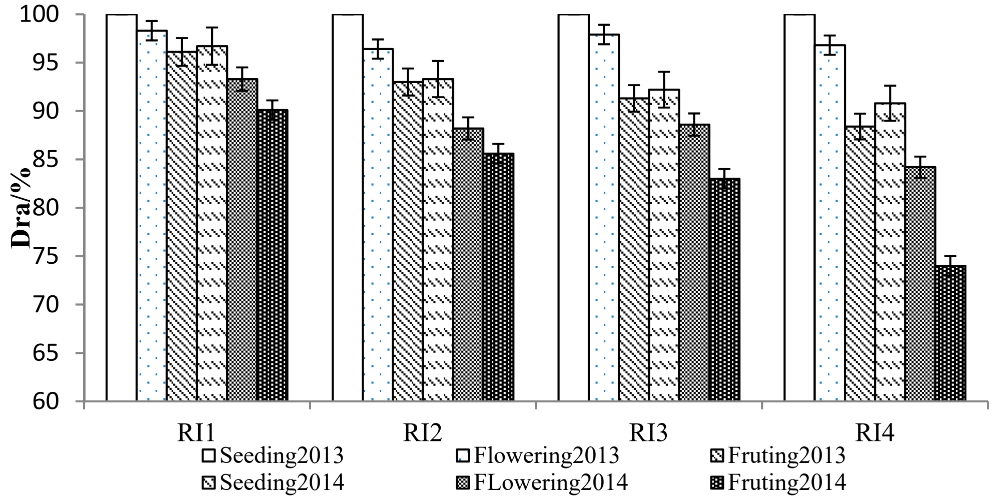


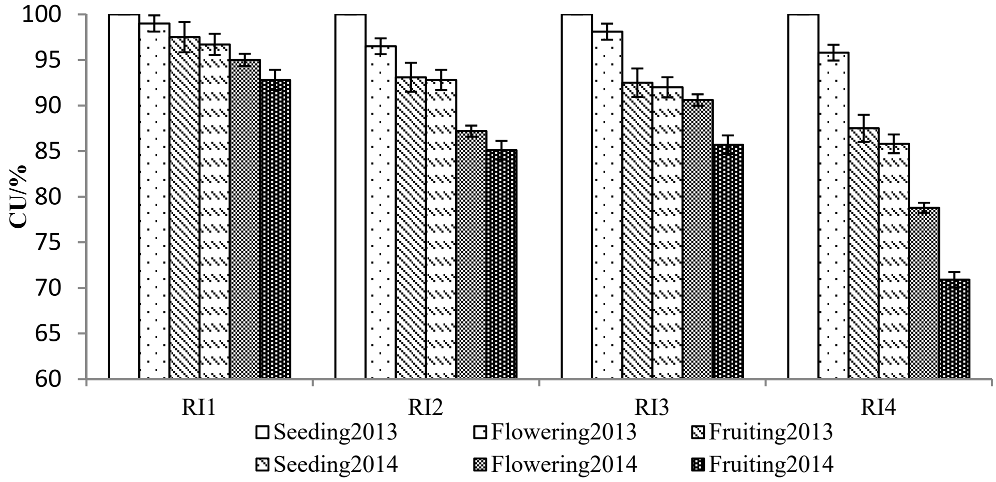
Figure 2. Variation in water temperature and electrical conductivity (EC) during the experiment.

3.2. Analysis On Clogging Characteristics of Emitters

Figure 3 illustrates the changes in outflow rates of the tested drip irrigation emitters during the growth season in 2013 and 2014. In the first growth season, the outflow rates declined as the processing tomatoes grew. During the flowering stage, the Dra of fresh water irrigation treatment (RI1 and RI3) was higher than the saline water irrigation treatment (RI2 and RI4). In the fruiting stage, when the RI3 changed into saline water irrigation, the Dra significantly decreased. Additionally, the Dra slightly declined when RI2 changed into saline water irrigation. At the end of the first growth season, the obtained Dra values of RI1, RI2, RI3, and RI4 were 96.1%, 93.0%, 91.3%, and 88.4%, respectively. Although the Dra of all the treatments decreased, none of them reached the clogging level. The CU values of RI1, RI2, RI3, and RI4 were 97.5%, 92.1%, 92.5%, and 87.5%, respectively. RI4 declined to medium grade, and the other treatments all obtained good grade. In the second growth season, the Dra of all the treatments recovered by the end of seeding stage, with slight margin of 0.6% to 2.4%. However, a similar trend was not observed for CU, as the CU of all the treatments declined constantly. During the flowering and fruiting stage, the Dra and CU presented the declined trend and the change rules were as same as last growth season. At the end of the second growth season, the obtained Dra values of RI1, RI2, RI3, and RI4 were 90.1%, 85.6%, 83.0%, and 74.0%, respectively, with RI4 reached the clogging level. The obtained CU values of RI1, RI2, RI3, and RI4 were 92.8%, 86.6%, 83.7%, and 70.9%. RI1 obtained good grade, RI2 and RI3 declined to medium grade, and poor grade was obtained by RI4. The significance test results listed in Table 3 (significance level of 0.01) shows that there were statistically significant differences in Dra and CU under different alternating irrigation models, except for RI2 and RI3.



