

Increasing Phosphorus Availability by Reducing Clogging in Drip Fertigation Systems

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Abstract: Phosphorus fertigation by drip irrigation (PFDI) system may offer an effective way to alleviate the soil and water pollution caused by the excessive input of phosphorus fertilizer, and also to cope with global phosphorus shortage. However, emitter clogging is the main obstacle to the application and popularization of PFDI, since also reduces the uniformity of phosphorus fertigation. The main results of experiment for assessing the clogging behavior of eight emitters using three types of phosphorus fertilizer (potassium phosphate monobasic, PPM; urea phosphate, UP; ammonium polyphosphate, APP) and three fertilization levels (0, 0.15 and 0.30 g/L) were that the performance of the emitters depended on the type of fertilizers, concentrations and emitters. Compared to non-fertigation, the application of APP induced the most serious emitter clogging as drastically promoted the deposition of carbonate and phosphate. PPM accelerated the precipitation of silicates and carbonates. UP reduced carbonate deposition while significantly increased silicate content and caused the slightest clogging. Consequently, the average discharge variation in UP, PPM, and APP decreased by 4.1%-19.4%, 16.0%-37.3%, and 43.9%-65.4%, respectively. Under the same amount of fertilizer, low concentration and long-term (LCLT) fertilization effectively relieved the clogging issue. The results suggested PFDI should choose UP as the fertilizer type and adopt LCLT fertilization mode, since UP fertigation with the concentration of 0.15 g/L did not significantly aggravate emitter clogging. Moreover, some anti-clogging measures were further proposed based on the clogging behavior of PFDI.

Key words: phosphate fertigation; phosphorus availability; drip irrigation; emitter clogging

1 Introduction

Phosphorus (P) is an essential nutrient for plants. However, phosphorus fertilizer is easily immobilized by soil and leads to low mobility and availability (Garg and Bahl, 2008), being the seasonal utilization efficiency of P always less than 20% (Nayakekorola and Woodard, 1995). Thus, P fertilizer is often excessively applied in agricultural production to meet crops demand. Excessive input of phosphorus fertilizer in agricultural production is the main source of global phosphorus export to soil and water (Ashley et al., 2011). In the past half century, nearly 500 million tons of P have been brought into the aquatic sphere mainly through agricultural production (Cordell et al., 2011), which lead to a serious agricultural non-point source pollution and water eutrophication (Awual, 2019; Goodwin et al., 2015; Marshall et al., 2017), damaging not only agroecosystem functions and the long-term sustainability of food production but also human health (Norse and Ju, 2015). Moreover, P resources are scarce and non-renewable and being depleted annually (Ober, 2016) in a rate that the global economically exploitable P-rock will only be mined for about 50 years in the future (Natasha, 2009). Thus, phosphorus scarcity linked with food security became one of the 21st century's global sustainability challenges (Cordell et al., 2011; Gérard, 2016; Kim et al., 2018; Li et al., 2019a; Nancharaiah et al., 2016). Therefore, reducing consumption of P fertilizer and improving its efficiency have become one of the important issues for increasing sustainability in agriculture.

Recently, some researchers tried to change the traditional application of P fertilizer as base fertilizer, using the enclosed pipeline system of drip irrigation technology to transport the P fertilizer dissolved in water to the root region of crops (Liu et al., 2017a; Wang et al., 2018), which significantly decreased the fixed amount of P fertilizer in soil (Yang et al., 2011). Previous

researches reported that compared with conventional soil application, the use efficiency of P fertilizer with drip irrigation technology increased by 50% (Rubeiz et al., 1989), 25.4% (Mohammad et al., 2004), and 70.4% (Shedeed et al., 2009). Despite the variation of P efficiency, drip irrigation has been demonstrated to be an effective technology for increasing P availability. However, most commonly used P fertilizers are slightly soluble and incompatible with the irrigation water (Mohammad et al., 2004), causing precipitation and clogging of drip irrigation system. Farmers still prefer to broadcast the phosphorus into the soil rather than inject it to the irrigation system due to emitter clogging (Enciso-Medina et al., 2007). In fact, emitter clogging problem would greatly decrease the fertigation uniformity of system (Capra and Scicolone, 2007), causing an uneven distribution of phosphorus in crop roots thereby drastically reducing the phosphorus availability. Moreover, the replacement cycle of pipelines would be sharply raised by emitter clogging, which significantly increased the input of plastics and caused environmental pollution. Overall, emitter clogging has become the main obstacle to the application and popularization of phosphorus fertigation by drip irrigation system.

As the emitter performance varies greatly among different fertilizer types (Bozkurt and Ozekici, 2006; Liu et al., 2017c), it can be inferred that the change of P fertilizer may offer an effective and the most direct way to alleviate emitter clogging. Haynes (1985) indicated that P could easily form insoluble precipitates with Ca^{2+} , Mg^{2+} and Fe^{3+} ions in irrigation water, being the traditional phosphate fertilizer not recommended for drip irrigation systems. Mikkelsen (1989) suggested to use acid fertilizer to prevent phosphate sedimentation. Moreover, researchers have found that the application of diammonium phosphate (Yang et al., 2019), potassium phosphate monobasic (Zhou et al., 2019b), and calcium phosphate (Liu et al., 2017b) greatly worsened clogging issue. Recently,

urea phosphate (UP) and ammonium polyphosphate (APP) have been identified as two potential anti-clogging water soluble fertilizers (Kafkafi and Tarchitzky, 2011). The dissolution of UP per kg produces 6.3 mol H⁺ (Goyal, 2015), making it a high concentration acidifier that inhibits the precipitation of phosphate (Yang et al., 2019). Polyphosphate cannot easily react with Ca²⁺ and Mg²⁺ ions in water under specific conditions, being often used as scale inhibitor (Gryta, 2012). However, to date, the effect of UP and APP on emitter clogging of a drip irrigation system has not firmly understood. Moreover, although some reports indicated that increasing the concentration of fertilizer may aggravate emitter clogging (Nakayama and Bucks, 1991; Tang et al., 2018), it remains unknown if, under the same amount of fertilizer, it is better to choose high concentration short-term fertilization or low concentration long-term fertilization.

Based on this, this paper studied the effect of three types of phosphorus fertilizers (potassium phosphate monobasic, urea phosphate, and ammonium polyphosphate) supplied at three different concentrations (0, 0.15 and 0.30 g/L) on the clogging behavior of eight flat emitters, and on the mineral composition of the clogging substances. The objectives of the study were to: (1) determine the responses of different phosphorus fertilizer types and concentrations on the blocking behavior of emitters; (2) clarify the mechanism that involves phosphorus fertilizer on emitter clogging; (3) propose the optimization measures for increasing phosphorus availability.

2 Material and methods

2.1 Experimental setup

The experiment was conducted at an irrigation station located at Ulanbuhe arid area in Bayinaoer, Inner Mongolia, China. The water used in this study was imported from the Yellow River in the Wushengan channel. The water quality parameters measured during the experiment are presented

in [Table 1](#). The testing system was a home-designed emitter clogging experimental platform with emitters combined with a fertigation drip system ([Fig. 1](#)). The filtration equipment of the system consisted of two sand filters (filled with particles whose size ranged 1.30-2.75 mm) followed by two disc filters (106 μm filtration level). The test platform had two sub-units, each one built in four layers which had eight drip irrigation laterals. The operating pressure was 0.1 MPa, and the amount of water and fertilizer entering the drip irrigation laterals were monitored by a pointer-wheel water meter.

#Table 1 approximately here#

#Fig. 1 approximately here#

Eight types of flat emitters (labeled as FE1-FE8) were selected for the experiment. The emitters' parameters are provided in [Table 2](#). Each drip irrigation lateral was 15 m in length with a 0.33 m spacing interval. Three types of phosphorous fertilizer: potassium phosphate monobasic (PPM), urea phosphate (UP) and ammonium polyphosphate (APP) at three concentration levels (0, 0.15 and 0.30 g/L, P_2O_5 concentration, see details in the [Appendix](#)) were used to explore the effect on the clogging behavior of the eight types of flat emitters. Seven treatments with different P fertilizers and concentrations were set up: CK (non-fertilization, using water from Yellow River with a total P content of 0.002 g $\text{P}_2\text{O}_5/\text{L}$, calculated upon P values shown in [Table 1](#) that was considered as 0.81 g/L), PPM_0.15, PPM_0.30, UP_0.15, UP_0.30, APP_0.15, and APP_0.30. Besides, UP and APP were produced by the thermal continuous technology and urea phosphate-phosphorus pentoxide technology, respectively (See details in the [Appendix](#)). The system ran once a day ([Han et al., 2019](#)), which represented actual irrigation and/or fertilization once. The system fertigation ran every other day. The amount of irrigation and fertilization per drip irrigation lateral (15 m) was 0.375 m^3/d and

25 g/d respectively, which is equivalent to 225 m³/ha and 15 kg/ha, respectively, when 9000 m drip irrigation lateral was laid per ha. According to the fertilizer concentrations, there were three fertigation and/or irrigation schedules: non-fertilization (0 g/L), low concentration long term (LCLT) fertilization mode (0.15 g/L), high concentration with short term (HCST) fertilization mode (0.30 g/L), as shown in Fig. A.1. In the control group (0 g/L), only irrigation was performed. LCLT and HCST mode were adopting the “(1) non-fertilization (only irrigation); (2) fertigation; and (3) non-fertilization” operating schedules, and the fertilization was applied at the center of the whole operation time (Li et al., 2007). Besides, the fertigation treatments did not fertigate every day, the system fertigation ran every other day.

