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Clogging formation and an anti-clogging method in subsurface irrigation system with porous ceramic emitter

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ABSTRACT

Emitter clogging negatively affects the performance of subsurface drip irrigation systems. The porous ceramic emitters of a subsurface irrigation system were investigated to identify the reasons for emitters clogging. Using 2-year operational data in an apple orchard, the soil water content and the emitters discharge were measured, the position and composition of the clogging substance were investigated, and the thickness of the adhesion layer in the channel of the emitter was calculated. Further, a flushing experiment using acid water with a pH of 6 was carried out to assess emitter clogging. The primary reason for the emitter clogging was substances precipitated at the inlet of the emitter, resulting in reducing the discharge of the emitter. At the same time, the water flow was affected by the clogging substance inside the micropore close to the channels. The main compounds of the clogging substances were SiO_2, $CaCO_3$, and $MgAl_2O_4$. Fe, Cl and K were also observed. Bacteria, fungus and microalgae secreted PLFAs to form biofilm. We have tested 4 flushing times (3 min, 10 min, 15 min, 20 min) and found that when the flushing time lasted 15 min, the corresponding emitter discharge were 0.046 L h^{-1} and 0.136 L h^{-1} under the working pressure of 2 kPa and 5 kPa, and discharge recovery rate were 51.11% and 75.56%, respectively. However, when the flushing time increased to 20 min, the discharge recovery was similar to that of 15 min. Therefore, it is recommended to flush with an acid solution for 15 min at flushing pressure of 100 kPa pressure to minimize the emitter clogging.

1. Introduction

Clogging of emitters, a common problem in any drip irrigation system, has become a major challenge to the application and improvement of irrigation technology (Niu et al., 2013). Emitter clogging changes the original hydraulic performance of the emitter, which reduces the discharge, thereby seriously affecting the operation effect and safety of the subsurface irrigation system. At the same time, emitter clogging reduces the service life of the irrigation system and increases the use cost of irrigation, becoming a widespread and difficult factor that restricts the promotion of subsurface irrigation technology (Gilbert et al., 1981; Nakayama and Bucks, 1981).

A number of researches have been carried out on the emitter clogging, mainly paying attention to clogging at labyrinth and orifice sections of emitters (Zhangzhong et al., 2019; Li et al., 2012). The emitter clogging may be caused by bacterial growth and particle deposition that inevitably occur after a long-time running due to the complex environment in the water. Given that water quality is complex, especially, water physical, chemical, and biological factors often exacerbate the emitter clogging. Literature suggested that suspended particles are not a trigger of the clogging processes but the accumulation of particles may initiate the formation of biofilm on the surface of the flow channel, which aggravates the blockage (Adin and Sacks, 1991). Zhou et al. (2013) concluded that when using reclaimed water, an extracellular polymer secreted from the biological growth may cause clogging by continuous adsorbing microorganisms and solid particles. Wu et al. (2004a, 2004b) also found that the main causes of the above clogging were the adsorption, deposition, and development of particles (or fine

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hairs) in the flow path of the emitters operated for eight years. In addition, particle deposition and biofilm growth in the inlet channel and initial vortex zones were found in most of these emitters that have only one flow channel, which causes the decreased discharge of the emitters (Ait-Mouheb et al., 2019). At the same time, some researchers proposed designs with a flushing system for the clogged emitters. In the flushing system, securing an appropriate pressure is very important to effectively dislodge and transport accumulated sediments at appropriate shear stress. Yu et al. (2018) suggested that the lifespan of drippers increased by 50% compared to those of the no-flushing system. Green et al. (2018) suggested that oxidation treatments using hydrogen peroxide or hypochlorite acid eliminate biofouling and prevented clogging. Chlorination treatment also has been proposed to enhance the treatment of clogging in drip irrigation systems and inhibiting the growth of bacteria in the water (Hao et al., 2018; Song et al., 2017). However, it was worth noting that a low concentration chlorination mode for a long duration has been recommended as a high concentration chlorination mode for a short duration. Song et al. (2019) found that the chlorination concentration of 5 mg L^{-1} for 0.5 h was more likely to induce adverse effects on soil than the chlorination concentration of 1.25 mg L^{-1} for 2 h.

In recent years, porous ceramic emitter, which is based in the theory of pot irrigation, has been developed for subsurface irrigation systems (Cai et al., 2017b, 2015). Because the emitter is applied underground, it reduces surface evaporation caused by atmospheric temperature, wind speed, humidity and so on. The emitter' pore size is micron level similar to a capillary channel that is capable of actively absorbing water. Since the working pressure of the porous ceramic emitter (2–5 kPa) is relatively low to save energy (Cai et al., 2018), it prevents the harm of suction mud from the negative pressure and the root intrusion (Cai et al., 2014, 2017a). Moreover, An (2017) found that yields and the irrigation water use efficiency in lettuce could be improved by the porous ceramic emitter. Cai (2019) also found the yield of apple tree improved 7.6% and irrigation water use efficiency improved 10.1% compared to conventional subsurface drip irrigation tape. Using porous ceramic emitter is a better way of irrigation.

However, the porous ceramic emitter clogging may be different from conventional emitters as the porous ceramic emitter has a larger area of passage and multiple channels. To explore the cause of the porous ceramic emitter clogging, Dong et al. (2019) found that the particles carried by irrigation water gradually form a sediment layer on the inner wall of the porous ceramic emitter as the particles are not sucked into the micropores. Chen et al. (2019) added $NaHCO_3$, Na_2SO_4, NaCl and $CaCl_2$ to form different kinds of saline water sources with different electrical conductivity and found that the flocculation of the $CaCO_3$ in the water was progressive to form stable and compacted aggregates with an increase of salt content. While these experiments were carried out in the air, the porous ceramic emitters are usually buried in the soil and the reason of the emitter clogging is not clear, and the degree of discharge recovery after flushing is questionable. Since fine substances such as silt, algae and bacteria are easy to be flocculated, previous studies indicated that eliminating the fine substances is closely related to a flushing time rather than flushing pressure (Yu et al., 2018). However, it is questionable how long the flushing needs to be conducted when the porous ceramic emitter is clogged.