(**a**)



(**b**)

Figure 3. Discharge ratio variation (Dra) (**a**) and Christiansen coefficient of uniformity (CU) (**b**) variation under different fresh-saline alternating irrigation model.

Table 3. *T*-test of Dra and CU under different fresh-saline alternating irrigation model.

Treatment	Dra				CU			
	RI1	**RI2**	**RI3**	**RI4**	**RI1**	**RI2**	**RI3**	**RI4**
RI1	-	-	-	-	-	-	-	-
RI2	0.004 *	-	-	-	0.001 **	-	-	-
RI3	0.024 *	0.739	-	-	0.021 *	0.755	-	-
RI4	0.022 *	0.050 *	0.025 *	-	0.017 *	0.048 *	0.020 *	-

Note: In the Table, * means significant ($p < 0.05$); ** means very significant ($p < 0.01$).

3.3. Quantitative Analysis of Clogging Substances

Figure 4 illustrates the DW change of clogging substances that clogged the internal surface of emitters during the growth seasons in 2013 and 2014. While the system was running, the clogging gradually increased inside the emitters flow path. During the first growth season, the DW of clogging substances that formed on the internal surface of emitters ranged from 0.033 g to 0.064 g. It increased to range from 0.059 g to 0.096 g in the second growth season, with growth rate of 30.1–77.0%. The DW of RI2 and RI3 were 16.3–19.1% less than that of RI4, and 31.0–35.4% higher than that of RI1. The fouling distribution of clogging was similar under different fresh-saline water alternating irrigation models, which showed that the DW increased along the drip irrigation pipe direction (Figure 4b). The DWs at the end of the pipes (DW_{end}) of RI1, RI2, RI3, and RI4 were 198.7%, 124.9%, 190.2%, and 130.6% higher than at the head of pipe (DW_{head}). The significance tests results that are listed in Table 4 (significance level of 0.01) shows that there were statistically significant differences in DW between the irrigation with and without saline water.

