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Elimination of Clogging of a Biogas Slurry Drip Irrigation System Using the Optimal Acid and Chlorine Addition Mode

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Abstract: As an emerging contaminant, the clogging substances of emitters in biogas slurry drip irrigation systems affect the efficient return and utilization of biogas slurry to the field to a great extent. This can be prevented using acid and chlorination as engineering measures. Through a hydraulic performance test and sampling detection and analysis, under the same acid addition conditions (pH = 5.5–6.0), three chlorine addition concentrations (0, 1–3, and 4–9 mg/L) and four chlorine addition cycles (6, 10, 14, and 20 days) were tested, aimed to clarify the influence of acid and chlorine addition parameters (chlorine adding cycle, chlorine adding concentration, etc.) on the anti-clogging performance of emitters in biogas slurry drip irrigation system. The results showed that compared with no acid and chlorination treatment (CK), only acid and a reasonable combination of acid and chlorination can significantly reduce the probability of serious and complete clogging of biogas slurry drip irrigation emitters, and they can stabilize the relative average flow of emitters by more than 75%. The measures of adding acid and chlorine change the distribution characteristics of clogging substances at the front and rear of the drip irrigation belt. Furthermore, they promote the migration of clogging substances to the rear of the drip irrigation belt, facilitating the clogging of emitters located thereat. The measures of acid addition and sequential addition of acid and chlorine significantly inhibit the growth of an extracellular polymer in the emitter, and the effect of inhibiting the increase in extracellular polymer concentrations is relatively poor when the acid addition period is excessively long or short. There exists a negative correlation between the extracellular polymer content in the emitter and the change in the emitter flow. Based on the obtained results, to ensure excellent anti-clogging performance of biogas slurry drip irrigation systems, for acid-only treatment measures, the acid dosing cycle is recommended to be 10 days. When acid and chlorination measures are implemented sequentially, the acid chlorination cycle is recommended to be 14 and 10 days when the chlorine concentration is 1–3 and 4–9 mg/L, respectively. This study has important scientific significance and practical value for the establishment of long-term operation management and protection technologies of large-scale biogas slurry drip irrigation systems.

Keywords: biogas slurry drip irrigation; emitter; acid and chlorine addition mode; anti-clogging performance; clogging change; extracellular polymer

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1. Introduction

In recent years, significantly large discharges of biogas slurry, one of the main forms of livestock and poultry manure resources, have severely damaged the ecological balance of water, soil, and the atmosphere around the world. Therefore, restriction of the large-scale development of aquaculture and sustainable development of the agricultural environment has become important research topics in most countries [1,2]. To solve the problem of biogas slurry absorption, in addition to converting biogas slurry into reclaimed water through sewage treatment technology, biogas slurry is returned to the field as an organic liquid fertilizer because it contains rich nutrient resources [3]. Therefore, biogas slurry returning technology is an important method for biogas slurry absorption, which will have great potential to reduce global warming and climate change. However, owing to the lack of reasonable biogas slurry returning technologies [4], traditional biogas slurry irrigation is not widespread [5]. With the large-scale promotion and application of water and fertilizer integration technologies [6], biogas slurry drip irrigation has become an important engineering carrier of biogas slurry returning technology; in other words, biogas slurry and clean water are diluted in a certain proportion and inputted into the field through a drip irrigation system. Thus, a new mode for the water and fertilizer integration technology is established under the biogas slurry drip irrigation system, which will achieve the dual goal of biogas slurry resource utilization and organic fertilizer instead of chemical fertilizer in a large range.

Although biogas slurry drip irrigation can serve as an important engineering carrier for biogas slurry return to the field, the safety, efficiency, and stability of the long-term operation of the drip irrigation system depend on the quality of irrigation water [7,8]. Studies have shown that drip irrigation systems based on unconventional water (sediment water and reclaimed water) are more vulnerable to damage than conventional drip irrigation systems [9,10]. As an unconventional water, the composition of biogas slurry is more complex, which puts forward higher anti-clogging requirements for the emitter, the core component of drip irrigation system. Furthermore, the long-term application of biogas slurry is more likely to cause clogging of the emitters in drip irrigation systems, resulting in a decline in their hydraulic performance [11].

Therefore, improving the anti-clogging performance of the emitters in biogas slurry drip irrigation systems has become necessary for the efficient return of biogas slurry to the field. In recent years, many related studies have been conducted. For example, Wang et al. clarified that the clogging substances composition of emitters in a biogas slurry drip irrigation system is a composite clogging of physics, chemistry, and biology [12]. Aiming at the biological clogging of an emitter, Xiao et al. [7] destroyed the interaction between microbial species through a nanobubble technology, thus reducing biofilm formation and improving the anti-clogging performance of the emitter. In addition, some scholars have also realized the biofilm control of emitters in biogas slurry drip irrigation systems through the use of an electromagnetic field [13]. However, in the above-mentioned studies, only the mechanism was explored, and feasible engineering measures were not determined. Currently, in an unconventional water (reclaimed water) drip irrigation system, an anti-clogging technical scheme based on acid and chlorination measures is formed [14]. Acid and chlorination treatment is more economical, practical, and efficient than other methods, and scholars have reported that low-concentration and long-time chlorination treatment can inhibit the biofilm better than high-concentration and short-time chlorination treatment [15]. Combined with emitter clogging and crop growth environment, a treatment mode of the chlorination frequency controlled at 4–8 weeks and the concentration range controlled at 2–10 mg/L was proposed [14]. The technical measures of regular acid and chlorine addition can effectively prevent serious clogging of emitters; however, as a new pollutant, the clogging substances of emitters in biogas slurry drip irrigation systems are obviously different from reclaimed water in their composition, which could lead to the undetected physical, chemical, or biological clogging. Some acid chlorine treatment may have a positive effect on the hydraulic performance of a biogas slurry drip irrigation system, but biogas slurry contains more suspended solids than reclaimed water. Too short chlorination cycle or too high chlorination concentration may also have some negative effects. Therefore, it is necessary to explore the influence mechanism of the acid and chlorine treatment on the anti-clogging performance of biogas slurry drip irrigation emitters and quantitatively determine technical treatment parameters. The study of the optimal adding mode of acid chlorine will provide an effective resource treatment scheme for the global excess biogas slurry, which is of great significance to promote the green development of global ecological agricultural environment.

The research purposes of this study include: (1) analysis of the influence of acid and chlorine combination measures on the anti-clogging performance of BS drip irrigation emitters; (2) determination of the optimal combination of parameters, such as acid and chlorine dosing cycle and chlorine dosing concentration, suitable for BS drip irrigation systems; and (3) investigation of the effect of combined acid and chlorine measures on the changes in the plugging substance and extracellular polymer substance (EPS) contents in the emitters.

