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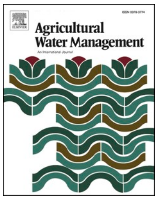

Effect of different filter media on emitter clogging using reclaimed effluents

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ABSTRACT

Pressurized media filters are the most effective means of preventing emitter clogging when reclaimed effluents are used in drip irrigation systems. In these filters, water pollutants are retained in a granular bed, which needs to be replaced once its life span has been reached. Silica sand is the most common material used as a filtration bed, but the use of alternative materials which may improve filtration efficiency and reduce environmental impact, should be explored. Thus, the aim of this study was to compare the effect of two different granular media (silica sand and recycled glass) used in three filters with different underdrain designs (collector arms, inserted domes, and porous media) on emitter clogging. Experiments were carried out by filtering a reclaimed effluent for the duration of 1000 h for each filter and material. Four irrigation laterals 90 m in length with a 2.3 l/h pressure-compensating emitter placed every 0.40 m along the dripline were placed after each filter. Filter performances were continuously assessed while emitter discharges at 8 selected locations across the laterals were measured at the beginning, after 500 h, and at the end of the experiment. Filtration cycles lasted longer with recycled glass, but turbidity removal was affected by the combination of bed material and underdrain. Only after 1000 h of irrigation, was the discharge significantly lower for those emitters protected with porous underdrain using glass compared with sand. Emitter discharge was considerably reduced at the end of the lateral due to a higher number of completely clogged emitters at this location, but there were not significant differences between granular materials and filter designs. Overall, the results show that using recycled glass does not significantly increase emitter clogging compared with silica sand.

1. Introduction

Irrigation with reclaimed effluents instead of fresh water has many potential advantages such as the conservation of potable water resources, the use of the nutrients present in the effluent by the crop and a favorable cost/benefit ratio (Trooien and Hills, 2007). Drip irrigation systems are especially suitable for applying reclaimed effluent since effluent exposure to plants and humans is minimized in regard to other irrigation methods such as sprinkler irrigation (Trooien and Hills, 2007). Although effluents contain many physical and chemical substances as well as microorganisms and their metabolites which can readily clog emitters and affect water distribution uniformity and system operation (Solé-Torres et al., 2021), continued advances in system design, management and monitoring have expanded the use of reclaimed effluents through drip irrigation systems (Trooien and Hills, 2007). However, preventing emitter clogging is still a challenge that can be tackled by installing suitable emitters (Trooien et al., 2000; Zhou et al., 2019), filtering the effluent properly and effectively (Ravina et al., 1997), and suppressing microbiological growth and chemical precipitation in the effluent using acidification, oxidation and disinfection treatments (Green et al., 2018; Hao et al., 2018). Flushing those accumulated sediments in the driplines (Puig-Bargués et al., 2010b; Li et al., 2015), and monitoring system performance to assure that partial clogging can be treated before it becomes unrecoverable (Ravina et al., 1997; Solé-Torres et al., 2019a) are also recommended practices.

Pressurized media filters, which have a granular bed placed inside a tank, are widely used in drip irrigation systems since they require less surface area than gravity media filters (Nakayama et al., 2007). Inorganic and organic particles carried by the irrigation water are trapped throughout the media bed by different and simultaneous mechanisms such as straining, sedimentation, interception, diffusion, inertia and hydrodynamic action (Cescon and Jiang, 2020). Since particles can be caught across the filtration bed and not only on its surface, media filters are more efficient in preventing emitter clogging when reclaimed

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effluents are used compared to other pressurized filters commonly used in drip irrigation systems such as screen and disc filters (Ravina et al., 1997; Capra and Scicolone, 2004; Duran-Ros et al., 2009a). As the media pores become plugged with pollutants, the pressure drop across the filter increases until it is necessary to backwash the granular bed to remove the accumulated contaminants and restore appropriate filtration conditions. The removal efficiency achieved by media filters highly relies on backwashing (Elbana et al., 2012), which, therefore, should be carried out as frequently as possible (Enciso-Medina et al., 2011). As both filtration and backwashing performance depend on filter design (de Deus et al., 2020), some researchers have been focused on improving the main auxiliary elements of these filters, i.e., diffuser plate (Mesquita et al., 2019) and underdrain (Pujol et al., 2016, 2020), aiming to have more uniform water flow across the media and, therefore, less pressure loss. The effect of these changes on filter design and its performance on emitter clogging has not been broadly analyzed. Recently, the study of the effect of different underdrain designs of sand filters on filter performance (Solé-Torres et al., 2019c) and emitter clogging (Solé-Torres et al., 2019b) showed some differences on emitter discharge regarding the underdrain design.

Filter removal efficiency is greatly affected by the physical characteristics of the granular media, such as grain size, shape and porosity (Cescon and Jian, 2020). Smaller grain sizes allow higher solid removal (Elbana et al., 2012; Wu et al., 2015), but head losses are subsequently higher.

Silica sand is the most commonly used medium in pressurized drip irrigation filters (Nakayama et al., 2007) due to its low cost and wide availability. Other naturally available materials such as anthracite, pumice (Kuslu and Sahin, 2013) and basalt (Zaki et al., 2021) have also been used in pressurized media filters. In gravity filters used for water treatment for urban, irrigation or environmental purposes, bark, activated charcoal (Dalahmeh et al., 2012), lapilli (Falcón-Cardona et al., 2015) and even some crop wastes (Ali et al., 2016; Kaetzl et al., 2019) have also been tested. The study of new materials that allow higher filter performance, lower costs and more energy efficient use is attracting more attention (Cescon and Jiang, 2020). In addition, since bed media need to be periodically replaced once they reach the end of their life span, the use of sustainable materials could facilitate a reduction in the environmental impact (Bové et al., 2018). Among these type of materials, recycled glass has been investigated as a possible replacement for sand due to its similar physical characteristics (Cescon and Jian, 2020). Soyer et al. (2010) found that recycled glass achieves equivalent turbidity outlet values and lower head loss than sand in pressurized filters. Nevertheless, there is no available information as to if there would be any effect of the use of recycled glass as a filter medium in drip irrigation systems on emitter clogging. Thus, the main objective of this study was to analyze the effect of two different granular media (silica sand and recycled glass) used in three sand filters with different underdrain designs on emitter clogging when a reclaimed effluent is used.