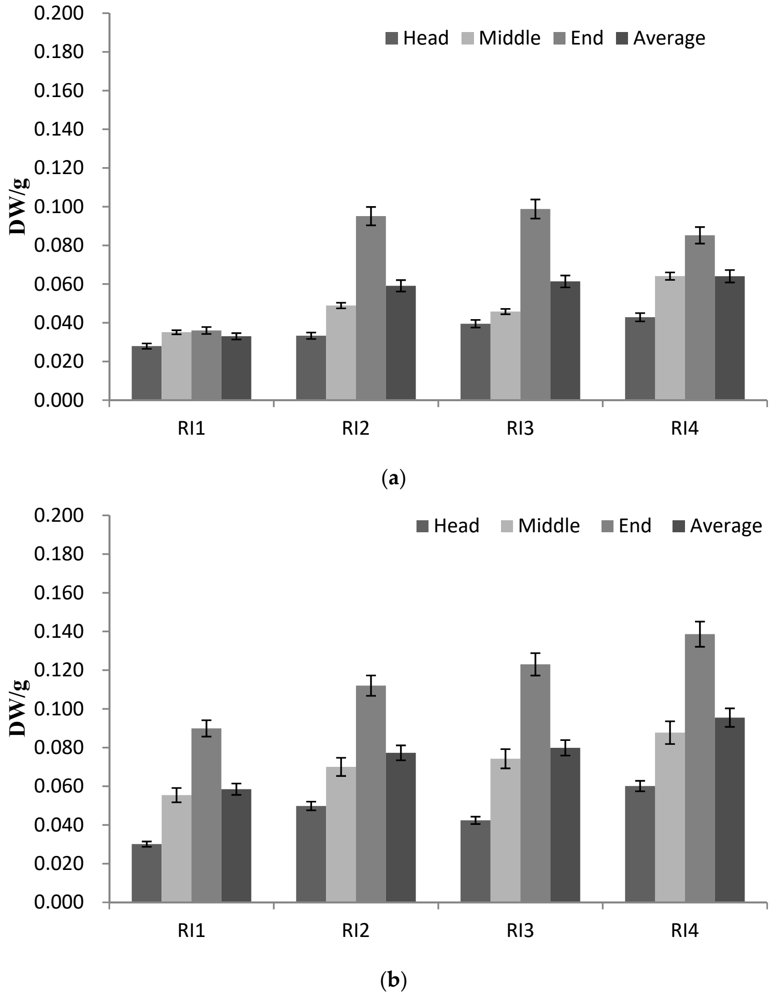


Figure 4. Quantitative analysis of dry weight (DW) under different fresh-saline alternating irrigation models in 2013 (**a**) and 2014 (**b**).

Table 4. *T*-test of DW under different fresh-saline alternating irrigation models.

Treatment	RI1	RI2	RI3	RI4
RI1	—	—	—	—
RI2	0.033 *	—	—	—
RI3	0.030 *	0.410	—	—
RI4	0.001 **	0.067	0.130	—

Note: In the Table, * means significant ($p < 0.05$); ** means very significant ($p < 0.01$).

3.4. Qualitative Analysis of Clogging Substances

Table 5 illustrates the chemical composition of clogging substances that clogged the internal surface of emitters during the growth season in 2013 and 2014. Similar chemical compositions of RI1, RI2, RI3, and RI4 were obtained, comprising of calcium-magnesium carbonates, quartz, silicates, and sodium chloride. There was primarily calcite, aragonite, magnesium calcite, and dolomite in calcium-magnesium carbonates, while muscovite, chlorite, and albite were found in silicates. In the second growth season, the content of each chemical component was changed. The quartz, calcite, and chlorite increased by 15.3–80.8%, 119.3–249.5%, and 46.4–112.9% than the first growth season, respectively. The magnesium calcite declined by 73.0–96.0%. The dominant clogging substance was Calcium carbonate ($CaCO_3$) scale in IRI1, RI2, RI3, and RI4, comprising 36.1–63.4% of clogging substances formation.

Table 5. Chemical constituents of clogging substances in the emitters.

Category	RI1 (mg)		RI2 (mg)		RI3 (mg)		RI4 (mg)	
	2013	2014	2013	2014	2013	2014	2013	2014
Calcite	8.697	26.122	15.508	32.957	20.445	44.627	12.292	43.231
Aragonite	0.573	1.281	2.222	1.218	3.003	2.870	1.035	3.001
Magnesium calcite	6.857	1.840	9.439	1.096	9.523	0.537	8.504	0.345
Dolomite	0.400	0.750	0.979	0.000	0.486	2.076	1.304	0.469
Muscovite	3.816	11.042	7.009	12.451	6.764	4.652	9.601	14.882
Chlorite	1.135	2.227	2.801	4.094	1.659	3.514	3.697	6.631
Albite	3.192	2.050	6.420	1.852	4.212	3.014	6.502	5.530
Quartz	7.876	13.133	12.888	23.257	13.387	17.464	18.329	21.265
Sodium chloride	0.454	0.553	1.736	0.075	1.521	0.246	2.736	0.648