In this study, the emitters that had been working with surface irrigation water in the field for 2 years were selected not only to better understand the clogging of the porous ceramic emitters used in irrigation with the degree of emitter clogging, but also to propose an efficient flushing time to restore emitter discharge. Optical microscope, electron microscope, and X-ray diffractometer were used for determining the thickness, position, and composition of clogging substances inside the emitter, respectively. We also analyzed the types of organism. Besides, a suitable anti-clogging method was proposed to effectively restore the discharge of the emitter corresponding to different flushing effects.

2. Material and methods

2.1. Layout of the subsurface irrigation system with porous ceramic emitter

This study selected an apple orchard in Zizhou County, Yulin City, Shaanxi Province of China, as an experimental site on the Loess Plateau, the local temperature during the irrigation season was 11–25 °C. Combining the patent of a subsurface irrigation system with porous ceramic emitters that utilizes mountain rainwater harvesting (Wu, 2018), a rainwater harvesting facility had been built for irrigation as shown in Fig. 1. The water was precipitated in rainwater harvesting facility and had a filter at the outlet. The system was composed of five laterals (each lateral length was 50 m) and a water tank (1.5 m^3) placed in front of each lateral to provide a water source. The porous ceramic emitter was mainly made of quartz sand that the porous parameter of 10–100 μm and the average discharge of non-used emitters was 0.09 L h^{-1} under 2 kPa. According to Cai et al. (2018), the working pressure of ceramic emitter would be 2–5 kPa controlled by the water tank. The water cellar supplied water to the water tank through a lateral and added water every 10 days. 20 samples were taken for analyzing water quality characteristics (chemical oxygen demand (COD), dry matter content, pH, NH_4^+-N, Ca, Fe and particle size distribution) as shown in Table 1. Since the pore size of the porous ceramic emitter was 10–100 μm, some particles could flow out of the emitter with the water flow. Valves were also installed at the front and the rear of each tank connection to control influent and effluent flows. The flushing valve was arranged at the end of the lateral. Since the growth of apple trees requires nitrogen, phosphorus and potassium fertilizers, N (23 kg/km^2), P_2O_5 (14.3 kg/km^2) and K_2SO_4 (24 kg/km^2) were used to meet the requirements of apple trees growth. The subsurface irrigation system with the porous ceramic emitter was arranged according to the arrangement of one tube and one row. 25 emitters were placed at each lateral every 2 m. In particular, a ceramic emitter was placed under each apple tree. As the work of Chen et al. (2018), the emitters were buried at a depth of 20 cm to reduce evaporation of soil water effectively. Based on the growing range of apple tree roots, the distance from the trunk was 90 cm.

Since it is difficult to detect the discharge of the emitter in the soil, the irrigation effect of the emitter can be judged by measuring the soil water content. For measuring the soil water content, 3 locations were selected for each lateral by TDR (time domain reflectometry) every 10 days except for rainy days. TDR tubes were installed at 10, 20, and 70 cm away from the plant. The soil water content was measured at 10, 20, 40, 60, 80 and 100 cm with 3 sampling locations for each tube. At the same time, the soil water content under the apple trees that were not irrigated was also measured as a control group. The average soil water content (θ, %) is as follows:

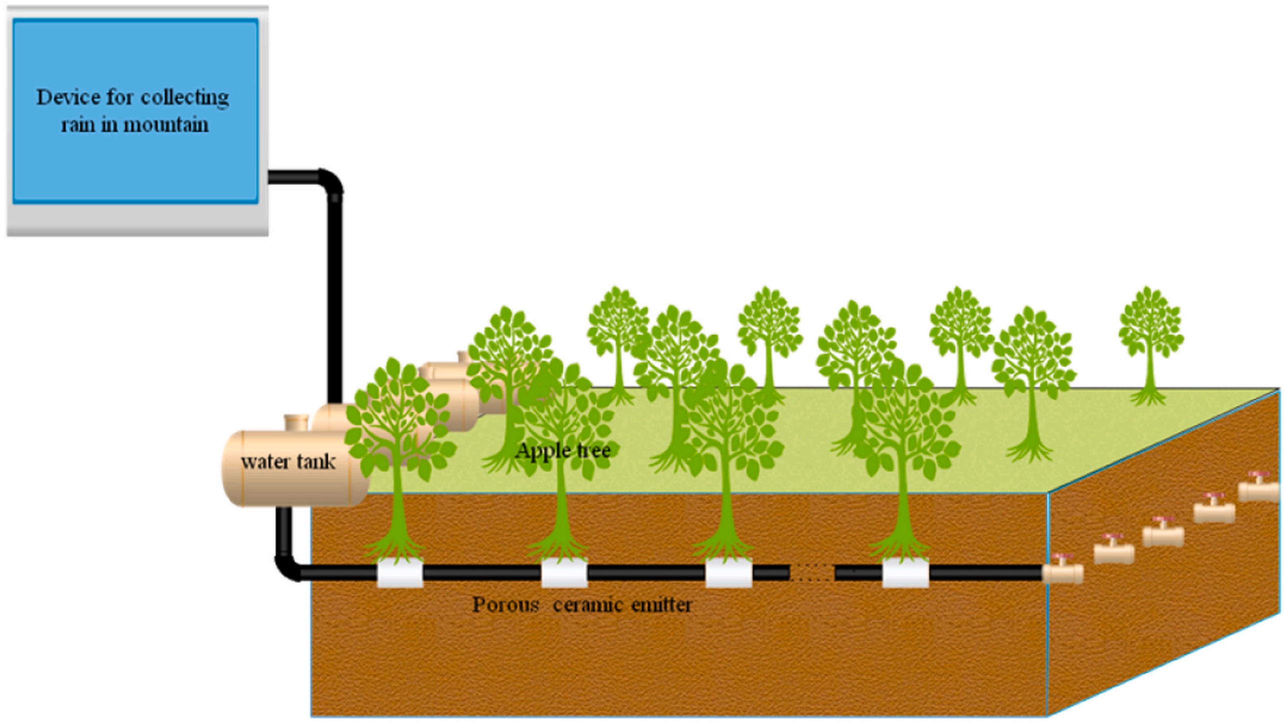
$$\theta = \frac{\sum (VWC_i \times SD_i)}{\sum SD_i} \quad (1)$$

