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Prevention and treatment of drip emitter clogging: a review of various innovative methods

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ABSTRACT

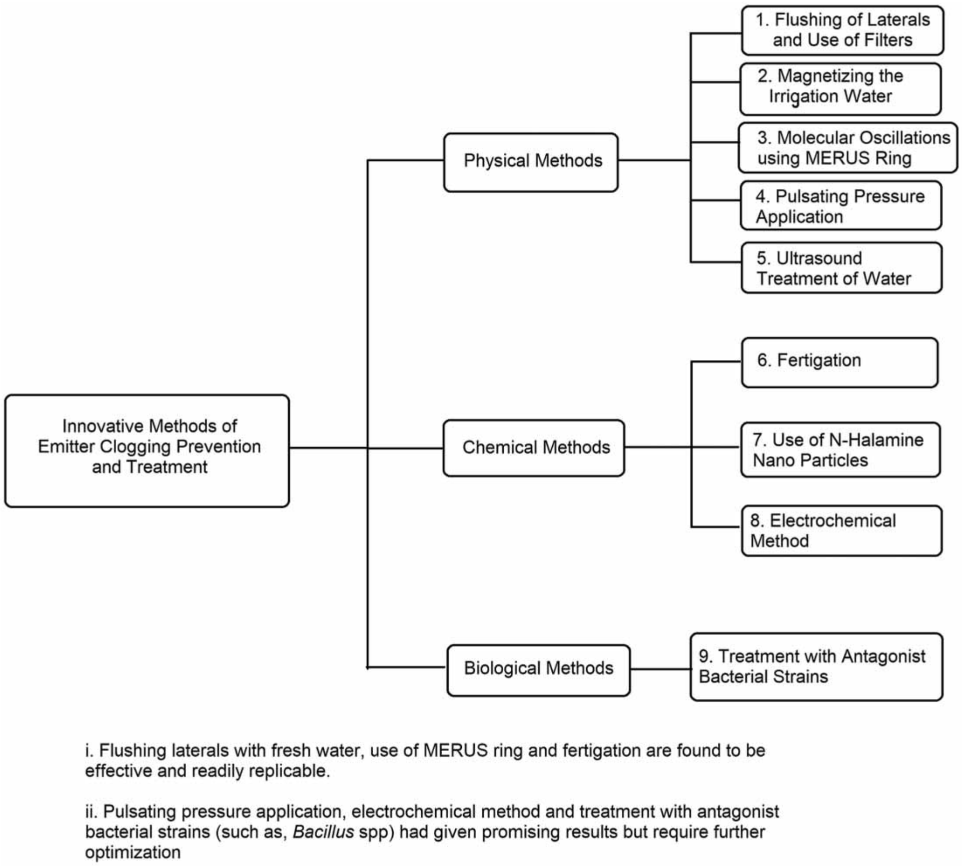
Various new and innovative methods of prevention and treatment of emitter clogging were demonstrated by researchers in recent years. A total of nine such innovative approaches were reviewed, classifying them under three broad categories, viz., physical, chemical and biological methods. Though flushing of laterals is a known method, it was found that increasing its frequency and at higher pressures improved the emission rate and uniformity of the emitters significantly. When Treated Waste Water (TWW) is used for irrigation, flushing with fresh water after every five irrigations effectively removed the emitter clogging. Among the various physical methods reviewed, use of MERUS ring, application of pulsating pressure with triangular wavefront and ultrasound treatment were found to be effective in removing composite clogging problem in drip emitters. Among the chemical methods, fertigation using urea phosphate (UP) at low concentrations for longer periods reduced the pH of irrigation water and contributed to the removal of chemical precipitates from the lateral pipes and emitters. Use of antagonist *Bacillus* bacterial strains helped in removing not only $CaCO_3$ precipitation but also biofouling due to the use of TWW in the drip systems. However, this method needs to be further developed and optimized for its effectiveness and replicability.

Key words: clogging of drip emitter, hydraulic performance of emitter, treatment of clogging

HIGHLIGHTS

- Conventional methods of prevention and treatment of emitter clogging are not very effective and require repetitive operations.
- Nine new and innovative methods from recent research work are reviewed and evaluated.
- Flushing of laterals with fresh water, use of MERUS ring and fertigation practice are found to be effective and ready for replication.

GRAPHICAL ABSTRACT



INTRODUCTION

Emitter clogging with foreign material is an annoying problem in drip irrigation systems. The clogging takes places due to the gradual deposition of sediments, organic matter and microorganism inside the lateral tubes and emitters. This deposition adversely affects the emitter discharge as well as the uniformity of discharge across the emitters (Yavuz *et al.* 2010). Emitters are more prone to clogging due to their smaller size and labyrinth flow path geometry.