4. Discussion

Use of both saline and non-saline water could be a viable approach to water management in many regions around the world. Irrigation management had direct impacts on moisture-nutrient-salinity distribution of soil, growth, and production of crops, and clogging substances accumulation in drip irrigation systems [19]. For mulched soil with polyethylene film, saline water could be applied to bell pepper plants during the fruiting stage without any yield reduction. For bare soil, the saline irrigation should be applied during vegetative and flowering growth stages instead [27]. The use of saline water (50%) and low saline water (50%) in drip irrigation could decrease the accumulation of potentially toxic ions without negative effects on maize yield [28]. Under the alternating irrigation between saline and fresh water, the root length density, the aboveground dry matter, the numbers of bolls per unit area, and the seed cotton yields were improved by 12–24% when compared to the results that were obtained with all saline water treatment [29].The current research indicates that the proper application of alternating irrigation between saline water and non-saline water could reduce the crop damage caused by salt when the crops irrigated directly with saline water [30]. However, the previous studies on developing reasonable alternating irrigation models merely focused on plants yield and quality in addition to soil, water, and salinity distribution, neglecting their effects on the efficiency of the drip irrigation system. Hence, we studied the effects of alternating irrigation models on the emitter clogging in saline water drip system for processing tomato production. After 2a growing of processing tomatoes, the results showed that using saline water for drip irrigation could cause severe clogging problems. The Dra of the all saline irrigation model (RI4) declined to 74.0%, leading to emitter clogging. Furthermore, the CU of RI4 degraded to 70.9%, which is classified as a poor performance level. These results are in good agreement with the results obtained by the drip irrigation experiments with saline water that did not involve crop planting (EC: 2.0–4.8 dS/m) [31,32]. The irrigation models using alternating saline-fresh water adopted in this study lowered the clogging degree of emitters. The Dra of RI2 and RI3 was 12.16–15.68% greater than that of RI4, and the CU of RI2 and RI3 was

18.05–22.14% higher than that of RI4. The analysis of the relationship between Dra and CU (Figure 5) depicted a linear relationship under different alternating irrigation model ($R^2 > 0.96$). Under the same Dra conditions, the CU of IR4 was lower than that obtained by the other irrigation models. This indicated that as the emitter clogging increased, the adverse effects on maintaining high CU were more significant under saline water drip irrigation system. The irrigation model using alternating saline-fresh water could keep better irrigation uniformity, which is more suitable for saline water use.

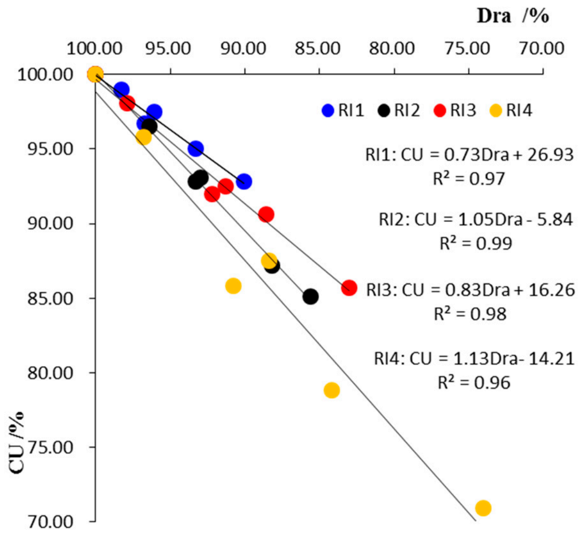


Figure 5. Relationship between Dra and CU under different fresh-saline alternating irrigation models.

For the processing tomatoes production, the yield is shown in Table 6. It showed that drip irrigation with saline water resulted in a yield reduction. But, the fresh-saline alternation irrigation model restricted the reduction. When compared to the all saline irrigation (RI4), the yields of RI2 and RI3 were improved 22.2–23.65% and 61.69–79.2%, respectively. The processing tomatoes yield is not only affected by the saline water, but also by the emitter clogging. The poor irrigation that is uniformly caused by the emitter clogging had adverse impacts on the water deficit stress and salinity management. Hence, the saline-fresh water alternating irrigation model was recommended as a viable option to use saline water for agriculture, as it somewhat reduced the clogging of the emitters. In practice, greater yield reductions should be expected with use of saline water. In this experiment, the use of a water meter allowed the same volume of water to be applied to all the treatments, so the effects are largely due to impaired uniformity. A typical farmer irrigation system will manage both timing and duration of irrigation with a timer and in these circumstances; the reduced average emission rate with clogging will increase the extent of water deficits, in addition to the effects of non-uniform water application.

Table 6. Processing tomato yield under different fresh-saline alternating irrigation model.

Yield (t/hm^2)	RI1	RI2	RI3	RI4
2013	108.00 a	70.90 b	97.80 a	58.00 c
2014	130.18 a	89.40 b	129.54 a	72.30 b

Note: In the same column and in the same year, means followed by the same letter (a, b, c) do not differ significantly at the 5% level according to a LSD test.

