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Efficiency of Backwashing in Removing Solids from Sand Media Filters for Drip Irrigation Systems

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Abstract: Sand media filters are especially recommended to prevent emitter clogging with loaded irrigation waters, but their performances rely on backwashing. Despite backwashing being a basic procedure needed to restore the initial filtration capacity, there is a lack of information about the solid removal efficiency along the media bed depth. An experimental filter with a 200 mm silica sand bed height was used to assess the effect of two operation velocities (30/45 and 60/75 (filtration/backwashing) m h^{-1}) and two clogging particles (inorganic sand dust and organic from a reclaimed effluent) on the efficiency of backwashing for removing the total suspended solids retained in different media bed slices. The average solid removal backwashing efficiency was greater with organic particles (78%) than with inorganic ones (64%), reaching its maximum at a 5–15 mm bed depth. A higher operation velocity increased the solid removal efficiency by 16%, using organic particles, but no significant differences were observed with inorganic particles. The removal efficiencies across the media bed were more uniform with organic particles (63–89%) than with inorganic (40–85%), which makes it not advisable to reduce the media height when reclaimed effluents are used. This study may contribute to future improvements in sand media filter design and management.

Keywords: irrigation technology; granular filter; filtration; fluidization; reclaimed effluent; water reuse; suspended solids

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1. Introduction

The actual increasing food demand, declining agricultural land, and water availability, alongside issues of environmental degradation, require intensification of agricultural production in a sustainable way [1]. Irrigation enhances crop yield and the productivity of other agricultural inputs, such as seeds, fertilizers, and labor, showing positive impacts on poverty and nutrition, but it also may have some negative impacts on health and environment, especially when irrigation systems are poorly managed [2]. The global irrigated area was 22% of the land area, around 352 Mha, in 2021 [3], but irrigation techniques that improve productivity, such as sprinkler and drip irrigation, are only being used in 41.1 Mha (12% of the irrigated area) and 27.3 Mha (8% of the irrigated area), respectively [4]. However, due to its higher water use efficiency, drip irrigation's surface is growing faster than those from other irrigation methods, especially in developing and emerging countries, where 80% of the drip irrigation surface is located [4].

The main constraints for drip irrigation's expansion are its high investment and energy costs [5], as well as emitter clogging, which reduces irrigation uniformity and crop yield and increases maintenance costs [6]. Nevertheless, drip irrigation allows a safe and sustainable reuse of reclaimed effluents, which can help address water scarcity [6,7]. However, the general higher loads of salt, nutrients, solid particles, and microorganisms in treated wastewater increase the risk of emitter clogging and pose an additional challenge for keeping the drip irrigation system operating as designed [6].

A key component in any drip irrigation facility is the filtration system, since it prevents emitter clogging by removing suspended particles from the irrigation water [8]. The solid particles conveyed by water can not only cause emitter physical clogging, but they can also be the support on which microorganisms attach and grow, and therefore initiate biological emitter clogging. Moreover, solid particles also participate in crystallization, flocculation, and aggregation of some chemical substances, which can, in turn, initiate chemical emitter clogging [9]. Thus, filters provide a broad protection against the different sources of emitter clogging.

The filter types commonly used in drip irrigation systems are hydrocyclones, screen, disk, and sand media filters [10]. Generally, disk or sand media filters, which provide three-dimensional filtration compared to single-plane filtration for screen filters, are installed when the irrigation water has greater organic loads [9]. In this regard, sand media filters, alone or followed with disk filters, usually show better performances, especially with loaded wastewaters [11–13].

Sand media filters for drip irrigation systems are pressurized tanks packed with granular materials that form a filtration bed where the particles conveyed by the irrigation water are trapped due to the action of diverse and concurrent mechanisms. Straining retains, mainly on the filter surface, those particles larger than the filter pore [14]. Interception catches near the grain surface those small particles transported in the flow streamlines. The inertia of some particles does not modify their trajectory when approaching media grains, colliding with them, and being retained on their surface. Sedimentation allows denser particles to precipitate on grain surfaces. Diffusion transfers the thermal energy of the fluid to very small particles, which drift form the streamlines and impact on the grain particles. Hydrodynamic action of each particle also causes collisions with media grains [14,15]. The coexistence of these different mechanisms explains the general better performance of sand media filters with loaded irrigation water.