The drip emitter clogging is broadly classified into three types, viz., physical, chemical and biological (Bucks *et al.* 1979; Liu & Huang 2009). Physical clogging is due to the suspended solid particles in water. Chemical clogging may occur due to the precipitation and deposition of dissolved iron, calcium and magnesium salts in water. Biological clogging, also named as biofouling, is clogging of emitter flow paths due to the growth and deposition of microorganisms such as fungi, algae and bacteria. Favorable conditions in drip irrigation systems may result in rapid growth of several species of fungi, algae and bacteria, resulting in slime and bio-film build-up. This build-up of slime may block the water flow partially or fully, affecting the discharge from the emitters. Further, some bacterial species may cause the precipitation of iron, manganese and sulfur compounds dissolved in irrigation water, resulting in emitter clogging (Wu *et al.* 2004).

Physical and chemical clogging are the predominant forms in fresh water irrigation, including that using groundwater. Biological clogging is a predominant problem when treated waste water (TWW) or reclaimed water (RW) is used in drip irrigation system (Li *et al.* 2009). In a typical drip system, it is common that composite clogging takes place involving all the three types of clogging, though varying in the intensity of each depending on the water quality. The earliest of the research works focussed on the assessment of quality and suitability of irrigation water for drip irrigation (Bucks *et al.* 1979; Nakayama & Bucks 1991). Yanfang *et al.* (2015) studied emitter clogging using water of known hardness levels and concluded that higher levels of dissolved salts in water pose increased risk of clogging. Bounoua *et al.* (2016) studied physical clogging of emitters by using irrigation water loaded with predetermined quantities of suspended particles. Some studies focussed on the emitter clogging behavior and biofilm formation characteristics on different types of drip emitters by using treated waste water (Dazhuang *et al.* 2009; Li *et al.* 2009; Fengzhen *et al.* 2017).

Filtration of irrigation water, flushing of laterals, acid injection and chlorination are the four widely known methods applied to control different forms of emitter clogging (Gilbert *et al.* 1979). Physical clogging can be eliminated with the use of filters and screens. Chemical precipitation can be controlled with acid injection. Chlorination is used in the prevention and treatment of emitter clogging caused by algae and bacteria. In a recent work, Shi *et al.* (2022) dealt in detail various causes and conventional treatment methods against physical, chemical and biological clogging, with emphasis on chemical clogging due to the fertigation practice and use of saline water for irrigation. However, various researchers demonstrated new and innovative approaches to prevent or treat emitter clogging recently. All these methods and approaches may be broadly divided into (i) preventive methods and (ii) treatment methods. Preventive methods involve taking preventive steps, such as, installation of filters, frequent flushing of laterals etc., that avoid clogging of emitters. Treatment methods are those which try to treat and remove the clogging materials, after they get deposited on the emitter flow areas.

More discerning classification is the segregation of the preventive or treatment methods based on the nature of material/method used against the emitter clogging. They may be broadly classified as (i) physical methods, (ii) chemical methods and (iii) bacterial methods. While most of the preventive measures fall under the first class, second and third classes encompass various treatment methods. In most cases, each of these methods is effective against a particular type of clogging, such as physical, chemical or biological. For example, chlorination, which is a chemical method, is effective against biological clogging.

In this article, a review of nine new and innovative methods against emitter clogging is presented. Some of them used only freshwater sources (canal water and groundwater) and some of them compared the results of the preventive or treatment method for freshwater and TWW/RW. Though the flushing and filtration methods are well-known conventional methods, few research works delved on effects of varying the flushing pressure as well as frequency and hence they were included for review. Table 1 lists different methods reviewed by this study.

Table 1 | Various innovative methods of prevention and/or treatment of emitter clogging

Physical methods	Flushing of laterals and use of filters Magnetizing the irrigation water Generating molecular oscillations using MERUS ring Pulsating or dynamic pressure application Ultrasound treatment of water
Chemical methods	Fertigation Application of N-halamine nano particles (NPs) Electrochemical method
Biological methods	Treatment with various antagonist bacterial strains (*Bacillus* spp, *Burkholdria* spp, *Lactococcus garvieae and Bacillus amyloliquefaciens)*

PHYSICAL METHODS

Flushing of laterals and filtration against emitter clogging

Flushing is the process of operating the drip irrigation system by opening the end-caps. This process dislodges undesirable substances from the lateral pipes and emitters and facilitates their excretion with water. Puig-Bargués *et al.* (2010) carried out experiments on flushing frequency and its influence on emitter clogging when treated waste water is used as input to the drip irrigation systems. Surface and sub-surface drip systems were evaluated, having both pressure compensating (PC) and non-pressure compensating (NPC) emitters. The experiment was done for a total of three irrigation seasons spanning over 540 hrs each. Three different flushing treatments, viz., (i) no flushing, (ii) one flushing end of each irrigation period and (iii) monthly flushing, were applied. The variation of flow rate at the drip mainline was measured during the experiment. The monthly flushing was found to be most effective in improving the flow rates in the drip lines. The flushing operations gave significant improvement in flow rates in case of surface drip lines having PC and NPC emitters, but not found effective in case of NPC emitters in subsurface drip lines.

