Effect of different sand filter underdrain designs on emitter clogging using reclaimed effluents

Carles Solé-Torres, Jaume Puig-Bargués[1], Miquel Duran-Ros, Gerard Arbat, Joan Pujol, Francisco Ramírez de Cartagena

Department of Chemical and Agricultural Engineering and Technology, University of Girona, Carrer Maria Aurèlia Capmany, 61, 17003 Girona, Catalonia, Spain

Abstract

Sand media filters are those that achieve a higher retention of organic and inorganic solids, which is why they are usually recommended when reclaimed effluents are used in drip irrigation systems. Sand filters usually differ on the design of their underdrain, where an important pressure drop is produced. However, the effect of the design of sand filter underdrain on emitter clogging has not been widely studied. Three sand media filters with different underdrain designs (collector arms, inserted domes and drainage with porous media) were used for filtering a reclaimed effluent in a surface drip irrigation system. Pressure-compensating emitters with 2.3 l/h nominal emitter discharge were placed every 40 cm in 4 irrigation laterals each measuring 90 m in length. Effluents were chlorinated after being filtered. The filters operated for 1000 h with sand media heights of 20 and 30 cm and filtration velocities of 30 and 60 m/h. At the beginning, after 500 h, and at the end of the experiment the emitter discharge of each one of the 2712 emitters that were installed was experimentally measured under field conditions. On average, there was a statistically significant reduction ($p < 0.05$) on emitter discharge regarding the initial value of 8.03% at 500 h and 10.84% at 1000 h. Emitter clogging was primarily affected by the interactions between underdrain design, emitter location and irrigation time. Differences on emitter discharge due to underdrain design were only observed at 1000 h, showing a significantly higher flow rate ($p < 0.05$) those emitters protected with the filter with a collector arm underdrain, despite the fact that this filter did not achieve the highest turbidity removals. Emitter location had also a significant effect after 500 h of operation, being discharge significantly lower ($p < 0.05$) only in the last 2 m of the laterals, with the minimum values found for the final two drippers. The three filters used in the experiment did not show a significant effect on the percentage of completely clogged emitters, which mainly depended on the interaction between irrigation time and emitter location.

Key words: wastewater; microirrigation; media filter; filtration; plugging

Highlights

- The effect of three sand filter underdrain design on emitter clogging was studied.
- The experiment used a chlorinated reclaimed effluent and lasted 1000 h.
- Clogging depended on the interaction between filter, time and emitter location.
- Collector arm design achieved higher emitter discharge at 1000 h.
- Percentage of completely clogged emitters did not depend on filter design.

[1] Corresponding author. Tel: +34.972.41.84.59; Fax: +34.972.41.83.99. *E-mail address:* jaume.puig@udg.edu (J. Puig-Bargués)

1. Introduction

The use of reclaimed wastewater in agriculture has become a viable, stable and economic alternative to confront the issue of water scarcity on our planet (Asano et al., 2007), because municipal and industrial wastewater may be used for irrigating a large variety of crops (Hamilton et al., 2007), thus releasing water of higher quality for other uses (Lazarova and Asano, 2005).

The best irrigation technique for using wastewater from the public health and environmental points of view is drip irrigation (Bucks et al., 1979; World Health Organization, 2006). However, the main problem using drip irrigation with reclaimed effluents is emitter clogging (Bucks et al., 1979; Ravina et al., 1992). Emitter clogging depends on factors such as wastewater characteristics, emitter type, system operation, maintenance and filtration (Capra and Scicolone, 2007; Duran-Ros et al., 2009).

As clogging is related to the quality of water used, Bucks et al. (1979) derived a hazard rating depending on the values of different physical, chemical and biological quality parameters. According to Bucks et al. (1979) an irrigation water with suspended solids below 50 mg/l, a pH below 7 and bacterial number smaller than 10000 cfu/ml should pose a minor clogging hazard. However, Capra and Scicolone (1998) suggest higher clogging hazard thresholds when emitters with higher discharge rates are used. Pressure compensating emitters (Puig-Bargués et al., 2010a; Pei et al., 2015), integrated emitters (Pei et al., 2014) and high discharge emitters (Ravina et al., 1992; Trooien et al., 2000) are more resistant to clogging. Some authors analyzed flow and particle movements within emitter components aiming to suggest designs that could prevent clogging development (Wei al., 2008; Al-Muhammad et al., 2016; Feng et al., 2018b). Clogging could also be reduced with lower irrigation frequencies (Zhou et al., 2015) and lateral flushing (Puig-Bargués et al., 2010a; 2010b; Tripathi et al., 2014; Feng et al., 2017).

Several authors have studied how biofilm and chemical precipitation, which are the most common clogging causes when reclaimed effluents are reused, affect emitter performance (Gamri et al., 2014; Green et al., 2018, Zhou et al., 2018). Chlorination has also resulted in being effective in reducing emitter clogging and it has been widely used to prevent biological clogging (Hills and Brennes, 2001; Dehghanisanij et al., 2005; Cararo et al., 2006) as the strong oxidation of chlorine inhibits the reproduction and growth of microorganisms and the formation of biofilms (Li et al., 2010) as well as, if combined with acidification, the precipitation of solid particles in the drip emitters (Hao et al., 2018).

Other authors analyzed the effect of different filter types on emitter clogging when reclaimed effluents were used (Ravina et al., 1992; Capra and Scicolone, 2004; Duran-Ros et al., 2009; Triphati et al., 2014). There is an agreement that filtration is an essential operation which can prevent emitter clogging (Oron et al., 1979), although it does not avoid it completely (Tajrishy et al., 1994). Sand filters are considered those that offer a better protection for drip irrigation systems (Trooien and Hills, 2007) since they remove efficiently suspended solids (Duran-Ros et al., 2009), organic compounds, phosphorus and microorganisms (Dalahmeh et al., 2012) and consequently prevent emitter clogging (Capra and Scicolone, 2007). In sand media filters the pressure loss is mainly located at filtration media and auxiliary elements such as the underdrain (Arbat et al., 2013). Several authors have studied the influence of underdrain designs on pressure loss (Mesquita et al., 2012; Bové et al., 2015; Pujol et al., 2016), but none of them have analyzed how filter design affects emitter clogging. On the other hand, sand filters have to be periodically backwashed for releasing those particles retained in the media, which increase pressure loss across filtration time. Backwashing is an important procedure for an effective filter performance (Nakayama et al., 2007) but the media cleaning pattern depends on the underdrain design (Burt, 2010). Usually, filter backwashing is carried out at pre-set pressure loss, nevertheless daily backwashing has been also verified to be a good practice for assuring good emitter performance (Enciso-Medina et al., 2011). Even though filter and backwashing operations in drip irrigation systems have been studied (Elbana et al., 2012) there are few studies which try to improve the design and performance of sand media filters. With this in mind, Bové et al. (2017) designed a new underdrain aiming to reduce pressure loss across sand filters for improving both water and energy use efficiency.