2. Material and methods

2.1. Experimental setup

The experiment was carried out at the facilities of the Celrà (Girona, Spain) wastewater treatment plant using the effluent of a sludge process that treats urban and industrial wastewaters. Three filters with different underdrain designs were used (Fig. 1). The first one (model FA-F2–188, Regaber, Parets del Vallès, Spain) had inserted domes, the second one (model FA1M, Lama, Gelves, Spain) arm collectors, and the third one was a prototype with a porous media underdrain (Bové et al., 2017) filled with silica sand sieved to 0.75–0.85 mm grain size. Further details regarding underdrain characteristics can be found in Solé-Torres et al. (2019c). After each filter, four laterals 90 m in length each with emitters spaced 0.4 m apart were installed. All the driplines had the same 2.3 l/h rated discharge integrated pressure compensating emitter (model Uniram AS 16010, Netafim, Tel Aviv, Israel), with a 3% manufacturing

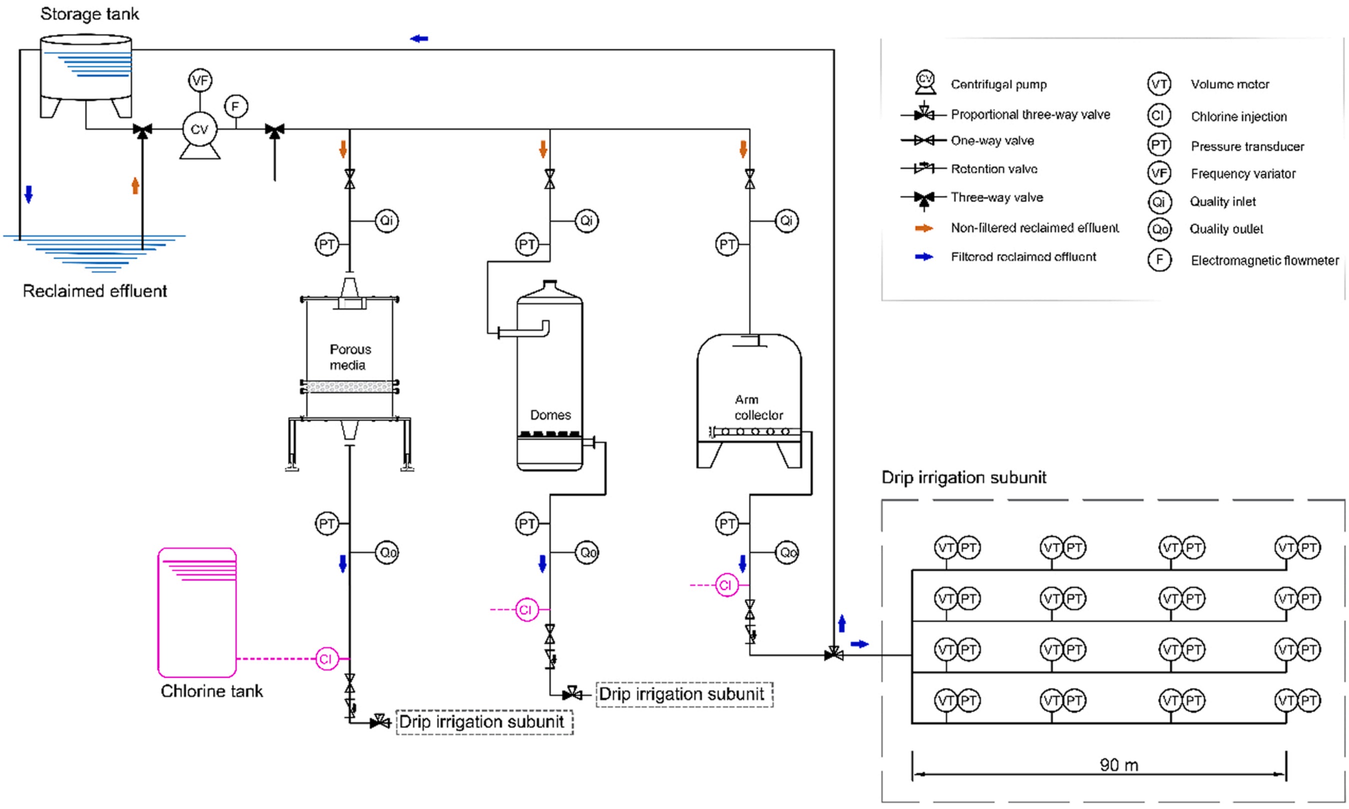

Fig. 1. Experimental setup.

coefficient of variation.

Two different filter media were tested. The first one was CA-07MS silica sand (Sibelco Minerales, Bilbao, Spain) with an effective diameter (D_{10}, size opening which passes 10% by dry weight of a representative sample of the filter material) of 0.48 mm, a uniformity coefficient (ratio of the size opening which passes 60% of the sand through the size opening which passes 10% through) of 1.73, and a porosity (fraction of the volume of voids over the total medium volume, which was determined following Bové et al., 2015 with the ratio between the bulk and real densities experimentally measured) of 0.39. The second media was NW2 recycled glass (Nature Works Tecnologías, L′Alfàs del Pi, Spain) with an effective diameter D_{10} of 0.44 mm, a uniformity coefficient of 1.59, and a porosity of 0.54.

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) pumped the reclaimed effluent from the WWTP outlet chamber to the filters. A DMED300T2 energy meter (Lovato Electric, Gorle, Italy) allowed the determination of the electrical energy consumption of the pump. The filter inlet flow was measured with an Isomag MS2500 (ISOIL Industria, Cinisello Balsamo, Italy) electromagnetic flowmeter. Once filtered, the effluent was conveyed to irrigation laterals. Since the filtrated flow was higher than what was needed for the laterals, a proportional electrohydraulic actuator SKD32 (Siemens, Munich, Germany) operated a three-way valve VXG41 (Siemens, Munich, Germany), so that the excess flow was carried to a water storage tank of 3000 l Aquablock (Shütz, Selters, Germany), which was used for filter backwashing. A chlorine deposit of 200 l was installed to continuously inject chlorine to achieve a concentration of 2 mg/l in the effluent after being filtered, using a DosTec AC1/2 membrane pump (ITC, Santa Perpètua de la Mogoda, Spain). When sand filters were backwashed, chlorine concentration of the backwashing water was increased by up to 4 mg/l.

Effluent electrical conductivity, pH and temperature were measured at the filter inlet using sensors CLS21-C1E4A and CPS11D–7BA21 (Endress+Hauser, Gerlingen, Germany), respectively, while turbidity and dissolved oxygen were determined at both the filter inlet and outlet with sensors CUS31-A2E and COS 61-A1F0 (Endress+Hauser, Gerlingen, Germany), respectively. Since the experimental facility had only one set of sensors for measuring effluent quality, each filter operated individually.

Two additional pressure transducers model TM-01/C (STEP Logística y Control, Barcelona, Spain) measured the pressure at the inlet and outlet of each filter. All the filters were automatically backwashed when the total pressure drop across them reached 50 kPa. Backwashing was carried out for 3 min, with backwashing water volume determined by a WP-Dynamic DN 50 (Sensus, Raleigh, NC, USA) turbine volume meter with an impulse emitter.

A supervisory control and data acquisition (SCADA) system previously developed (Duran-Ros et al., 2008) allowed irrigation system operation. In addition, the SCADA system recorded data of pump electricity consumption, pressure, filter inlet flow, filtration cycle duration, backwashing volume, and those quality parameters of the effluent at both the filter inlet and outlet every minute. The SCADA system was programmed to stop irrigation when inlet turbidity was above 50 FTU, avoiding operation with high particle loads.

2.2. *Operational procedure*

Each filter and media were tested for 1000 h since this is the media lifespan recommended by the manufacturers. Experiments with silica sand took place between March and November 2018, with a pause during June due to a breakdown of turbidity sensors. Recycled glass was tested from June 2019 to March 2020, with several breakdowns due to high turbidity loads caused by operational problems in the treatment plant. Each filter ran for two daily sessions of 4 h.