Yu *et al.* (2018) conducted the flushing experiments on drip emitter lines considering the influence of three variables, viz., flushing pressure, flushing frequency and flushing time. Laterals having flat type emitters were used in this experiment. The discharge and the particle size distribution in the discharged water from the emitters were periodically monitored. A laser particle size analyzer was employed for the study of particle size distribution. When compared with those laterals not subjected to flushing, flushing operation extended the functional life of treated laterals by 35.2% on average. It was observed that coarser particles in water are more easily trapped in the emitters, causing the clogging effect. The flushing operation effectively dislodged and removed the sediments along with the water. Increasing the flushing pressure had more influential effect on the removal of coarse particles. But, longer flushing times helped to dislodge and excrete finer particles settled in the laterals and emitters.

Li *et al.* (2019) conducted studies on the influence of water quality and flushing frequency on the emitter hydraulic performance, when the treated effluent water is used for drip irrigation. Combinations of two water types (treated effluent and fresh groundwater) and two flushing frequencies (after every irrigation event and after every five irrigation events) were studied against the control treatment of 'no flushing'. Treated effluent samples had total suspended solids of 57–172 mg L^{-1}, electrical conductivity of 3.5–6.5 dS m^{-1} and the total bacterial count of 1,000–45,000 CFU mL^{-1}. In contrast, the fresh groundwater samples were found with suspended solids of 18–25 mg L^{-1}, dissolved solids of 0.5–0.9 dS m^{-1} and a total bacterial count of 0–160 CFU mL^{-1}. Lateral pipes with flat inline labyrinth emitters were used for this experiment. The irrigation duration was one hour daily for a total period of 91 days. Emitter discharge was recorded periodically. At the end of the study, the mean emitter discharge decreased about 7–8% in the fresh water treatment, 9% in the treated effluent treatment and 13% in the control treatment. Using fresh groundwater for flushing reduced emitter clogging better than using treated effluent. Fresh groundwater, with much lesser load of suspended solids, dissolved salts and microorganism, caused less fresh deposition during the flushing operation and was effective in dislodging the already formed deposits during the irrigation operations. But there was no significant difference found between the two flushing frequencies. The study concluded that, when treated effluent is used for drip irrigation, emitter clogging should be controlled by flushing with fresh water every five irrigation events.

Use of various filters (sand, disk and screen filters), is common in drip irrigation systems for pre-screening and filtering the irrigation water against sediment loads. Presence of higher sediment loads, organic matter and microorganisms rapidly cause composite clogging in drip emitters. To resolve this issue, Liu *et al.* (2021) studied the benefits of using a horizontal roughing filter (HRF) to prevent composite clogging of drip emitters. The HRF was tested by varying the thickness of filter bed from 0.20 m to 0.80 m. The results indicated that, compared with the control treatment without HRF, the HRF treatment improved the uniformity coefficient and the average discharge ratio of the drip irrigation system by 9.2–27.1% and 12.3–22.5% respectively, for varying thickness of the HRF filter bed. The HRF effective removed the larger physical particles in irrigation water and prevented their deposition on the emitters. Thus, the discharge from individual test emitters and its variability across the emitters reduced significantly. The HRF bed thickness of 0.60 m was found to be optimum.

Magnetization of irrigation water

Kiani *et al.* (2015) studied the effect of magnetization of irrigation water on the emitter clogging for different levels of water salinity. Two different methods of magnetization were installed on the feed sublines, such as electromagnet and permanent (ceramic) magnet. The magnetization is expected to alter the structure and physical properties of water, such as density, salt solubility and deposition ratio of solid particles. Relatively weak magnetic influence is known to increase the viscosity of water, caused by stronger hydrogen bonds in the water molecules. A field experiment was done with magnetic (M), non-magnetic (N) and acidic water (A). In each case, water at three salinity levels, viz., well water (S1), saline water of 7 dS m^{-1} (S2) and saline water of 14 dS m^{-1} (S3), was applied. The results indicated that, in case of well water, there is no relative advantage of using magnetized water over non-magnetized water. However, in case of water with higher salinity levels, there is minor advantage of using magnetized water in terms of lesser emitter clogging levels. Also, the treatment-A produced worser results of emitter discharge and uniformity compared to both treatment-M and treatment-N. Overall, this study found that the benefits of using magnetized water were only marginal.

In a similar study done by Khoshravesh *et al.* (2018), The magnetized and non-magnetized water were applied through drip irrigation and compared their effect on drip emitter clogging. Three variants of irrigation water were used, viz., well water, well water added with 150 mgL^{-1} $CaCO_3$ and well water added with 300 mgL^{-1} $CaCO_3$, in this experiment. In contrast to the findings of Kiani *et al.* (2015), it was concluded that there is a significant positive effect on emitter discharge and uniformity of discharge when magnetized water was used in irrigation. For the non-magnetic water treatment, end of the experiment, the average reduction in discharge was 10%, while it was 2% for the magnetic water treatment. Also, the average reduction in distribution uniformity for the non-magnetic water treatment was 6%, while it was 2% for the magnetic water treatment. The stark difference in results produced by Kiani *et al.* (2015) and Khoshravesh *et al.* (2018) rises the concern about the consistency of results from magnetization.