The main objective of this study was to analyse the effect of three sand filters with different underdrain designs (the prototype designed by Bové et al. (2017) and two commercial ones) on emitter clogging when a reclaimed effluent is used.

2. Material and methods

2.1. Experimental setup

Reclaimed effluent from the Celrà (Girona, Spain) wastewater treatment plant (WWTP), which treats urban and industrial effluents using a sludge process, was used in the experiment.

The experimental irrigation system consisted of three sand filters with three underdrain different designs (Fig. 1): a sand filter model FA1M (Lama, Sevilla, Spain), a sand filter model FA-F2-188 (Regaber, Parets del Vallès, Spain) and an experimental sand filter built with an underdrain designed by Bové et al. (2017). Table 1 shows the main characteristics of the different sand filters used. The underdrain of the filter model FA1M (Lama, Sevilla, Spain) consisted of 7 parts with slots which overlapped each other forming striated tubes converging in a central tube which worked as a manifold. This contained a total of 10 striated tubes with 5 tubes on each side of the manifold. In model FA-F2-188 (Regaber, Parets del Vallès, Spain) the underdrain consisted of 12 inserted domes on a back plate. These domes were pyramidally shaped with vertical slots, mounted on a manifold. Finally, the underdrain designed by Bové et al. (2017) consisted of a cylinder that occupied the entire surface of filtration of the filter. This cylinder was confined by two 0.75 mm meshes, one at the top and one at the bottom, and was filled with silica sand sieved to 0.63 – 0.75 mm grain size, with an equivalent diameter of 0.71 mm, bulk density of 1.478 kg/m^3, real density of 2.573 kg/m^3 and a porosity of 42.2% (Bové et al., 2017).

*** Table 1 ***

*** Figure 1 ***

All the filters were filled with silica sand CA-07MS (Sibelco Minerales SA, Bilbao, Spain) with an effective diameter (D_e, size opening which will pass 10% by dry weight of a representative sample of the filter material) of 0.48 mm and a coefficient of uniformity (ratio of the size opening which will pass 60% of the sand through the size opening which will pass 10% through) of 1.73. Each filter had an irrigation subunit associated, which consisted of four laterals, each with a total length of 90 m (Fig. 2). Each lateral had 226 emitters, so for each emitter location there were 4 replications per subunit. However, for location 226 only there were 3 emitters per subunit.

Commercial integrated and pressure compensating emitters Uniram AS 16010 (Netafim, Tel Aviv, Israel), with 2.3 l/h of nominal flow discharge, a distance between emitters of 0.4 m, a nominal working pressure of 50-400 kPa and a manufacturing coefficient of variation of 0.03 were used. This emitter was selected since its design improves clogging resistance and its pressure compensation allows to use it in a wide range of topographical conditions.

The reclaimed effluent was pumped from the WWTP to the filters using a multicellular centrifugal pump model CR-15-4 (Grundfos, Bjerringbro, Denmark) governed by a frequency variator model FRN-4 (Fuji Electric, Cerdanyola del Vallès, Spain). The inlet flow was measured with an electromagnetic flowmeter Isomag MS2500 (ISOIL Industria SpA, Cinisello Balsamo, Italy) with a pulse transmitter. The experimental setup allowed that only one filter was operating at a time. After being filtered, the reclaimed effluent was carried to the drip irrigation subunits. Since the filtrated flow was higher than which was needed for the irrigation subunits, a proportional electrohydraulic actuator SKD32 (Siemens, Munich, Germany) operated a three-way valve VXG41 (Siemens, Munich, Germany), so that the excess flow was brought to a water storage tank of 3000 l Aquablock (Shütz, Selters, Germany) that was used for filter backwashing.

A chlorine deposit of 200 l was installed, to continuously inject chlorine for achieving a concentration of 2 ppm in the water after being filtered, using a DosTec AC1/2 membrane pump (ITC, Sta. Perpètua de la Mogoda, Spain). When sand filters were backwashed, backwashing water entering the filters was chlorinated to reach a 4 ppm chlorine concentration.

Several effluent quality parameters before and after being filtered were measured and recorded every minute in a supervisory control and data acquisition system (SCADA) previously developed (Duran-Ros et al., 2008). The parameters measured before filtration were the electrical conductivity using a transmitter LIQUISYS-M CLM253-CD0010 and a sensor CLS21-C1E4A, the pH and the temperature using a transmitter LIQUISYS-M CPM253-MR0010 and a sensor CPS11D-7BA21. The parameters measured before and after filtration were turbidity using a transmitter LIQUISYS-M CUM253-TU0005 with and a sensor CUS31-A2E and dissolved oxygen with a transmitter LIQUISYS-M COM253-WX0015 and a sensor COS 61-A1F0. All the transmitters and sensors used were manufactured by Endress + Hauser (Gerlingen, Germany).

The filters were washed automatically when the total pressure drop across them measured by pressure transducers reached 50 kPa (Ravina et al., 1992). The backwashing time was 3 minutes throughout the entire test, and during that time, backwashing water did not reach the laterals. The water used for the backwashing, came from the filtered water storage tank.

*** Figure 2 ***

2.2. Operational procedure

The experiment lasted 1000 h for each filter, taking place uninterruptedly between March and November 2018, except for the month of June, where the installation did not work due to a breakdown of turbidity sensors. Whenever possible, six daily irrigation sessions of 4 h each (i.e. two daily sessions of 4 h per filter) were carried out. In practice, it was attempted to establish irrigation sessions as homogeneous as possible, which was not always possible due to small breakdowns that prevented the use of a filter for a certain period of time. When these breakdowns were solved, the operation time of the affected filter was increased to equalize the hours of operation.

During the 1000 h that the experiment lasted, two different media heights were tested (20 and 30 cm), and two different filtration velocities (30 and 60 m/h) for each one, which made a total of four different operating conditions. The operating conditions were the same for each filter with each being tested for 250 h. Working pressure was set to 172 kPa at drip irrigation subunit inlet. No lateral flushing was carried out during the experiment.

2.3. Assessment of filter and emitter performance

Filter performance for removing turbidity and dissolved oxygen was assessed through the removal efficiency (E) achieved in the filters, which was calculated as:

$$E = \frac{No-N}{No} \times 100 \qquad (1)$$

where N_0 and N are the values of turbidity and dissolved oxygen at filter inlet and outlet, respectively.