Two different media heights (20 and 30 cm), and two different filtration velocities (30 and 60 m/h) were tested during 250 h for each media and underdrain design. 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 by computing the removal efficiency (E) achieved in the filters as:

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

being N_0 and N turbidity and dissolved oxygen values at filter inlet and outlet, respectively.

At the beginning (0 h), middle (500 h) and end (1000 h) of the experiment, flow discharges for two contiguous emitters placed at 0%, 10%, 33%, 40%, 59%, 66%, 90% and 100% of the distances along the lateral length were measured. These measurement locations include those suggested by Merriam and Keller (1978) and Juana et al. (2007). Emitter discharge was collected for 5 min in collection dishes and then transferred to a graduated cylinder to be measured.

During the emitter discharge measurements, pressure was also determined in four locations on each lateral (0%, 33%, 66% and 100% of lateral length) using a Leo 2 digital manometer (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 as:

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

being p_{25} the average pressure of 25% of the positions with the lowest pressure (kPa), $\overline{p}$ the average pressure of all the tested positions (kPa) and x the emitter flow exponent, which was experimentally determined in the laboratory as 0.03.

At the end of the experiment, the percentage and location of fully clogged emitters (i.e., emitters that had 0 l/h discharge) was also determined.

2.4. *Characterization of inlet reclaimed effluent*

As filter media were tested in different periods and filters could not operate simultaneously as explained in Section 3.1, reclaimed effluent parameters at filter inlets (Table 1) were analyzed to assess if there were differences during the experiment that could have an effect on results.

Significant differences ($p < 0.05$) were observed for all the analyzed parameters, but they did not mean increased emitter clogging risks. According to Bucks et al. (1979), since pH was between 7 and 8, there was a moderate chemical clogging hazard for all filters and media. Electrical conductivity (EC) values showed a moderate chemical hazard (Capra and Scicolone, 1998) for all media and filters although they were significantly ($p < 0.05$) smaller for the experiments carried out with recycled glass due to changes in the composition of some of the industrial wastewaters treated in the plant. Turbidity values, which are highly related to total suspended solids (Elbana et al., 2012), showed a low physical clogging risk. Water inlet temperatures were significantly higher ($p < 0.05$) during the experiments with recycled glass and may have helped the formation and growth of biofilms, which are closely related to emitter clogging (Zhou et al., 2013). Dissolved oxygen (DO) was also significantly higher ($p < 0.05$) when recycled glass was tested. Considering that higher temperatures and higher salt content (i.e., EC) reduce DO, DO saturation values should be smaller when glass was used instead of sand (8.51 vs. 9.02 mg/l). Therefore, higher DO values observed within the recycled glass experiment would mean that microorganism levels were smaller than when sand was used. Some isolated water sampling revealed that mesophilic aerobic bacteria (determined following the ISO 6222 standard (ISO, 1999)) at filter outlets were $2.30 \times 10^5 \pm 1.78 \times 10^5$ cfu (average ± standard deviation), meaning that the biological clogging risk of the reclaimed effluent

Table 1

Average ± standard deviation of the effluent physical and chemical parameters at each filter inlet and media. Different letters mean that there were significant differences ($p < 0.05$) in the values of each parameter for each filter underdrain design and media.

Media material	Filter underdrain design	Number of filtration cycles	pH (-)	Temperature (°C)	Electrical conductivity (dS/m)	Dissolved oxygen (mg/l)	Turbidity (FTU)
Recycled glass	Porous media	159	7.48 ± 0.24 **b**	23.64 ± 4.11 **a**	1.42 ± 0.28 **c**	3.87 ± 0.98 **a**	6.63 ± 2.92 **ab**
	Inserted domes	169	7.45 ± 0.28 **bc**	23.62 ± 4.28 **a**	1.47 ± 0.36 **c**	4.12 ± 1.14 **a**	7.40 ± 3.54 **a**
	Arm collector	222	7.55 ± 0.21 **a**	22.35 ± 3.85 **b**	1.36 ± 0.25 **c**	4.15 ± 1.12 **a**	6.62 ± 2.97 **ab**
Silica sand	Porous media	175	7.32 ± 0.19 **d**	20.56 ± 3.29 **c**	2.66 ± 0.46 **a**	3.24 ± 0.82 **b**	6.34 ± 2.03 **b**
	Inserted domes	215	7.39 ± 0.22 **c**	19.78 ± 3.50 **c**	2.54 ± 0.49 **b**	3.30 ± 1.19 **b**	6.33 ± 2.94 **b**
	Arm collector	206	7.31 ± 0.20 **d**	19.60 ± 3.53 **c**	2.64 ± 0.44 **ab**	3.25 ± 1.05 **b**	6.56 ± 2.79 **ab**

was high (Bucks et al., 1979) when both media were tested.

2.5. Data treatment and statistical analyses

Statistical analyses carried out using SPSS Statistics software (IBM, New York, USA). Tukey's pairwise comparison test was used for assessing if averages were significantly different with a probability of 0.05 or less.

Filter performance parameters (cycle duration, the ratio filtered volume/electricity consumption, and turbidity and dissolved oxygen removals) were assessed using an analysis of the variance (ANOVA). The model included as fixed effects the filter media and the filter underdrain design, as well as their interaction. Cycle duration was the time elapsed from the end of a backwashing to the beginning of the following one. Not all the filtration cycles carried out were considered for data treatment. Specifically, those cycles which did not reach a 50 kPa head loss or those for which some recorded data were not valid for the whole cycle (e.g., due to maintenance, calibrating processes, scaled down sensors, lower nominal filtration flow or forced backwashing issues) were discarded. Moreover, following Duran-Ros et al. (2009b) procedure, cycles with inefficient backwashing (i.e., those with head loss thresholds across the filter greater than 40 kPa after being backwashed) were also not computed for statistical treatment, as they cannot release most of the particles retained. The total number of cycles included in the statistical analysis are shown in Table 1.

Emitter discharge was also analyzed by means of an ANOVA, which in this case included as fixed effects filter media, filter underdrain design, emitter location and time as well as all the double and triple interactions since some of them were statistically significant ($p < 0.05$). In this case, the lateral was considered as a covariate. A final ANOVA was carried out for assessing the percentage of completely clogged emitters including as fixed effects the filter media and the filter underdrain design, and also their interaction.

3. Results and discussion

3.1. Filter performance

Results of the analysis of variance for the statistical model, media type, underdrain design and the interaction between the media and underdrain for the filtration cycle duration, the ratio between filtered volume and electricity consumption, and turbidity and dissolved oxygen removals are shown in Table 2. The model was significant ($p < 0.05$) for all the cases, as it was the interaction between the media material and the underdrain design. However, the media type by itself was not significant ($p > 0.05$) to explain either turbidity removal or the filtered volume per energy consumption. The underdrain design alone did not have a significant effect on the cycle duration. Since the interactions between the media and underdrain design were also significant, they will be discussed in this section. Least square means and their associated standard errors were computed for the different filter performance parameters (Figs. 2–5) because of their greater statistical accuracy in means separation when there are differences in sample size. As it was explained in Section 2.3 and can be seen in Table 1, the number of valid cycles were not the same for each underdrain and media.