#Table 2 approximately here#

2.2 Evaluation parameters of emitter performance

The outflow of each emitter was collected for 5 min. Based on the weight of collected water, the emitters' discharge was calculated. The effect of water temperature on emitters' discharge was eliminated by computing emitter discharge with Eq. (1) (Pei et al., 2014).

$$q_{T_i} = \left(1 + \frac{57.35x - 28.24}{100} \times \frac{T_i - 20}{20} \right) \times q_{20} \quad \text{Eq. (1)}$$

where, q_{T_i} is the corrected discharge of emitters, L h⁻¹; T_i is the water temperature during the test, °C; q_{20} is the design discharge of emitters under 20 °C, L h⁻¹; x is flow index.

The corrected emitters' discharge was used to calculate the average discharge variation rate (*Dra*) (Zhou et al., 2015) of the lateral, as shown in Eq. (2).

$$Dra = \frac{\sum_{i=1}^n \frac{q_{it}}{q_{i0}}}{n} \times 100\% \quad \text{Eq. (2)}$$

where q_{i0} is the initial discharge for emitter i , L h⁻¹; q_{it} is the discharge at t hour for

emitter i , $L h^{-1}$; and n is total number of emitters installed along the lateral.

The outflow uniformity of the drip irrigation emitters can be represented by the Christiansen of uniformity (CU), as shown in Eq. (3) (Christiansen, 1942):

$$CU = 100 \left(1 - \frac{\sum_{i=1}^n |q_i - \bar{q}|}{n\bar{q}} \right) \quad \text{Eq. (3)}$$

where q_i is the discharge of emitter i , $L h^{-1}$; \bar{q} is the average discharge of emitters in a treatment; n is the number of emitters in a treatment.

2.3 Extraction and testing of clogging substances in emitters

(1) Dry weight of clogging substances

Dry weight was tested every 8 days, when 10 drip irrigation emitters were intercepted at the head, middle and tail of a lateral, respectively. The mixed 30 emitters in total were dried for 20 min at $60^{\circ}C$ and get the weight of samples. Then, 100 ml deionized water was added to the mixed emitters to remove the clogging substances using an ultrasonic cleaner (manufacturer: Chaowei, China; type: GVS-10L; frequency: 100 Hz). Weighing the clean samples, the average dry weight of clogging substances in mixed emitters was obtained based on the weight difference.

(2) Mineral composition of clogging substances

30 ml of treated suspension (separated from the 100 ml suspension mentioned in the previous section) were centrifuged. The solid residue in the bottom was dried at $60^{\circ}C$ to obtain the dry clogging substances. The solid clogging substances were mixed evenly and tested by the X-ray diffractometer (manufacture: Bruker, Germany; type: D8-Advance) to get polycrystalline diffraction patterns (Fig. A.2). The patterns were analyzed by the Topas software to obtain the mineral components of the clogging substances under the condition of 40 kV voltage and 40 mA electric

current. Copper target was applied, and the wavelength was 1.5406 Å. Results in pre-experiment indicated that the mineral composition was similar in the treatments with different concentrations (0.15 g/L and 0.30 g/L) using the same fertilizer. Therefore, only the samples in CK, PPM_0.30, UP_0.30, and APP_0.30 treatments were selected for testing every 16 days.

(3) Amorphous components of clogging substances

In APP treatments, amorphous components were found. The component of amorphous components was tested by Fourier transform infrared spectrometer (FTIR) (manufacturer: PerkinElmer, USA; type: PE Spectrum 400), and scanning electron microscope with an energy Dispersive Spectrometer (SEM-EDS) (manufacturer: Jeol, Japan, type: JSM-6510A).

2.4 Statistical analysis

The Pearson analysis was applied to study the correlations among the *Dra*, *CU* and mineral contents. Paired t-test was used to analyze the differences between different treatments. During these processes, the significance thresholds of the independent variables were determined at $p < 0.05$ and $p < 0.01$, respectively. The regressions and statistical analyses were carried out using SPSS (ver. 20.0, IBM Analytics).

3 Results

3.1 Effect of phosphorous fertigation on emitter performance

The *Dra* and *CU* in eight emitters (Fig. A.3) showed a slow decline in the early stage (0-16 d) and a rapid decline in both the middle and late stages (16-64 d). The correlation between CK and P fertigation treatments (Fig. 2) indicated that emitter clogging was aggravated after fertilization. Compared with CK, the *Dra* in UP, PPM, and APP decreased by 4.1%-19.4%, 16.0%-37.3%, and 43.9%-65.4%, respectively. While the *CU* decreased by 3.6%-13.1%, 9.4%-21.6%, and 33.8%-

52.2%, respectively. No statistical significances ($p < 0.05$, Table 3) were found between UP_0.15 and CK, while other fertigation treatments showed significant ($p > 0.05$) differences with CK. Moreover, the *Dra* and *CU* were significantly different among different phosphorus fertilizer types ($p < 0.05$). Compared with PPM, the application of APP aggravated the emitter clogging since *Dra* and *CU* decreased by 19.6%-24.1% and 22.9%-24.6%, respectively. While UP alleviated emitter clogging to some extent, *Dra* and *CU* increased by 10.3%-13.8% and 4.6%-7.4%, respectively. Under the same amount of fertilization, low P concentration (0.15 g/L) and long-term (LCLT) fertilization effectively relieved the emitter clogging issue. Compared to LCLT mode, the *Dra* and *CU* in high P concentration (0.30 g/L) and short-term (HCST) fertilization treatments decreased by 12.6%-15.9% and 8.0%-11.8%, respectively.

#Fig. 2 approximately here#

#Table 3 approximately here#

3.2 Main mineral components of clogging substances in emitters

The main mineral components inside the emitters are shown in Fig. 3. The primary mineral components of emitter clogging substances were quartz (SiO_2), calcite ($\text{CaCO}_3\text{-R}$), dolomite (CaMgCO_3), aragonite ($\text{CaCO}_3\text{-O}$), muscovite ($\text{K}(\text{Mg},\text{Al})_{2.04}(\text{Si}_{3.34}\text{Al}_{0.66})\text{O}_{10}(\text{OH})_2$), alkaline feldspar ($\text{KNaAlSi}_3\text{O}_8$), chlorite ($(\text{Mg},\text{Al})_6(\text{Si},\text{Al})_4\text{O}_{10}(\text{OH})_8$), and trace amounts of sodium chloride (NaCl) and ferric oxide (Fe_2O_3) in four treatments. Among them, quartz, muscovite, alkaline feldspar, chlorite, and calcite dolomite were the majority of the contents. The six primary mineral components could be divided into quartz, silicate and carbonate, according to the main chemical elements. The primary mineral components under four treatments accounted for: 29.4%-55.0% (quartz), 21.6%-45.2% (silicate), and 14.5%-33.4% (carbonate), respectively. Remarkably, phosphate did not precipitated in PPM_0.30 and UP_0.30 treatments, but amorphous components

appeared in APP_0.30 treatment and were 16.8%-19.3% of the total clogging substances.

#Fig. 3 approximately here#

3.3 Dynamics of carbonate content and its correlations with clogging parameters

The carbonate content in the eight types of emitters increased slowly in the early stage of the experiment (0-32 d) and increased rapidly in the middle and late stage (32-64 d) (Fig. A.4). The average content of carbonate in eight emitters and its correlation with *Dra* and *CU* are shown in Fig. 4 and Fig. 5, respectively. These figures indicate that the content of carbonate in UP and PPM treatments showed a significant linear negative correlation with *Dra* and *CU* ($p < 0.05$, $R^2 > 0.95$), while there was a significant quadratic function correlation in APP treatment ($p < 0.05$, $R^2 = 0.98$). The content varied significantly in different fertigation treatments ($p < 0.01$, Table 4). Compared to CK, the content of carbonate in PPM and APP treatment increased by 8.9%-20.1% and 32.8%-55.3%, respectively. On the other hand, UP inhibited the precipitation of carbonate, decreasing its content by 9.0%-36.6%.