The formation and growth of clogging substances is a major cause of emitter clogging. Similar clogging substances distribution was obtained under different alternating irrigation models, illustrating the trend of $DW_{headv} < DW_{middle} < DW_{end}$. The clogging distribution was in good agreement with the results that were observed for reclaimed water and high-sandy content water in drip irrigation systems [23,33]. This could be attributed to the fact that the hydraulic field inside the drip irrigation system had a direct impact on clogging substances distribution. Under the effect of frictional head loss, the flow velocity declined gradually along the direction of drip irrigation pipes. The lower flow velocity led to smaller flushing forces on the fouled emitters, leading to more clogging substances being accumulated at the end of drip irrigation pipes. However, the different irrigation models that were tested in study had impacts on the DW of the formed clogging substances. The DW declined by 16.3–19.1% when the irrigation model using alternating fresh-saline water was applied, while the difference between IR2 and IR3 DW was not significant.

Verifying the material properties of fouling composition is key to understand the clogging mechanism and develop the appropriate clogging control method for saline water drip irrigation systems. Similar chemical composition of clogging substances was obtained under the different irrigation models to grow processing tomatoes using drip irrigation with saline water in the Hetao irrigation district. This was owing to the relationship between the irrigation water quality and the chemical characteristics of clogging substances [34]. The critical materials caused the emitter clogging in the processing tomatoes drip irrigation system with saline water was $CaCO_3$ scale. The $CaCO_3$ scale was also found in the indoor experiment conducted using hard water for drip irrigation [35]. The formation process could be as follows: the ground water absorbed the CO_2 in the air and from the decomposition of organic matters in the soil. As the CO_2 increased, the H_2CO_3 formed in the ground water under changing pressure conditions. Then, the H_2CO_3 combined with the inorganic compound, which dissolved the $CaCO_3$, to create the $Ca(HCO_3)_2$. As the ground water flowed into drip irrigation system, the $CaCO_3$ scale generated under the pressure change and temperature elevation, and then caused the chemical clogging in the drip irrigation system. The different alternating irrigation models affected the accumulated amounts of $CaCO_3$ scale. As the amount of saline water increased in the irrigation model, the higher the amount of $CaCO_3$ scale formed in the drip irrigation system. This was owing to the effect of pH, ions contents, temperatures, etc. on the formation of the $CaCO_3$ scale [36]. The saline water with higher pH and ions contents promoted the $CaCO_3$ generation; which therefore aggravated the emitter clogging in the tested drip irrigation system. We also found the silicate and quota in the clogging substances. The origin of the Si and Al was the sediment particles in irrigation water. The sediment concentration of the local underground water in Hetao irrigation district was relatively high.

5. Conclusions

This study showed that emitter clogging under different alternating irrigation model to grow processing tomatoes using drip irrigation with saline water illustrated the trend $Dra_{RI1} > Dra_{RI2} > Dra_{RI3} > Dra_{RI4}$ and $CU_{RI1} > CU_{RI2} > CU_{RI3} > CU_{RI4}$. Similar clogging substances distribution clogged the internal surface of emitters under different alternating irrigation models. The DW increased along the direction of drip irrigation pipes. The irrigation model significantly affected the accumulation amounts of clogging substances, as the DW of RI2 and RI3 was 16.3–19.1% less than that of RI4. The dominant substance caused the emitters clogging was $CaCO_3$ scale, comprising 36.1% to 63.4% of the clogging substances formation. Alternating fresh-saline water irrigation models could efficiently control chemical clogging to grow processing tomatoes using the saline water drip irrigation systems in the Hetao irrigation district.