3.1.1. Duration of filtration cycles

The interaction between media and filter underdrains for cycle duration is shown in Fig. 2. Filtration cycle duration was not significantly different ($p > 0.05$) within the same media using any of the three filter underdrain designs tested. However, porous media and inserted domes designs showed significantly ($p < 0.05$) longer cycles (335 and 330 min on average, respectively) when recycled glass was used instead of silica sand (203 and 190 min, respectively). The arm collector design also tended to have longer filtration cycles with glass (257 min), although they were not significantly different ($p > 0.05$) from those carried out with silica sand (227 min). Filtration cycle duration was affected by irrigation water quality as well as pressure loss across the filter. Turbidity, and therefore suspended solid load, was slightly higher when silica sand was used, but the difference was only significant for the inserted domes underdrain. However, these differences in turbidity averages were not great enough alone (maximum of 1.07 FTU, Table 1) to justify these different cycle durations. The average initial pressure loss after a backwashing was slightly higher with glass than with sand at 30 m/h for all the filters (22.3 vs. 13.6 kPa, 14.9 vs. 11.9 kPa and 19.9 vs 16.5 kPa for porous underdrain, inserted domes and arm collector, respectively) but reduced at 60 m/h (37.2 vs. 38.1 kPa, 28.5 vs. 30.4 kPa, and 39.7 vs 40.6 kPa, for porous underdrain, inserted domes and arm collector, respectively). Pujol et al. (2020) found that greater head loss observed with the arm collector underdrain was caused by an imbalance of water flow across each arm. This poorer hydraulic performance explains that filtration cycles tended to be shorter with this underdrain since the pressure loss threshold for carrying out backwashing was reached sooner. On the other hand, the increase of pressure loss across the filtration cycle was quicker with silica sand and therefore filtration cycles carried out with this material were shorter. Effective

Table 2

F and significance levels (p-value) of the statistical model, each factor (media and filter underdrain design) and the interaction for explaining the different filter performance parameter variability during the experiment.

Parameter	Filtration cycle duration		Filtered volume/electricity consumption		Turbidity removal		Dissolved oxygen removal	
Statistic	F	p	F	p	F	p	F	p
Model	9.60	* **	6.29	* **	9.73	* **	10.52	* **
Media material	39.15	* **	2.04	n.s.	0.16	n.s.	32.54	* **
Underdrain design	1.03	n.s.	10.12	* **	18.83	* **	4.33	* *
Media material x underdrain design	5.14	* *	3.19	*	5.68	* *	3.58	*

n.s.: not significant, $p > 0.05$; * : $p < 0.05$; * *: $p < 0.01$; * ** : $p < 0.001$.

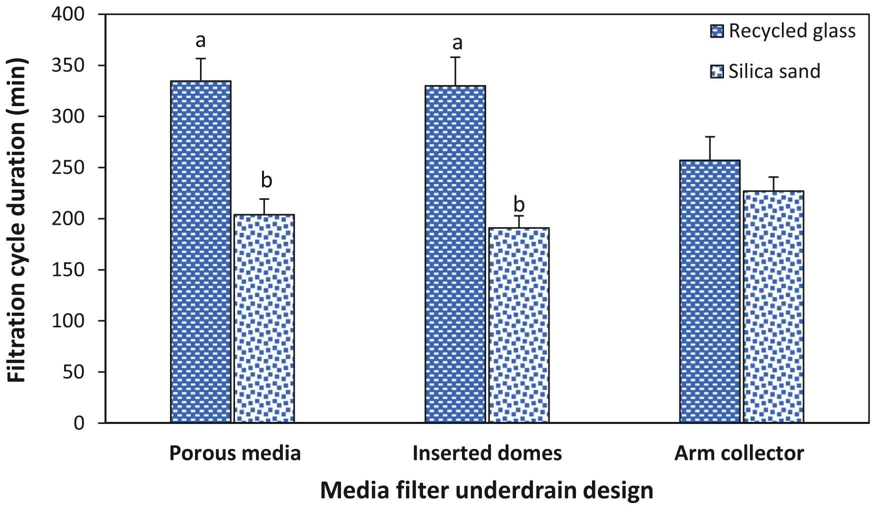

Fig. 2. Least square means values and standard error of the filtration cycle duration (min) regarding media material and filter undrain design. No significant differences ($p > 0.05$) were found between filter underdrain designs with a given media material. For each underdrain design, different lower case letters mean significant differences ($p < 0.05$) between media materials.

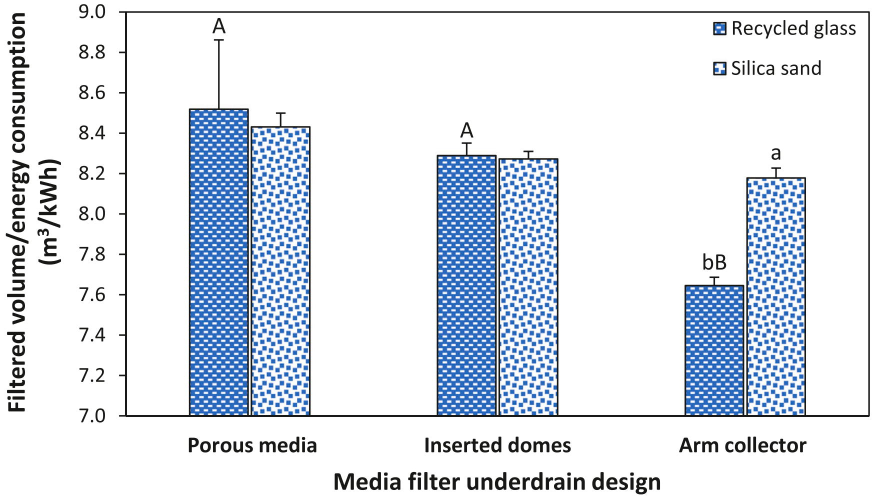

Fig. 3. Least square means values and standard error of the filtered volume per electrical energy consumption (m^3/kWh) regarding media material and filter undrain design. For each media material, capital letters mean significant differences ($p < 0.05$) among filter underdrain designs. For each underdrain design, different lower case letters mean significant differences ($p < 0.05$) between media materials.

grain size (D_{10}) was similar between sand (0.48 mm) and glass (0.44 mm), but the grain uniformity coefficient was greater with sand (1.73 vs. 1.59) meaning that D_{60} was also higher with sand (0.83 mm) than with glass (0.70 mm). The higher the grain size, the lower the head loss across the media filters (Mesquita et al., 2012). Conversely, greater pressure loss was observed using silica sand compared to recycled glass. Soyer et al., (2010, 2013) also observed this behavior, which was attributed to the higher porosity of recycled glass because it is more angular. This was the case of the materials tested, since the porosity of the recycled glass used was 0.54 while that of silica sand was 0.39. Thus, grain porosity is a key parameter that should be taken into account in addition to other characteristics of granular media which are easier to determine, such as effective size (D_{10}).