#Fig. 4 approximately here#

#Fig. 5 approximately here#

#Table 4 approximately here#

3.4 Dynamics of silicate content and its correlations with clogging parameters

Similar to the changes of carbonate, the silicate content in the eight emitters increased slowly in the early stage (0-32 d) and increased rapidly in the middle and late stage (32-64 d) (Fig. A.5). The average content of carbonate in eight types of emitters and its correlation with *Dra* and *CU* are shown in Fig. 6 and Fig. 7, respectively. The content of silicate in all treatments had a significant linear negative correlation with *Dra* and *CU* ($p < 0.05$, $R^2 > 0.94$), and the fitting parameter *K* for *Dra*

and *CU* ranged -7.80~-3.64 and -9.39~-4.52, respectively. The silicate content varied significantly in different fertigation treatments ($p < 0.01$, Table 5). Compared to CK, the content of silicate in PPM and UP treatment increased by 37.6%-54.2% and 53.0%-82.8%, respectively. There was no significant difference between CK and APP treatment.

#Fig. 6 approximately here#

#Fig. 7 approximately here#

#Table 5 approximately here#

3.5 Dynamics of quartz content and its correlations with clogging parameters

The quartz content in the eight emitters increased slowly in the early stage (0-16 d) and then rapidly in both the middle and late stage (16-64 d) (Fig. A.6). The average content of carbonate in eight types of emitters and its correlation with *Dra* and *CU* are shown in Fig. 8 and Fig. 9, respectively.

The content of quartz in all treatments has a significant linear negative correlation with *Dra* and *CU* ($p < 0.05$, $R^2 > 0.90$), and the fitting parameter *K* for *Dra* and *CU* ranged -6.63~-2.97 and -7.98~-3.77, respectively. There was no significant difference in quartz content among different fertilization modes (Table 6). Besides, amorphous components only appeared in APP treatment, and the content also showed a trend with a gradual increment at early stage and sharp increase in the later stage (Fig. A.7), reaching 4.01-5.66 mg/cm² when the operation of the system ended (64 d).

#Fig. 8 approximately here#

#Fig. 9 approximately here#

#Table 6 approximately here#

4 Discussion

4.1 Mechanism of phosphorous fertilizer on emitter clogging

Many researches have reported that phosphorus fertigation could easily induce the precipitation of phosphate (Goyal, 2015; Haynes, 1985; Kafkafi and Tarchitzky, 2011; Mikkelsen, 1989). The results of the present study showed that phosphate precipitation did not occur under PPM and UP fertigation, while carbonate precipitates were formed. This was mainly due to the smaller solubility of carbonate (Zhou et al., 2019b), and Ca^{2+} and Mg^{2+} ions would preferentially react with bicarbonate in water source to form carbonate precipitation, therefore Ca^{2+} and Mg^{2+} ions were not available for the phosphate precipitation reaction.

After the application of UP, the content of carbonate reduced. Similarly, Yang et al. (2019) recently reported that the application of UP reduced the content of carbonates in a saline water drip irrigation system (Table 7). Compared with CK, PPM, and APP treatments, the application of UP reduced the pH of water (Table S1). When the acidity of water increases, the equilibrium of calcium and carbonate shifts to a unsaturated state, which reduces the content of carbonate ions, thus restraining the precipitation of carbonate (Hammes and Verstraete, 2002). Moreover, UP easily reacts with calcium ions, and forms soluble super phosphate and phosphate complexes (Hayden et al., 1982), which could be easily discharged to the outside of the emitters, thus further reducing the risk of calcium and magnesium precipitation. While the pH was higher in PPM and APP, causing the contents of carbonate were comparatively higher than UP treatments. However, unlike the results reported by Yang et al. (2019) that UP mitigated emitter clogging with saline water, we found that UP fertigation still aggravated emitter clogging. This is mainly due to the water used in this experiment contained some silicates, the reduction of pH could promoted the condensation of silanol

structure, and impelled the polymerization of silicate gel, and finally accelerated the deposition of silicates (Neofotistou and Demadis, 2004; Umar and Saaid, 2013).

Compared to non-fertigation, the application of PPM promoted the precipitation of carbonate and silicate, the result was fit well with the findings reported by Zhou et al. (2019b) (Table 7). Similarly, Bozkurt and Ozekici (2006) also found that the application of PPM and other fertilizers aggravated emitter clogging. The reason for the increase of silicate content was more like the application of UP reduced the pH of water quality to a certain extent, thus aggravating the deposition of silicate. Besides, the water alkalinity in PPM was comparatively higher than UP, which caused the content of silicate in PPM lower than UP treatments. As APP fertigation did not reduce the pH of water, thus there was no significant ($p>0.5$) difference between APP_0.30 and CK. The adsorption of PPM exacerbated the displacement between the particles and the ions, and thus promoted the precipitation and deposition of carbonate particles, and then attached to the surface of sediment particles, resulting in the carbonate content also showing a gradual increase trend (Zhou et al., 2019b). In addition, Li et al. (2019b) reported that the carbonate content showed significant exponential pattern with quartz content inside drip irrigation emitters ($p<0.05$), which concurred with results found in this study (Fig. A.8). This might be due to that, with the emitter clogging, the surface area of clogging substances inside emitters increased, which indirectly promoted the deposition of carbonate precipitates.

Compared to non-fertigation, the application of APP induced the most serious emitter clogging as dramatically promoted the deposition of carbonate and amorphous substances. The reason for the increment of carbonate content was like the application of PPM. As APP fertigation did not reduce the pH of water, carbonate precipitations were more easily promoted in comparison with UP and

PPM. Moreover, APP are usually mixtures of compounds with different chain lengths (Wærstad and McClellan, 1976), and produce colloidal precipitates with Ca^{2+} ions at a certain concentration. Besides, polyphosphate may shield Ca^{2+} at a specific concentration, thus preventing the formation of colloidal suspensions (Noy and Yoles, 1979) (Table 7). To determine the amorphous substances, FTIR and SEM-EDS were used to predict that the possible component. The results indicated that the amorphous substances were calcium phosphate (Fig. A.9, A.10), which further aggravated emitter clogging problem. Unlike APP, amorphous substances were not deposited in UP and PPM treatments, mainly due to the two P fertilizers were monomolecular compounds and Ca^{2+} and Mg^{2+} ions preferentially reacted with massive bicarbonate. Besides, all P fertilizers did not significantly ($p < 0.05$) affected the content of quartz, owing to the physicochemical characteristics of quartz is extremely stable.

It was found that under the same fertilization content, high concentration and short-term (HCST) fertilization accelerated the emitter clogging process. In fact, the fertilization was applied at the center of the whole operation time, and there was almost none fertilizer residue inside emitters after the system stopped running every day, which indicated that the clogging substances of the emitters were easier to form in the fertilization process. The HCST mode increased the rate of chemical reaction, accelerated the clogging process though reduced the fertigation time. The above combined effects eventually lead to the increase of clogging substances in the emitters (Fig. A.11). Besides, the application of P fertilizer greatly acted on the deposition of carbonate, silicate, and phosphate (APP treatments). Since the content of salt ions (such as Ca^{2+} , Mg^{2+} , HCO_3^-), silicate and microorganisms, it can be inferred that water quality might be an important factor that influence the clogging behavior of a phosphate drip fertigation system. For example, if the silicate content in

water is very low, the application of UP might could clean up the clogging substances. Thus, future research should assess the effect of water quality on emitter clogging in a phosphate drip fertigation system.

4.2 Anti-clogging strategies for drip phosphorus fertigation system

Based on the clogging behaviors in drip phosphorus fertigation system, some anti-clogging measures were further proposed.