where VWC_i and SD_i are the soil water content (%) and soil layer thickness (mm) of each layer, respectively.

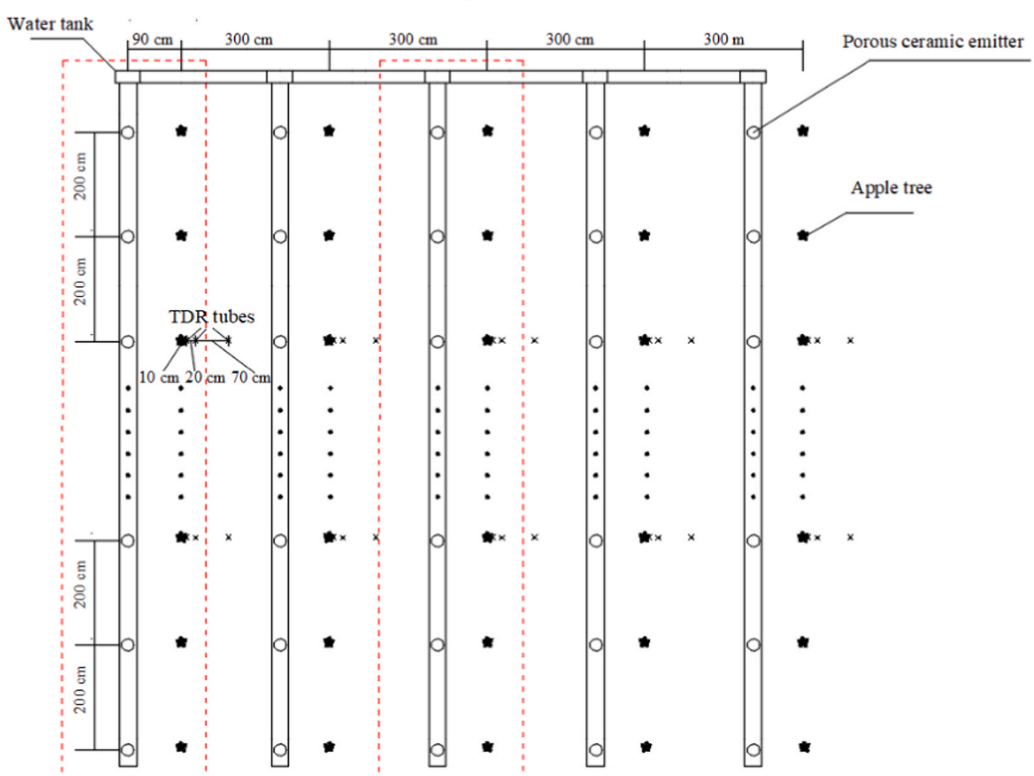
During the experiment, the end valve kept open to drain the water from the tank and lateral at the end of the growth period (from May to October). After the end of the 2-year trial, 50 emitters from only 2 laterals (Fig. 1**b**) were randomly selected. The place 1 m away from the side of the tree was excavated to determine the position of the emitter for reducing the damage to the root system. When the excavation was finished, the soil was backfilled, and each emitter was sealed in a bag for the next test.

2.2. The discharge of emitter

Discharge is an important indicator to evaluate the degree of clogging of the emitter. Once emitters were dug out, 10 emitters were placed



a: Profile



b: Plan

Fig. 1. Layout of the subsurface irrigation system with porous ceramic emitter (5 rows of apple trees × 25 emitters), Note: The areas of the red dotted lines represent the layout area of the studied emitter. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Average water quality characteristics and particle size distribution of water used during the experiment.

pH	TS (mg L^{-1})	COD (mg L^{-1})	NH_4^+-N (mg L^{-1})	Ca (mg L^{-1})	Fe (mg L^{-1})
7.5 ± 0.05	0.82 ± 0.04	7.82 ± 1.15	0.15 ± 0.01	0.3 ± 0.08	0.2 ± 0.01
1–2 μm	2–5 μm	5–10 μm	10–15 μm	15–20 μm	
56.7%	34.7%	7.0%	1.2%	0.4%	

COD: chemical oxygen demand, TS: dry matter content.

on a platform of the hydraulic performance test to measure the discharge (Fig. 2). The end valve in the test of the hydraulic platform in Fig. 2 was closed, and the water only flowed from the emitter. The working pressure of 2 kPa was controlled by the height difference between the piezometric tube in the Mariotte bottle and the emitter in order to better judge the blockage. The discharge of each emitter was measured 3 times for half an hour per each test and a value averaged over 3 measurements was obtained as the final discharge for each emitter. The discharged water was collected in a cup that is weighed at 0.01 g accuracy using an electronic balance and unified treatment of water.

The emitter performance is evaluated by the relative discharge (q_{po}) that is calculated by Eq. (2):

$$q_{po} = \frac{q_i}{q_0} \times 100\% \qquad (2)$$

where i is the serial number of the emitters; q_i is the discharge of the i-th emitter L h^{-1} and q_0 is the average discharge of non-used emitters, 0.09 L h^{-1} in this study (the mean discharge of 25 emitters under 2 kPa, the standard deviation is 0.04).