The filtration process is more efficient with the passing of time because successively smaller particles can be filtered out as the flow paths become smaller. However, with filter operation, resistance to water flow and pressure drop across the filter increase; therefore, flowrates are reduced [10]. To restore appropriate filtration conditions, the filter is backwashed by reversing the flow for fluidizing the media bed and releasing the retained particles out of the filter bed [16]. Backwashing is a critical part of media filter operation and performance [10], and its frequency considerably affects the irrigation uniformity [17]. Both the filtration and backwashing operation make these filters more complex to operate and, consequently, only suitable for farms with a high technological and professional level [18].

Different studies have analyzed the number of solids retained across the sand media filter bed. De Deus et al. [19] and Mesquita et al. [20] assessed the retention and removal efficiency of inorganic particles achieved by filtration and backwashing in a commercial sand filter that operated with four different filtration velocities, three sand granulometries and three consecutive filtration cycles with a pre-set time of 4 h. They found declining retained solids and removal efficiencies with the media bed height, which also concurs with the observations of other researchers [16,21,22]. In addition, the solid removal efficiency increases with higher velocities and smaller sand particle sizes [20,23,24].

Duran-Ros et al. [21], using a scaled porous media filter, evaluated the suspended particles retained during the filtration in thin slices across the media bed at two filtration velocities using two irrigation water sources with inorganic and organic particles. They found that the solids retained depended on the interaction between the filtration surface velocity, the bed height, and the type of particle. Moreover, they observed more organic particles from a reclaimed effluent at deeper bed slices than inorganic ones, which suggested differential retention depending on the characteristics of the filtered particles.

The effect of different media materials was studied by Song et al. [23], who found that sand beds retained more solids and coarser particles in its surface than crushed glass and glass beads. Other authors have found that the removal of particle-related parameters such as turbidity was also affected by the design of the underdrains of the sand filters [25]. Despite the importance of the solid retention within the media bed, the studies focused on improving sand filter hydraulics [26–28] do not usually consider it due to the limitations of the actual models. Trying to cope with this shortcoming, Pujol et al. [29] carried out a sensitivity analysis to find the most relevant parameters that affect the mass retention in sand media filters, which were filtration velocity and inlet particle concentration. They also observed that the effect of media height, which was the third in relevance, increased with filtration time. However, more information is needed on the solids removed with backwashing to complete a model [30] that, for now, only allows computing particle retention and its spatial distribution at the end of filtration cycle.

Thus, the main objective of the present study was to assess the efficiency of backwashing in removing suspended solids from the filter bed with two filtration and backwashing velocities using two types of clogging particles.

2. Materials and Methods

2.1. Experimental Setup

2.1.1. Experimental Filter

The experiments were conducted using a cylindrical media filter built in polymethyl methacrylate, with a 340 mm height and 110 mm internal diameter. The experimental filter diameter was scaled down by a factor of 4.54 from a commercial 500 mm internal diameter sand media filter to allow for to conducting the experiments at filtration water velocities common in real practice. A cylindrical diffuser fixed to the filter top homogenously distributed the flow on the bed media surface. The filter underdrain was an iron–steel, perforated plate placed at the filter bottom. This underdrain could be raised with a screw system to obtain media bed slices of desired thickness for further analysis. Further details on the experimental filter can be found in Duran-Ros et al. [21]. The same experimental filter was used in the tests carried out at the laboratory and at a wastewater treatment plant.

2.1.2. Laboratory Setup

Besides the experimental media filter, the laboratory experimental setup (Figure 1) had a 0.06 m^3 frustoconical tank as water reservoir, a digital thermometer with an accuracy of ± 1 °C, a Niza 60/3 (Hidráulica Alsina, La Llagosta, Spain) centrifugal pump, a CZ3000 DN15 (Contazara, Zaragoza, Spain) flow meter with an accuracy of $\pm 1\%$, and the necessary fittings. The pressures at filter inlet and outlet were measured using a Leo 2 (Keller, Winterthur, Switzerland) pressure gauge with an accuracy of $\pm 0.07\%$. By properly changing the fittings, the experiments could be conducted under filtration mode, which worked as a closed circuit, since filtered water was conveyed to the frustoconical tank, or under backwashing mode (Figure 1). The target filtration and backwashing velocities were reached by modifying the opening of a general gate valve placed after the water tank. A pressure relief valve located just before the filter inlet was set to open when the pressure reached 200 kPa to prevent any break of the polymethyl methacrylate filter.