(1) Selection of P fertilizer type

We suggest UP as the P fertilizer for drip irrigation system. Firstly, previous studies have demonstrated that fertigation with diammonium phosphate (DP), potassium phosphate monobasic (PPM), and calcium phosphate (CP) aggravated clogging issue ([Liu et al., 2017b](#); [Yang et al., 2019](#); [Zhou et al., 2019b](#)), also the application of APP greatly worsened clogging issue. Though phosphoric acid (H_3PO_4) could be used to avoid emitter clogging, however, storage and field application of phosphorus acid could be toxic for farmers' health and corrode drip irrigation equipment ([Kafkafi and Tarchitzky, 2011](#)). It was found that the emitter clogging was relatively light under UP treatment after fertilization, and its risk was not significantly increased under low concentration conditions. Secondly, the price of urea phosphate is relatively low. The purchasing prices of UP, PPM and APP mainly ranged 650-840 \$/t, 870-1090 \$/t and 945-1310 \$/t ([China Fertilizer website, 2019](#)), respectively. Although the price of DP (540-760 \$/t) and CP (360-430 \$/t) was lower than UP, DP and CP are not recommended in a drip irrigation system due to both fertilizers would greatly exacerbate emitter clogging. Besides, the soil application amount of DP and CP would be much higher than fertigation with UP. Thirdly, crops only absorb monovalent phosphorus in $H_2PO_4^-$ form ([Marschner, 2011](#)), as UP fertigation could reduce the pH of water and soil, and promote the

conversion of phosphate to H_2PO_4^- form, thus enhance phosphorous availability and use efficiency (Kafkafi and Tarchitzky, 2011). Moreover, drip irrigation technology is mainly used in arid and semi-arid areas, where saline-alkali soils are common (Jordán et al., 2004). Thus, UP can be used as a soil amendment to mitigate soil salinity and alkalinity in arid and semi-arid areas (Ali and Stroehlein, 1991), which could further increase P availability. It is remarkable that in few cases, drip fertigation with P fertilizer may be used in acid soil. To avoid the risk of soil acidification, UP should not be used in acid soils, or some soil amendment measures should be taken when using UP. Besides, future studies should investigate the movement and availability of different types of phosphorus in soil.

(2) Selection of P fertilizer concentration

The results of this study indicated that low concentration and long-term (LCLT) P fertilization effectively relieved the emitter clogging problem. Moreover, LCLT mode could further promote the migration of P fertilizer in soil and increase the availability of P (Kafkafi and Tarchitzky, 2011). However, the optimum concentration of P fertilizer differs in crops (Azcón et al., 2003; Havlin et al., 2016). Thus, the selection of P fertilizer concentration should take emitter clogging and crops growth into consideration. We suggest choosing the lowest P concentration that met the demand for crops.

(3) Selection of emitters

Emitter structure is one of the most direct factors that affect emitter clogging. Fig. A.3 shows that the anti-clogging capacity of the eight emitters varied greatly. Interestingly, we found that anti-clogging capacity of emitters was mainly due to the emitter structural characteristics, instead of being affected by the different working conditions (seven groups in the experiment). Consequently,

we proposed an anti-clogging relative index (*CRI*) for rapidly selecting anti-clogging drip emitter products (Zhou et al., 2019a).

(4) Quartz and silicate control

There were a lot of quartz and silicate in the clogging material. Both are inherent particles in the water. It is necessary to further improve the filtration efficiency and reduce the content of solid suspended matter in the irrigation water. Capra and Scicolone (2007) pointed out that the total suspended solids concentration in irrigation water should not greater than 50 mg L⁻¹. However, this threshold did not take the effect of fertilizer application into account. Suspended solids in the water may serve as a bridge between physical flocculation and chemical adsorption (Liu et al., 2018). Thus, additional research needs to be carried out to quantify the control threshold of total suspended solids. Moreover, the majority of solids could be discharged to the outside of emitters' channel (Niu et al., 2013). Through optimizing the channel structure of the emitters, the self-propelled sand ability of the emitters could be improved (Feng et al., 2018). Regular lateral flushing could reduce the risk of sediment entering the emitters channel to avoid the deposition of quartz and silicate (Puig-Bargués and Lamm, 2013).

(5) Carbonate control

Increasing the irrigation frequency could reduce carbonate deposition during operation (Zhou et al., 2015). Besides, high frequency irrigation was also conducive to improving soil moisture content, promoting fertilizer utilization, and improving crop yield and quality under the same irrigation quota (Katsoulas et al., 2006). In drip irrigation systems, the most common way to remove carbonate precipitation is adding acid regularly (De Kreij et al., 2003), but the precipitation of silicate maybe increases greatly after adding acid. Therefore, the silicate content in the water source

should be reduced during the regular acidification process.

At last, we focus on the residual P in drip irrigation emitters. It was found that phosphate was deposited in the emitters after APP fertigation. Although phosphate precipitation did not occur under PPM and UP fertigation, in some cases (such as high salt water is applied), UP and MKP might induce phosphate precipitation (Yang et al., 2019). As P resources are scarce and non-renewable, it is necessary to recover P from the blocked emitters and the drip laterals. In fact, the clogged laterals could be recycled for producing the new drip line, the whole process consists of recycling, cleaning, smashing, blending and reprocessing. During the cleaning process, the phosphate precipitates could be washed away from the wall of flow channels of laterals, and sinking to the bottom of the cleaning basin. Then, the insoluble phosphate precipitations could be recycled.

5 Conclusions

The types and concentrations of P fertilizer greatly affected the emitter clogging issue. Compared with non-fertigation, emitter clogging was exacerbated with P fertigation, and APP induced the most serious clogging and UP caused the slightest clogging. X-ray diffraction demonstrated that APP fertigation drastically promoted the deposition of carbonate and phosphate, PPM accelerated the precipitation of silicates and carbonates, and UP drastically reduced carbonate deposition while significantly increase in silicate content. Under the same amount of applied fertilizer, low concentration and long-term (LCLT) fertilization effectively relieved emitter clogging. The results suggested PFDI should choose UP as the fertilizer type and adopt LCLT fertilization mode to mitigate emitter clogging.

Conflict of interest

The authors declare no financial or commercial conflict of interest.

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Captions for Figures and Tables in the Paper

Fig. 1 Layout of emitter clogging experimental system

Fig. 2 Correlation of emitter performance parameters between CK and fertilization treatments.

Fig. 3 Main mineral components of clogging substances found inside emitters.

Fig. 4 Changes on average \pm standard error of carbonate content for the different treatments across the experiment.

Fig. 5 Correlation between the carbonate content and the emitter performance parameters.

Fig. 6 Changes on average \pm standard error of the silicate content for the different treatments across the experiment.

Fig. 7 Correlation between the silicate content and the emitter performance parameters.

Fig.8 Changes on average \pm standard error of the quartz content for the different treatments across the experiment.

Fig.9 Correlation between the quartz content and the clogging parameters.

Table 1 Average \pm standard deviation of the water quality parameters.

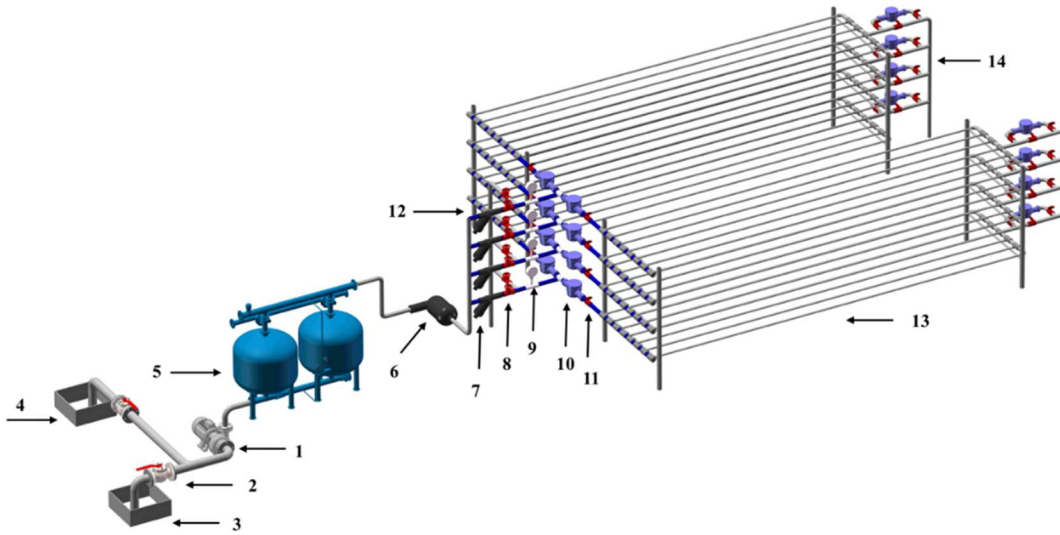
Table 2 Main parameters of the drip irrigation emitters.

Table 3 t-test analysis of the average discharge variation rate (*Dra*) and Christiansen of uniformity (*CU*) between pairs of treatments.

Table 4 t-test analysis of the carbonate content among different fertilization treatments.