2.3. Analysis of emitter clogging

Since the working pressure of the emitter in the yield and discharge test were 2 kPa, the discharge test didn't induce clogging. After the discharge test, the 10 emitters also were used to analyze emitter clogging. To verify the emitter clogging, the deposition thickness, clogging position, the types of organism and clogging composition were measured. In order to prevent the sample from polluting the clogging composition during the experiment, the part of the emitter was reserved when measuring the thickness, as shown in the Fig. 3, from the surface boundary of the clogging substance to the inner wall of the emitter (Zeiss Axio Scope. A1 MAT material metallographic microscope). In this study, the thickness of the adhesion layer for 10 emitters was measured by the image processing software digitizer at 3 positions within each emitter, and measured 5 times per position to ensure the thickness less affected by sampling. The averaged thickness of 5 measurements was taken as the thickness of the position, and the averaged thickness of the 3 positions was taken as the thickness of the adhesion layer of the emitter to reduce the accidental error. A small cutting machine was used to dissect the emitter during the experiment. Some powders adhered to the edge of the emitter during the dissection, were excluded to avoid interfering with the experimental results.

In addition, this study used a random sampling method to detect the position of micro-pore clogging. There were two parts to collect the information; 1) the inlet of the emitter (Fig. 4, 1) and 2) the outlet of the emitter (Fig. 4, 2). They were used to make a SEM (scanning electron microscope, Nano SEM-450) observation sample to obtain a digital image acquisition.

Composition analysis was also conducted for the clogging substances attached to the inner wall of the ceramic emitter and the composition in a dried condition was scanned by the X-ray diffraction (XRD, Bruker D8 Advance A25, angle multiple linear ± 0.0001°, goniometer radius ≥ 200 mm, Angle range 10~80°). The internal clogging substances of 3 emitters were taken, and grinded them into powder for composition analysis. The obtained polycrystalline diffraction image was qualitatively analyzed using an analysis software (MDI Jade 6 for XRD software application) to determine the composition of the clogging substances. At the same time, the clogging substances shown in the image were subjected to an energy spectrum analysis to determine its constituents. Moreover, the clogging substance of emitters were mixed together for the types of microorganisms testing. We divided the collected biofilms into 3 samples randomly and equally. They were tested for the

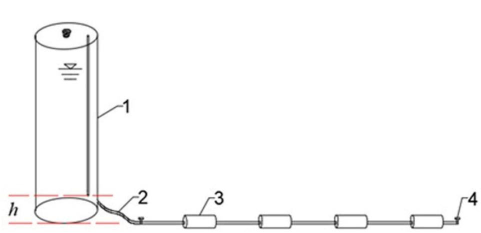


Fig. 2. The hydraulic performance test platform, 1-Mariotte bottle 2- lateral 3-porous ceramic emitter 4- water valve h-working pressure.

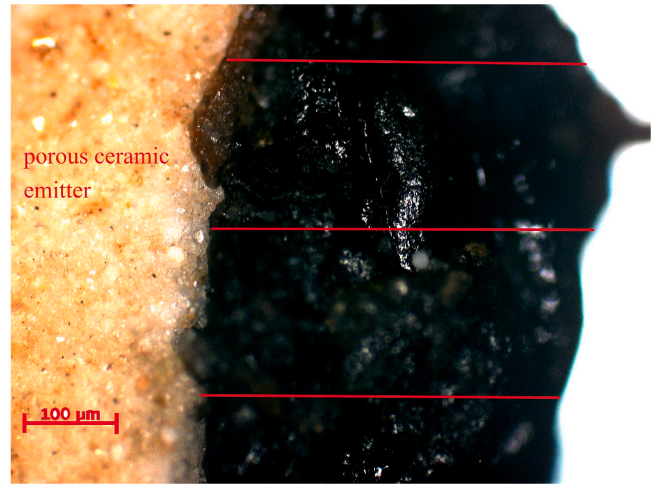


Fig. 3. Clogging substance deposition in the emitter, Note: the red line represents the selected measurement position. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

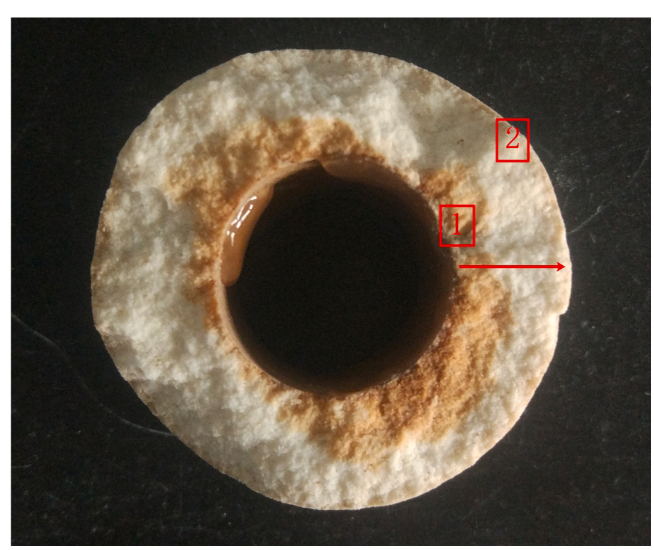


Fig. 4. Observation zone inside the porous ceramic emitter, Note: Arrow indicates the direction of water flow. 1 and 2 indicate the sampling part of the emitter for SEM.

Phospholipid fatty acids (PLFAs) to get the types of microorganisms: testing methods were based on details described by Zhou et al. (2013). PLFAs biomarkers of indicated microorganisms also referred to Zhou et al. (2013).