2. Materials and Methods

2.1. Test Material

In this study, the widely used non-pressure compensation inner inlaid patch labyrinth channel emitters were selected (Figure 1). The flow specification is 1.38 L/h. After a clean water test [16], the manufacturing deviation coefficient of the emitter was 4.5%. According to the classification of the emitter quality standard [17], the emitter quality is "excellent." The original biogas slurry was provided by the biogas station of Beijing, Haihua Baili Energy Technology Co., Ltd. The test biogas slurry was filtered using a 120-mesh centrifuge and mixed with clean water at a ratio of 1:10. The background values of the original biogas slurry and the test biogas slurry are shown in Table 1. The test acid (pH = 5.5–6.0) is composed of clean water and a certain proportion of industrial hydrochloric acid (22%). The chlorine used in the test is a stable chlorine dioxide disinfectant (20,000 mg/L). Next, an activator (citric acid) is added at a proportion of 10:1 (V chlorine dioxide: V activator) and used after being allowed to stand for 30 min.

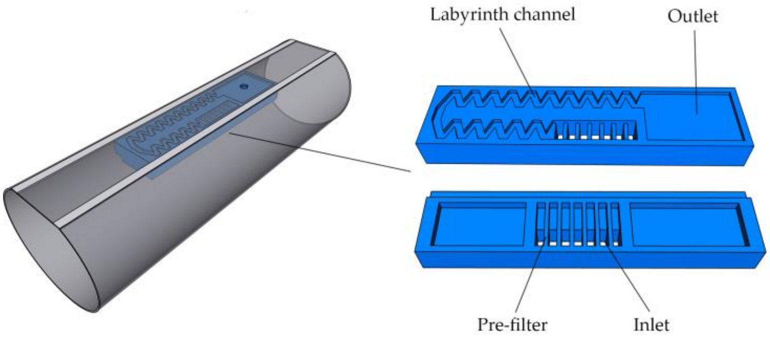

Figure 1. Model diagram of test emitter.

Table 1. Background values of original BS and test BS.

Original BS							Test BS			
EC (ms/cm)	pH	T/°C	SS (mg/L)	N (mg/L)	P (mg/L)	K (mg/L)	EC (ms/cm)	pH	T/°C	SS (mg/L)
11.87 ± 0.43	9. 15 ± 0.74	22 ± 1.2	1984 ± 87	2068 ± 216	337 ± 35	513 ± 32	2.20 ± 0.26	8.71 ± 0.69	21 ± 2.3	170 ± 36

2.2. Test Device

The test platform (Figure 2) mainly includes a horizontal centrifugal pump (rated head: 25 m, rated flow: 6 m^3/h), a mesh filter (120 mesh), a pressure gauge (measuring range: 0–0.25 MPa), a test BS tank (0.7 m^3), an acid chlorine tank (0.7 m^3), a mobile sampling platform, an inclined PVC water tank (9 m), an aluminum profile frame, and valve fittings. The test platform includes BS drip irrigation and acid and chlorine dosing systems, and the two systems operate at intervals and do not interfere with each other. The tanks are composed of a biogas slurry fertilizer tank (BS tank) and acid chlorine tank. A ball valve and check valve are set in front of each tank to ensure that there is no interaction between different water sources. The downstream of the check valve at the outlet of the centrifugal pump is equipped with a return valve. The filter is located between the return valve and the main valve, and the inlet of each branch pipe is equipped with a pressure-regulating valve. The working pressure of the drip irrigation system is always adjusted to 0.1 MPa to ensure that the test can be reproduced. The gate valves are set at the front and back of each drip irrigation belt to facilitate the control the addition of acid and chlorine to drip irrigation belt in batches according to the concentration of chlorine addition from small to large. The tail valve is equipped with BS valve and blowdown valve to control the return of biogas slurry and the discharge of sewage, respectively. The BS drip irrigation test system and the acid chlorine dosing system share the same irrigation pipe network and PVC water tank. The drip irrigation belt is laid in two layers, and each layer is laid with 13 drip irrigation belts. The drip irrigation belt of the first layer corresponds to different treatments, and the second layer is the repeat test of the first layer. Lateral line is 9 m. The laying spacing between emitters is 30 cm, and the water outlets of the emitters are arranged upward.

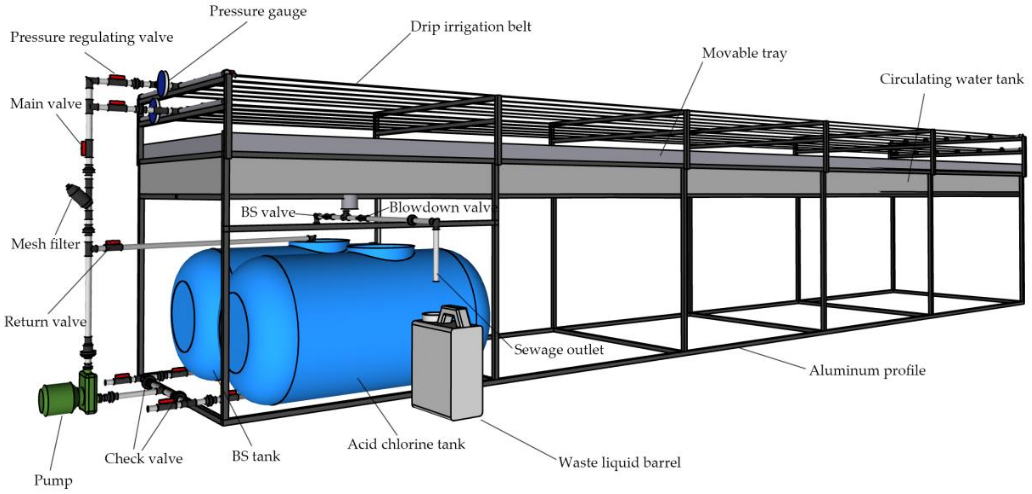

Figure 2. Schematic of test platform.

Therefore, BS drip irrigation is a circulating test system. BS is pressurized by a centrifugal pump, enters the drip irrigation belt through a filter, and finally returns to the test BS tank along the inclined tank. During the biogas slurry drip irrigation cycle test, it is necessary to close the valve of the acid chlorine tank and the blowdown valve of the tail valve, and open the valve of the BS tank and the BS valve of the tail valve. Similarly, acid and chlorine dosing is a one-way test system. Before the acid and chlorine dosing, the initial pH or the chlorine dosing concentration is configured in the acid and chlorine tank. The acid or chlorine solution is pressurized into the drip irrigation belt through the centrifugal pump and finally flows out from the sewage outlet along the inclined tank. When adding acid chlorine, it is necessary to close the valve of BS tank and the BS valve of the tail valve. At the same time, open the valve of the acid chlorine tank and the blowdown valve of the tail valve. Before switching the two systems, clean the PVC water tank with clean water and drain all the sewage through the blowdown valve.