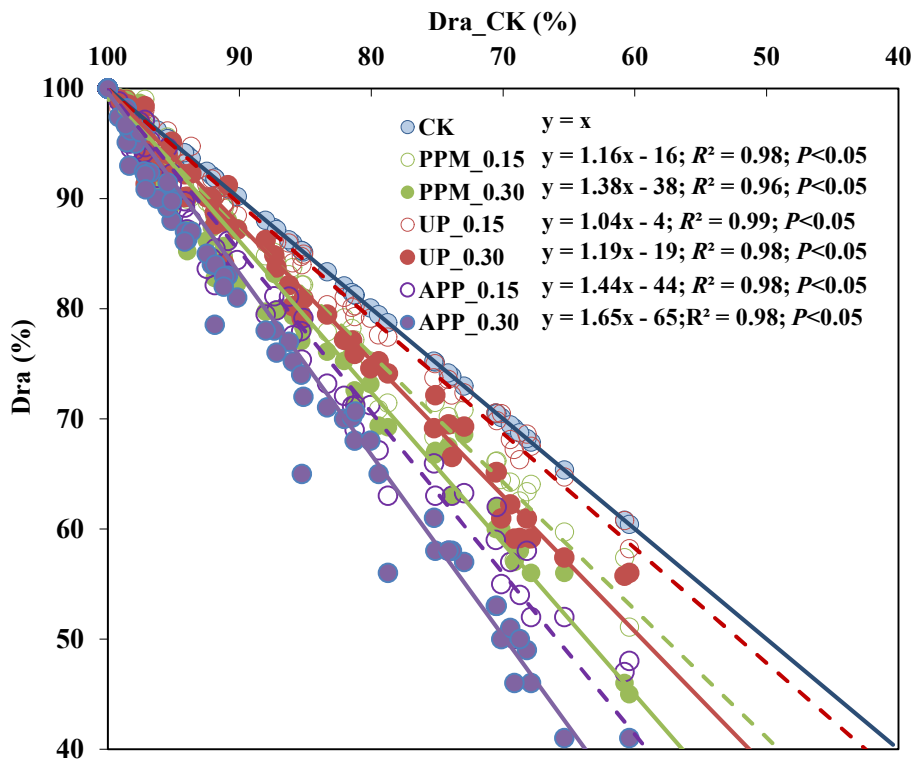
Table 5 t-test analysis of the silicate content between different fertilization treatments.

Table 6 t-test analysis of the quartz content among different fertilization treatments.

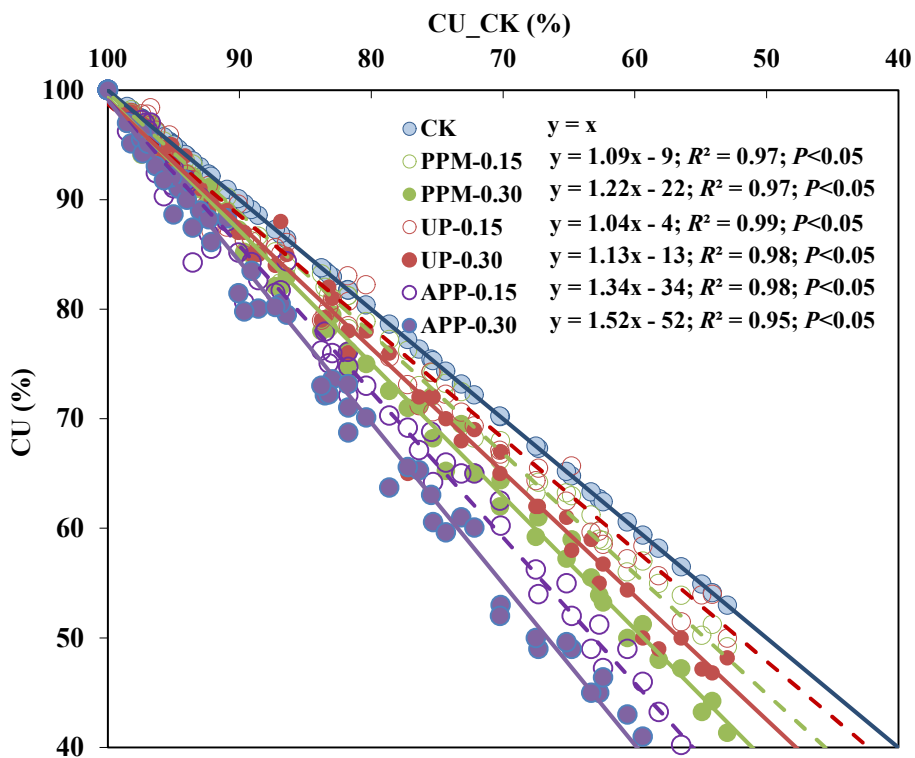


1-water pump, 2-butterfly valve, 3-fertigation sources, 4-water source, 5-sand filter, 6-disc filter, 7-small disc filter, 8-precise adjusting valve, 9-pressure gauge, 10-flow meter, 11-small ball valve, 12-pipes, 13-drip laterals, 14-flushing devices

Fig. 1. Layout of emitter clogging experimental system.



(a) Dra



(b) CU

Fig. 2. Correlation of emitter performance parameters between CK and fertilization treatments.

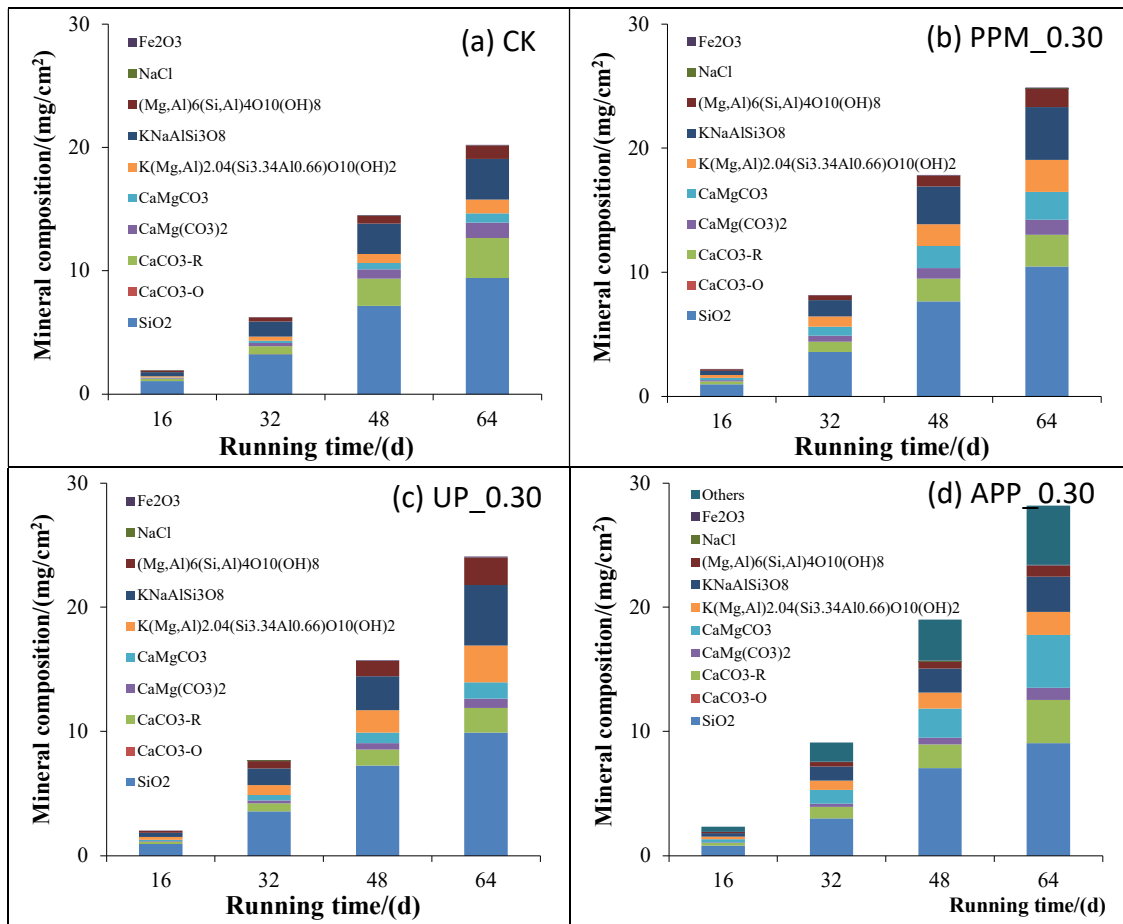


Fig. 3. Main mineral components of clogging substances found inside emitters. As the mineral components were similar in the different types of emitters, only results of FE1 are shown as an example.