Flow discharge for all the emitters of all the laterals (i.e. a total of 2712 emitters) was measured in the experimental field at the beginning, after 500 h and at the end of the experiment (1000 h). The flow of each dripper was collected for 5 min in collection dishes and then transferred to a 500 ml graduated cylinder to measure its discharge. The experimental determination of emitter discharge lasted for about 20 h after the target time (0, 500 and 1000 h) due to the number of emitters being measured. In addition, the percentage of completely clogged emitters (i.e. emitters that had 0 l/h discharge) was also computed at each control time.

During the emitter discharge measurements, pressure was also determined in four positions on each lateral (at the beginning, one third of the lateral length, two thirds of the lateral length and at the end) using a digital manometer Leo 2 (Keller, Winterhur, Switzerland) with a precision of ± 0.07% that was placed at a pressure intake (Ein-tal, Or-Akiva, Israel). Pressure uniformity of pressures (Uplq) (Bliesner, 1976) was calculated according to the formula:

$$Uplq = \left(\frac{p25}{\bar{p}}\right)^{x} \times 100 \qquad (2)$$

where p_{25} is the average pressure of 25% of the positions with the lowest pressure (kPa), $\bar{p}$ is the average pressure of all the tested positions (kPa) and x is the emitter flow exponent, which was considered 0.05.

At the end of the experiment, emitters from the locations 1, 224, 225 and 226 of the first and second lateral for each irrigation subunit were analysed for visual evidence of clogging. These emitters were cut and opened for external and internal inspection. Pictures were taken with a DMC-FZ150 (Panasonic Corporation, Osaka, Japan) camera.

2.4. Characterization of inlet water

The main water quality parameters for each filter were recorded each minute, as was explained in Section 2.1. Since the filters did not operate simultaneously, it was necessary to assess if effluent characteristics were different during the experiment. Table 2 presents the mean values of the pH, temperature, electrical conductivity, dissolved oxygen and turbidity values recorded through the 1000 hours the experiment lasted.

*** Table 2 ***

Significant differences ($p < 0.05$) were observed for pH, temperature, electrical conductivity and dissolved oxygen for the reclaimed effluents available at each filter inlet. Reclaimed effluent used during the experiment with the dome underdrain filter had a pH significantly higher ($p < 0.05$) than that for both porous media and arm collector underdrain filters. According to Bucks et al. (1979) classification, there was a moderate chemical clogging hazard regarding the pH for all the filters. Water inlet temperatures when the porous media underdrain was tested were significantly higher ($p<0.05$) than those for the arm collector underdrain but not for those of the dome underdrain. These differences between temperatures may have helped the formation and growth of biofilms, which are closely related to emitter clogging (Li et al., 2012; Zhou et al., 2013). Electrical conductivity when porous media and collector arm filters were used was significantly higher ($p < 0.05$) than that with the dome underdrain. Effluent used during the operation of dome underdrain filter had a dissolved oxygen level significantly higher ($p<0.05$) than those for both porous media and arm collector filters. This means that microorganism levels should be smaller when an inserted dome filter was used. No significant differences were observed in turbidity values in inlet water for any of the tested filters, meaning that the risk of physical clogging was the same. All these variations are due to the usual variability present when reclaimed effluents are treated in the WWTP.

2.5. Statistical analyses

Statistical analyses carried out using SPSS Statistics 25 software (IBM, New York, USA). In order to analyze pressure uniformity, emitter discharge and percentage of completely clogged emitters, an analysis of the variance was carried out. The model that was used included as fixed effects the filter underdrain design, the time of measurement and the position of the emitters (for Uplq it was lateral position) as well as the double interactions between the filter and time, filter and position, and time and position. Triple interactions were initially assessed but, as they were not significant ($p>0.05$), they were excluded from the final analyses. To differentiate the averages that were significantly different with a probability of 0.05 or less, the Tukey's pairwise comparison test was used.

3. Results and discussion

3.1. Filter performance

Variations caused by the different underdrain designs on the quality of the reclaimed effluents were characterized. Table 3 presents the percentages of oxygen and turbidity removals, computed using the equation (1), for the different underdrain designs.

*** Table 3 ***

The porous media underdrain filter showed turbidity removals of 26.29%, significantly higher ($p<0.05$) than those reached by dome (18.53%) and arm collector (13.45%) underdrain filters, which were not significantly different from each other. Previous experiments with effluents of the same WWTP and using a dome underdrain sand filter with a filtration media height of 50 cm achieved turbidity removals of 57.57% with an inlet 6.76 FTU (Duran-Ros et al., 2009) and 70.6% with an inlet 9.78 FTU (Elbana et al., 2012). Tripathi et al. (2014) observed turbidity reductions of 51.1% using effluents with inlet 55 FTU. Wu et al. (2015) obtained reduction efficiencies of suspended solids from 11.4 to 48.0% using a sand filter filled with different media with equivalent diameters ranging between 2.1 and 0.45 mm. No details about sand filter design were provided in either of the two previous papers. The smaller turbidity removal observed in the present experiment (19.4% on average) for all of these three underdrain designs may be due to the smaller inlet levels of turbidity of the effluent used (6.15 FTU on average) and to the reduced height of sand media bed in the filters, which was between 40 and 60% lower than the heights used by Duran-Ros et al. (2009) and Elbana et al. (2012) with a dome underdrain filter. Lower media heights used in the present experiment are explained by the limitation caused by reduced maximum height of arm collector underdrain filter (40 cm) and the need to carry out the experiment under the same experimental conditions for each filter.

The increase of dissolved oxygen achieved by the porous media (11.20%) and arm collector underdrain (11.03%) filters were greater than that observed with the dome underdrain filter (6.68%), although no significant differences were noted between these values. The smaller increases in dissolved oxygen achieved by the dome underdrain filter might be explained by the significantly ($p<0.05$) higher values of this parameter at this filter inlet (Table 2). Dissolved oxygen increases in the dome underdrain filter were higher than those observed by Duran-Ros et al. (2009) (0.49% for inlet DO values of 2.80 mg/l and working with an effective sand size of 0.40 mm) and Elbana et al. (2012) (3.75% for inlet DO values of 4.00 mg/l and using an effective sand size of 0.48 mm), which were obtained in an experiment without any chlorination treatment. Although DO increase can be attributed to minor imperfections that result in air intrusions (Maestre-Valero et al., 2010), the main reason is related to chlorination of backwashing water which reduced microbial population (Li et al., 2010) that consumes oxygen.