3.1.2. Filtered volume per energy consumption

The average filtered volumes per electrical energy consumption needed to carry out both filtration and backwashing (Fig. 3) were similar for each media, being on average 8.30 and 8.09 m^3/kWh with sand and glass, respectively. There were no significant differences ($p > 0.05$) among underdrain designs using silica sand but, with glass, the arm collector showed significantly ($p < 0.05$) smaller values (7.65 m^3/kWh) than porous (8.52 m^3/kWh) and dome (8.29 m^3/kWh) underdrains. Only the arm collector showed significantly different values ($p < 0.05$) regarding granular media, filtering more volume per energy consumption with sand (8.18 m^3/kWh). Overall, porous media underdrain filtered more volume per energy consumption (8.49 m^3/kWh) than the inserted domes (8.28 m^3/kWh) and arm collector (7.89 m^3/kWh) underdrains. This result could have been anticipated since the porous underdrain was designed to have a more uniform flow across the bed and therefore it needs less energy (Bové et al., 2017), although reductions are small, between 2.5% and 8%. Little information is available regarding energy consumption for drip irrigation units and specifically for filters, but the values observed were higher than those found by Soto-García et al. (2013) at farm level (5.26–6.25 m^3/kWh) and Espinosa-Tasón et al. (2020) for irrigation in Spain in 2017 (5.88 m^3/kWh), which were both obtained with higher crop area and therefore with greater irrigation water volumes and energy consumption.

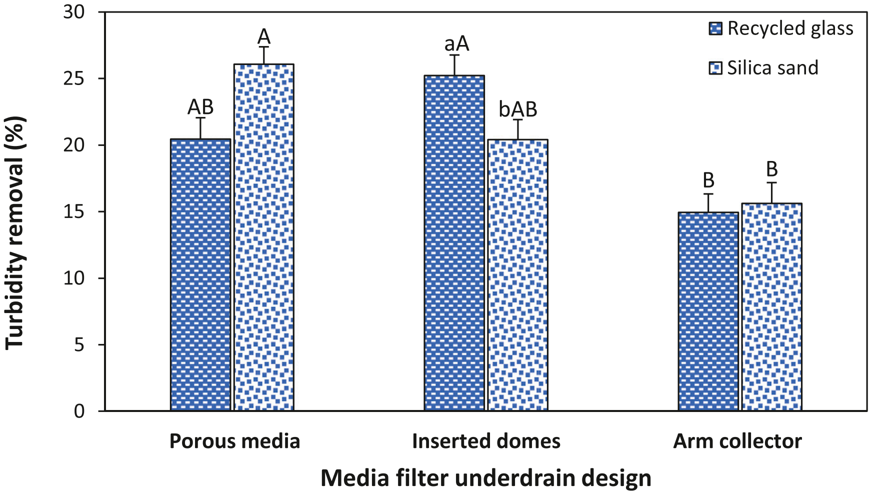

Fig. 4. Least square means values and standard error of the turbidity removal (%) regarding media material and filter undrain design. For each media material, different capital letters mean significant differences ($p < 0.05$) among filter underdrain designs. For each underdrain design, different lower case letters mean significant differences ($p < 0.05$) between media materials.

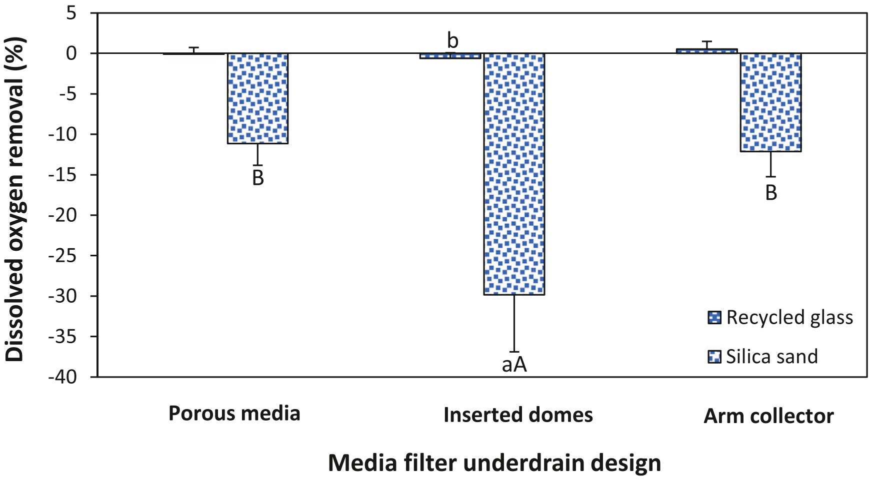

Fig. 5. Least square means values and standard error of the dissolved oxygen removal (%) regarding media material and filter undrain design. For each media material, different capital letters mean significant differences ($p < 0.05$) among filter underdrain designs. For each underdrain design, different lower case letters mean significant differences ($p < 0.05$) between media materials.

3.1.3. *Turbidity removal*

Turbidity removal (Fig. 4) showed a different pattern regarding filter media. With recycled glass, inserted domes design achieved significantly higher ($p < 0.05$) turbidity reductions (25.2% on average) than the arm collector (14.9%), while porous media (20.5%) did not perform differently from the other two underdrain designs. Using silica sand, porous underdrain achieved significantly greater turbidity removals (26.1%) than the arm collector (20.4%), and in this case with the inserted domes underdrain (15.6%) having no differences compared with the other two. Only inserted domes underdrain performed differently between media since it achieved significantly greater average turbidity removals with glass (25.2%) than with sand (20.5%). The porous media and the arm collector showed more turbidity removals with sand than with glass, but without any statistical difference between both media. In all the underdrain designs, turbidity removals were 20.7% for sand and 20.2% for recycled glass. As the media size was quite close between both media (D_{10} of 0.48 and 0.44 mm for sand and glass, respectively), no big differences in turbidity removal were expected. Similar turbidity reductions achieved by recycled glass and sand were also observed by Soyer et al., (2010, 2013), although particle retention is slightly greater with sand (Rutledge and Gagnon, 2002; Soyer et al., 2013).

Overall, turbidity removals have been smaller than those previously obtained (51.1–70.6%) with several sand sizes (D_{10} =0.33–1.5 mm) and different effluents (Duran-Ros et al., 2009a; Elbana et al., 2012; Tripathi et al., 2014). The smaller turbidity removal observed in the present experiment (20.5% on average) for all of these three underdrain designs may be due to the smaller inlet levels of turbidity of the effluent used (6.65 FTU on average) and to the reduced height of sand media bed in the filters, which was between 40% and 60% shorter than the heights used by Duran-Ros et al. (2009a) 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 the reduced maximum height of the arm collector underdrain filter (40 cm) and the need to carry out the experiment under the same experimental conditions of bed height for each filter. With lower bed heights, there is less chance some filtration mechanisms such as interception, diffusion, inertia and hydrodynamic action that allow catching particles across the media could act. These filtration mechanisms, which are depth-depending, are the most common in media filters (Cescon and Jiang, 2020).