2.3. Acid and Chlorine Treatment Design

The duration of the addition of acid and chlorine in the test was set to 60 min and 30 min, respectively. The purpose of acid treatment is not only to relieve clogging, but also provides acidic conditions for chlorine treatment (Song et al., 2017) to enhance the effectiveness of chlorine dioxide. Therefore, the acid addition concentration and the time of each test treatment were kept the same, and the acid addition cycle was the same as that of the chlorine addition. The chlorine treatment was conducted after the acid treatment. Chlorine treatment is intended as a predictive measure to provide the possibility of biofilm destruction. The test platform ran for 12 h from 7:00 to 19:00 every time in a two-day cycle (one day of system operation and one day of shutdown). The test started on

24 June 2021 and ended on 2 September 2021. The frequency of the acid and chlorination treatment was set with four gradients: three cycles (every 6 days), five cycles (every 10 days), seven cycles (every 14 days), and ten cycles (every 20 days). Each cycle had three chlorination concentrations: no chlorination (0 mg/L), low concentration (1–3 mg/L), and high concentration (4–9 mg/L). A drip irrigation belt without acid or chlorine was selected as the control treatment (CK). The design of the acid and chlorine treatment is presented in Table 2.

Table 2. Acid chlorination treatment design.

Treatment	**Acid**		**Chlorine**		**Cycle**
	pH	**Duration (min)**	**Concentration (mg/L)**	**Duration (min)**	
NC3	5.5–6.0	60	-	-	3
NC5	5.5–6.0	60	-	-	5
NC7	5.5–6.0	60	-	-	7
NC10	5.5–6.0	60	-	-	10
LC3	5.5–6.0	60	1–3	30	3
LC5	5.5–6.0	60	1–3	30	5
LC7	5.5–6.0	60	1–3	30	7
LC10	5.5–6.0	60	1–3	30	10
HC3	5.5–6.0	60	4–9	30	3
HC5	5.5–6.0	60	4–9	30	5
HC7	5.5–6.0	60	4–9	30	7
HC10	5.5–6.0	60	4–9	30	10
CK	-	-	-	-	-

2.4. Emitter Performance Index

2.4.1. Emitter Flow and Relative Average Discharge (Dra)

Several measuring catch-cans were set on the test platform to calculate the flow of the sample emitters on the drip irrigation belt using the weighing method. Under each treatment, 15 sample emitters were evenly selected from the front, middle, and back of each drip irrigation belt to measure the flow of the emitters and calculate the Dra [18]. The distribution positions of the sample emitters to be measured under each treatment were the same along the length of the drip irrigation belt. The test platform ran for 384 h for a total of 32 samples. The sampling time was fixed at 17:30–19:00. The sampling time for a single emitter was 3 min. The Dra of the emitters in the drip irrigation belt was calculated using Equation (1):

$$\mathrm{Dra} = 100\frac{\sum_{i=1}^{n} q_i^t}{n\overline{q^0}} \tag{1}$$

where $\overline{q^0}$ represents the average value of the flow of each emitter on the drip irrigation belt under the clear water test (L/h), q_i^t represents the flow of the ith emitter at time t under BS drip irrigation (L/h), and n is the total number of emitters on the drip irrigation belt.

2.4.2. Clogging Rate of Emitters

Generally, the percentage of emitters with a certain clogging degree in the total number of emitters is defined as the clogging rate of emitters under this clogging degree. The flow of a single emitter accounting for more than 95% of the initial flow is defined as non-clogging; 80–95%, as slight clogging; 50–80%, as general clogging; 20–50%, as severe clogging; and <20%, as complete clogging [19]. The clogging rate of the emitters with different degrees of clogging is calculated using Equation (2):

$$\mathrm{N} = 100\frac{n_1}{n} \tag{2}$$

where n_1 indicates the number of emitters meeting a certain degree of clogging, N represents the non-clogging rate of emitters (Dra $\geq$ 95%) or the clogging rate of emitters of different degrees (Dra < 95%), and n is the total number of emitters on the drip irrigation belt.

2.5. Dry Weight of Clogging Substances

When the CK Dra changed to 95% (early stage of operation) and 65% (late stage of operation), for each test treatment, the drip irrigation belt containing three emitters was cut at the front, middle, and rear of its corresponding drip irrigation belt. In this manner, the dry weight of the plugging substances was determined (including plugs in the emitters and sediments in the pipe wall of the drip irrigation belt). After drying the cut drip irrigation belt, the dry weight (S_1) was measured on a high-precision electronic scale (manufacturer: METTLER TOLEDO, Switzerland; model: ME104E; accuracy: 0.0001 g). Subsequently, the impurities on the pipe wall of the drip irrigation belt were cleaned and peeled off. The emitter was then cut with a knife and placed in a self-sealing bag with 10 mL of pure water. Next, it was placed into an ultrasonic instrument (manufacturer: ULTRASONIC CLEANER, China; model: JT-410HT) for a 40 min ultrasonic treatment. The clogging substances in the emitter were cleaned. Finally, the pipe wall of the drip irrigation belt and the emitter were dried after cleaning, and the dry weight was measured (S_2). The sum of the dry weight of the clogging at the front, middle, and rear emitters of the drip irrigation belt and the sediment in the capillary drip irrigation belt was calculated using Equation (3), which is collectively referred to as the dry weight of the clogging substances (DW).

$$\mathrm{DW} = S_1 - S_2 \tag{3}$$

where S_1 represents the total dry weight of the emitter and its drip irrigation belt, emitter plug, and sediment in the drip irrigation belt (mg); S_2 represents the dry weight of the emitter and its drip irrigation belt (mg); and DW is the weight of the plug in the emitter and the sediment in the drip irrigation belt after drying (mg).

2.6. EPS in the Emitter

At the end of system operation, for each test treatment, three emitters were cut out before, during, and after the corresponding drip irrigation belt to measure the EPS content (C) in the plug in the emitters. The emitter and its pipe wall were placed in 10 mL test tubes, and ultrasonic treatment at a temperature of 70 °C for a duration of 40 min was carried out in the ultrasonic instrument. Next, the EPS was evenly extracted by mixing with a vortex oscillator (manufacturer: SCILOGEX, America; model: MXS). The polysaccharide concentration (C_1) was determined at 490 nm using a UV spectrophotometer, with reference to the phenol sulfuric acid method [20]. The protein concentration (C_2) was measured at 500 nm according to the Folin phenol reagent method [21]. The sum of the polysaccharide concentration and protein concentration represents the EPS concentration:

$$\mathrm{C} = C_1 + C_2 \tag{4}$$

where C represents the EPS concentration of each treatment group (mg/L), C_1 represents the polysaccharide concentration of the sample (mg/L), and C_2 represents the protein concentration of the sample (mg/L).