2.4. Anti-clogging experiment

In the field test, since no suitable flushing method has been studied, the lateral was not flushed, and only the end valve was opened after the end of the fertility period to drain the water in the lateral. Therefore, an efficient flushing mode is needed to solve the emitter clogging in the field experiment. The test platform for flushing was that replaces the Markov bottle with a pump and loads a pressure gauge to control head pressure (Fig. 2). At present, the traditional flushing pressure is 300–500 kPa (Yu et al., 2018; Puig-Bargues et al., 2010). However, the ceramic emitter and the lateral were connected by viscous glue, and the maximum pressure at the connection cannot exceed 100 kPa. In order to reduce the emitter clogging to the greatest extent, the flushing test was implemented with a pressure of 100 kPa with 10 emitters per group for testing and 4 groups. At the same time, the flushing water used in this study was acid-added water (pH = 6, it is not harmful to the field environment) to improve the flushing efficiency. As the flow passage area of the ceramic emitter is large, this study tested various flush times to select the appropriate flushing time by gradually increasing the flushing time (i.e., 3 min, 10 min, 15 min and 20 min) in irrigation. Depending on the pH value measured before the experiment, HCL (0.1 mol L^{-1}) was added to the water to obtain the designed pH value. During the acidification process, repeated water cycles increased the possibility of acid consumption. Whenever the acid was injected, a pH meter was used to measure the pH value in water every 3 min. The designed pH value was maintained by injecting the amount of acid during the acidification process based on pH monitoring by the acidity meter. The efficiency of flushing time on the emitters was evaluated corresponding to the recovery rate of the discharge.

Once the flushing was completed, the discharge after the emitter flushing was still measured by a device (refer to 2.2) with some adjustments. When the discharge of each emitter was measured, the average discharge of the emitters was employed as a flow indicator of each emitter type to fairly compare the changes of the discharge. The discharge available for the flushed emitter was obtained from the 2 pressures of 2 kPa and 5 kPa. At the same time, the selected emitter sample was scrutinized with an electron microscope after the lateral was flushed. This test may provide a certain reference as to how much the clogged emitter discharge can increase for subsequent field tests.

3. Results

3.1. Emitter performance

Fig. 5 shows that the relative discharge (q_{po}) of the porous ceramic emitters that were operated for a period of time. It is found that the relative value is below 20% for the emitters. ISO (2003) specifies that the emitter relative discharge below 25–30% may cause serious clogging, indicating that the emitters used in this study are severely clogged.

The reason for the discharge decreased is that there is a blockage in the emitter. Eq. (3) shows the linear relationship between emitter discharge and the thickness of the adhesion layer. Even though the porous ceramic emitter is composed of a porous structure that provides many flow channels and many possibilities of outflow, the discharge of the emitter decreases gradually with an increase in thickness. Generally speaking, an irrigation system operated for a while usually may cause the thicker layer deposition of clogging substances. Researches showed that the low flow velocity caused more deposits in the pipeline due to a reduced shear stress of water (Mietta et al., 2009; Douterelo et al., 2012). Under the working pressure (2–5 kPa, 0.09 L h^{-1} and 0.18 L h^{-1}, respectively) used in this study, the velocity was very low (7.9×10^{-5} m s^{-1} and 15.8×10^{-5} m s^{-1}, respectively), resulting in more substance deposit in the emitter because the emitter is equivalent to a filter which causes different clogging degrees of the emitters. Moreover, the clogging substances are difficult to remove due to low discharge rate (Park et al., 2011; Paul et al., 2012), consequently there is a thick adhesive layer in the inside of the porous ceramic emitter.

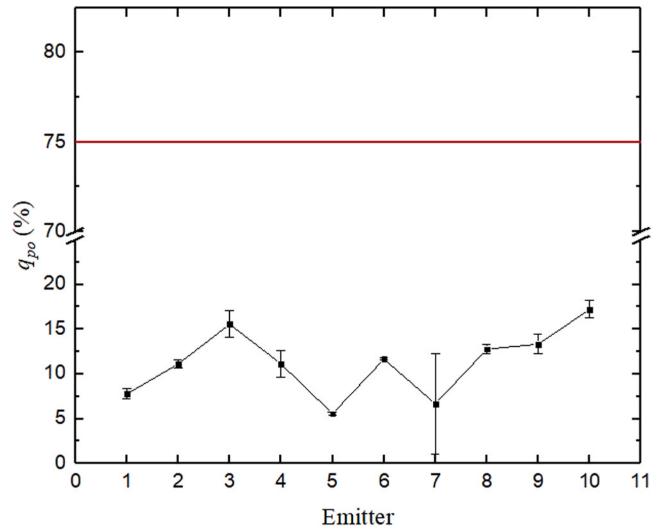


Fig. 5. Relative discharge (q_{po}) of clogged porous ceramic emitters, Note, the red line represents the relative discharge of 75%, and the criterion for judging the occurrence of dripper clogging is defined as: the actual discharge of the emitter is less than 75% of the designed discharge (ISO, 2003). Emitter number is a selected number of emitters. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$q = -0.0234t + 0.0197 \quad R^2 = 0.9297 \quad P = 0.004 \tag{3}$$

Where q is the discharge of emitter, L h^{-1}, t is the thickness of the adhesion layer, mm, R^2 is the goodness of fit, $P < 0.05$ means significant.

3.2. Clogging position

During the experiment, clogging occurred in the emitter. Fig. 6 shows microscopic photo of the sampling of emitters at different positions. The brand new emitter's pores are clearly shown in Fig. 6**a**. At the inlet of the clogged emitter (Fig. 6**b**), the clogging substances clogged the pores and there were some filamentous fibers. In contrast, at emitter outlet, more fine particles were found on the pores as shown in Fig. 6**c** because the soil's particles attached to the emitter surface. The micropores were clearly visible without substances clogged when away from the boundary as the same with the inlet of the clogged emitter.