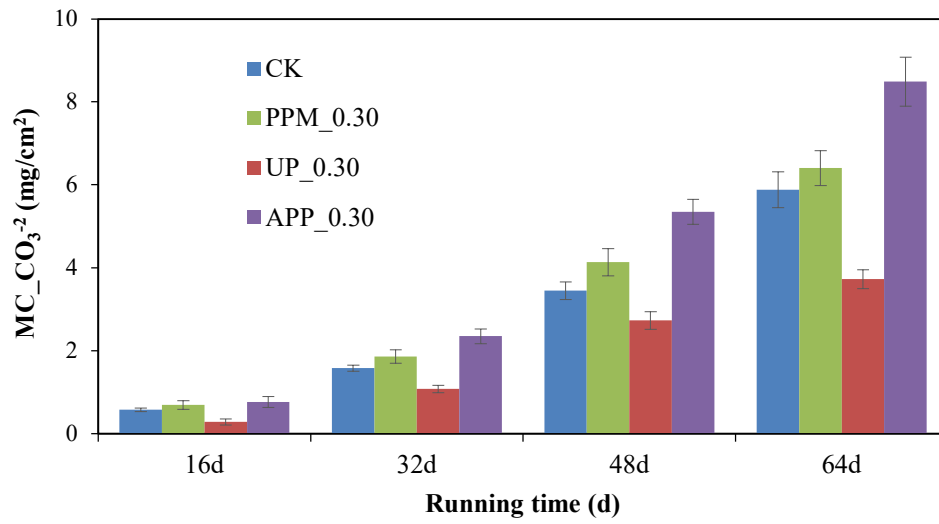


Fig. 4. Changes on average \pm standard error of carbonate content for the different treatments across the experiment.

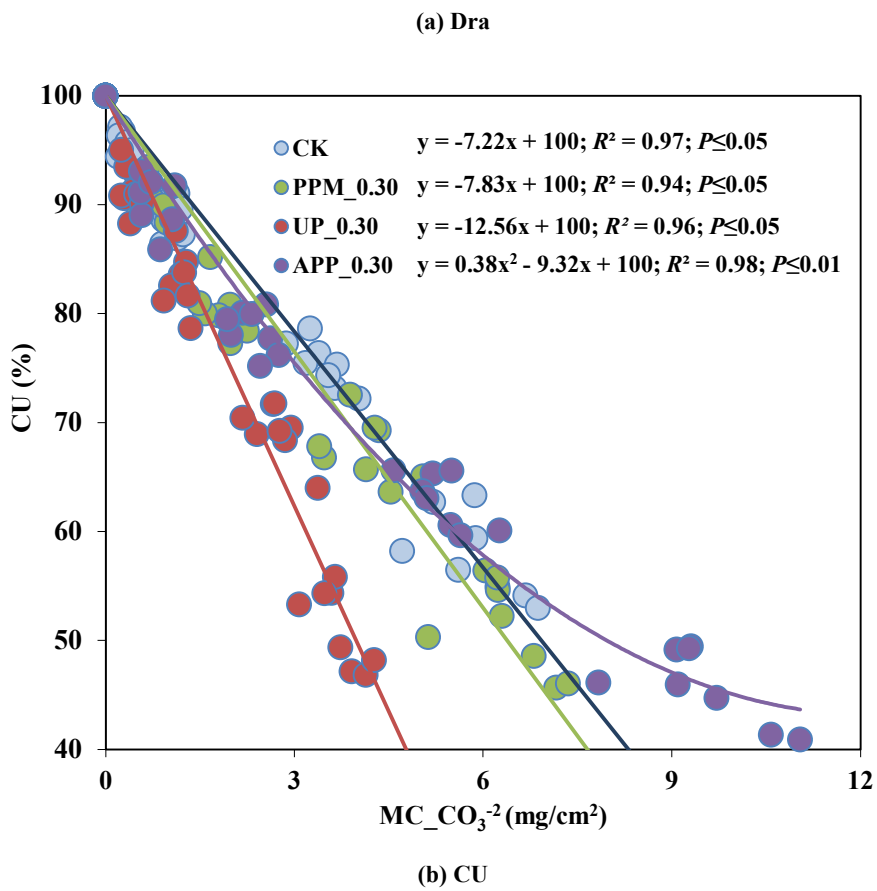
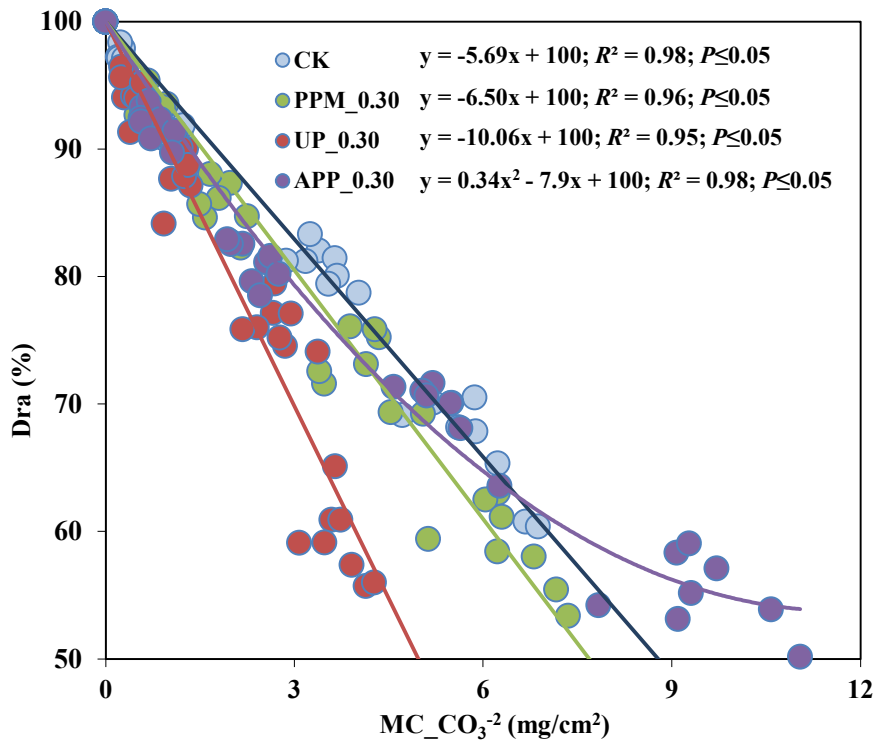


Fig. 5. Correlation between the carbonate content and the emitter performance parameters.