3. Results

3.1. Variation Law of Emitter Dra

The change in the emitter Dra corresponding to each treatment with the operation time under the combination of different chlorination concentrations and acid chlorination cycle parameters is shown in Figure 3. From Figure 3a, it can be seen that the Dra of NC3, NC5, NC7, and NC10 at the end of the test are 85%, 95%, 85%, and 95%, respectively. These treatments increased significantly by 30.8–46.2% compared with the control group (Dra = 65%). The lowest Dra of 81% is noted for NC3. The Dra of the emitters treated with NC5 remained above 95% during the test, which was the best of all treatments with only acid and no chlorine. Regarding the sequential addition of acid and chlorine, the emitter Dra was 76%, 85%, 92%, and 69% at the end of system operation (Figure 3b,c) for low chlorine concentrations of LC3, LC5, LC7, and LC10, respectively (Figure 3b). Hence, the LC7 treatment performed best. At the end of system operation, the Dra of emitters HC3, HC5, HC7, and HC10 for the high-concentration chlorination treatment (Figure 3c) were 59%, 95%, 88%, and 75%, respectively, among which HC5 treatment performed best. Therefore, based on the premise of acid addition, different combinations of chlorination concentrations and chlorination cycle parameters have different effects on the Dra of the emitters. Among them, the Dra of the emitters under HC3 treatment is 6% lower than that under CK, which indicates that, under the condition of high-concentration chlorination, excessive chlorination aggravates the clogging of the emitters to a certain extent. Moreover, Figure 3 shows that LC3 and HC3 decrease by 9.5% and 29.8%, respectively, compared with NC3. Furthermore, LC7 and HC7 increase by 9.5% and 4.8%, respectively, compared with NC7, this shows that under the condition of sequential acid and chlorine addition, the chlorination cycle is too short, which reduces the anti-clogging performance of the emitter. Additionally, compared with only the acid treatment, matching the appropriate chlorination cycle and chlorine concentration after acid addition can further improve the anti-clogging performance of the biogas slurry drip irrigation system. In general, compared with the treatment without acid and chlorine, the decrease rate of Dra of the emitters with time is significantly reduced under adding acid only or adding acid and chlorine sequentially. At the end of the test, the relative average flow rate of the emitters in most treatments (except HC3 and LC10) was more than 75%, and there was no significant clogging [16].

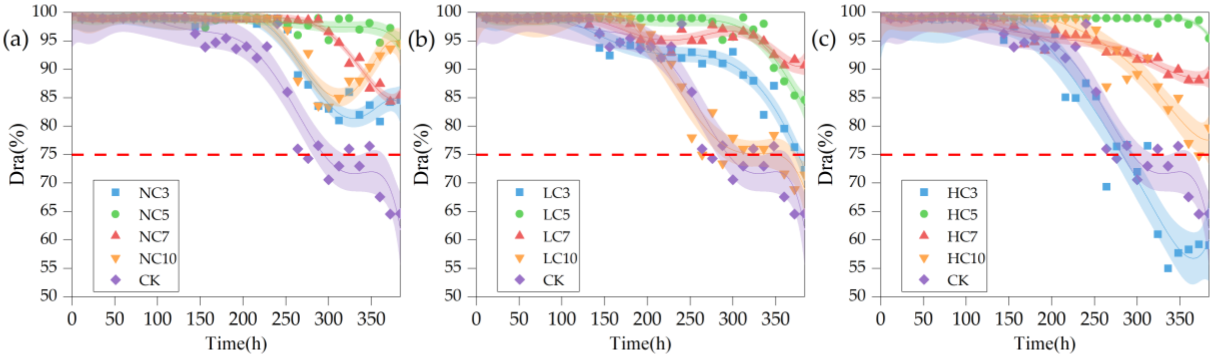

Figure 3. Dynamic changes in Dra of emitters under different combinations of chlorination concentrations and chlorination cycle parameters. (**a**) No chlorination (0 mg/L). (**b**) Low-concentration chlorine (1–3 mg/L). (**c**) High-concentration chlorine (4–9 mg/L). Note: color band is the 95% confidence band of sample data fitting

3.2. Distribution Characteristics of Emitter Clogging along Drip Irrigation Belt Direction

The distribution characteristics of the emitter clogging along the direction of the drip irrigation belt in each treatment are shown in Figure 4. In general, whether CK or other acid and chlorine treatment is performed, the proportion of slight clogging and above in the emitter at the back of the drip irrigation belt is greater than that in the front and middle of the drip irrigation belt. Furthermore, the proportion of serious or complete clogging of the emitters at the back exceeds that at the front and middle. Compared with CK, different acid and chlorination cycle and chlorine concentration combinations changed the temporal and spatial distribution characteristics of the clogging of the emitters at the front, middle, and rear of the drip irrigation belt. In terms of time, it causes delays when the emitter is clogged for the first time. In terms of space, at the end of system operation, the proportion of the emitters with serious or complete clogging at the back of the drip irrigation belt in CK is 13%. Meanwhile, the proportion of the emitters with serious or complete clogging at the back of the drip irrigation belt in most other treatments is less than that in CK. For example, under NC5 and LC7, the proportion of the emitters with serious or complete clogging at the back of the drip irrigation belt is 0% and 7%, respectively. Meanwhile, for HC3 and LC10, the proportion of the emitters with serious or complete clogging at the back of the drip irrigation belt reaches 27% and 20%, respectively, which is significantly higher than that in CK.