The clogging of porous media is more complicated than a labyrinth path because of the deepening of flow channels. The low discharge rate causes a slower transfer rate of nutrients and subsequently solid particulate matters at the inlet are more abundant than the outlet of the emitter, the micropores are not capable of providing suitable growth space and nutrients (Zhou et al., 2014). The pores inside the emitter were clearly visible. Such results indicate that the main trigger of the emitter clogging is the adhesion layer and clogging substance in the pores. The reason why there are so many clogging substances inside the emitter is the presence of nutrients and microorganisms in the water, the rise in temperature affects the quality of the water. Under the local temperature of 11–25 °C during the irrigation season, the biological activity in the water is stronger, causing more serious blockages (Tong et al., 2019; Sanz-Lázaro et al., 2015).

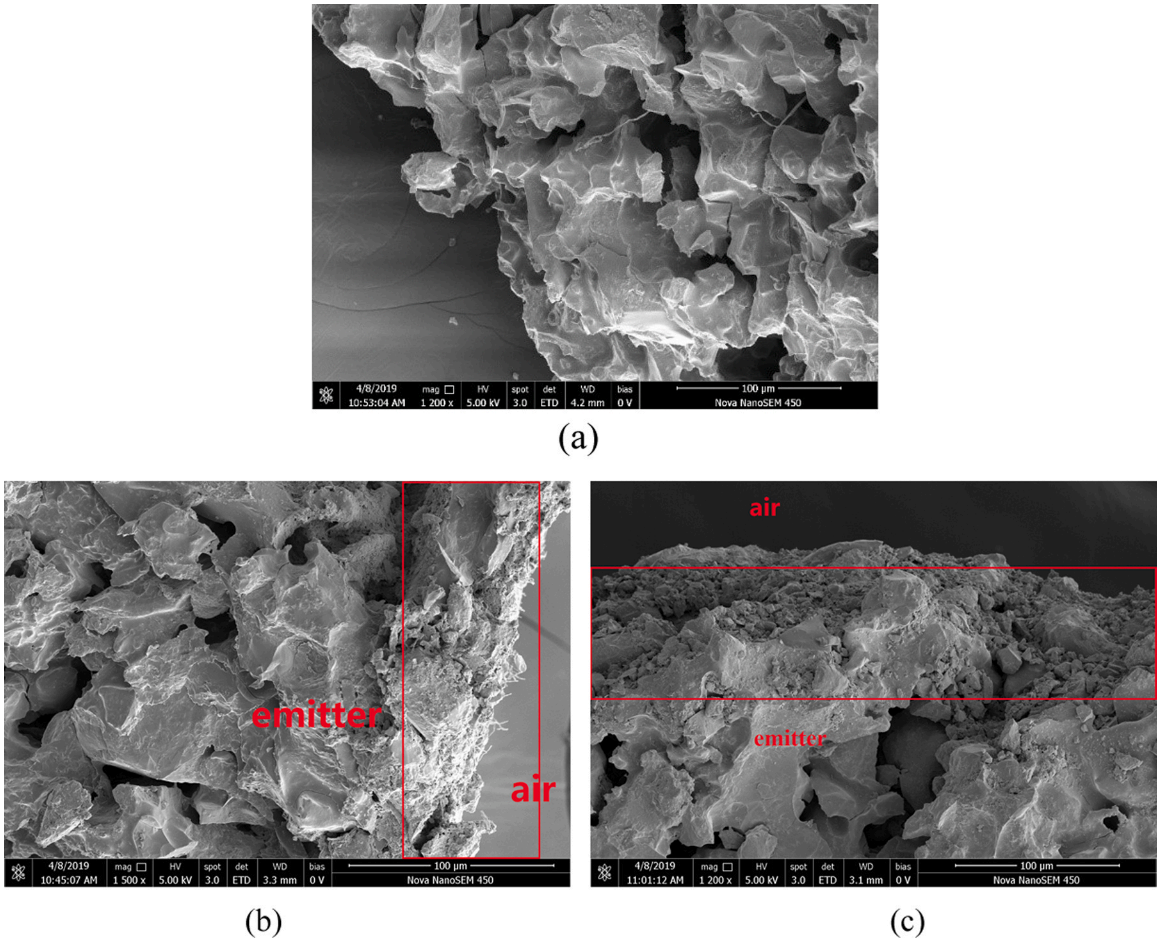


Fig. 6. The inner wall of porous ceramic emitter observed by SEM. (a) clean emitter; (b) The inlet of emitter; (c) The outlet of emitter.

3.3. Clogging composition

Fig. 7 demonstrates the composition of clogging substance. It is found that SiO_2 accounted for the highest portion in the inorganic crystal among the crystal components mainly due to the presence of particles in the water. The clogging substances were also composed of $CaCO_3$, $MgAl_2O_4$. An analysis of elemental composition also shows that C, O, and Si are relatively high while the clogging substances contained little Fe, Cl and K (Table 2). Besides, the clogging substance mainly contained bacteria (14:0, i15:0, i16:0, 16:1×7t, 16:1×9t, 17:0, i17:0, a17:0, 18:0, 18:1×7c and 20:0), fungus (18:2w6,9c), microalgae (16:3w3). They grow and secrete PLFAs, which constituted biological clogging (Zhou et al., 2013). It is worth noting that the clogging substances contain both Fe^{2+} and Ca^{2+} that promote the production of microorganisms and precipitation of solid particles, resulting in increasing the risk of clogging (Hao et al., 2017).