3.1.4. *Dissolved oxygen removal*

Dissolved oxygen (DO) increased more at filter outlet (17.7% on average) using silica sand than recycled glass (0.05%), which had almost no effect on this parameter (Fig. 5). The different underdrain designs only performed statistically different ($p < 0.05$) between them when silica sand was used. Moreover, only the inserted domes underdrain design showed significantly ($p < 0.05$) higher increases in DO with sand (29.8%) than with glass media (0.61%). Considering bed heights and filter flows, the residence time of effluent within the media bed was always below 1 min. Since the filters were closed and pressurized, intense contact with air that could easily increase DO levels was not possible, although Maestre-Valero and Martínez-Álvarez (2010) observed slight DO increases in non-airy irrigation equipment such as pumps due to some minor imperfections that cause air intrusions. According to Elbana et al. (2012), DO recovery depends on the number of backwashings carried out because they reduce organic load in the filter, lowering microbial activity and oxygen consumption. Thus, smaller DO increases achieved when using recycled glass could be attributed to the overall longer filtration cycles observed with this medium (Fig. 1), which implied that fewer backwashings were performed. In addition, when glass was used, DO was significantly ($p < 0.05$) higher at filter inlet (Table 1), which could explain that a lower DO decrease could have been achieved. Moreover, chlorination treatment of backwashing water had some breakdowns during the experiments with recycled glass. Since chlorination reduces microbial population (Li et al., 2010) that consumes oxygen, increases in DO at the filter outlet could not have been so high. The arm collector design was the only one that showed a slight DO reduction (0.55%) with glass. Solé-Torres et al. (2019c) also observed some DO reductions with this design with sand working at higher filtration velocities, which might be attributed to the different flow rates between collectors (Pujol et al., 2020) that reduced the contact between the effluent and filtration bed. However, since differences in turbidity (Fig. 4) were not as affected with this underdrain design, further research is needed to identify if there is any different diffusion mechanism on glass surface under the flows and pressures used in this study that might cause such a different performance.

3.2. Emitter performance

Average pressure uniformity coefficient (Uplq) for the three irrigation subunits was always above 96%, which was the lowest value, observed at the end of the experiment with recycled glass. The high Uplq shows that the pressure distribution across the laterals was very uniform. Since there were no hydraulic problems that affected the irrigation system performance and the emitter manufacturing coefficient of variation was low (3%), emitter discharge reductions were mainly due to emitter clogging.

Emitter discharge values were statistically analyzed and there was (Table 3) a significant effect ($p < 0.05$) caused by three of the fixed factors (underdrain design, time and emitter location) as well as five double interactions (media material and time, media material and emitter location, underdrain design and time, underdrain design and emitter location, and time and emitter location) and two triple interactions (media material, underdrain design and time; and underdrain design, time and emitter location). Although material media was not significant as a single factor ($p > 0.05$), it was involved in several of the significant double and triple interactions. The significant triple interactions will be analyzed and discussed in the following sections.

Table 3
F and significance level (p-value) of the statistical model and of each factor and interaction for explaining flow rate variability during the experiment.

	F	p
Model	17.21	* **
Media material	1.63	n.s.
Underdrain design	6.78	* *
Irrigation time	258.09	* **
Emitter location	86.56	* **
Media material x underdrain design	1.83	n.s.
Media material x irrigation time	14.12	* **
Media material x emitter location	6.31	* **
Underdrain design x irrigation time	4.29	* *
Underdrain design x emitter location	2.34	* *
Irrigation time x emitter location	45.81	* **
Media material x underdrain design x irrigation time	2.45	*
Media material x underdrain design x emitter location	1.31	n.s.
Media material x irrigation time x emitter location	1.61	n.s.
Underdrain design x irrigation time x emitter location	1.55	*

n.s.: not significant, $p > 0.05$; * : $p < 0.05$; * *: $p < 0.01$; * ** : $p < 0.001$.

3.2.1. Effect of the media material, underdrain design and irrigation time

Emitter discharge regarding media material, filter underdrain design and irrigation time is shown in Fig. 6. The effect of time is clear since the discharge of all the tested emitters was reduced by 8.1% after 500 h of operation and by an additional 13.7% after 1000 h. Overall, at the end of the experiment, those emitters protected by porous and inserted domes underdrains both reduced their discharge by 22.7%, while those that had an arm collector underdrain had 17.2% less flow. Regarding media material, emitter discharge was 18.6% and 19.4% lower after 1000 h when silica sand and recycled glass were used, respectively. Clogging usually worsens with irrigation time because deposited and adhered sediments considerably increase (Zhang et al., 2020) and there is more chance that chemical precipitates or biological growth could affect emitters, as it has been widely observed (Ravina et al., 1997; Duran-Ros et al., 2009a; Oliver et al., 2014). However, emitter clogging is a complex process that also depends on emitter geometric and hydraulic parameters (Li et al., 2019), variations on mineral content (Zhang et al., 2020) as well as on the biofouling kinetics and changes in bacterial communities (Lequette et al., 2020).

At the beginning of the experiment (0 h), neither the media material nor the filter underdrain had a significant effect ($p > 0.05$) on emitter discharge (Fig. 6). Once the experiment reached 500 h, there was not any difference between the underdrain designs for a given media material. Only the emitters with a porous underdrain showed an average discharge significantly greater ($p < 0.05$) with recycled glass (2.28 l/h) than with silica sand (2.11 l/h). At the end of the experiment, emitter clogging was more widely spread. There were no significant differences between underdrain designs with sand media. However, emitter discharge with the arm collector underdrain (2.01 l/h) was significantly higher ($p < 0.05$) than that achieved by the porous underdrain (1.81 l/h) when recycled glass was used. The discharge of those emitters protected with dome underdrain using recycled glass as filter bed were not statistically different from that achieved with arm collector and porous media. Neither arm collector nor inserted domes underdrain performed significantly different between them with glass or sand. Moreover, only porous underdrain significantly ($p < 0.05$) caused less emitter discharge using recycled glass than using sand as filtration medium at 1000 h. According to these results, the porous media underdrain performed somewhat worse with recycled glass, although this was only evident at the end of the experiment when more completely clogged emitters appeared, as it will be discussed later on in Section 3.3.