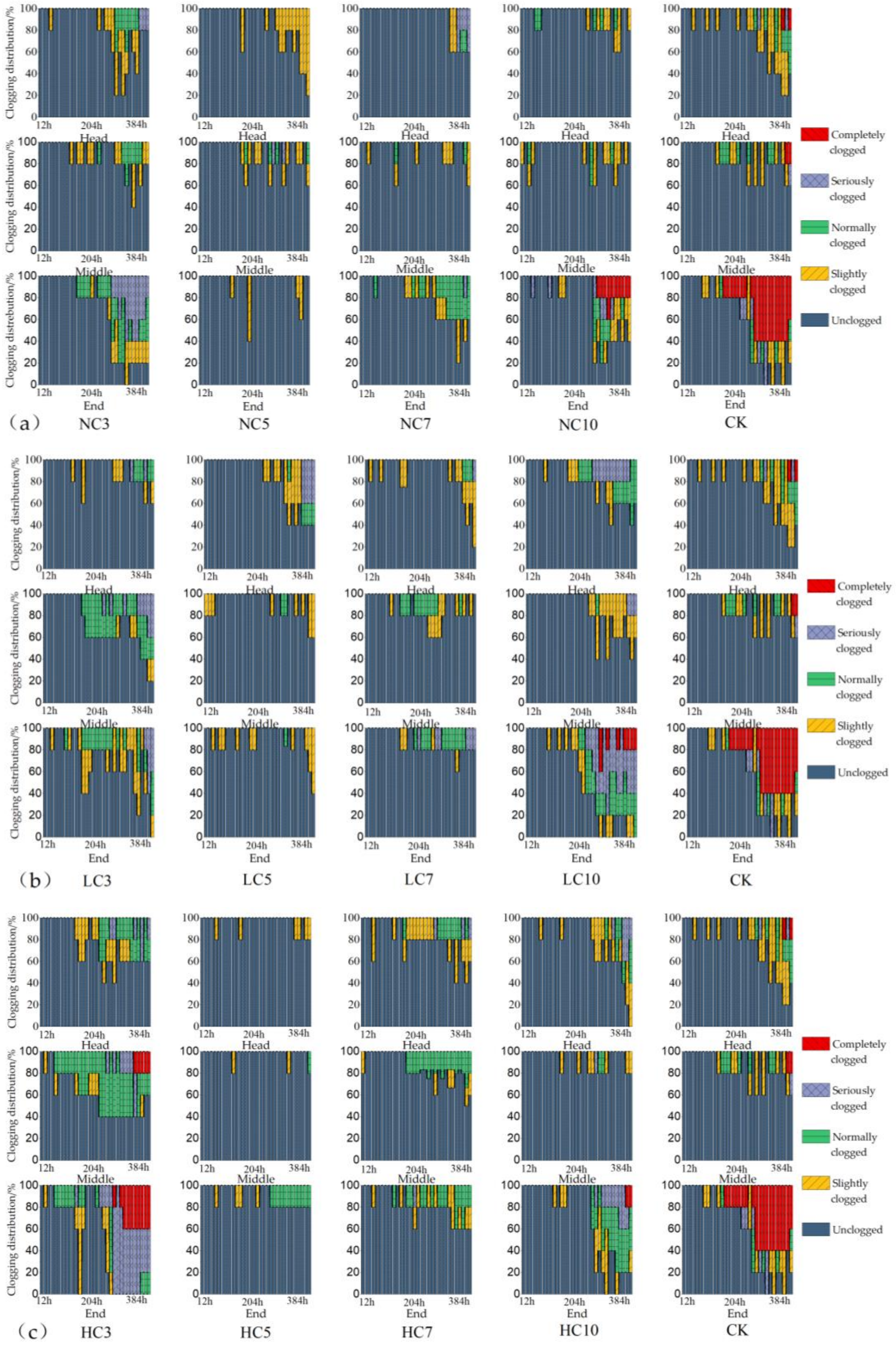

Figure 4. Dynamic change in emitter clogging rate under different combinations of chlorination cycle and chlorination concentration parameters: (**a**) No chlorination (0 mg/L). (**b**) Low-concentration chlorine (1–3 mg/L). (**c**) High-concentration chlorine (4–9 mg/L).

For the treatments with acid and no chlorine (Figure 4a), at the end of system operation, the average unclogging rates of the emitters at the front, middle, and rear of drip irrigation belts are 60%, 75%, and 55%, respectively. For all treatments with acid and chlorine concentrations of 1–3 mg/L (Figure 4b), at the end of system operation, the average unclogging rates of the emitters at the front, middle, and rear of the drip irrigation belt are 45%, 60%, and 30%, respectively. For treatments with acid and chlorine concentrations of 4–9 mg/L (Figure 4c), at the end of system operation, the average unclogging rates of the emitters at the front, middle, and rear of the drip irrigation belt are 50%, 70%, and 40%, respectively. For CK, at the end of system operation, the non-clogging rates of the emitters at the front, middle, and rear are 40%, 60%, and 20%, respectively. These values are clearly less than those for the treatment with acid alone or the combination of acid and chlorine. These results show that the treatment with acid and chlorine generally reduces the probability of clogging of the emitters in the BS drip irrigation system.

3.3. Dry Weight Distribution Characteristics of Clogging in Drip Irrigation Belt

Table 3 indicates that the combination of different chlorination concentrations and acid chlorination cycles has a significant impact on the dry weight distribution characteristics of the clogging. For the treatment with acid and without chlorine, whether in the early stage of the test (Dra = 95%) or at the end of the test (Dra = 65%), compared with CK treatment, it generally reduces the clogging content in the front of the drip irrigation belt and increases the clogging content in the rear of the drip irrigation belt. For example, at the end of the test (Dra = 65%), the dry weight of clogging in front of drip irrigation belts NC3, NC5, NC7, and NC10 decreased significantly by 73.36%, 12.09%, 75.59%, and 56.16%, respectively ($p < 0.05$). Compared with CK, the dry weight of clogging at the back of the drip irrigation belt increased generally, and the dry weight of clogging at the back of NC3, NC5, and NC7 drip irrigation belt increased significantly by 58.17%, 55.23%, and 32.67%, respectively ($p < 0.05$). When the chlorine concentration was 1–3 mg/L, the results in the early stage of the test (Dra = 95%) showed that the dry weight of the front clogging of the LC3, LC5, LC7, and LC10 drip irrigation belts was significantly reduced by 29.32%, 48.59%, 59.44%, and 20.08%, respectively, compared with CK ($p < 0.05$). In addition, the dry weight of the rear clogging was significantly increased by 138.10%, 38.10%, 27.38%, and 139.68%, compared with CK ($p < 0.05$). This also shows that low-concentration chlorination treatment can significantly reduce the clogging content at the front of the drip irrigation belt and significantly increase the clogging content at the back of the drip irrigation belt. At the end of system operation (Dra = 65%), the dry weight of the clogging in front of the LC3 and LC10 drip irrigation belts increased by 10.9% and 93.6%, respectively, compared with CK ($p < 0.05$). Meanwhile, the dry weight of the clogging in front of the LC5 and LC7 drip irrigation belts decreased by 71.56% and 40.52%, respectively, compared with CK ($p < 0.05$). Under low-concentration chlorination, different chlorination cycles generally increased the concentration of the clogging substances at the back of drip irrigation. When the chlorine concentration was 4–9 mg/L, the results in the early stage of the test (Dra = 95%) showed that the dry weight of the HC3, HC5, HC7, and HC10 front clogging decreased by 19.28%, 14.46%, 44.98%, and 42.97%, respectively ($p < 0.05$). Furthermore, the dry weight of the rear clogging increased by 309.13%, 105.56%, 92.86%, and 194.05%, respectively ($p < 0.05$). The dry weight of the clogging at the back of the drip irrigation belt under the HC3 treatment was three times that under CK. At the end of operation (Dra = 65%), under high-concentration chlorination, different chlorination cycles significantly reduced the clogging content at the front of the drip irrigation belt ($p < 0.05$) and increased the clogging content at the rear of the drip irrigation belt to varying degrees.

Table 3. Dry weight distribution of the emitter clogging in different periods (mg).