Acknowledgments: We are grateful for financial support from the Major Program of the National Natural Science Foundation of China (NSFC) (Grant No. 51339007), and the project funded by China Postdoctoral Science Foundation.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "Peiling Yang and Wengang Zheng conceived and designed the experiments; Chong Zhang performed the experiments; Lili Zhangzhong and Caiyuan Wang analyzed the data; Caiyuan Wang and Minglei Niu contributed analysis tools; Lili Zhangzhong wrote the paper". Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Schmautz, Z.; Loeu, F.; Liebisch, F.; Graber, A.; Mathis, A.; Bulc, T.G.; Junge, R. Tomato Productivity and quality in aquaponics: Comparison of three hydroponic methods. *Water* **2016**, *8*, 533. [CrossRef]
2. Thevs, N.; Streng, E.; Aliev, K.; Eraaliev, M.; Lang, P.; Baibagysov, A.; Xu, J.X. Tree shelterbelts as an element to improve water resource management in central Asia. *Water* **2017**, *9*, 842. [CrossRef]
3. Zhang, H.; Liu, H.; Sun, CT.; Gao, Y.; Gong, X.W.; Sun, J.S.; Wang, W.N. Root development of transplanted cotton and simulation of soil water movement under different irrigation methods. *Water* **2017**, *9*, 503. [CrossRef]
4. Huang, Y.; Wang, Y.D.; Zhao, Y.; Xu, X.W.; Zhang, J.G.; Li, G.J. Spatiotemporal distribution of soil moisture and salinity in Taklimakan desert highway shelterbelt. *Water* **2015**, *7*, 4343–4361. [CrossRef]
5. Qi, Z.J.; Zhang, T.B.; Zhou, L.F.; Feng, H.; Zhao, Y.; Si, B.C. Combined effect of mulch and tillage on soil hydrothermal conditions under drip irrigation in Hetao Irrigation Disctrict, China. *Water* **2016**, *9*, 504. [CrossRef]
6. Chen, M.; Kang, Y.H.; Wan, S.Q.; Liu, S.P. Drip irrigation with saline water for oleic sunflower (*Helianthus annuus* L.). *Agric. Water Manag.* **2009**, *96*, 1766–1772. [CrossRef]
7. Wan, S.Q.; Kang, Y.H.; Wang, D.; Liu, S.P.; Feng, L.P. Effect of drip irrigation with saline water on tomato (*Lycopersicon esculentun* Mill) yield and water use in semi-humid area. *Agric. Water Manag.* **2007**, *90*, 63–74. [CrossRef]
8. Karlberg, L.; Rockström, J.; Annandale, J.G.; Steyn, J.M. Low-cost drip irrigation—A suitable technology for Southern Africa? An example with tomatoes using saline irrigation water. *Agric. Water Manag.* **2007**, *89*, 59–70. [CrossRef]
9. Bustan, A.; Sagi, M.; Malach, Y.D.; Pasternak, D. Effects of saline irrigation water and heat waves on potato production in an arid environment. *Field Crop Res.* **2004**, *90*, 275–285. [CrossRef]
10. Wu, L.T.; Xiao, J.; Ping, W.J.; Zhong, L.Z. Experimental investigation on the effects of saline water drip irrigation on water use efficiency and quality of watermelons grown in saline soils. *J. Hydraul. Eng.* **2003**, *4*, 85–89. (In Chinese)
11. Kang, Y.H.; Wang, R.S.; Wan, S.Q.; Hu, W.; Jiang, S.F.; Liu, S.P. Effects of different water levels on cotton growth and water use through drip irrigation in an arid region with saline ground water of northwest China. *Agric. Water Manag.* **2012**, *109*, 117–126. [CrossRef]
12. Zhang, J.G.; Wang, Y.D.; Zhao, Y.; Xu, X.W.; Li, G.J.; Li, S.Y. Spatial-temporal distribution of soil salt crusts under saline drip irrigation in an artificial desert highway shelterbelt. *Water* **2016**, *8*, 35. [CrossRef]
13. Li, X.B.; Kang, Y.H.; Wan, S.Q.; Chen, X.L.; Xu, J.C. Effect of drip-irrigation with saline water on Chinese rose (*Rosa chinensis*) during reclamation of very heavy coastal saline soil in a field trial. *Sci. Hortic.* **2015**, *186*, 163–171. [CrossRef]
14. Feng, D.; Kang, Y.H.; Wan, S.Q.; Liu, S.P. Lateral flushing regime for managing emitter clogging under drip irrigation with saline groundwater. *Irrig. Sci.* **2017**, *35*, 217–225. [CrossRef]
15. Dehghanisanij, H.; Anioji, H.; Riahi, H.; Abou, E.W. Effect of emitter characteristics and irrigation schemes on emitter clogging under saline water use. *J. Arid Land Stud.* **2007**, *16*, 225–233.
16. Camp, C.R. Subsurface drip irrigation: A review. *Trans ASAE* **1998**, *41*, 1353–1367. [CrossRef]
17. Pitts, D.J.; Haman, D.Z.; Smajstria, A.G. *Causes and Prevention of Emitter Plugging in Micro Irrigation Systems*; BUL 258; IFAS, University of Florida: Gainesville, FL, USA, 1990.
18. Hao, F.Z.; Li, J.S.; Wang, Z.; Li, Y.F. Effect of ions on clogging and biofilm formation in drip emitters applying secondary sewage effluent. *Irrig. Drain.* **2017**, *64*, 687–698. [CrossRef]
19. Zhangzhong, L.L.; Yang, P.L.; Ren, S.M.; Li, Y.K.; Liu, Y.; Xia, Y.H. Chemical clogging of emitters and evaluation of their suitability for saline water drip irrigation. *Irrig. Drain.* **2016**, *65*, 439–450.
20. Zhou, B.; Li, Y.K.; Liu, Y.Z.; Xu, F.P.; Pei, Y.T.; Wang, Z. Effect of drip irrigation frequency on emitter clogging using reclaimed water. *Irrig. Sci.* **2015**, *33*, 221–234. [CrossRef]
21. Malash, N.M.; Flowers, T.J.; Ragab, R.; Ragab, R. Effect of irrigation systems and water management practices using saline and non-saline water on tomato production. *Agric. Water Manag.* **2005**, *78*, 25–38. [CrossRef]
22. Uniter States Department of Agriculture, Natural Resources Conservation Service (USDA-NRCS). *National Engineering Handbook, Irrigation Section 15, Chapter 7. Trickle Irrigation*; USDA-NRCS: Washington, DC, USA, 1985.