3.2. Pressure distribution across laterals

Table 4 shows the average pressure uniformity coefficient (Uplq) for the 4 driplines placed after each different filter in the three periods where emitter discharge was assessed under field conditions. For all the irrigation subunits, Uplq was above 98% during the whole experiment, so the pressure distribution for the driplines can be considered uniform. Since the emitter manufacturing coefficient of variation was low (3%), discharge reductions can mainly be explained by emitter clogging. However, slightly smaller pressure values were observed on the irrigation subunit after the dome underdrain filter. The reason was a clogged screen located inside the volume meter placed at the beginning of these laterals that was discovered after 800 h. However, since pressure compensating emitters were used, the effect of this smaller pressures on emitter discharge should have been minimum since pressure across the whole lateral was always within the acceptable pressure range for the tested emitter (50-400 kPa).

*** Table 4 ***

In order to assess if there were a possible effect of Uplq on results, a statistical treatment was carried out analyzing Uplq of each dripine. No significant ($p>0.05$) effects were observed either for the different laterals, or for the different assessment times, the position of the four driplines and for any interaction between these factors. These results confirmed that values of Uplq did not have any differential effect on any of the laterals of the experimental setup.

3.3. Emitter performance

Emitter discharge values were treated statistically and there was (Table 5) a significant effect ($p<0.05$) of each fixed factor (time, emitter position and filter underdrain design) as well as the interactions of underdrain design and time, underdrain design and emitter location and time and emitter location. Each interaction will be analyzed and discussed in the following sections.

Overall, there was a significant reduction ($p<0.05$) of emitter discharge, which gradually decreased from an average measured discharge of 2.49 l/h at the beginning of the experiment, to 2.29 l/h at 500 hours and 2.22 l/h at 1000 h. Globally, there has been a 10.8% reduction of emitter discharge from the beginning to the end of the experiment. This emitter discharge reduction throughout irrigation time due to clogging incidence has been widely observed (Ravina et al., 1992; Duran-Ros et al., 2009; Tripathi et al., 2014; Wu et al., 2015, Pei et al., 2014).

*** Table 5 ***

3.3.1. Effect of the underdrain design and irrigation time

Emitter discharge with regard to filter underdrain design and irrigation time is shown in Figure 3. There was a significant reduction in emitter discharge over time for all the filter designs. Emitters protected by an arm collector underdrain sand filter showed a discharge reduction of 7.6% at 500 h and 9.6% at 1000 h from the initial value. These discharge diminutions were smaller than those observed for those emitters protected by the porous media and dome underdrain filters (8.76 and 8.06% at 500 h and 12.35 and 11.29% at 1000 h, respectively). Most of discharge rate reductions took place during the first 500 h, compared with those from 500 to 1000 h (3.93% for the porous media, 3.51% for the dome and 2.16% for the arm collector underdrain). Wu et al. (2015) also observed major emitter discharge reductions in first testing stages (from 0 to 150 h) compared to reductions in final testing stages (from 150 to 300 h). However, in an experiment operated for 540 h with pressure-compensating emitters (Pei et al., 2014), the relative average emitter discharge reduced 4.1-13.1% during the first period (0-204 h) but reduced 37.5-67.3% at the end of the experiment (204-540 h).

At the beginning of the experiment, no differences in emitter discharge between underdrain designs were found (Fig. 3). After 500 h, the average discharge of emitters protected by an arm collector design (2.31 l/h) was significantly higher ($p<0.05$) than with the dome underdrain (2.28 l/h) but not with the porous media design (2.29 l/h). After 1000 h, the average discharge of emitters protected by the arm collector design (2.26 l/h) was significantly higher ($p<0.05$) than those from both dome and porous media (2.20 l/h) underdrain filters. However, these differences were only about 3% of emitter discharge, on average.

*** Figure 3 ***

Further research on the hydrodynamics conditions under filtration and, especially, backwashing, since the last has an important effect on filter performance (Burt, 2010; Enciso-Medina et al., 2011), for each underdrain design should be carried out in order to identify different patterns on particle removal that may have an effect on emitter clogging.

3.3.2. Effect of the underdrain design and emitter location

Emitter discharges related to filter underdrain design and emitter location are shown in Figure 4. For each underdrain sand filter design, significant differences ($p<0.05$) in emitter discharge were found, but only for emitters placed at the end of each lateral. In addition, slight variations were observed between filter designs. Thus, for both porous media and dome underdrain designs, emitter discharge of the three last emitters (last 1.2 m of the dripline) was significantly ($p<0.05$) lower than the discharge of emitters located at the first 88.8 m of the lateral, i.e. emitters 1-222. For the arm collector underdrain, the smallest emitter discharge was only observed in the two last emitters (last 0.8 m) regarding emitter discharge of emitters 1-223. For all the underdrain designs, last emitter had clearly the lowest emitter average discharge (1.09 l/h for the porous media, 1.31 l/h for the dome and 1.57 l/h for arm collector designs).

*** Figure 4 ***

For each emitter position, differences in emitter discharge between underdrain designs were only found in 11 emitters, which accounted for only 5 % of the emitters on each dripline. The distribution of these emitters did not follow any pattern since they were emitter number 20, 31, 43, 105, 110, 111, 112, 153, 156, 160 and 217. In 27% of these emitters (emitters number 105, 111 and 112), discharge achieved with porous media underdrain sand filter was significantly higher than with arm collector filter while just the opposite happened with 18% of the emitters (emitters 20 and 217). For another 18% of these emitters (emitters 31 and 110) dome underdrain sand filter achieved more emitter discharge than arm collector but for emitters 156 and 160 the results was exactly the opposite. These differences might be explained by the randomness that is commonly observed in emitter clogging (Feng et al., 2018a).

3.3.3. Effect of time and emitter location

The interaction between time and location on emitter performance was also significant (Table 5). At the beginning of the experiment, there were no significant differences among locations, although after 500 and 1000 h significant differences ($p < 0.05$) appeared (Fig. 5), with smaller discharges observed in the emitters at the end of the 90 m long driplines. After 500 h, the three last emitters (positions 224, 225 and 226) had significantly lower ($p<0.05$) discharges than the rest of emitters, with average values of 1.83, 1.83 and 1.49 l/h respectively. After 1000 h, the last four emitters (locations 223, 224, 225 and 226) had a lower discharge ($p<0.05$) than the 222 previous ones, with values of 1.45, 1.22, 0.61 and 0.00 l/h respectively. This means that all the final emitters were completely clogged at the end of the experiment, whatever the filter was. In addition, the emitter located in position 221 showed also a smaller discharge than that of the previous 220 emitters, with the exception of emitters 213 and 218. After 1000 h, there was a flow discharge reduction in almost all the emitters compared with 500 h emitter flow rates, with this reduction accentuated along the lateral. Greater discharge reductions at the end of laterals have been widely observed by many authors (e.g. Ravina et al., 1992, 1997; Trooien et al., 2000; Puig-Bargués et al., 2010a; Wu et al., 2015).