Treatment	Dra = 95%				Dra = 65%			
	Head	**Middle**	**End**	**Mean Value**	**Head**	**Middle**	**End**	**Mean Value**
NC3	15.5 e	9.4 g	38.7 ef	21.2 f	10.8 g	42.1 b	48.4 b	33.8 d
NC5	13.8 f	24 de	37.1 f	25 e	37.1 d	32.7 cd	47.5 b	39.1 c
NC7	26.6 a	28.1 c	42 e	32.2 cd	10.3 g	30.6 d	40.6 c	27.2 fg
NC10	20.2 c	22.4 ef	24.6 h	22.4 ef	18.5 f	25.7 e	31.8 fgh	25.3 gh
LC3	17.6 d	20.6 f	60 c	32.7 cd	46.8 b	50.2 a	29.5 h	42.2 b
LC5	12.8 f	23.1 def	34.8 fg	23.6 ef	12 g	6.7 g	32.9 efgh	17.2 j
LC7	10.1 g	30 bc	32.1 g	24.1 ef	25.1 e	9.6 f	37 cd	23.9 hi
LC10	19.9 c	20.9 f	60.4 c	33.7 bc	81.7 a	34.2 c	36.4 de	50.8 a
HC3	20.1 c	54.6 a	103.1 a	59.3 a	24.9 e	27.4 e	35.4 def	29.2 ef
HC5	21.3 c	30.9 b	51.8 d	34.7 bc	25.2 e	4 h	34.3 defg	21.2 i
HC7	13.7 f	29.8 bc	48.6 d	30.7 d	18.5 f	34.2 c	37.9 cd	30.2 e
HC10	14.2 ef	21.3 f	74.1 b	36.5 b	12.6 g	44.6 b	75.6 a	44.3 b
CK	24.9 b	25 d	25.2 h	25 e	42.2 c	30.5 d	30.6 gh	34.4 d

Column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

3.4. Effect of Acid and Chlorine Addition on EPS Content in Emitters

The EPS content at the end of system operation (Dra = 65%) in the emitters at different positions of each treatment drip irrigation belt is listed in Table 4. The mean EPS content in the emitters under CK was 1.61 mg, and the EPS content in the emitters of other treatments decreased significantly by 14.70%–66.74% ($p < 0.05$). The EPS content in the emitters in CK decreased gradually along the direction of the drip irrigation belt, and the EPS content in the emitters at the end of the drip irrigation belt decreased by 47.3%, compared with the front end. For the treatment with acid and without chlorine, the EPS content in the emitter at the front of the NC3, NC5, NC7, and NC10 drip irrigation belts was significantly reduced by 48.96%, 81.48%, 61.18%, and 49.58%, respectively, compared with CK ($p < 0.05$). Furthermore, the EPS content in the emitter at the end of the drip irrigation belt was increased by 34.40%, 55.75%, −4.60% and −1.70%, respectively, compared with the CK values. The EPS content in the emitter at the end of the drip irrigation belt was significantly higher than those at the middle and front of the drip irrigation belt. For each treatment with acid and chlorine, except for at the end of the drip irrigation belt in HC10 treatment, the EPS content in the emitters at the front and rear of the drip irrigation belt was significantly lower than that in CK. Among them, the reduction range at the front of the drip irrigation belt was 36.3–79.6% ($p < 0.05$), and the reduction range at the rear of the drip irrigation belt was 9.6–62.3% ($p < 0.05$). Overall, the EPS content in the emitter at the end of the drip irrigation belt was significantly lower than that at the middle and front. In addition, the average EPS content in the emitters treated with HC5, HC7, and HC10 was significantly increased by 16.6%, 78.5%, and 12.0%, respectively, as compared with LC5, LC7, and LC10 treated with low concentrations of chlorine ($p < 0.05$). However, the average EPS content in the HC3-treated emitters was significantly reduced by 46.7%, compared with LC3 treatment ($p < 0.05$). This indicates that the increase in the chlorination concentration may promote the secretion of EPS, but chlorination filtration is frequent, that is, the chlorination cycle is too short, and higher chlorination concentration may inhibit or decompose the formation of extracellular polymers, which further illustrates the importance of the optimal combination of chlorination concentration and chlorination cycle.

To explore the EPS content–Dra relationship in the emitters, a correlation between the average EPS content and the Dra in the emitters at the end of system operation was established, as shown in Figure 5. As shown in the figure, there exists a significant correlation between the EPS content and the Dra content in the emitter within a certain range. With the increase in extracellular polymer content in the emitters, the relative average flow of the emitters generally shows a trend of first stabilizing and then decreasing, This shows that the content of the extracellular polymer will not have a great impact on the change in emitter flow in a certain range, but with the further increase in the content of the extracellular polymer in the emitter, the relative average flow of the emitter will be significantly reduced, resulting in the occurrence of emitter clogging.

Table 4. Distribution of extracellular polymer content in each treatment along the drip irrigation belt direction at the end of system operation.

Treatment	EPS (mg)			
	Head	**Middle**	**End**	**Mean Value**
NC3	1.02 d	0.59 d	1.41 c	1.01 de
NC5	0.37 f	0.14 e	1.64 b	0.71 h
NC7	0.77 e	0.62 d	1 def	0.8 fg
NC10	1 d	0.88 c	1.03 de	0.97 e
LC3	1.17 c	1.16 b	0.95 ef	1.09 d
LC5	0.71 e	0.81 c	0.67 h	0.73 gh
LC7	0.41 f	0.8 c	0.4 i	0.54 i
LC10	1.01 d	1.82 a	0.85 g	1.23 c
HC3	0.71 e	0.64 d	0.4 i	0.58 i
HC5	0.78 e	1.13 b	0.64 h	0.85 f
HC7	1.27 b	0.67 d	0.93 fg	0.96 e
HC10	1.28 b	0.81 c	2.03 a	1.37 b
CK	1.99 a	1.79 a	1.05 d	1.61 a

Column means followed by the same letter are not significantly different at the $P_{0.05}$ level.

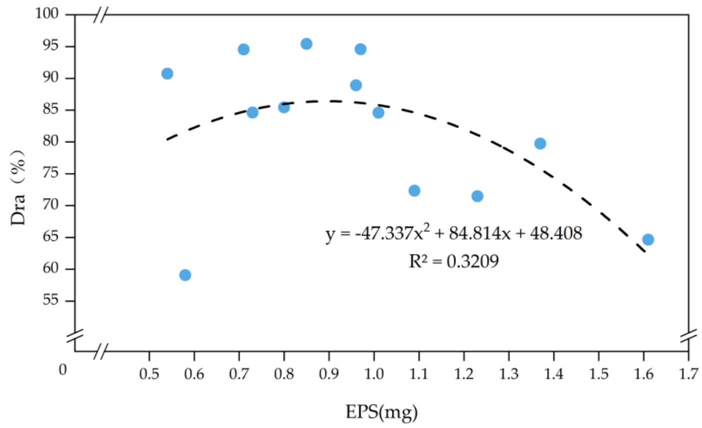

Figure 5. Correlation between Dra rate of emitters under each treatment and extracellular polymer content at the end of system operation.