23. Pei, Y.T.; Li, Y.K.; Liu, Y.Z.; Zhou, B.; Shi, Z.; Jiang, Y.G. Eight emitters clogging characteristics and its suitability evaluation under on-site reclaimed water drip irrigation. *Irrig. Sci.* **2014**, *32*, 141–157. [CrossRef]
24. *Clogging Test Methods for Emitters*; ISO/TC 23/SC 18/WG5 N4; Standards Institution of Israel: Tel Aviv, Israel, 2003.
25. Bratls, V.F. Field performance and evolution. In *Trickle Irrigation for Crop Production, Design, Operation and Management*; Elsevier: Amsterdam, The Netherlands, 1986; Volume 3, pp. 216–240.
26. Nakayama, F.S.; Bucks, D.A. Water-quality in drip/trickle irrigation—A review. *Irrig. Sci.* **1991**, *12*, 187–234. [CrossRef]
27. Morales-Garcia, D.; Stewart, K.A.; Seguin, P.; Madramootoo, C. Supplemental saline drip irrigation applied at different growth stages of two bell pepper cultivars grown with or without mulch in non-saline soil. *Agric. Water Manag.* **2011**, *98*, 893–898. [CrossRef]
28. Barbosa, F.D.S.; Lacerda, C.F.D.; Gheyi, H.R.; Farias, G.C.; Silva Júnior, R.J.D.C.; Lage, Y.A. Yield and ion content in maize irrigated with saline water in a continuous or alternating system. *Ciência Rural* **2012**, *42*, 1731–1737. [CrossRef]
29. Huang, J.O.; Jin, M.G.; Li, X.W. Effects of alternative irrigation with brackish and fresh water on cotton yields and solute transport in soil. *Trans. CSAE* **2015**, *31*, 99–107.
30. Zhai, Y.; Yang, Q.; Hou, M. The effects of saline water drip irrigation on tomato yield, quality, and blossom-end rot incidence -a 3a case study in the south of china. *PLoS ONE* **2015**, *10*, e0142204. [CrossRef] [PubMed]
31. Hills, D.J.; Nawar, F.M.; Waller, P.M. Effects of chemical clogging on drip-tape irrigation uniformity. *Trans. ASAE* **1989**, *32*, 1202–1206. [CrossRef]
32. Aali, K.A.; Liaghat, A.; Dehghanisanij, H. The effect of acidification and magnetic field on emitter clogging under saline water application. *J. Agric. Sci.* **2009**, *1*, 132–141.
33. Jiang, S.; Fang, X.K.; Ye, C.H. Anti-clogging performance of drip Emitters under silt content water irrigation. *J. Irrig. Drain.* **2012**, *29*, 7–10. (In Chinese)
34. Lamn, F.R.; Ayars, J.E.; Nakayama, F.S. Microirrigation for Crop Production: Design, Operation and Management; Elservier BV: New York, NY, USA, 2007.
35. Liu, Y.F.; Wu, P.T.; Zhu, D.L.; Zhang, L.; Chen, J.Y. Effect of water hardness on emitter clogging of drip irrigation. *Trans. CSAE* **2015**, *31*, 95–100. (In Chinese)
36. Chen, J.; Qian, H.; Li, P.Y. Mixing precipitation of $CaCO_3$ in natural waters. *Water* **2013**, *5*, 1712–1722. [CrossRef]