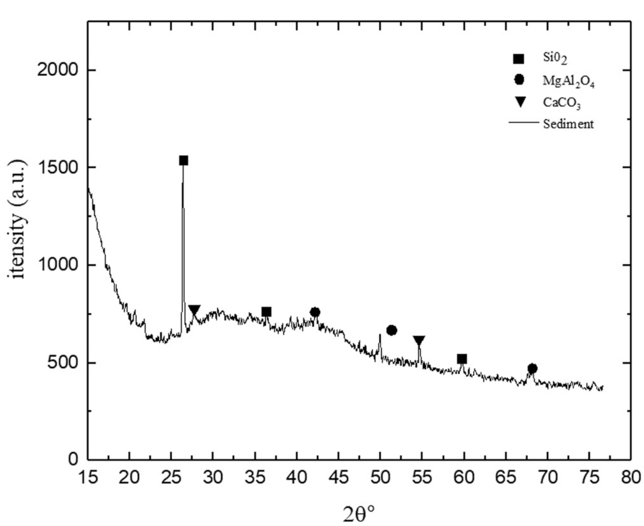


Fig. 7. The crystal of the clogging substance analyzed with XRD.

3.4. Anti-clogging method

The capacity of discharge recovery is closely dependent on flush times as shown in Fig. 8. For a short flushing time (i.e., 3 min, 10 min), the adhesion layer was not removed effectively and resulted less discharge of the emitter. Given a longer 15 min flushing time, for example, the discharge was 0.046 L h^{-1} at 2 kPa and the corresponding discharge recovery rate was only 51.11% compared to the non-used emitter discharge. Moreover, the discharge recovery rate was 75.56% under 5 kPa. Emitter discharge after flushed has been improved and this result indicates that the discharge recovery rate of the emitter can be improved as the working pressure increases. Unfortunately, a longer flushing time is not always effective to solve the clogging of the emitter. The discharge recovery rate not improved significantly although the flushing time increased by 20 min. It was recommended to apply 15 min flushing time at 100 kPa to effectively improve the emitter discharge.

4. Discussion

As the increase of time, the emitter gradually became clogged, the

Table 2
Mass percentage analysis of each element of the clogging substance.

Element	C	O	Mg	Al	Si	S	Cl	K	Ca	Fe
Percentage (%)	21.43	43.1	2.97	4.60	17.28	0.22	0.22	0.98	4.19	5.02

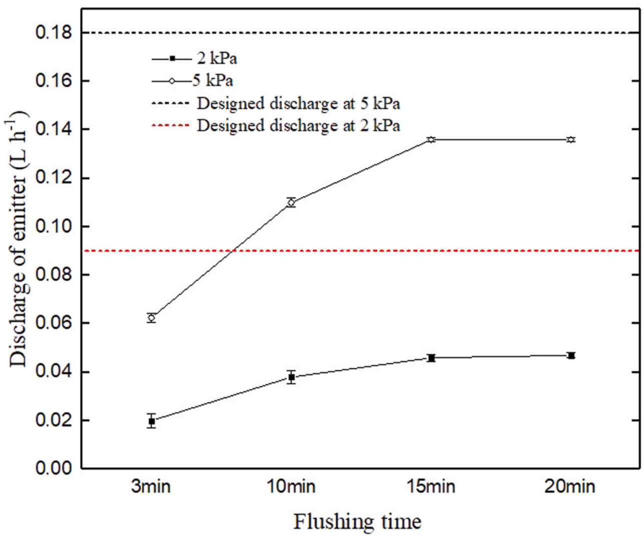


Fig. 8. Changes in emitter discharge under different flushing times and pressures.

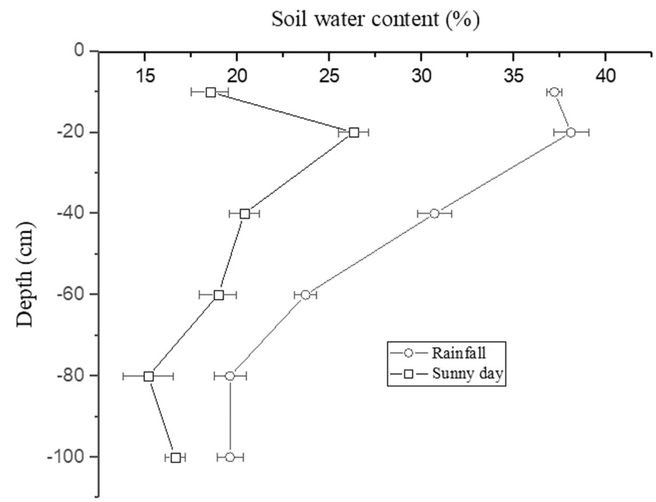


Fig. 10. Changes in soil water content of different soil depth on different weather.

soil water content after irrigation was close to that in the non-irrigated soil in the second year as shown in Fig. 9. Research shows that the maximum water requirement for the apple trees should be 80% of the field capacity (0.25 cm^3 cm^{-3}) (Xu et al., 2016). In the Fig. 9, the soil water content is greater than 20% even when the emitter was clogged, which is still above the maximum requirement of the soil water content for the apple trees. This indicates that porous ceramic emitter can still provide some water needed for apple trees after 2 years of operation. It seems to indicate that the relative discharge to evaluate the emitter clogging may be not suitable for the porous ceramic emitters. At the same time, we sampled the soil water content on different weather conditions: sunny day (cloud cover less than 10%) and rainfall in second year (Fig. 10). Even in sunny day, the soil water content can meet the apple tree's growth conditions within the range of soil depth of 0–60 cm. Since the emitter discharge is considerably sensitive to the change of pressure (Cai et al., 2018), when the emitter discharge is greater than the infiltration rate of the soil, the soil produces a positive pressure that further suppresses the outflow of the emitter. Wu et al. (2004a, 2004b) also pointed out that the positive pressure of the soil could reach 0.15 MPa which was greater than the working pressure of the emitter. Given that a stable level of the soil water content causes a small discharge of the emitter, the emitter discharge in the soil can be less than a designed discharge in a long-term stable environment. However, ceramic irrigation systems always continuously provide part of the irrigation water to the soil over time even the emitter discharge is small. Such result indicates that continuous irrigation from the porous ceramic emitters may reduce the deviation of soil water content caused by emitter clogging. Instead, the uniformity of the soil water content in a certain period of time might be a better index to evaluate the irrigation quality to reduce the requirement for the deviation of discharge.