For further exploring the influence of changes in the acid and chlorination cycle on the relative flow of the emitters and the change in the EPS content in the emitters, CK was regarded as the longest acid and chlorination cycle. The relationship between the acid and chlorination cycle and the change in the EPS content in the emitter Dra was established, as shown in Figure 6. As is evident from the figure, there exists a good correlation between the acid and chlorine dosing cycle and the changes in the Dra and EPS content in the emitters (regression coefficient, R^2, is between 0.72–0.98). When acid was added without chlorine (Figure 6a), with the extension of the acid addition cycle, the Dra of the emitters increased slowly and then decreased rapidly, whereas the EPS content in the emitters decreased first, tended to be stable, and then increased rapidly. For each sequential acid and chlorine addition (Figure 6b,c), with the extension of the acid and chlorine addition cycle, the emitter Dra first increased, tended to be stable, and then decreased rapidly. With the addition of acid and low concentrations of chlorine, the EPS content in the emitter also decreased first, tended to be stable, and then increased rapidly. For the treatment with acid and high concentrations of chlorine, the EPS content in the emitters increased rapidly with the extension of the acid and chlorine addition cycle. Overall, large Dra and low EPS content in the emitter reduce the risk of emitter clogging. According to the analysis results in Figure 6, excessively short or long acid and chlorine dosing cycles or the absence of acid and chlorine are not conducive to alleviating the clogging risk of the emitters.

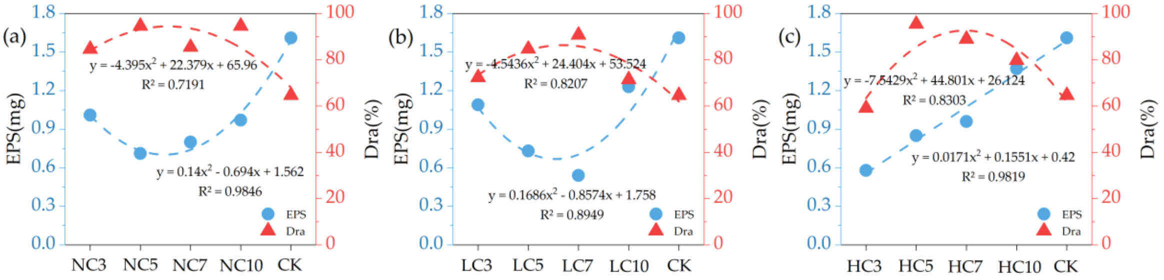

Figure 6. Changes in Dra rate and extracellular polymer content of emitters under different chlorination concentrations at the end of system operation. (**a**) No chlorination (0 mg/L). (**b**) Low-concentration chlorine (1–3 mg/L). (**c**) High-concentration chlorine (4–9 mg/L).

4. Discussion

4.1. Effect of Acid and Chlorine Addition on Anti-Clogging Performance of Emitters

The results of this study show that different chlorination concentrations and acid chlorination cycle parameter combinations have a significant impact on the anti-clogging performance of emitters in the BS drip irrigation system. Overall, the measures of adding acid only and adding acid and chlorine sequentially significantly delayed the time of emitter clogging and reduced the probability of serious and complete emitter clogging. This is similar to the research results of Hao et al. [22] in the reclaimed water drip irrigation system. They found that all chlorination measures significantly improved the anti-clogging performance of emitters. In addition, based on the biogas slurry drip irrigation system, this study defined the measures of adding acid and no chlorine, which significantly slowed down the clogging process of emitters and the probability of serious and complete clogging. Compared with CK, the Dra values of the emitters were significantly improved. The addition of acid without chlorine generally reduced the content of clogging substances at the front of the drip irrigation belt and increased the content of clogging substances in the rear of the drip irrigation belt. These results indicate that the acid treatment promoted some clogging substances at the front of the drip irrigation belt to migrate to the rear of the drip irrigation belt with the water flow. This is also one of the main reasons why the proportion of serious and complete clogging of the emitter in the rear of the drip irrigation belt is greater than that at the front and middle. Zhou et al. [23] also found that the content of clogging at the back of the drip irrigation belt was large and that emitters with serious clogging first appeared at the back of the drip irrigation belt [19]. As the acid addition period changed from long to short, the content of clogging at the back of the drip irrigation belt showed a gradually increasing trend (Table 3). This indicates that, the higher the acid addition frequency, that is, the shorter the acid addition period, the greater is the amount of clogging that migrates to the back of the drip irrigation belt; this is more likely to cause serious or even complete clogging of the emitter at the back of the drip irrigation belt, this conclusion is similar to the research results of Zhou et al. [23], who believe that high-frequency irrigation increases the risk of clogging of emitters. The test results also show that NC3 has the largest Dra drop among all the acid and non-chlorination treatments. When the acid addition cycle was too long, the Dra of the emitters also decreased rapidly (Figure 6), and the proportion of serious or complete clogging of the emitters at the back of the drip irrigation belt was the highest. This shows that the acid addition cycle should not be too short, but the interval should not be too long. Further analyses based on the test results showed that, when only acid addition measures were adopted and the acid addition period was 10 days, excellent anti-clogging performance of the BS drip irrigation system could be more effectively guaranteed.

With the sequential addition of acid and chlorine, the combination of the chlorine concentration and acid and chlorine addition cycle also had a significant impact on the anti-clogging performance of the emitters. When acid was added and the chlorine concentration was 1–3 mg/L, the emitter Dra decreased with the shortening of chlorination cycle. When the acid chlorination cycle was too long, the emitter Dra decreased significantly (Figures 3b and 6b). This shows that under the condition of low-concentration chlorination, the acid chlorination cycle should not be too short or too long. When acid was added and the chlorine concentration was 4–9 mg/L, the emitter Dra decreased with the extension of the chlorination cycle. If the acid and chlorine addition cycle was too short, the Dra also decreased significantly (Figures 3c and 6c), and the proportion of the emitters with serious or complete clogging was the highest, such as in the HC3 treatment. This shows that under the condition of high-concentration chlorination, the acid and chlorine dosing cycle should also not be too short or too long. This conclusion is different from the research results of Hao et al. [22]. They found that the proportion of emitter clogging increases with the extension of the chlorination cycle, which may be related to the fact that the content of suspended solids in reclaimed water is significantly lower than that in biogas slurry. Compared with CK, the measures of the acid and chlorine addition also reduced the content of clogging at the front of the drip irrigation belt and increased the content of clogging at the rear of the drip irrigation belt (Table 3). This led to a greater proportion of clogging of the emitters at the rear of the drip irrigation belt than those at the front and middle. Zhang et al. [24] also found a similar experimental phenomenon, that is, there is a negative correlation between the dry weight of the clogging and the relative average flow of the emitter. For each treatment with sequential acid and chlorine addition, the higher the chlorine concentration, the greater the content of clogging at the rear. This indicates that the greater the chlorine concentration, the more evident the effect of promoting the migration of clogging to the middle and rear drip irrigation belts. By contrast, compared with acid treatment alone, partial acid and chlorine treatment showed less clogging and a more stable flow change. For example, HC5 treatment was better than NC5 treatment, and HC7 and LC7 treatments were better than NC7 (Figure 3). These results show that matching appropriate chlorination cycle and chlorination concentration after acid addition can further improve the anti-clogging performance of BS drip irrigation systems. Using these test results, we can further confirm that, under the sequential addition of acid and chlorine, the appropriate acid and chlorine addition period is 10–14 days. When the chlorine addition concentrations are 1–3 and 4–9 mg/L, the optimal acid and chlorine addition periods are 14 and 10 days, respectively.