2.1.3. Wastewater Treatment Plant Setup

The experimental layout previously described in Section 2.1.2 was shifted to the wastewater treatment plant (WWTP)g of Celrà (Girona, Spain). In these batches of experiments, the water source was the reclaimed effluent of a sludge process, which was pumped from the outlet chamber of the settling tanks of this WWTP. The filtered effluent was conveyed to the WWTP outlet chamber and given its volume and the low residence time of water in it; the filtration experiments could not work in a closed circuit (Figure 2). The backwashing water was also released to the outlet chamber.

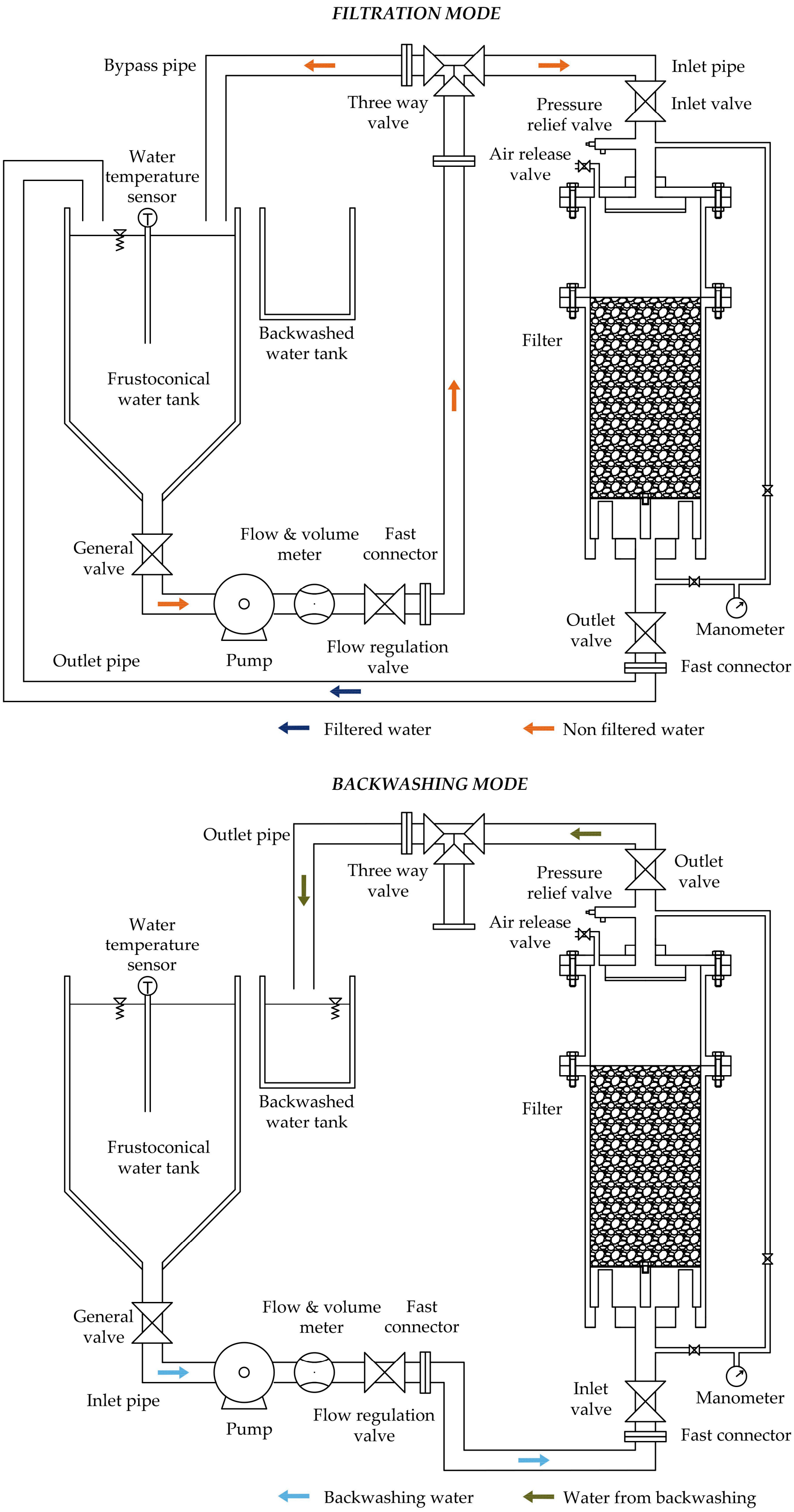

Figure 1. Experimental laboratory setup for the filtration and backwashing modes.

Figure 2. Experimental setup prepared for filtration mode tests placed at the wastewater treatment plant.

2.2. Experimental Methodology

2.2.1. Filtration and Backwashing Experiments

The effect of backwashing on the mass of total suspended solid particles retained across the filter bed depth of two water sources with different types of clogging particles and two filtration and backwashing velocities (Table 1) was assessed in the present study.

Table 1. Clogging particles, target operation velocities, and media bed slice thickness studied.

Type of Clogging Particle Added	Target Filtration (and Backwashing) Velocity (m h^{-1})	Media Bed Slices Depth (mm) [1]
Inorganic (sand dust)	30 (45) 60 (75)	0–5 5–10 10–15 15–20 20–40 40–60 60–80 80–100 100–120 120–140 140–160 160–180 180–200
Organic (reclaimed effluent)	30 (45) 60 (75)	0–5 5–10 10–15 15–20 20–40 40–60 60–80

Table 1. *Cont.*

Type of Clogging Particle Added	Target Filtration (and Backwashing) Velocity (m h^{-1})	Media Bed Slices Depth (mm) [1]
Organic (reclaimed effluent)	30 (45) 60 (75)	80–100 100–120 120–140 140–160 160–180 180–200

[1] From the top of the bed to the bottom.