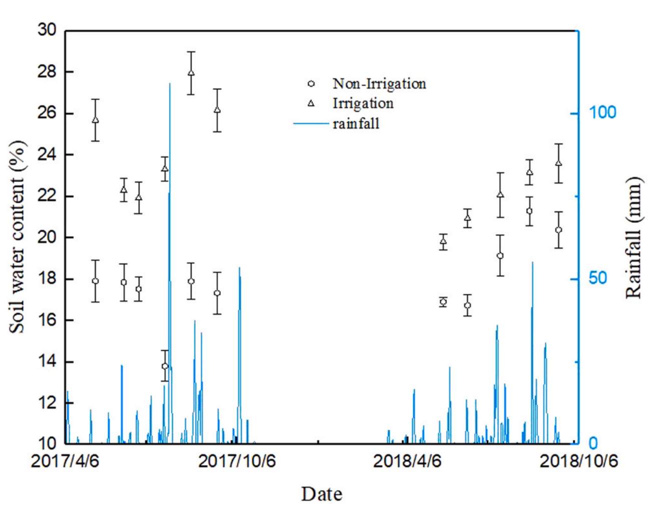


Fig. 9. Changes in soil water content and rainfall at different date.

Even if the porous ceramic emitter can provide enough irrigation water for crops when it is clogged, it is still necessary to solve the blockage for the good operation of the system. Lateral flushing removes sediments accumulated within lateral, these sediments will not clog emitters. However, the pore' clogging substances still remain in the micropore even after the flushing. We have tested 10 samples of flushed emitters, and found that there were some clogging substances in the pores of the emitter (Fig. 11) compared to a clean emitter (Fig. 6**a**), which explains the reason that the discharge improved less than expected. The flushing time effectively reduces the substance deposited on the inner wall of the emitter, but it was difficult to achieve effective removal of the substance in the micropores. The clogging substance continues to prevent the flow of water from the inlet to the outlet. It is difficult to restore the emitter discharge as much as a non-used emitter discharge.

Besides, the inside of the porous ceramic emitter consists of a number of capillary channels that have a strong adsorption effect (Tang et al., 2018). The air in the water is absorbed into the inner wall, which deteriorates the discharge rate by reducing the capacity of the flow channel (Lazouskaya and Jin, 2008). At the same time, gas accumulation occurs on the surface of the channel from CO_2 produced by the respiration of the organism (e.g., aeruginosa, fungus). When biological respiration

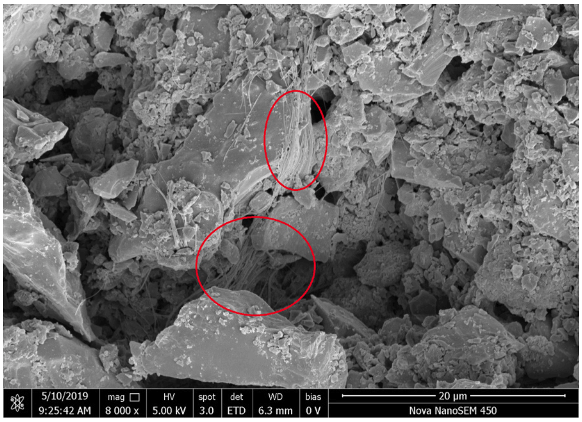


Fig. 11. The inner wall clogging substance of porous ceramic emitter under the flushing time of 15 min observed by SEM.

produces CO_2, it dissolves in water to form HCO_3^-, and the pH of the water is slightly alkaline, forming $CO3^{2-}$, and Ca^{2+} in the water reacted with it to form $CaCO_3$, which exacerbated the blockage. Meanwhile, Han et al. (2019) found that the presence of gas–water interfaces, mixed gas–water fluids, clearly promoted pore-clogging because finer particles are readily collected at the gas–water interfaces, resulting in high particle concentration. At the same time, the substances accumulated in deep inside of the micropores are not removed efficiently. The emitter used in this study had a wall thickness of 2 cm, the internal structure is intricate and not uniform (Zhou et al., 2020). Given that the pressure presses clogging substances accumulated in the inside of the emitter, the more clogging is likely to occur due to the change in the pore size (Salvatore Citoa, 2012). Therefore, it's necessary to explore the frequency of flushing laterals during irrigation. In addition, antagonistic microorganisms have an influence on reducing emitter clogging and it provides a better way to suppress the clogging of the porous ceramic emitters (Sahin et al., 2005).

5. Conclusions

This paper mainly analyzed the causes of the clogging for the porous ceramic emitters and suggested suitable solutions. The results of this study were:

– About 75% clogging occurred inside the emitter continuously operated for two years in the field test, subsequently causing less discharge for the apple trees. The relationship between the thickness of the adhesion layer and the of emitter discharge was congruous with a linear relationship which is one of the reasons that the emitter discharge decreased. However, the continuous irrigation with the ceramic emitters enhanced the capacity to keep a certain level of soil moisture.
– When the emitter flowed out, the substances in the water were precipitated at the inlet of the emitter. In contrast to the micropores of the outlet of emitter, clogging substances were only found at the inlet pores of the emitter.
– The clogging substances were mainly contained SiO_2, $CaCO_3$ and $MgAl_2O_4$ and the element: Fe, Cl and K. Further, the clogging substances contained bacteria, fungus and microalgae, which secrete PLFAs to form biofilm.
– It was recommended to apply an acid solution with a pH of 6 for the flushing time of 15 min at 100 kPa pressure for the clogged emitter, and the discharge could be restored up to 75.56% of the designed discharge under the 5 kPa. This method is to reduce blockages for already clogged emitter, and future studies need to focus on the frequency of flushing laterals during irrigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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