*** Figure 5 ***

Moreover, significant differences ($p<0.05$) in discharges between different times were found in almost all emitter locations, with the following combinations for emitter discharges: 0 h>500 h>1000 h, 0 h> (500 h=1000 h), 0 h=500 h=1000 h, (0 h=500 h)>1000 h, and (0 h=500 h and 500 h=1000 h but 0 h>1000 h). A total of 77.68% of the emitter discharges were significantly higher ($p<0.05$) at 0 h, but not between 500 h and 1000 h, and 11.61% were significantly different for all the measured times. In 5.80% of the emitters, discharge at 0 h was significantly different from that at 1000 h, but there were neither differences between 0 h and 500 h nor between 500 h and 1000 h. For 4.02% of the emitters, discharge at 0 h and 500 h was significantly higher than at 1000 h. Finally, 0.89% of emitters did not show any significant difference in discharge over time (Table 6).

*** Table 6 ***

3.4. Completely clogged emitters

The total number of totally clogged emitters after 500 h was 5 emitters (0.56% of the total) for the laterals protected by the porous media underdrain filter and 2 (0.22% of the total) for the dome underdrain filter. No clogged emitters for the arm collector underdrain filter were found. After 1000 h, the total number of clogged emitters was 10 for the porous media filter (1.13% of the total), 8 for the dome (0.91% of the total) and 6 for the arm collector underdrain filter (0.68% of the total). The emitter protected with dome underdrain in location 223 recovered from total clogging after 500 h to a flow rate of 0.36 l/h after 1000 h. Some authors had observed the recovery of clogged emitters and attributed this fact to a release of the material that plugged the emitter (Ravina et al., 1992; Duran-Ros et al., 2009) due to pressure variations or deformation of organic particles. Although the filter with porous media underdrain had turbidity removals significant higher than the other two designs, it presented a higher percentage of completely clogged emitters. A possible explanation could be that other particles such as small sized sand released from the filter might have clogged the emitter, but this was not observed, and it will be discussed on Section. 3.5. Thus, the randomness observed in clogging (Feng et al., 2018a) might also explain this observation.

The percentage of totally clogged emitters for each location was treated statistically, and there was a significant effect of time, emitter location and the interaction of both (Table 7). Either the effect of underdrain sand filter design or its interaction between time and emitter location were found to be significant ($p>0.05$). These means that the different underdrain designs tested in the present experiment did not explain the percentage of completely clogged emitters. Regarding experiment time, after 500 h of irrigation significant differences ($p<0.05$) of the percentage of completely clogged emitters among locations were found, with locations 224 and 225 (each one with 16.66 % of completely clogged emitters) being significantly different from the rest except emitter number 223 (8.33% of totally clogged emitters) and emitter 226 (22.22% of completely clogged emitters). Completely clogged emitters for location 226 were significantly higher than those observed in locations 1-223. After 1000 h, location 226 had a significantly higher percentage of completely clogged emitters than the rest of emitter locations at this time. Emitter 225 also had a significantly higher percentage of completely clogged emitters (58.33%) than the emitters placed before and emitters 223 and 224 had, at the same time, a higher percentage of totally clogged emitters (25 and 33.33 %, respectively) than that observed for the first 222 emitters (Fig. 6).

All the clogged emitters were located at the end of the lateral. Several studies show this same clogging emitter tendency (Trooien et al., 2000; Duran-Ros et al., 2009, Puig-Bargués et al., 2010a; Oliver et al., 2014) which can be attributed to a reduction flow rate at the end of the lateral (Shannon et al., 1982) and a greater concentration of particles (Wu et al., 2015). Despite the fact that reclaimed effluent was chlorinated after being filtered, at the end of laterals emitter discharges were lower (Sections 3.3.2 and 3.3.3) and more emitters became fully clogged. Some qualitative measurements of chlorine at the emitter outlet at the end of the lateral were made using chlorine test strips and, as it may be anticipated, the chlorine level was very low at this point since injection was carried out at a long distance away from the filters. Free chlorine levels between 1.5-2.5 mg/l at the end of the laterals effectively reduced emitter clogging (Li et al., 2010; Song et al., 2017).

It should be pointed out that no lateral flushing was carried out during the experiment in order to have more clogging incidence. Flushing reduces sediment deposition within driplines (Puig-

Bargués et al., 2010b; Li et al., 2018) as well as biofilm formation (Oliver et al., 2014; Li et al., 2015). However, the number of completely clogged emitters was relatively small.

*** Table 7 ***

*** Figure 6 ***

For each emitter location, only significant differences in the percentage of completely clogged emitters (Table 8) were found at position 224 (being the percentage at 1000 h higher than at 0 h but not than at 500 h) and 226 (being the percentage of 1000 h higher than the other two times).

*** Table 8 ***

3.5. Emitter observation

Emitters from the beginning and the end of the laterals were taken for observation after 1000 h. While there were not visually appreciable deposits on the emitters placed at the beginning of the laterals (Fig. 7A) for any irrigation subunit, biofilm growth was observed in those emitters located at the end of the laterals, especially at the final position (Fig. 7B), where biofilm covered the total surface of the emitter and the dripline. The amount of deposits increased along the ending locations and it was formed mainly of biofilm and sludge particles. These observations were in accordance with the findings of Ravina et al. (1992), Trooien et al. (2000), Duran-Ros et al. (2009) and Puig-Bargués et al. (2010a). No visual differences in the amount of deposits were observed between irrigation subunits, being the emitter of the last location completely covered in all the samples observed. No sand particles, which might be released from the sand filters, were visually observed in any of the emitters that were cut and opened. On the other hand, the observation of emitter labyrinths of the final locations (Fig. 7C) show an important biofilm growth near the water outlet. Biofilm composition was not analyzed since it was out of the scope of the paper and emitter sampling was carried out under conditions that not allowed to have representative biofilm results for each treatment. However, further research should be undertaken in order to characterize the features of the biofilm formed.