Molecular oscillation technology for removing emitter clogging

Barati *et al.* (2014) evaluated a new and novel product called MERUS ring, manufactured by MERUS, Germany. The MERUS ring is a simple metallic device that is fixed to the water carrying pipes (Figure 1). This device emits specifically modulated molecular or lattice oscillations into the water and modify the natural molecular oscillations of different substances carried by or dissolved in water. Thus, the undesirable sediments and chemical precipitates disintegrate and get flushed out with water from the pipelines. In contrast to the repetitive nature of conventional treatment methods, the MERUS ring works on its own after the one-time installation. It removes the clogging material already deposited in emitters and pipes, as well as retards the precipitation of dissolved salts present in the water. There is a fundamental and natural molecular oscillation for every substance contained in fluids. MERUS ring emits new active oscillations from the carrier hardware made of silica-aluminum alloy in its core, without the need for any external energy source. The active oscillations modify the characteristics of the substances by resonating in-phase with their natural molecular oscillations. The modified oscillations at the molecular level are spread through the water to the emitter flow paths through the lateral pipes of the drip system. As a result, the clogging substances that are carried by water as well as the those already got deposited on the emitters transform, disintegrate and become unstable. These clogging substances are finally excreted along with water through the emitter outlets.

Figure 1 | MERUS ring of 63 mm internal diameter (representative picture).

Barati *et al.* (2014) installed and tested a MERUS ring of 1.9 cm diameter on a drip irrigation device for its effectiveness. The drip system contained 2 subunits, one for treatment with the ring and the other one without the ring (control). Each of these subunits have nine laterals of 25 m length each. Each lateral pipe had a total of 50 inline long-path emitters at a spacing of 0.5 m. Each of these subunits were divided again into three sections, each one having three laterals, for three different levels (0.47, 1.7 and 2.9 dS m^{-1}) of water salinity treatments. End of 30 irrigation applications, at an interval of 3 days between each, it was found that the emitters treated with the MERUS ring have better hydraulic performance. The treatment with the ring resulted in much higher discharge ratio and uniformity of emission compared to that of control treatment. However, as the salinity level increased in the water, the clogging also increased progressively with time in both the treatments. The study concluded without any ambiguity that the MERUS ring is quite effective in clogging attenuation in the drip irrigation emitters at different levels of salinity in water.

Pulsating or dynamic pressure conditions in drip systems

Zhang *et al.* (2017a) studied the effects of pulsating versus constant pressure on average emitter flow rate (q), the Christiansen uniformity coefficient (Cu) and the location of clogged emitters. An automatic pressure control system was installed to produce pulsating pressure of desired qualities. A sine wave pulsating pressure was created, having an average pressure of 4 m, maximum pressure of 7 m and a minimum of 1 m. The pulsation period was kept as 30 s. As for constant pressure, it was kept at 4 m throughout the irrigation cycle. Sand particles of size lesser than 0.125 mm were mixed with water at a concentration of 2.0 g L^{-1} and stirred on a continuous basis throughout the irrigation period. Five drip tapes, each having 8 flat type emitters of 1.4 L h^{-1} nominal discharge at 4 m pressure, were used for the experiment. The short-cycle test method prescribed by ISO (2003) was used. Two irrigation trials were done, one each for constant pressure and pulsating pressure. In each trial, a total of 32 irrigation events were conducted, each irrigation event having 30 min of irrigation and 30 min of intermission. At the end of the irrigation cycle, the average emitter flow rate at constant pressure decreased to 63.5%, whereas the average emitter flow rate at pulsating pressure only decreased to 85.3% of the nominal discharge. It indicated that the emitters with constant pressure were clogged very seriously, whereas the emitters with pulsating pressure were mildly clogged. For the constant pressure, the uniformity coefficient decreased rapidly, and the magnitude of the decrease was about 68.2% at the end of the last irrigation event. However, for the pulsating pressure, the uniformity coefficient began to decrease after the 13th irrigation. The decline was mild, and the magnitude of the decrease was about only 22.6% at the end of the last irrigation event. It appeared that the pulsating pressure destabilized and dislodged the sand particles settled on the emitters, resulting in better flow performance. These results clearly confirm that the anti-clogging performance of emitters with pulsating pressure is better than that with constant pressure.

Zheng *et al.* (2017), in a similar experimentation, studied the particle movement characteristics in labyrinth channels under different forms of dynamic pressures, such as, trigonometric, triangular, step and rectangular waveforms. When the triangular pressure wavefront was used, they observed the shortest particle residence time in the flow stagnation areas of the emitters. They concluded that the triangular dynamic pressure form is effective in improving the anti-clogging performance.