Before beginning each filtration or backwashing experiment conducted in the laboratory or in the WWTP, the experimental system was run with tap water until the outlet water turbidity was below 1.5 FNU (formazin nephelometric units) to ensure the cleanliness of the experimental equipment, according to the EN 16713-1 standard [31]. An HI 93703 portable turbidimeter (Hanna Instruments, Woonsocket, RI, USA) was used for the turbidity measurements. Once the turbidity values were correct, the filter was filled with 2.67 kg of CA-07MS silica sand (Sibelco Hispania, Bilbao, Spain) for reaching a 200 mm bed height, which was selected since this is a minimum value recommended for commercial filters [25]. The silica sand used in the experiment had a D_{10} (size of the screen opening which allows 10% of the sand sample mass to pass) of 0.48 mm, a D_{60} (screen size opening that allows the 60% of the sand weight to pass) of 0.83 mm, a uniformity coefficient (D_{60}/D_{10}) of 1.73, and a porosity (ratio between the pore volume and the total volume occupied by the media) of 0.40.

To remove the finest particles from the sand media, the filter bed was backwashed with tap water until the turbidity of the outlet water was below 1.5 FNU. Then, the filter was fully drained, and tap water was filtered for 5 min. If the turbidity of the filter outlet water exceeded the 1.5 FNU threshold, the tap water in the experimental setup was completely replaced, the filter was operated for 5 additional min. This procedure was repeated until the outlet water turbidity was lower than 1.5 FNU. Thereafter, the filtration experiments were conducted, adjusting the inlet gate valve until the filtration velocity was around the target (i.e., 30 or 60 m h^{-1}). Moreover, the outlet gate valve was also adjusted to reach 120 kPa, which was the filtration working pressure. Although the gates valves were carefully regulated to meet the desired velocities, the actual velocities slightly differed from those targeted (Table 2).