4. Conclusions

The present study was carried out to determine the effect of three different underdrain designs used for sand media filters on emitter clogging when using a chlorinated reclaimed effluent, with an average turbidity of 6.15 FTU and dissolved oxygen of 3.17 mg/l, during 1000 irrigation hours of 90 m length laterals that were not flushed during the whole experiment.

Emitter clogging was affected by the interactions between underdrain design, emitter location and irrigation time. Emitter location had a significant effect only after 500 h of operation, with significant differences among emitter discharge ($p<0.05$) in the last three emitters (last 1.2 m of the lateral) and after 1000 h for those emitters located at the last 2 m of the laterals. There was also a significant reduction in emitter discharge that ranged from 9.6% to 12.35% depending on the filter design after 1000 h of irrigation. A significantly higher emitter discharge ($p<0.05$) was observed in those emitters protected by a sand filter with arm collector underdrain, although this filter did not achieve the highest turbidity removals. There was also a location effect on emitter discharge among underdrain designs. The emitter discharge values were significantly lower from the final 4, 3, and 2 emitters when sand filter with a porous media, dome and arm collector underdrains, respectively, were used.

On the other hand, the percentage of completely clogged emitters depended on the interaction between irrigation time and emitter location, without any significant effect of any of the three different sand filter underdrain designs.

Based on the results, a sand filter with an arm collector underdrain design showed less emitter clogging when reclaimed effluent was used, but only after 1000 h of irrigation. For shorter times, clogging protection between the different tested filters was not different. However, emitter clogging, which is a complex process, depended also on the interaction between irrigation time and emitter location. Further research should be carried out to analyse if different sand filter designs have a specific effect on any of the emitter clogging agents.

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Tables

Table 1. Underdrain design and main operation characteristics of the different filters used in the experiment. Data was obtained from manufacturers.

Filter underdrain design	Filter nominal diameter (mm)	Filter filtration surface (m^2)	Underdrain opening surface/filter filtration surface (%)	Maximum filtration flow (m^3/h)	Maximum filter media height (m)	Average initial pressure loss* (kPa)
Porous media	500	0.1960	37.95	20	0.70	27.86
Domes	508	0.2026	3.71	18	0.69	29.89
Collector arms	500	0.1960	4.65	23	0.40	33.94

* experimentally measured and averaged for the different media heights and filtration velocities

Table 2. Average ± standard deviation of the effluent physical and chemical parameters at filter inlets. Different letters mean that there were significant differences (p<0.05) in the values of each parameter at the different filter inlets.

Filter underdrain design	pH (-)	Temperature (ºC)	EC (dS/m)	DO (mg/l)	Turbidity (FTU)
Porous media	7.33 ± 0.20 **b**	20.61 ± 3.26 **a**	2.64 ± 0.46 **a**	3.27 ± 0.83 **b**	6.22 ± 2.11
Inserted domes	7.43 ± 0.24 **a**	20.12 ± 3.49 **ab**	2.46 ± 0.53 **b**	3.57 ± 1.02 **a**	5.82 ± 3.08
Arm collector	7.31 ± 0.22 **b**	19.68 ± 3.57 **b**	2.63 ± 0.44 **a**	3.28 ± 1.04 **b**	6.42 ± 2.77

Table 3. Average ± standard deviation of the removal efficiencies of dissolved oxygen and turbidity achieved by the different underdrain design filters, expressed in percentage reductions of the inlet values. Negative values indicate an increase of the parameter. Different letters mean that there were significant differences (p<0.05) in the removal efficiency for a parameter.

Filter underdrain design	Removal efficiency (%) Dissolved oxygen	Turbidity
Porous media	-11.20 ± 33.84	26.29 ± 16.50 **a**
Domes	-6.68 ± 30.53	18.53 ± 24.38 **b**
Arm collector	-11.03 ± 35.89	13.45 ± 25.07 **b**

Table 4. Average ± standard deviation of the pressure distribution coefficients (Uplq) of irrigation subunits of the three different underdrains at the beginning, after 500 h and at the end of the experiment. No significant differences (p>0.05) were found.

Underdrain	Uplq (%) 0 h	500 h	1000 h
Porous media	98.99 ± 0.05	99.02 ± 0.07	99.23 ± 0.33
Domes	98.93 ± 0.06	98.43 ± 0.55	99.22 ± 0.04

Arm collector	99.04 ± 0.04	99.30 ± 0.04	99.14 ± 0.15

Table 5. Significance level (P-value) of the statistical model and of each factor and interaction for explaining flow rate variability during the experiment.

	Significance level (*P*-value)
Model	< 0.001
Time	< 0.001
Emitter location	< 0.001
Underdrain design	< 0.001
Underdrain design x time	< 0.001
Underdrain design x emitter location	< 0.001
Time x emitter location	< 0.001

Table 6. Gradation and frequency of significant differences (p<0.05) on emitter discharge and their location regarding assessment times.

Gradation regarding assessment times	**Frequency of observations (%)**	**Emitter position (from 1 to 226)**
0 h >500 h > 1000 h	11.61	11, 12, 14, 15, 28, 36, 42, 66, 74, 127, 144, 145, 146, 148, 169, 170, 172, 181, 183, 195, 196, 198, 202, 214, 220, 226
0 h > (500 h =1000 h)	77.68	Rest of emitters
0 h= 500 h =1000 h	0.89	75, 216
(0 h =500 h)> 1000 h	4.02	205, 208, 210, 211, 213, 218, 219, 221, 225.
0 h >1000 h; 0=500 h and 500=1000 h	5.80	23, 72, 76, 77, 82, 124, 147, 204, 209, 212, 215, 223, 224

Table 7. Significance level (P-value) of the statistical model and of each factor and interaction for explaining the percentage of completely clogged variability during the experiment.

	Significance level (*P*-value)
Model	< 0.001
Time	< 0.001
Emitter location	< 0.001
Underdrain design	0.074
Underdrain design x time	0.572
Underdrain design x emitter location	0.994
Time x emitter location	< 0.001

Table 8. Gradation and frequency of significant differences ($p<0.05$) over assessment time on the percentage of completely clogged emitters (%) for each emitter location.

Gradation regarding assessment times	Frequency of observations (%)	Emitter position (from 1 to 226)
0 h =500 h =1000 h	99.12	Rest of emitters
1000 h > 0 h; 0 h =500 h and 500 h = 1000 h	0.44	224
1000 h > (0 h = 500 h)	0.44	226

Figures

Figure 1. Different underdrain designs: porous media (A), inserted domes (B) and arm collector (C).