Ultrasound method of treating the drip emitter clogging

An innovative technology using ultrasound was applied by Reinders & Van Niekerk (2018) to clean the drip lines. It was named as Greendrum technology, which uses only sound to clean and maintain the drip lines. The technology is an environmentally-friendly one without use of any chemicals in the process. Ten different models of emitters, both PC and NPC type, were used for this evaluation. In the laboratory setup, an ultrasound source was set up with a sound bath. A pulley system was motorized and that pulled the drip lines through the sound bath at a constant speed. Exposure to the high-frequency sound loosened the dirt particles in the drip lines and emitters. The flushing operation removed this dirt from the drip lines. At the end of this experiment, it was found that the coefficient of variation of the emitter discharge improved from 10.6% to 2.85%. Thus, it was found that the ultrasound treatment was extremely effective and totally restored the drip lines to their original performance.

CHEMICAL METHODS

Fertigation and clogging of emitters

Fertigation is the application of fertilizers to the plants through a venturi apparatus connected to the drip irrigation system (Figure 2). Generally, water-soluble fertilizers applied through the drip system avoid wastage of fertilizer and reduce overall costs to the farmers. There are a good number of studies on the effects of fertigation on emitter clogging. Depending on the type of fertilizer and the quality of irrigation water, fertigation may clog the emitters further or may remove existing clogs. Both these cases are reviewed below.

Samani & Nasab (2012) applied ammonium phosphate (46%), in two concentrations, to three different types of emitters and tested its effect on the emitter discharge and uniformity of discharge across emitters. Apart from a control treatment (F_0), Ammonium Phosphate at 5 g L^{-1} and 8 g L^{-1} were applied as treatment F_1 and F_2 respectively. Three types of emitters, viz., type A and B of inline long path with 4 L h^{-1} nominal discharge and type C of online long path with 8 L h^{-1} nominal discharge, were tested in this study. Three laterals, each having 16 emitters, one for each of the three types of emitters, were installed in the laboratory. The test was conducted for 72 days, 12 hours daily, at a constant pressure head of 7 m. The discharge from the emitters was measured every four

Figure 2 | Fertigation equipment connected to the drip irrigation system (representative picture).

days during the experiment. It was observed that the addition of fertilizer to the irrigation water accelerated the emitter clogging compared to the control treatment without the fertilizer. The reduction in both emission rate and the uniformity of emission were higher in case of F_1 and F_2 treatments compared to the F_0, for all the three emitter types. The percentage reduction in emission rate was 19.9, 20.78 and 11.0 for emitter types A, B and C in treatment F_0. Treatment F_1 reported 26.48, 26.49 and 16.65 and treatment F_2 reported 33.67, 33.06 and 18.59. This study recommended not to use ammonium phosphate in fertigation to avoid emitter clogging.

This study by Samani & Nasab (2012) reveals that there is need for careful selection of fertigation fertilizer to prevent emitter clogging. Ammonium phosphate, which is alkaline in solution, may be avoided and those fertilizers that reduce the pH of water in solution are to be preferred for fertigation purposes. There are a number of water-soluble fertilizers available in the markets that supply primary nutrients of nitrogen (N), phosphorus (P) and potassium (K) to the soil. The choice of the fertilizer has to be made based on its pH value in solution. Those fertilizers that do not cause major shift towards higher pH may be used for fertigation (Tiwari 2017). In a study similar to that of Samani & Nasab (2012), Gharcheh *et al.* (2015) carried out their fertigation experiments with ammonium nitrate and urea on different emitters and found that emitters clogged due to the bacterial slime formation with increased nitrogen availability. They observed a maximum discharge reduction of 39 and 44% while using ammonium nitrate and urea, respectively. They also concluded that the water quality and the geometric features of emitters pay a role in the extent of emitter clogging and discharge reduction.

Mostafa *et al.* (2021) conducted field experiments for longer period of 180 days at the Soils and Water Research Department, Nuclear Research Centre, Atomic Energy Authority, Inshas, Egypt. Variants of NPC and PC emitters of 2 L h^{-1} and 4 L h^{-1} were tested in these experiments. Water from an irrigation canal with pH of 7.53 and electrical conductivity (EC) of 0.38 dS m^{-1} was used in this experiment. Four plots were set up under the drip irrigation system, each plot for one variant of NPC/PC emitter. For fertigation, six different fertilizer combinations were used, viz., (i) control (F_0), (ii) humic acid (H), (iii) ammonium nitrate (N), (iv) ammonium sulfate (S), (v) H + N 50% each and (vi) H + S 50% each. The emitter clogging rate and emission uniformity were calculated periodically during the experiment. Also, the soil infiltration rate under the influence of fertigation was recorded. End of the 180 days of experiments, both the clogging rate and emission uniformity reduced for all the treatments, though to a different degree compared to the treatment F_0. Among all the emitter variants, NPC emitters of 2 L h^{-1} discharge recorded the maximum values of clogging ratios among all the six fertigation treatments. For NPC emitters of 2 L h^{-1} discharge, ammonium sulfate (S) fertigation caused the highest (21.91%) clogging ratio and ammonium nitrate (N) fertigation caused the least (17.4%). Both these are higher compared to 14.98% caused by the F_0 treatment. Similarly, PC emitters of 4 L h^{-1} discharge recorded the minimum values of clogging ratios for all the six fertigation treatments. For this emitter variant, again Ammonium Sulfate (S) fertigation caused the highest (16.46%) clogging ratio and ammonium nitrate (N) fertigation caused the least (11.44%), which are higher compared to 7.93% caused by the F_0 treatment. This latest study by Mostafa *et al.* (2021) demonstrates that, even for the surface water with lower content of dissolved minerals, fertigation using nitrogen fertilizers poses significant risk of emitter clogging. Drip emitters are least prone to clogging when Ammonium Nitrate is used for nitrogen fertigation.