3.2.2. Effect of underdrain design, emitter location and irrigation time

The interaction between filter underdrain design, emitter location and irrigation time was also significant (Table 3). Emitter discharge was significantly lower ($p < 0.05$) at the end of the lateral in relation to the other locations for porous media underdrain at 500 h and for all the filters at 1000 h (Fig. 7). When different irrigation times were compared (Fig. 8), significant differences ($p < 0.05$) only appeared at 66%, 90% and 100% of the lateral length (Fig. 8) At 66% of the length, only the emitter discharge achieved with inserted dome underdrain was significantly lower at 1000 h than before, but no differences were observed among underdrains. At 90% of the lateral length, those emitters protected with porous and inserted dome underdrains had significantly less

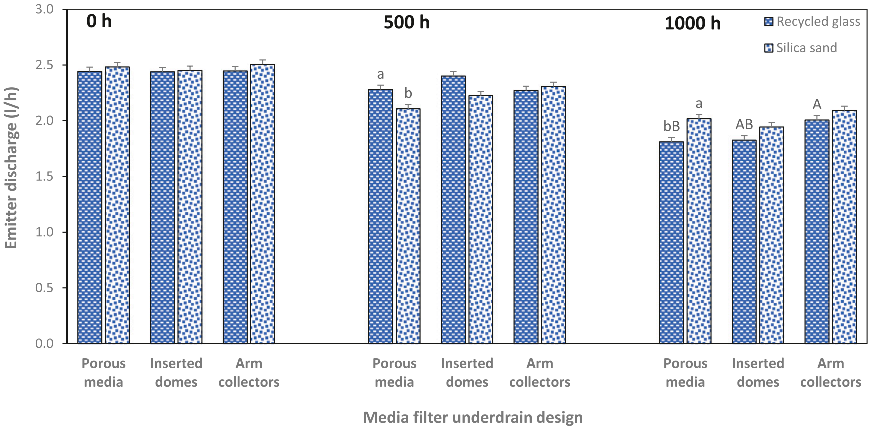

Fig. 6. Least square means values and standard error of the emitter discharge (l/h) regarding media material, filter undrain design and time. At a given time, different capital letters for a media material mean significant differences ($p < 0.05$) among filter underdrain designs. For each underdrain design, different lower case letters mean significant differences ($p < 0.05$) between media materials.

discharge than those with the collector arm underdrain after 1000 h. At this position, despite the fact that emitter discharge decline was observed for all underdrains, with the arm collector there were no significant differences in emitter discharge measured at the beginning, the middle and the end of the experiment. It was at the distal location of the dripline when differences were most noticeable. After 500 h, an almost completely clogged emitter appeared at this position in the laterals protected by the porous underdrain and, therefore, the emitter discharge at this position was significantly smaller ($p < 0.05$) than those of the emitters with the other underdrain designs. After 1000 h of irrigation, some completely clogged emitters appeared at the end of the lateral. Thus, the emitters placed at the distal end showed a significantly lower ($p < 0.05$) discharge than the emitters in any other location, whatever the underdrain design was. In fact, average emitter discharge at the end of the lateral was, on average, 76.9% less than discharge of those emitters located at the beginning of the dripline. At end of the lateral there was not any significant difference ($p > 0.05$) for the emitter discharge between the different tested underdrain designs. Despite slight differences appearing during the experiment, once it had finished, the different underdrains did not show a differential effect on emitter clogging at any location tested across the lateral. The smaller emitter discharge observed at the end of the lateral agreed with previous research (Ravina et al., 1997; Trooien et al., 2000; Duran-Ros et al., 2009a;), which found increased sediment deposition, biological growth and emitter clogging at the end of the driplines.

3.3. Completely clogged emitters

The number of totally clogged emitters was assessed at the end of the experiment (Fig. 9). On average, 0.88% of emitters were completely clogged when sand media was used, ranging from 0.66% for the arm collector, 0.88% for the inserted domes and 1.11% for the porous underdrain. Using recycled glass, the average percentage of totally clogged emitters was higher (2.13%), being 1.31% for the inserted domes, 1.88% for the arm collector and 3.20% for the porous media underdrain. Higher temperatures (Table 1) during the experiment with recycled glass could have promoted microbiological growth and also chemical precipitates (Oliver et al., 2014) that increased emitter clogging.

An analysis of variance was carried out for assessing if media material, underdrain design and their interaction could explain the percentage of completely clogged emitters. However, neither the factors nor their interaction had a significant effect. So, the percentage of completely clogged emitters is not affected by underdrain design and the media used.

All the clogged emitters were located at the end of the lateral, which concurs with the results of previous studies (Trooien et al., 2000; Oliver et al., 2014; Pei et al., 2014). Due to the drip emitter lateral hydraulics, there is less flow rate at the end of the laterals (Shannon et al., 1982) and a greater concentration of sediments (Wu et al., 2015), which promote clogging. In addition, qualitative measurements of chlorine at the emitter outlet at the end of the lateral were made using chlorine test strips and confirmed that the chlorine level was very low at this point since injection was carried out at a long distance away from the filters. Since chlorine levels between 1.5 and 2.5 mg/l were not reached at the end of the laterals (Li et al., 2010; Song et al., 2017), emitter clogging could not be effectively reduced. A possible solution might be specific chlorine treatments applied at the end of laterals, but high residual chlorine concentration damages the diaphragm membrane of pressure-compensating emitters (Green et al., 2018) and reduces their discharge. Alternative biocide treatments that avoid this problem such as hydrogen peroxide (Green et al., 2018) could be carried out instead.

It should also be highlighted that the laterals were not flushed during the experiment, with the aim of having more clogging incidence, and carrying out the experiment under more unfavorable conditions. Despite flushing reduces sediment deposition within driplines (Puig-Bargués et al., 2010b; Li et al., 2018) and biofilm formation (Oliver et al., 2014; Li et al., 2015), the percentage of completely clogged was relatively small and comparable to that obtained by Puig-Bargués et al. (2010a), who observed 1.25% of totally clogged emitters after 1620 h working with sand media filter and a similar emitter without carrying out any flushing treatment.

Some completely clogged emitters from the end of the laterals were dissected once the experiment ended. Biofilm growth was the main cause of clogging, without any important visual difference between those emitters that used glass and sand as filter media. Observations did not differ from those carried out by Solé -Torres et al. (2009b) with silica sand medium. Important biofilm growths were observed in some points of the emitter labyrinth as well as near the emitter outlet. These emitter areas with low flow velocity enhance the adhesion and deposition of clogging substances on the wall, making them more sensitive to biofouling (Ait-Mouheb et al., 2019). Biofilm composition was not analyzed since it was out of the scope of the paper and emitter sampling was carried out under conditions that did not allow representative biofilm results for each treatment.

4. Conclusions

Filtration cycles were 132–140 min longer using recycled glass than with silica sand as filter bed with porous and inserted domes underdrains, respectively. Filter runs with sand in the arm collector only lasted 30 min longer. The filtered volume per electrical energy consumed