Table 2. Target (and actual average ± standard deviation) filtration and backwashing velocities (m/h) in the experiments.

Type of Particle Added	Filtration Experiments	Backwashing Experiments	
	Filtration Velocity (m h^{-1})	Filtration Velocity (m h^{-1})	Backwashing Velocity (m h^{-1})
Inorganic (A4 sand dust)	30 (30.5 ± 0.8) 60 (59.5 ± 1.6)	30 (30.7 ± 0.8) 60 (60.8 ± 1.7)	45 (45.9 ± 0.6) 75 (76.6 ± 4.5)
Organic (reclaimed effluent)	30 (31.4 ± 2.1) 60 (62.0 ± 2.7)	30 (29.4 ± 1.0) 60 (60.4 ± 2.9)	45 (47.9 ± 3.3) 75 (71.9 ± 3.4)

In the laboratory experiments, 0.28 g of A4 dust sand (Powder Technology Inc., Arden Hills, MN, USA), with D_{10} = 5.1 µm and D_{60} = 43.9 µm, were added to the frustoconical tank every 5 or 2.5 min, for the 30 and 60 m h^{-1} filtration velocities, respectively, to maintain a 0.5 g L^{-1} solid load at filter inlet, following the EN 16713-1 standard [31]. The volume, flow rate, inlet and outlet pressures, and temperature were recorded every 2.5 min. The ranges of the initial filter pressure losses were 2–4 and 5–7 kPa at 30 and 60 m h^{-1} filtration velocities, respectively. When the total pressure drop across the filter surpassed the initial filter pressure loss by 50 kPa, it was considered that the media bed was clogged. Then, the filtration cycle was terminated, and the solids retained in the media bed were measured, as will be explained in Section 2.2.2.

In another batch of experiments, the clogged media beds were backwashed with tap water for 3 min by modifying the experimental setup (Figure 1) to reverse the flow, and by opening the inlet valves to reach the desired backwashing velocity. The backwashing velocity was 15 m h^{-1} higher than the target filtration velocity, i.e., 45 and 75 m h^{-1} for filtration velocities of 30 and 60 m h^{-1}, respectively, since the dimensions of the experimental cylinder did not allow higher backwashing velocities. As happened with the filtration experiments, the actual backwashing velocities were not exactly the desired ones (Table 2) due to difficulty in adjusting the gate valves.

The same procedure for filtration and backwashing was followed in the experiments conducted in the WWTP, but, in this case, the experimental filter worked with reclaimed effluent in the filtration mode and with tap water in the backwashing mode, as was described before in Section 2.1.3.

All the experiments both in the laboratory and in the WWTP facilities were quadrupled for each velocity and operation mode, i.e., filtration and backwashing. However, results from one replication of the backwashing experiments with A4 dust sand for each velocity and one at 30 m h^{-1} with the reclaimed effluents had to be discarded due to some inconsistencies observed when processing the data. The average experimental conditions of each set of experiments considered in the present study are shown in Table 3.

Table 3. Average ± standard deviation of the mass of added solids, filtered volume, and water temperature during the different experiments. N is the number of replications of each experiment.

Experiment	Type of Clogging Particle	Target Filtration Velocity (m h^{-1})	N	Added Solids [1] (g)	Filtered Volume (m^3)	Water Temperature (°C)
Filtration	Dust sand	30	4	8.38 ± 2.13	0.72 ± 0.18	24.2 ± 1.3
		60	4	3.95 ± 0.88	0.32 ± 0.07	22.8 ± 1.1
	Reclaimed effluent	30	4	7.84 ± 3.99	0.46 ± 0.14	19.9 ± 1.4
		60	4	20.28 ± 8.75	1.68 ± 1.06	17.6 ± 1.2
Backwashing	Dust sand	30	3	11.22 ± 2.95	0.90 ± 0.22	29.6 ± 1.0
		60	3	4.66 ± 0.90	0.39 ± 0.09	26.5 ± 4.0
	Reclaimed effluent	30	3	8.61 ± 5.26	1.32 ± 0.76	30.0 ± 2.1
		60	4	10.92 ± 2.64	1.70 ± 0.60	25.5 ± 4.3

[1] For the reclaimed effluent, the added solids were computed by multiplying the total suspended solids of the influent with the volume of the effluent filtered.