Yang *et al.* (2019) carried out on-site drip fertigation experiments, using both groundwater and saline water, for suitable phosphorous fertilizer application through the drip system. Two types of emitters – plain and labyrinth channel types – were used for this experiment. Three types of phosphate fertilizers, (i) mono-ammonium phosphate (MAP), (ii) di-ammonium phosphate (DAP) and (iii) urea phosphate (UP) were used for fertigation. The fertigation was done for a total of eight times, with a gap of two days between the fertigations. Treatment without the fertigation fertilizer is denoted as 'control'. The discharge rate from the test emitters was measured after every two fertigation events. The dry weight of the clogging substances accumulated on the selected sample emitters was also recorded. For the case of groundwater, the fertigation using MAP and UP showed better anti-clogging performance. However, with increasing salinity in irrigation water, the discharge rates declined significantly in case of DAP and MAP to below 60%. However, the UP treatment, except in case of water with extreme salinity of 6 dS m^{-1}, has given the discharge rates equal to or above 90%. The experiment concluded that the water quality and fertilizer type play a key role in the extent of emitter clogging. The pH of irrigation water after fertigation is the important factor that influences precipitation of dissolved minerals. The UP fertigation resulted in acidic pH value of 2.7 in groundwater as well as at higher salinity levels. Therefore, UP fertigation is found to be the best option for application of phosphorus.

The experiment by Xiao *et al.* (2020) also confirmed the findings of Yang *et al.* (2019) that UP is a promising option for phosphorus fertigation. Xiao *et al.* (2020) conducted fertigation experiment on eight types of emitters. Three types of phosphorus fertilizers, potassium phosphate monobasic (PPM), urea phosphate (UP) and ammonium polyphosphate (APP), were used for fertigation. Also, two different concentrations (0.015 and 0.30 g L^{-1}) of these fertilizers were applied, and emitter discharge recorded at intervals. The study found that the extent of emitter clogging end of the experiment depended on the type of fertilizer, their concentration and the type of emitter geometry. It was found that the APP caused most clogging, followed by the PPM. However, the performance of UP was found to cause the slightest clogging and also contributed to reduced carbonate deposition on the emitters. The average discharge reduction in UP, PPM and APP across the emitters and fertilizer concentrations varied in the range of 4.1–19.4%, 16.0–37.3% and 43.9–65.4% respectively. Application of UP fertilizer at low-concentrations and over a long period of time relieved the clogging issue.

Nanoparticles for removal of biofilms

TWW use in drip irrigation systems results in biofouling and clogging of drip emitters over time. Natan *et al.* (2019) used a novel approach to treat and limit the biofilms in flat-type drip emitters. They developed and embedded N-halamine derivatized cross-linked polymethacrylamide NPs in the polyethylene material used to fabricate the drip emitters. The NPs were activated by chlorinating with Sodium Hypochlorite (NaOCl). These nano-functionalized drippers were tested in the field and found to have excellent antifouling abilities, at least for a period of five months. Since the NPs are rechargeable, this approach is a long-lasting and cost-effective solution against biofouling when TWW was used in drip systems.

Electrolysis to treat biological and chemical clogging

Use of TWW or RW in drip irrigation may cause physio-chemical and biological clogging over time. Zhang *et al.* (2017b) tried electrolysis method for sterilization of biological clogging and for removal of hardness from the clogged emitters. A low-voltage electrolysis unit was designed with anode and cathode made of Titanium and Stainless Steel respectively. The electrolysis was done with two configurations, (i) voltage varied (0.5, 2 and 4 V) for 12 hours of fixed treatment time, and (ii) treatment time varied (3, 6, 12, 24 and 48 hours) for the fixed voltage of 4 V. The hardness and number of bacteria in the irrigation water were measured before and after the treatment. The removal rate of hardness and bacteria were highest at 23.93% and 66.85% respectively, at the applied voltage of 4 V and treatment time of 48 hours. This was achieved at an accumulated treatment time of 160 hours. But, beyond an accumulated treatment time of 320 hours, there is significant decline in sterilization and hardness removal rates. The study demonstrated that the electrochemical method is effective in removing emitter clogging. However, there is a need for improving the robustness and efficiency of the reactor and the choice of anode material.