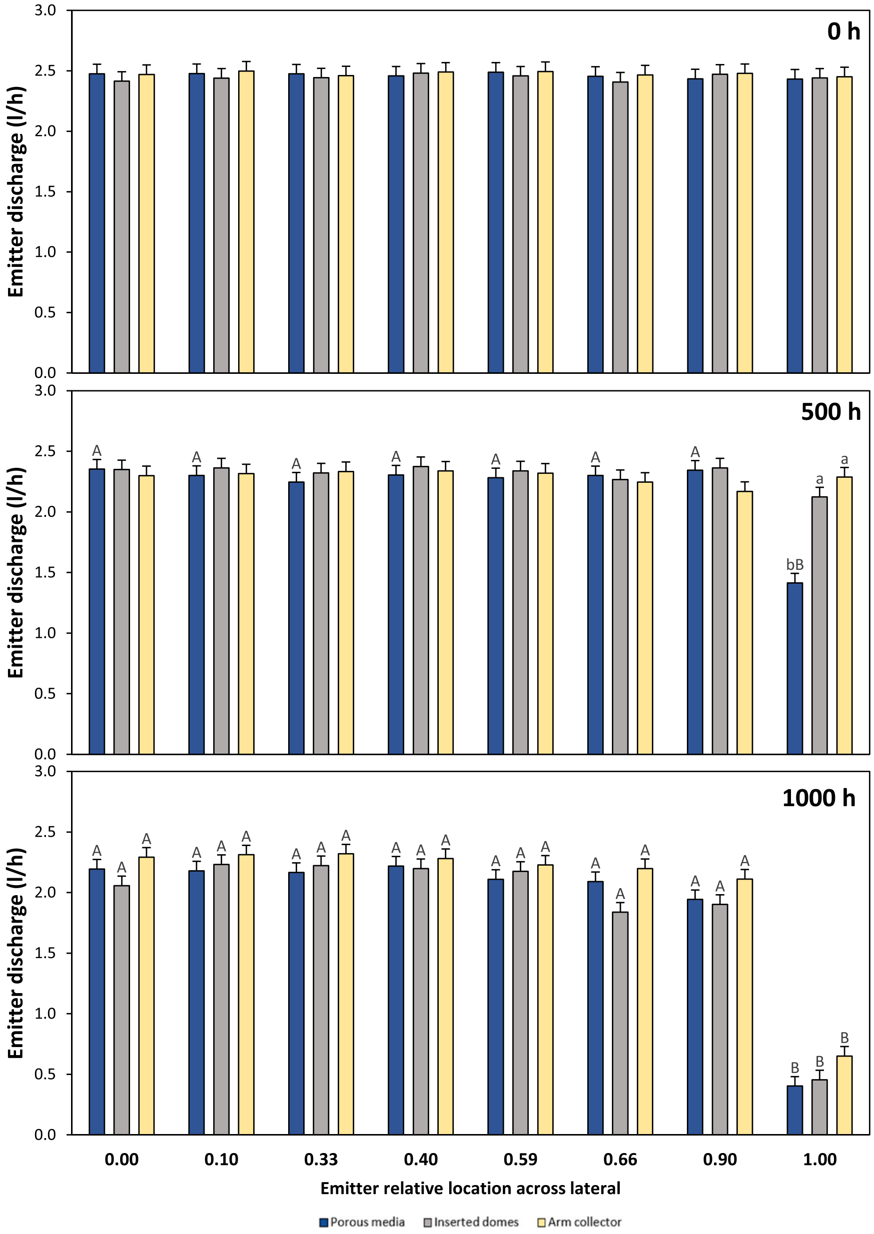

Fig. 7. Least square means values and standard error of the emitter discharge (l/h) regarding filter undrain design, emitter location and time. At a given time, different lower case letters for a location mean significant differences ($p < 0.05$) among filter underdrain designs. For each underdrain design, different capital letters mean significant differences ($p < 0.05$) among emitter locations.

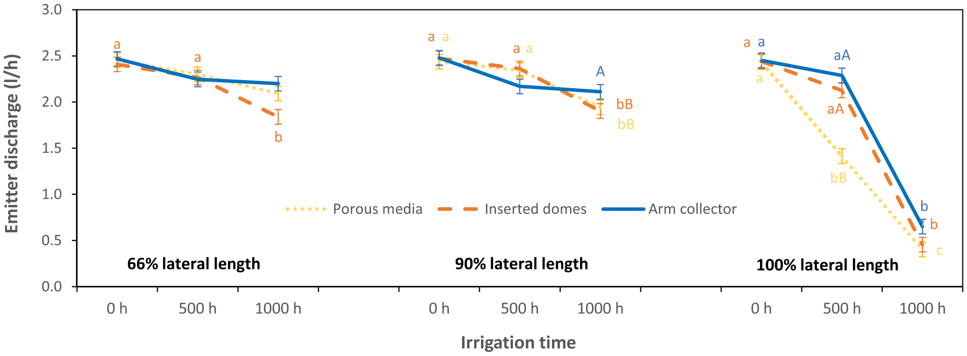

Fig. 8. Least square means values and standard error of the emitter discharge (l/h) regarding irrigation time at the third last locations tested in the laterals, when significant differences appeared. For a given lateral length, different lower case letters show significant differences ($p < 0.05$) on emitter discharges for a specific underdrain design with time. For each irrigation time, different capital letters mean significant differences ($p < 0.05$) among underdrain designs.

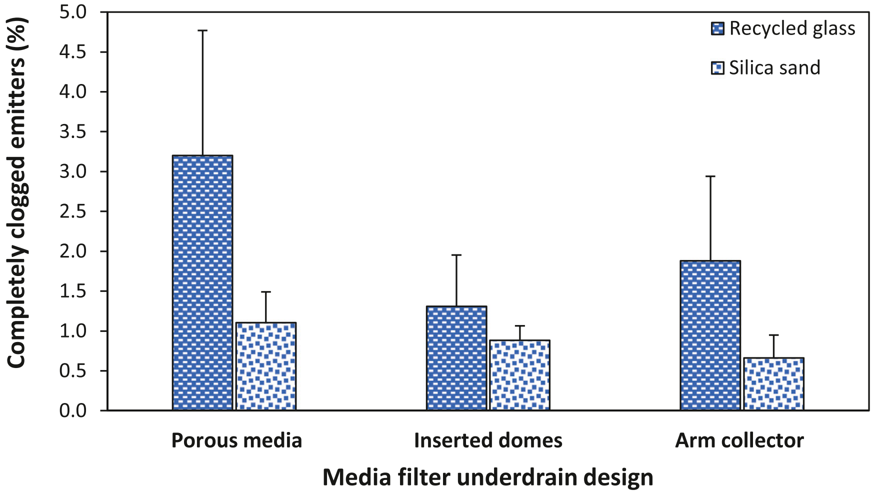

Fig. 9. Least square means values and standard error of the completely clogged emitters (%) regarding media material and filter undrain design. No significant differences ($p > 0.05$ were found).

during filtration and backwashing, was very similar with glass and sand, being on average 8.20 m^3/kWh. This ratio was significantly reduced to 7.65 m^3/kWh when the arm collector underdrain was used.

Turbidity removals were around 20.4% and were mainly affected by the underdrain design. Porous media and inserted domes achieved the highest turbidity removals while the arm underdrain showed the lowest. Differences between turbidity removals regarding bed materials were only observed with the dome underdrain, where recycled glass performed better. Dissolved oxygen was almost unchanged with recycled glass but was increased by 17.7% by silica sand.

Emitter clogging is a complex process that is affected by the interaction of several factors. Emitter discharge was reduced by 21.8% after 1000 h of irrigation. Emitter discharges were not different between underdrains when silica sand was used, but with recycled glass, those emitters protected by the porous underdrain had a significantly lower discharge than those with the arm collector underdrain. Emitter clogging was mainly located at the distal end of lateral (90–100% of the dripline length) at the end of the experiment.

Recycled glass as the filter bed caused lower emitter discharge and a higher number of completely clogged emitters after 1000 h of irrigation, but the differences with silica sand were not statistically significant.

Declaration of Competing Interest

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

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