4.2. Effect of Acid and Chlorine Addition on EPS Content in Emitters

Previous research has shown that, in drip irrigation, the growth of microorganisms affects the anti-clogging performance of emitters to a certain extent [25]. Microorganisms in biogas slurry secrete viscous EPS [26], which enables them to adhere to emitters or capillaries, and continuously absorb nutrients from biogas slurry through these extracellular polymers to maintain their own life activities. At the same time, because there are many suspended solids in the biogas slurry, the particles or aggregates may form larger clogging substances in the emitter or capillary under the adhesion of EPS [27,28]. The measures of adding acid and chlorine can significantly inhibit the growth of microorganisms [15], so as to reduce the content of EPS. From the research results, only adding acid and sequentially adding acid and chlorine significantly reduced the content of the extracellular polymer in the emitters; therefore, the risk of the emitters clogging is reduced. Compared with CK, adding acid alone significantly reduced the EPS content in the emitter at the front of the drip irrigation belt ($p < 0.05$) but sequentially increased the EPS content in the emitter at the rear. This may be due to the relatively weak destructive effect of adding acid alone on microorganisms and may not completely destroy the growth of microorganisms through dehydration [29]. Nevertheless, it promotes the migration process of some EPS from the front to the rear of the drip irrigation belt [30]. In addition, the acid addition period affects the decomposition or migration of EPS in the drip emitter. With the addition of acid without chlorine, the average EPS content in the emitter increases with the acid addition period (Table 4 and Figure 6a). However, the EPS content increases significantly when the acid addition period is too short, such as during the NC3 treatment. This shows that the effect of excessively long or short acid addition periods on inhibiting the increase in EPS content is relatively poor.

With the sequential addition of acid and chlorine, the EPS content in the emitters at the front and rear of the drip irrigation belt was significantly reduced ($p < 0.05$). It can be seen that further chlorination measures under the condition of acid addition can significantly affect the change in extracellular polymer content in the emitters at the front and rear of the drip irrigation belt, and can effectively avoid the accumulation of EPS in the emitters at the rear of the drip irrigation belt. Under both low- and high-concentration chlorination, the average EPS content in the emitter gradually increased with the extension of the acid chlorination cycle (Table 4, Figure 6b,c). This shows that the effect of long acid chlorination cycles on the inhibition of microbial growth is relatively poor, resulting in an increase in the EPS content in the emitter [23]. When the period of acid and chlorine addition was too short, for example, when the period was 6 days, the EPS content increase in the emitter was significant under the condition of low-concentration chlorination ($p < 0.05$). This result shows that under the condition of low-concentration chlorination, more frequent acid and chlorine addition measures are not conducive to reducing the content of EPS in the emitter. Under the condition of high-concentration chlorination, when the acid chlorination cycle is 6 days, such as in the HC3 treatment, although the EPS content in the emitter is low, the emitter Dra decreases significantly, which is also not suitable. When the acid chlorination cycle is 10–20 days, compared with the low-concentration chlorination measures (1–3 mg/L), the high-concentration chlorination measures (4–9 mg/L) significantly increased the EPS content in the emitters ($p < 0.05$). This result indicated that an increase in the chlorination concentration may promote the secretion of EPS [31]. This is likely to increase the EPS content in the emitters further under long-term application. When the EPS content in the emitter reaches a certain critical value, the emitter flow decreases rapidly with the increasing EPS content in the emitter (Figure 5), resulting in serious or even complete clogging of the emitter.

Based on the afore-discussed analysis, to ensure excellent anti-clogging performance of the BS drip irrigation system, when only acid and chlorine addition measures are adopted, the acid addition period is recommended to be 10 days. When the acid and chlorine addition measures are adopted sequentially and the chlorine addition concentration is 1–3 mg/L, the acid and chlorine addition period of 14 days is appropriate. When the chlorine addition concentration is 4–9 mg/L, an acid and chlorine addition period of 10 days is sufficient. Based on the research findings, with the long-term application of high concentrations of chlorine (4–9 mg/L) every 10–20 days, the EPS content in the emitters may increase. Determining whether the risk of emitter clogging increases when extending the operation time of BS drip irrigation systems requires further research and verifications. From the current research results, compared with the measures of CK and acid addition alone, under the condition of synchronous acid and chlorine addition, a reasonable combination of the acid and chlorine addition cycle and chlorine addition concentration can effectively improve the anti-clogging performance of the BS drip irrigation system.

5. Conclusions

The influence of combined acid and chlorine addition measures on the anti-clogging performance of the emitters of the BS drip irrigation system was revealed, and the following conclusions were drawn:

(1) Compared with CK, acid addition alone and a reasonable combination of acid and chlorine can significantly reduce the probability of serious or complete clogging of BS drip irrigation emitters. A reasonable combination of the acid and chlorine dosing

cycle and chlorine dosing concentration can effectively improve the anti-clogging performance of the BS drip irrigation system, compared with acid dosing alone.

(2) Acid and chlorination measures promote the migration of clogging substances to the rear of the drip irrigation belt, resulting in increased clogging of the emitters at the rear of the drip irrigation belt. Compared with low-concentration chlorination under the same acid and chlorination rate cycle, high-concentration chlorination measures further increase the concentration of clogging substances at the back of the drip irrigation belt.

(3) Acid-only treatment and sequential acid and chlorine addition significantly inhibit the growth of EPS in the emitter. Compared with the measures of acid addition alone, the sequential addition of acid and chlorine can more effectively prevent the accumulation of EPS in the emitter at the back of the drip irrigation belt.

(4) To ensure excellent anti-clogging performance of the BS drip irrigation system, when acid-only treatment measures are adopted, the acid dosing cycle is recommended to be 10 days. When acid and chlorination measures are adopted sequentially, the acid chlorination cycle is recommended to be 14 and 10 days when the chlorine concentration is 1–3 and 4–9 mg/L, respectively.

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