BIOLOGICAL METHODS

Between 2005 and 2012, few researchers from Turkey (Department of Genetics and Bioengineering, Yeditepe University and Department of Agricultural Structures and Irrigation, Faculty of Agriculture, Atatürk University) tried the application of different bacterial strains for treating biological and chemical clogging in emitters. In a first of its kind, Sahin *et al.* (2005) used three antagonistic bacterial strains in the genus *Bacillus* spp (ERZ, OSU-142) and *Burkholdria* spp (OSU-7) to treat drip irrigation emitters effected by biological clogging. Fungi and bacterial strains separated from the irrigation water samples in the tomato greenhouses in the eastern Anatolia region of Turkey were used to induce biological clogging in selected drip systems. A total of 121 bacterial strains and 25 fungi were isolated in the laboratory and used in this study. A drip irrigation system with two lateral pipes of the same configuration was used for this experiment. Each lateral pipe of length 12 m has the design specifications of 0.33 m emitter spacing, 4 m operating pressure and 2.3 L h^{-1} emitter discharge. A mixture of a suspension of 2 L prepared from bacterial strains (109 CFU mL^{-1}) and fungi isolates (104 spores mL^{-1}) with sterile water was injected into the tank of the drip irrigation system three times at 7-day intervals. The irrigation system was operated 8 hours daily for 30 days and the discharge of emitters was measured daily. Then, 500 mL of a mixture of antagonistic bacterial suspension (109 CFU mL^{-1}) and sterile distilled water was applied to the treatment and control lateral, respectively. This application was repeated twice at 48 h intervals. The irrigation system was operated for another 30 days and the flow rate of each emitter was measured daily. Results showed that *Bacillus* strains (OSU-142, ERZ) inhibited all the fungi isolates but only 18 and 42% of the bacterial strains respectively. However, *Burkholdria* OSU-7 inhibited the development of all the fungi and bacterial strains tested. Within two weeks of the start of the treatment, the clogging was effectively removed in the test lateral pipe and the discharge rate was restored to 100% of their design rate.

While Sahin *et al.* (2005) focussed on treating biological clogging, Eroglu *et al.* (2012) applied biological control agents on chemical clogging, more specifically due to $CaCO_3$. Chemical clogging due to $CaCO_3$ precipitates is a concern for water with higher dissolved $CaCO_3$. Higher pH of irrigation water is a favorable condition for the precipitation to occur. Eroglu *et al.* (2012) demonstrated an environmental-friendly alternative to the conventional acid treatment method for treating the chemical clogging of emitters. Six lateral pipes, each of 12 m length, were used to establish the drip irrigation test setup. During the clogging period, $CaCO_3$ at a concentration of 80 mg L^{-1} was added to water and applied for 3 hours daily for 70 days. These artificially clogged emitters with $CaCO_3$ were treated with two bacterial strains, viz., *Lactococcus garvieae* (named A1) and *Bacillus subtilis* OSU-142, which were extensively studied earlier as a plant growth promoting rhizobacteria. These two bacterial strains were selected from among a large collection of 307, based on their competent performance in dissolving Ca^{+2} concentration in the laboratory culture. At the end of the clogging period, flow rate from 18 selected emitters, equally selected from upper, middle and lower segments of lateral lines, was measured. It was found that the average flow rate got reduced by 40% due to $CaCO_3$ clogging. As a part of the treatment process, the drip lines were flushed with water for 24 hrs period, after an incubation period of 24 hrs after the application of bacterial broth. The flow rates of emitters were measured at 4th and 24th hours of flushing period. Average flow rate of 18 selected emitters from upper, middle and lower segments of the drip lines was calculated, before as well as after the treatments. Out of the two bacterial strains, the *B. subtilis* OSU-142 was found to be more effective in removing the $CaCO_3$ precipitates on emitters. The flow rate recovery is about 20 and 10% for the *B. subtilis* OSU-142 and A1 respectively. The flow rates after 4 hrs and 24 hrs after flushing were not significantly different. Scanning electron microscopy and fluorescence microscopy techniques were used to study the residual clogging material on the emitters. Overall, the OSU-142 strain was found to be effective in chemical and physical destabilization and removal of $CaCO_3$. Earlier, Sahin *et al.* (2005) already established that this bacterial strain was effective in removing bacteriological clogging in drip emitters.

Biofilm formation is an unavoidable problem while using RW or TWW in drip irrigation systems. There are chemical bactericides available in the markets for treatment of biofilms in drip systems. However, their efficacy and environmental impacts are not fully established. Wen *et al.* (2021) treated the biofilm with the frequent application of *Bacillus amyloliquefaciens* Inoculum (BAI), a well-known antagonist bacterial strain. Three different types of NPC flat type emitters and two types of RW were employed in this laboratory experiment. A total of nine laterals, each of 2 m long and having six emitters, were employed. The system was operated 12 hours daily, for a total period of 60 days. The BIA was injected into the emitters at a frequency of 10 days, for a duration of 24 hours each time. The emitter discharge and uniformity of emission were quantified at every 60 hours of the experiment. The analysis of results from this experiment revealed that the BIA application through the drip irrigation system increased the emitter discharge rate by 31.9–44.3% compared to the control group that were used with RW. Also, the uniformity of emission increased by 58.1–67.1%. The BIA treatment was found to have broad spectrum characteristics, as these results were observed for both the input water types and all the three emitter models employed. Thus, the *B. amyloliquefaciens* bacterial species, which is known for its plant growth promotion characteristics, is also a promising environmental-friendly alternative for treating biofilms formed in drip emitters.