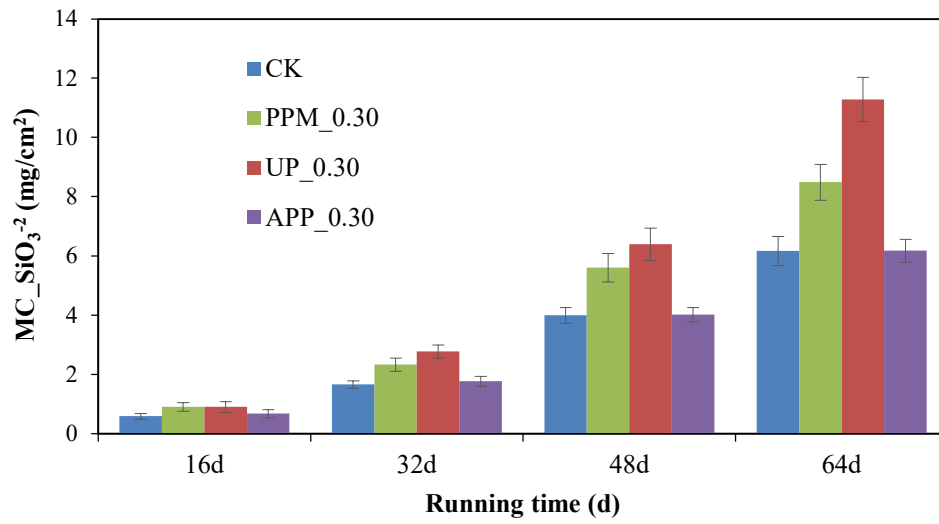
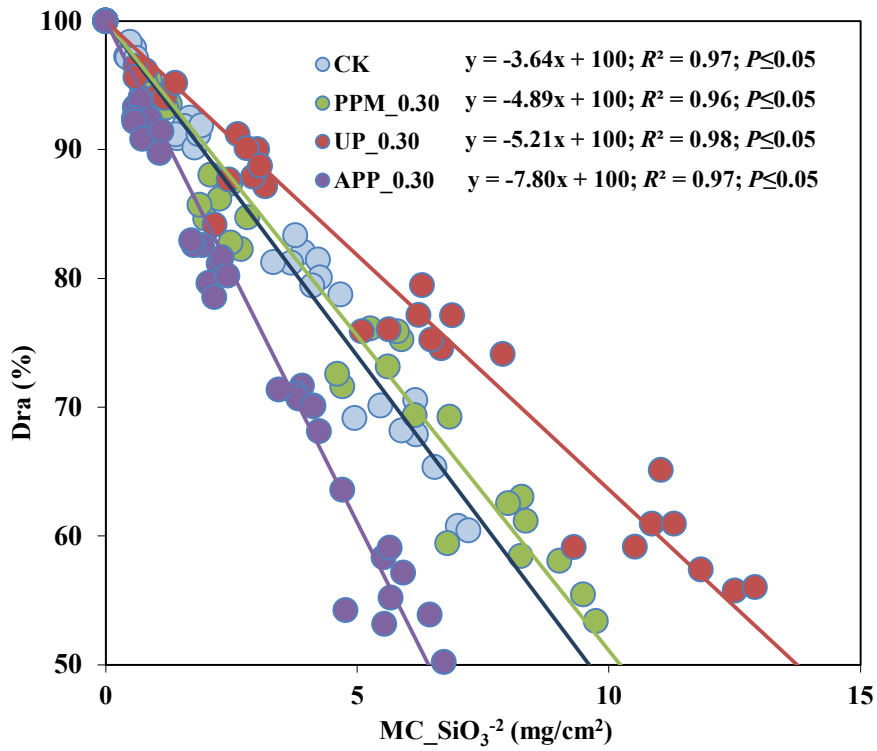
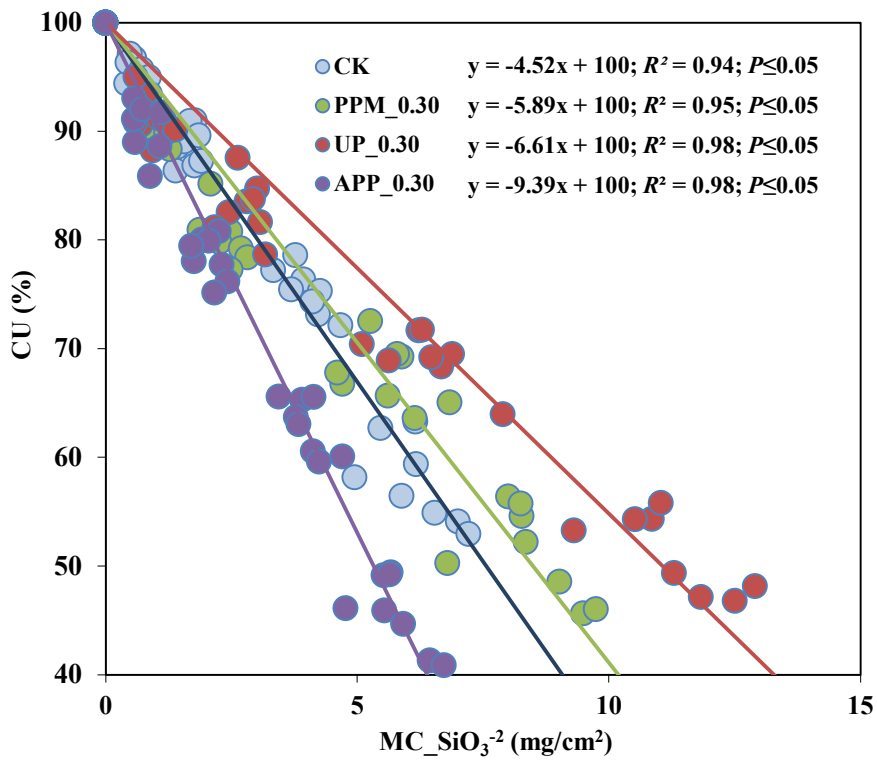


Fig. 6. Changes on average \pm standard error of the silicate content for the different treatments across the experiment.



(a) Dra



(b) CU

Fig. 7. Correlation between the silicate content and the emitter performance parameters.

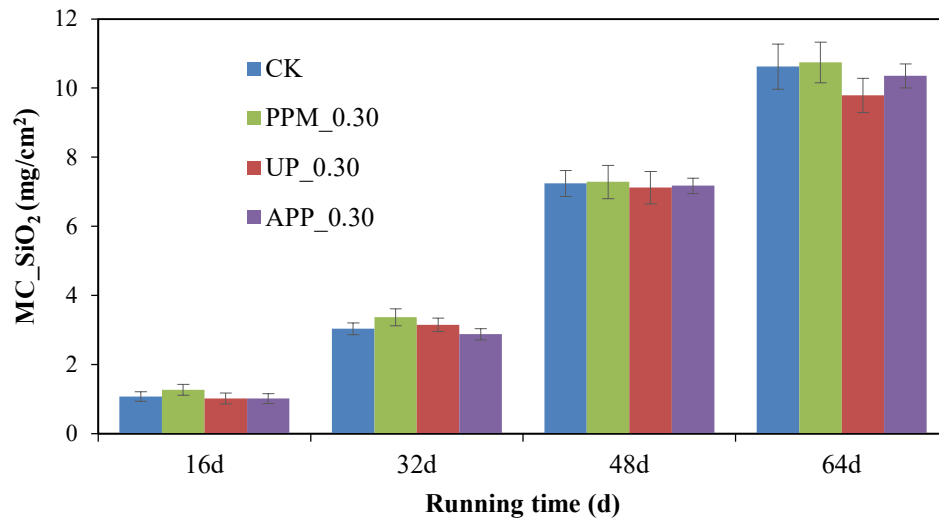
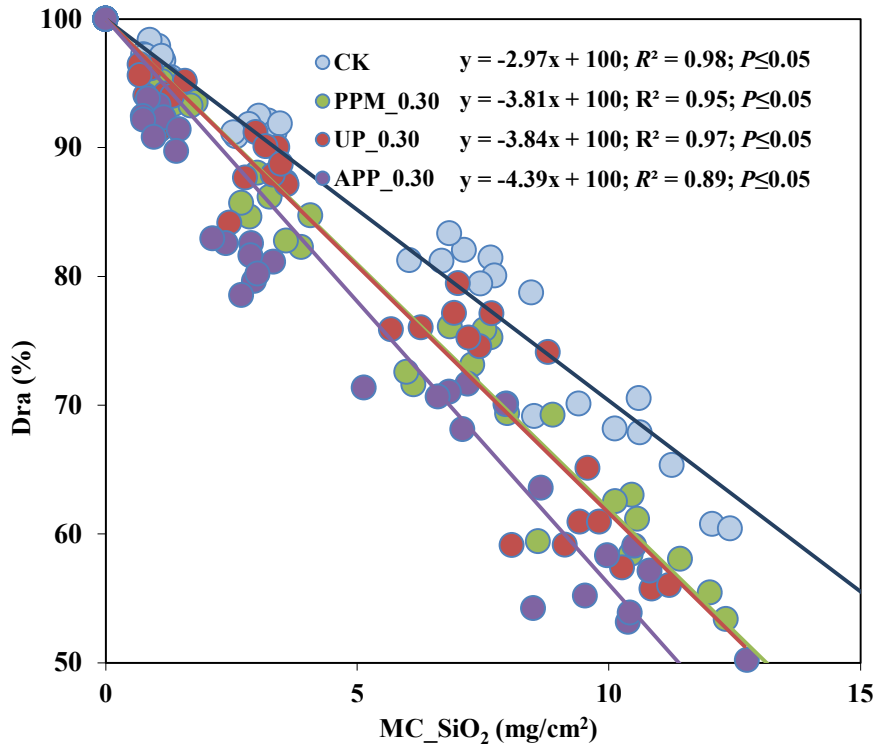
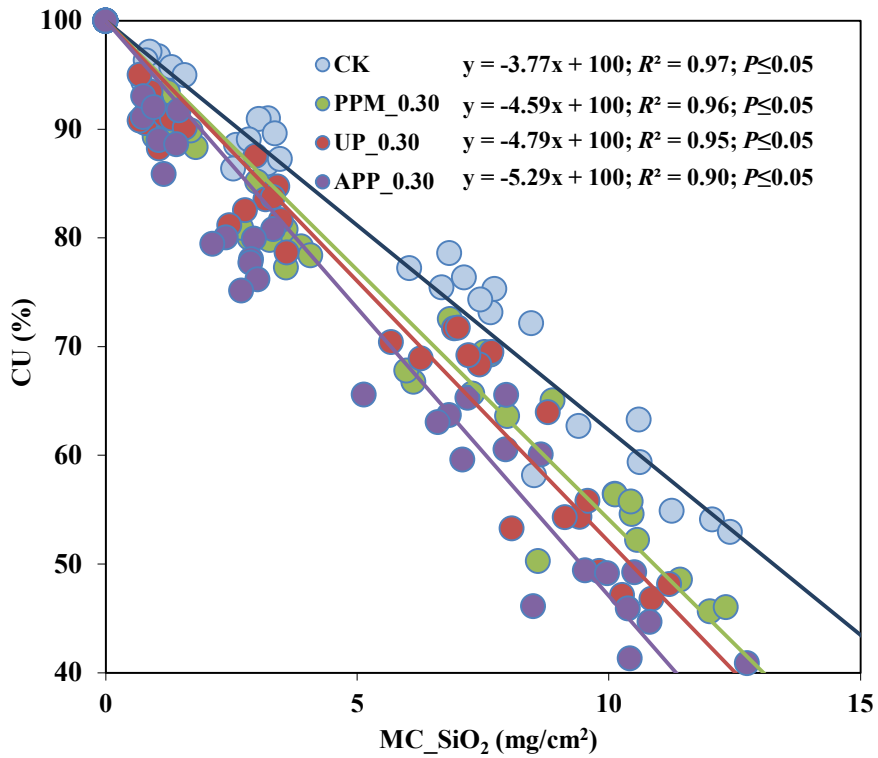


Fig. 8. Changes on average \pm standard error of the quartz content for the different treatments across the experiment.