2.2.2. Quantification of the Suspended Solids Retained in Each Bed Slice

Once each filtration and backwashing test was finished, thirteen portions of the media bed (Figure 3) were taken by lifting the underdrain using the screw of the experimental filter. The thickness of these slices was 5 mm in the top 20 mm of the bed and 20 mm from 20 to 200 mm bed depth. The slices were detached from the bed and placed in a plastic container for further analysis (Figure 3).

The van Staden and Haarhoff procedure [32] was followed to determine the total suspended solids present in the sand media slices. In the first four media slices, whose thickness was 5 mm, 100 mL of distilled water was added to the recipient that contained the whole slice. In the 20-mm-thick slices, 100 mL of distilled water was also added to a media sample of 50 mL. Then, the plastic container was agitated and inverted energetically 20 times before decanting the supernatant. This procedure was carried out five times per sample (except for the superior slice, for which the obtention of a clear supernatant required repeating this process 10 times), and allowed for obtaining solid suspensions.

Figure 3. Removal of the bed slices after an experiment carried out in the WWTP.

The total suspended solids were determined in samples of these suspensions, which were pumped with a 1C (Vacuubrand, Wertheim, Germany) vacuum pump to a magnetic filter funnel (Pall Corporation, East Hills, NY, USA) with 1.2 µm GMFC-52047 (Scharlab, Sentmenat, Spain) glass microfiber filters previously dried at 105 °C in a Digitheat 190L (Selecta, Abrera, Spain) heater for 12 h and weighed with a HM-200 (A&D Instruments Ltd., Tokyo, Japan) balance with a precision of ±0.01 mg. Once the suspensions were filtered, the glass microfiber filters were dried in the heater for 2 h at 105 °C. Then, they were placed in a desiccator for 2 h and weighed, which allowed for calculating the mass of the total suspended solids present in each bed portion. Since each media portion was also dried at 105 °C for 24 h and its weight determined with a GX-4000 (A&D Instruments Ltd., Tokyo, Japan) balance, with an accuracy of ±10 mg, the ratio between the mass of those suspended solids retained per mass of sand slice could be computed.

The removal efficiency of the total suspended solids found in each media bed slice achieved by backwashing was calculated following this Equation:

$$E_{TSS\ slice_i} = \frac{\left(\frac{TSS_i}{m\ slice_i}\right)_F - \left(\frac{TSS_i}{m\ slice_i}\right)_{BW}}{\left(\frac{TSS_i}{m\ slice_i}\right)_F} \cdot 100 \quad (1)$$

where $E_{TSS\ slice_i}$ was the removal efficiency of the total suspended solids retained in the bed slice i (%), and $\left(\frac{TSS_i}{m\ slice_i}\right)_F$ and $\left(\frac{TSS_i}{m\ slice_i}\right)_{BW}$ were the ratio of total suspended solids at slice i regarding the mass of this slice after filtration (F) and after backwashing (BW) (g g^{-1}), respectively.

2.3. Statistical Treatment

The backwashing efficiency in removing the total suspended solids along the filtration bed was evaluated with an analysis of variance (ANOVA) using the SPSS statistics software version 28.0 (IBM, Armonk, NY, USA). The statistical model included as fixed effects the target operation velocity, the type of particle and the bed depth slice, as well as their double and triple interactions. Tukey's pairwise comparison test was used for assessing if least square means were significantly different ($p \leq 0.05$). Least square means were used due to their greater statistical accuracy in the mean separations when there are differences in sample size.

3. Results

The results of the analysis of variance of the model for the total suspended solids removal efficiency achieved by backwashing are shown in Table 4. The model, all the independent factors (target operation velocity, type of clogging particle, and bed depth slice), and two double interactions (operation velocity × type of clogging particle and type of clogging particle × bed depth slice) were statistically significant ($p < 0.05$). Only the double interaction between the type of clogging particle and the bed depth slice as well as the triple interaction were not significant ($p > 0.05$). The statistically significant double interactions will therefore be further presented in this section.