DISCUSSION

All the innovative methods reviewed are tested at a laboratory scale or through limited field trials. Since these methods are innovative and new, there is a lack of large experimental data representing a wide variety of water quality, emitter type and drip operational conditions. Therefore, the effectiveness of the methods is judged for the given limited experimental data. Secondly, the success of a new technology shall not be judged based on the experimental results alone, but also based on the ease in its replication. Drip irrigation is a decentralized form of technology deployed and used by a large number of farmers with varying degrees of literacy and technological understanding. Therefore, ease of installation, ease of operation, technological simplicity and replicability are important parameters of success of these new methods.

Four of the five physical methods, viz., magnetization, use of a MERUS ring, application of pulsating pressure and ultrasound treatment of water, involve use of additional apparatus or equipment for their implementation. Use of HRF also involves constructing an additional filter structure and sand bed. Flushing of laterals at higher pressure requires a variable-head pump-set and a pressure regulation mechanism for its execution. Intermittent flushing of laterals with fresh water, while using the TWW as irrigation water, is a relatively simpler, except that it requires a source of fresh water. The method of application of pulsating pressure has shown promising results in terms of treating the composite clogging in emitters. However, its replicability depends on the availability of a ready-to-use device for introducing pulsating pressure in the existing drip systems. Compared to all the other physical methods, the MERUS ring merits attention as it is found to be effective as well as it is amenable to replication due to its availability in the markets.

Out of the three chemical methods reviewed, application of NPs is quite sophisticated and is supported by a small amount of experimental data. Though the electrochemical method is based on the known science, its application against the emitter clogging problem is novel. The results of this method, in terms of sterilization of microorganism and removal of hardness in water, is encouraging. However, this method is limited by its longer process times, suboptimal reactor efficiency and limited choice of anode materials. In contrast, the fertigation method was widely experimented using a variety of fertilizers, for its utility to treat emitter clogging. Lowering of pH of water on dissolving the fertilizer is the key characteristic that identifies the fertilizers that are suitable to treat emitter clogging. Fertigation is a low-hanging fruit yet to be exploited fully. It is widely practiced by farmers using drip irrigation systems in many countries, primarily for uniform and efficient application of fertilizer to plants. Therefore, capacity building of farmers on the use of suitable fertilizer and its dosage will facilitate to double its use to treat emitter clogging.

Like in the case of NP application, there is an elaborate process involved in collection and culture of antagonistic bacteriological strains. Though the current evidences on the effectiveness of biological methods are limited, the *Bacillus* strains of bacteria have given promising results. However, there is a need for standardization of the processes, making this method scalable.

Overall, three methods, viz., (i) flushing of laterals with fresh water, (ii) use of a MERUS ring and (iii) fertigation, stand out in terms of their effectiveness and replicability at a larger scale. Though the methods like pulsating pressure, electrochemical treatment and use of antagonistic bacterial strains have given promising results in the experiments, there is need for further optimization and standardization for wider adaptation. Across all the methods, it is also evident that the source water quality played an important role in their effectiveness in reducing emitter clogging. However, the reviewed works did not discuss the effectiveness of different methods in relation to the emitter geometry. There is need for further studies in this direction.

CONCLUSION

The efficacy of conventional methods, such as filtration, flushing of laterals, acid treatment, and chlorination are already well established. However, these methods also suffer from the limitations, such as, need for repetitive treatments, high cost of acquiring the chemicals and lack of skills among farmers. Some new and innovative methods discussed and reviewed in this study are found to be promising and seemed to overcome such limitations.

Physical methods, such as use of appropriate filtration system, magnetization of irrigation water and installation of a MERUS ring, do not involve periodic investments. They also need little or no investment on maintenance. Among all the physical methods, use of a MERUS ring, introduction of pulsating or dynamic pressure and ultrasound treatment gave promising results. Among them, a MERUS ring merits over the others in terms of its portability, ease of implementation and the costs. The biological treatment with the *Bacillus* bacterial strains apparently gave significant results against biological and chemical clogging. However, it may take more time to standardize and see them available as products in the open markets. The cost of buying such bacterial treatment solutions may also become a hindrance to their rapid spread in popularity. The same is the case with NPs and electrochemical methods under chemical treatments. The efficacy of them needs to be established through further experimentation for wider range of water qualities and emitter types. However, the method of fertigation has been widely experimented compared to the other chemical methods. The use of fertigation against clogging has the double advantage of not only improving the hydraulic performance of the drip system, but also optimal application of plant nutrients. But, many of the fertigation fertilizers are found to be unsuitable, as they increase the alkalinity in irrigation water, resulting in aggravated clogging. Use of UP at low concentrations as the fertigation chemical is proven to be most effective in reducing the clogging problems.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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