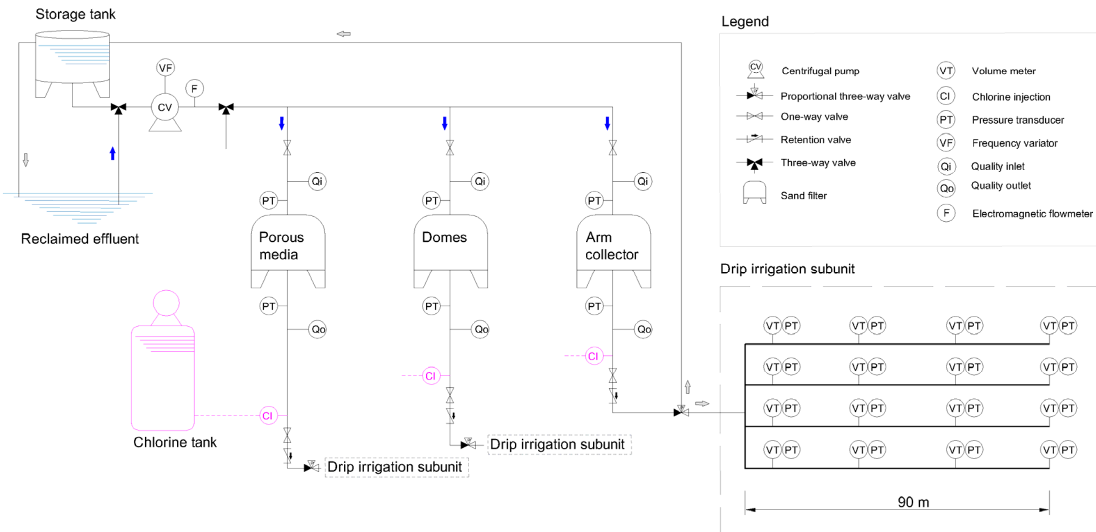

Figure 2. Diagram of the experimental irrigation system.

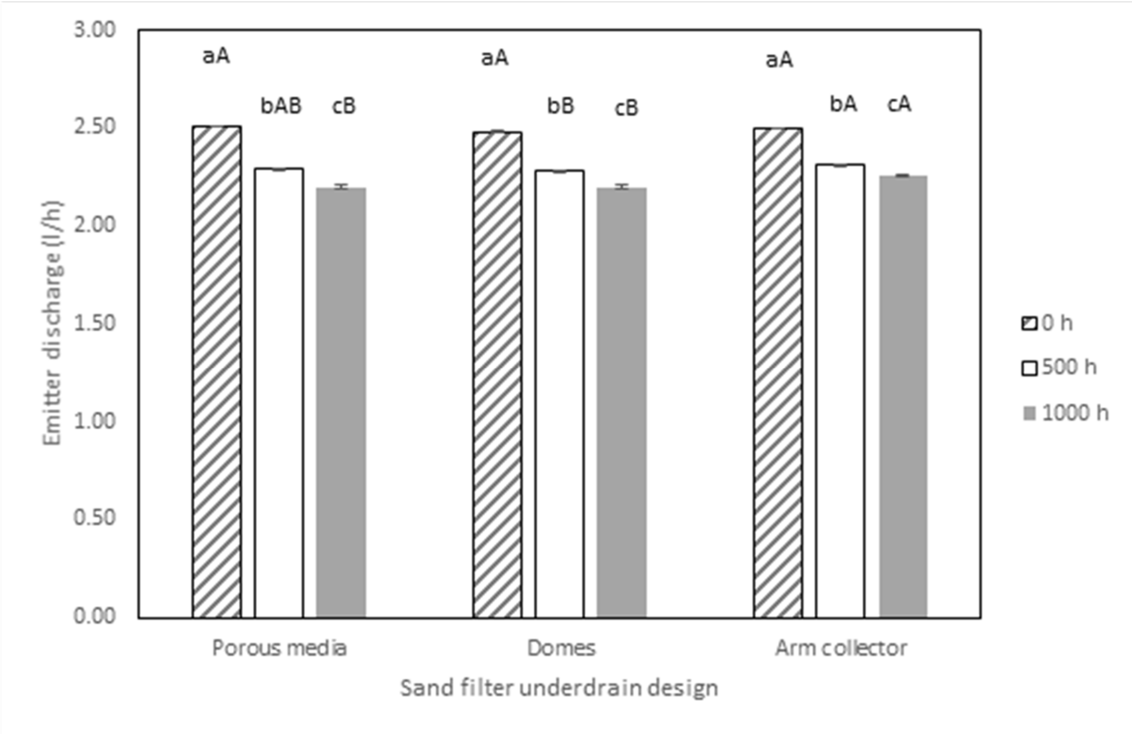

Figure 3. Average emitter discharge and standard error (l/h) of all the emitters protected by sand filters with different underdrain designs at three measurement times. For each filter underdrain design, different small letters mean significant differences (p<0.05) among times. For each measured time, different capital letters mean significant differences (p<0.05) among filter underdrain designs.

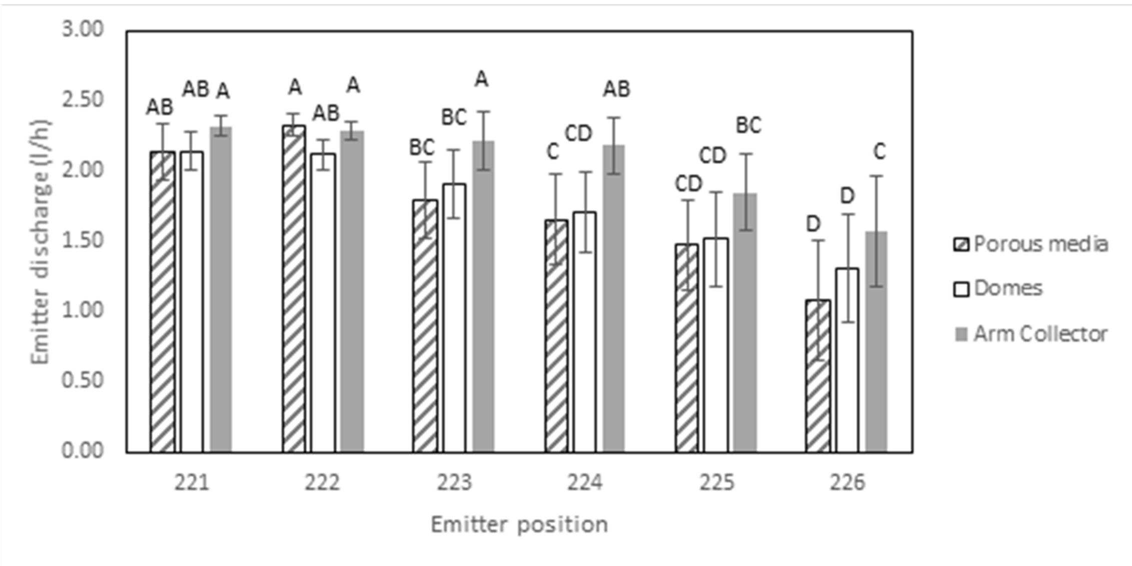

Figure 4. Average emitter discharge and standard error (l/h) of the last 6 emitters of the lateral for each filter underdrain design. For each underdrain design, different capital letters mean significant differences (p<0.05) among locations.