Table 4. Significance levels (p-value) of the statistical ANOVA model, each independent factor (operation velocity, type of clogging particle, and bed depth slice) and their double and triple interactions for explaining the removal efficiency achieved by the backwashing in each media bed slice.

Parameter	*p*-Value
Model	<0.001
Operation velocity	<0.001
Type of clogging particle	<0.001
Bed depth slice	<0.001
Operation velocity × type of clogging particle	<0.001
Operation velocity × bed depth slice	>0.050
Type of clogging particle × bed depth slice	<0.001
Operation velocity × type of clogging particle × bed depth slice	>0.050

<0.001 and >0.05: significant at 0.1% and not significant by F test.

3.1. Effect of the Operation Velocity and the Type of Clogging Particle

The interaction between the target operation velocity and the type of particle filtered is shown in Figure 4. The total suspended solid removal efficiency across the whole filter media bed was around 64% when sand dust was added, without statistically significant ($p > 0.05$) differences observed between both velocities. However, working with the reclaimed effluent, the removal efficiency was significantly higher ($p < 0.05$) at an operation velocity of 60/75 m h^{-1} (filtration/backwashing) (86%) than at 30/45 m h^{-1} (70%). Solid removal efficiencies tended to be better when the reclaimed effluent was used, but they were only significantly higher ($p < 0.05$) at 60/75 m h^{-1} operation velocities.

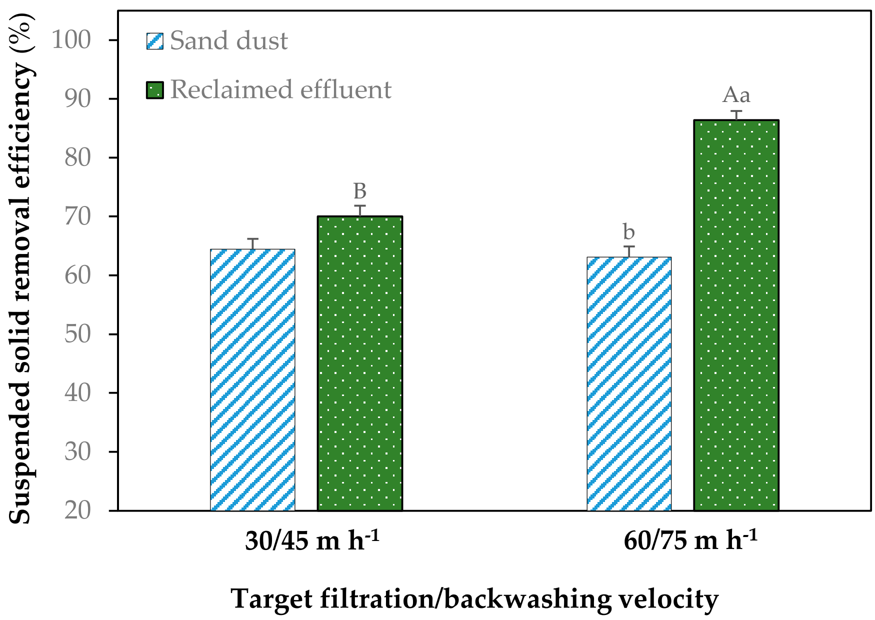

Figure 4. Least square means (±standard errors) of the total suspended solids removal efficiency achieved by backwashing regarding the type of clogging particles added and the target operation velocity. Different lowercase letters show significant differences ($p < 0.05$) between the clogging particles within a same target velocity. Different capital letters show significant differences ($p < 0.05$) between operation velocities within a same type of clogging particle.

3.2. Effect of the the Type of Clogging Particle and Media Bed Depth Slice

Figure 5 shows the effect of the type of clogging particle and media bed depth on the total suspended solid removal achieved by backwashing. Overall, the higher removal efficiencies were observed at depths between 5 and 20 mm. When the reclaimed effluent was used, removal efficiencies from 5 to 20 mm depth (87% on average) were significantly higher ($p < 0.05$) than in the 180–200 mm depth slice (63%). No other significant differences were observed between bed slices, although the second minimum removal efficiency was found in the first 5 mm (68%).