(a) Dra



(b) CU

Fig. 9. Correlation between the quartz content and the clogging parameters.

Table 1. Average \pm standard deviation of the water quality parameters.

pH	Total suspended solids (mg L ⁻¹)	Electrical conductivity (μ s cm ⁻¹)	COD (mg L ⁻¹)	BOD ₅ (mg L ⁻¹)	Total phosphorus (mg L ⁻¹)	Total nitrogen (mg L ⁻¹)	Ca ²⁺ (mg L ⁻¹)	Mg ²⁺ (mg L ⁻¹)
7.5 \pm 0.4	41.2 \pm 9.3	790 \pm 17	17.8 \pm 2.4	12.7 \pm 2.6	0.81 \pm 0.14	1.47 \pm 0.23	34.7 \pm 4.8	25.9 \pm 1.7

Note: COD and BOD₅ indicate chemical oxygen demand and five-days biochemical oxygen demand, respectively. pH and electrical conductivity were measured by a pH meter (manufacture: Rex, China; type: PHSJ-6L) and a conductivity meter (manufacture: Rex, China; type: DDSJ-319L). Other water quality parameters were tested in a professional third-party institution (Pony testing international group Co., Ltd., China). The content of total suspended solids, COD, BOD₅, total phosphorus, total nitrogen, was tested by gravimetric method, dichromate method, dilution and inoculation method, ammonium molybdate spectrophotometry, potassium persulfate oxidation ultraviolet spectrophotometry, respectively. Both of Ca²⁺ and Mg²⁺ were tested by inductively coupled plasma optical emission spectrometry.

Table 2. Main parameters of the drip irrigation emitters.

Emitters	Rated discharge (L h ⁻¹)	Flow channels' dimensions (mm)			Discharge coefficient	Flow index
		Length	Width	Depth		
FE1	2.00	24.5	0.61	0.60	6.5	0.61
FE2	1.90	73.0	0.62	0.65	6.3	0.50
FE3	1.75	51.0	0.64	0.58	5.7	0.51
FE4	1.60	27.1	0.56	0.50	5.4	0.52
FE5	1.60	19.0	0.55	0.49	5.2	0.51
FE6	1.40	47.0	0.56	0.55	4.9	0.51
FE7	1.20	52.5	0.55	0.63	3.6	0.51
FE8	0.95	85.0	0.55	0.51	3.1	0.51

Note: The flow channels' dimensions were obtained by an electron microscope after peeling the emitters, and the rated discharge, discharge coefficient, flow index were tested according to China standard (GB/T17188-1997).

Besides, $q = k \times h^x$, where q , k , and x indicate the emitter discharge, discharge coefficient, and flow index, respectively.

Table 3. t-test analysis of the average discharge variation rate (*Dra*) and Christiansen of uniformity (*CU*) between pairs of treatments.

Parameter	CK & PPM_0.15	CK & PPM_0.30	CK & UP_0.15	CK & UP_0.30	CK & APP_0.15	CK & APP_0.30	PPM & UP	PPM & APP	UP & APP	PPM_0.15 & PPM_0.30	UP_0.15 & UP_0.30	APP_0.15 & APP_0.30
<i>t</i>	10.19**	11.78**	1.06NS	10.80**	11.56**	11.68**	11.29**	13.04**	15.13**	9.69**	8.97**	8.39**
<i>Dra</i>												
<i>r</i>	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
<i>RMSE</i>	0.29	0.47	0.04	0.31	0.59	0.81	0.19	0.30	0.40	0.27	0.29	0.33
<i>t</i>	13.76**	14.34**	2.89NS	15.43**	13.91**	14.61**	9.53**	9.88**	14.63**	9.15**	11.86**	9.94**
<i>CU</i>												
<i>r</i>	0.99	0.98	0.99	0.99	0.99	0.98	0.99	0.99	0.99	0.99	0.99	0.99
<i>RMSE</i>	0.29	0.43	0.05	0.32	0.4	0.58	0.17	0.2	0.25	0.23	0.25	0.28

Note: NS indicates not significant, **indicates extremely significant ($p < 0.01$); *r* indicates the correlation coefficient, *RMSE* indicates the root-mean square error.

Table 4. t-test analysis of the carbonate content among different fertilization treatments.

Mineral	Parameter	CK &	CK &	CK &	PPM_0.30 &	PPM_0.30 &	UP_0.30 &
		PPM_0.30	UP_0.30	APP_0.30	UP_0.30	APP_0.30	APP_0.30
	<i>t</i>	-9.20**	3.78**	-7.10**	-6.51**	-5.27**	-5.89**
Carbonate	<i>r</i>	0.99	0.98	0.99	0.99	0.99	0.98
	<i>RMSE</i>	0.05	0.14	0.20	0.16	0.18	0.34

Note: **indicates extremely significant ($p < 0.01$).

Table 5. t-test analysis of the silicate content between different fertilization treatments.

Mineral	Parameter	CK & PPM_0.30	CK & UP_0.30	CK & APP_0.30	PPM_0.30 & UP_0.30	PPM_0.30 & APP_0.30	UP_0.30 & APP_0.30
	<i>t</i>	-6.88**	-5.93**	-2.30NS	4.74**	5.43**	5.21**
Silicate	<i>r</i>	0.99	0.99	0.99	0.99	0.99	0.99
	<i>RMSE</i>	0.14	0.30	0.02	0.17	0.17	0.33

Note: NS indicates not significant, **indicates extremely significant ($p < 0.01$).

Table 6. t-test analysis of the quartz content among different fertilization treatments.

Mineral	Parameter	CK & UP-0.30	CK & PPM-0.30	CK & APP-0.30	UP-0.30 & PPM-0.30	UP-0.30 & APP-0.30	PPM-0.30 & APP-0.30
	<i>t</i>	1.07NS	-2.77NS	2.92NS	-2.13NS	-0.49NS	2.81NS
Quartz	<i>r</i>	0.99	0.99	0.99	0.99	0.99	0.99
	<i>RMSE</i>	0.20	0.06	0.05	0.19	0.17	0.08

Note: NS indicates not significant.

Table 7. Comparison of different chlorination references.

Fertilizer type	Fertilizer content	Water source	Emitter clogging	Reference
UP	0.15g/L & 0.30g/L	Surface water	UP_0.15 g/L treatment did not significantly aggravate emitter clogging	This study
UP	EC (0.5-6 dS m ⁻¹)	Saline water	UP relieved emitter clogging	Yang et al. (2019)
PPM	0.15g/L & 0.30g/L	Surface water	PPM accelerated the deposition of carbonate and silicate	This study
PPM	0.15g/L	Surface water	PPM accelerated carbonate content	Zhou et al. (2019b)
PPM and other fertilizer ^a	561 kg ha ⁻¹	Ground water	Fertigation treatments aggravated emitter clogging	Bozkurt and Ozekici (2006)
APP	0.15g/L & 0.30g/L	Surface water	APP drastically promoted the deposition of carbonate and phosphate	This study
APP	—	—	APP could shield Ca ²⁺ at suitable concentration	Noy and Yoles (1979)

Note: UP, urea phosphate; PPM, potassium phosphate monobasic; APP, ammonium polyphosphate; EC, Electrical conductivity. ^a the fertilizer were PPM + Ca(NO₃)₂ + KNO₃ + K₂SO₄ + NH₄NO₃ and PPM + NH₄NO₃ + K₂SO₄.