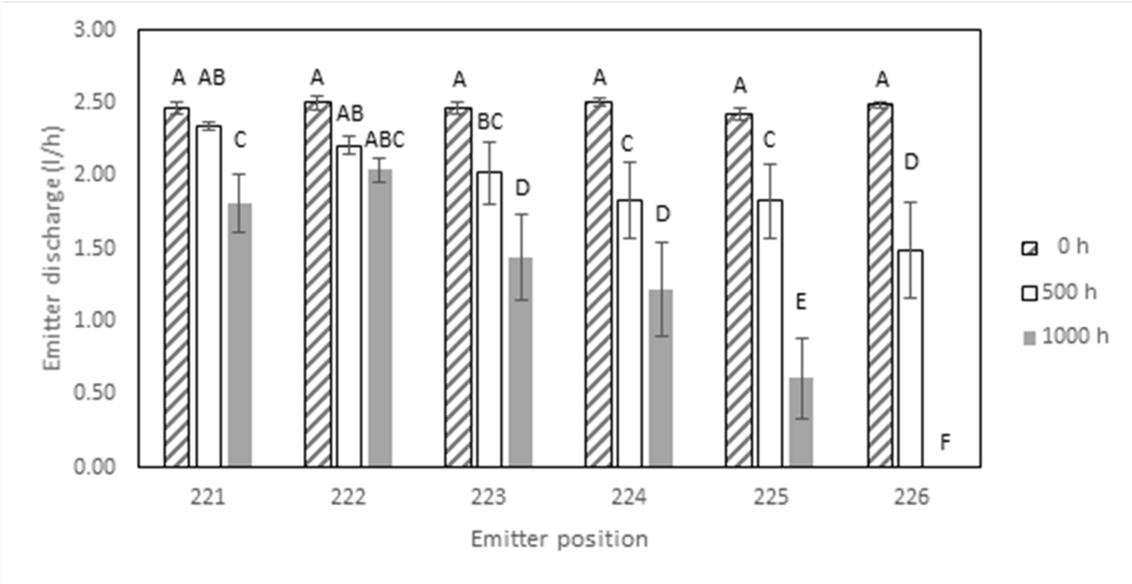

Figure 5. Emitter discharge averages and standard error (l/h) for the last 6 emitters of the lateral at each measured time. For each measured time, different capital letters mean significant differences (p<0.05) among locations.

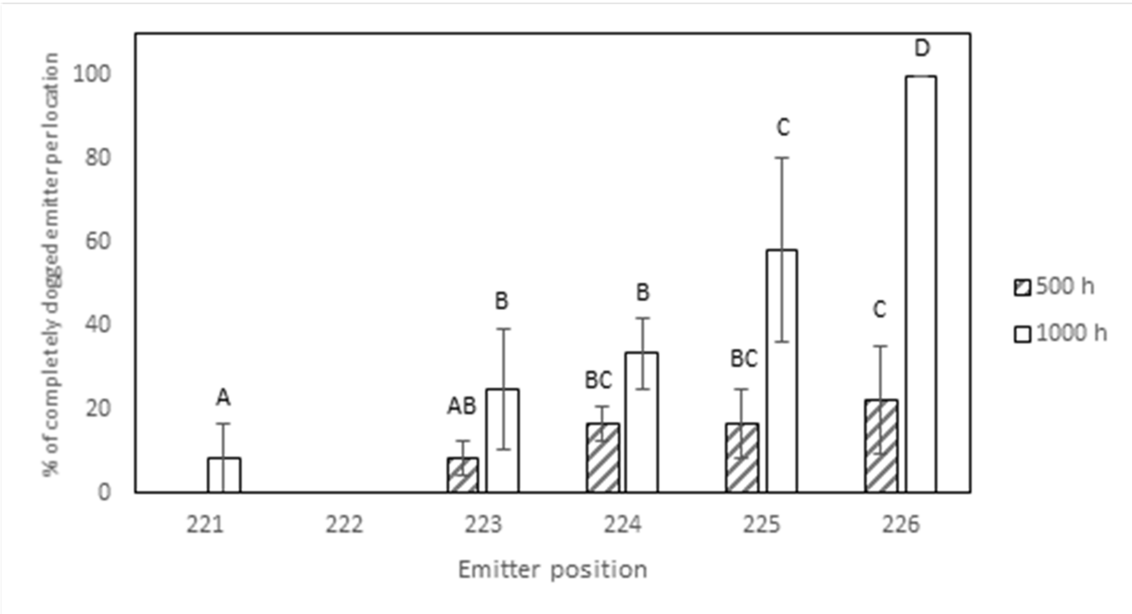

Figure 6. Percentage of completely clogged emitters (%) per emitter location, after 500 and 1000 testing hours. For each time, different capital letters mean significant differences (p<0.05) among locations.

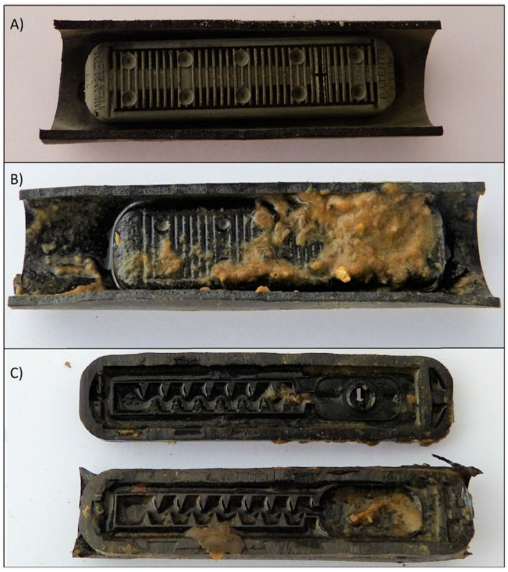

Figure 7. External views of an emitter protected by the porous media underdrain filter placed at the first location (A) at last location (B), and inside view of the last one (C) after 1000 h of irrigation.