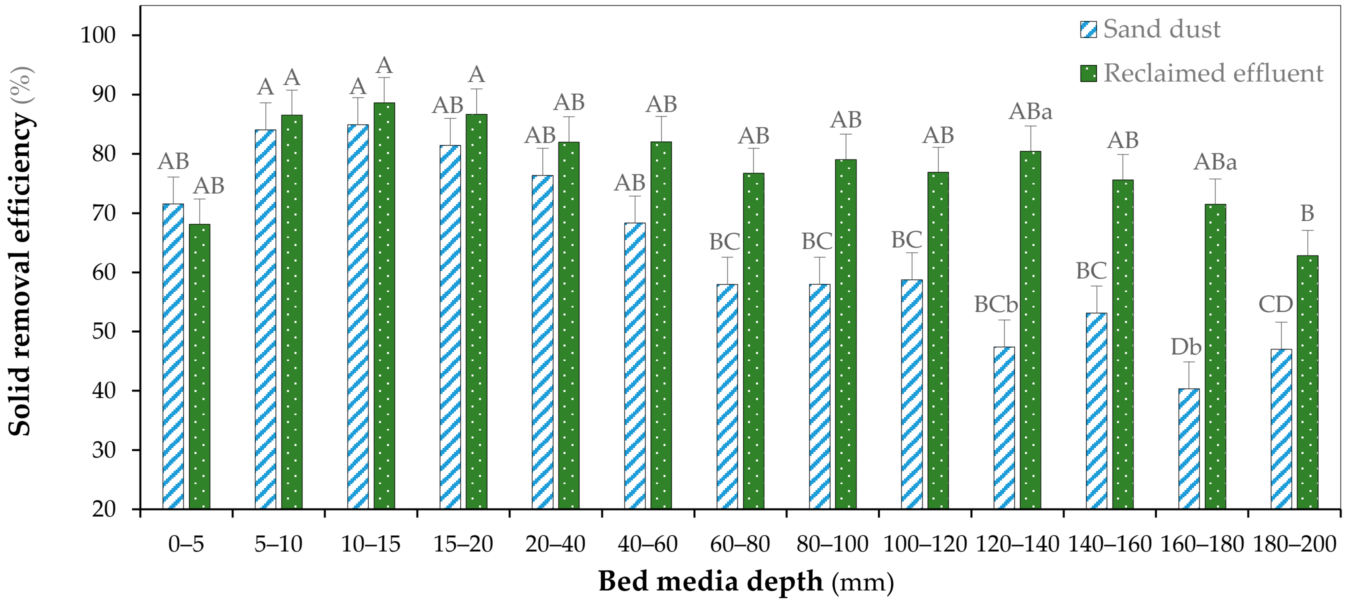

Figure 5. Least square means (±standard errors) of the total suspended solids removal efficiency achieved by backwashing regarding the type of clogging particles and the filter media depth. Different lowercase letters show significant differences ($p < 0.05$) between the clogging particles within a given bed media depth. Different capital letters show significant differences ($p < 0.05$) between bed slices within the same type of clogging particle added.

With sand dust, the efficiencies were significantly higher ($p < 0.05$) in the first 5–15 mm (84% on average) than from 60 to 200 mm (52% on average). The lowest efficiency (40%) was observed between 160 and 180 mm, but it was not statistically different than that observed between 180 and 200 mm (47%).

Significant differences between the type of clogging particles were only observed for 120–140 and 160–180 mm slices, with solid removal efficiencies being statistically higher ($p < 0.05$) with reclaimed effluent than with sand dust.

4. Discussion

A scaled pressurized sand filter was used to analyze the effect of the filter operation mode (filtration and backwashing), its operation velocity (30 and 60 m h^{-1} filtration velocity and backwashing velocity increased in 15 m h^{-1}), and the main type of clogging particles (inorganic and organic) present in the irrigation water on the efficiency of backwashing for removing those total suspended solids retained across the media bed depth. Due to limitations of the experimental filter, which should also be moved from the laboratory to a wastewater treatment plant facility, the bed height was restricted to 200 mm. This height is the minimum in commercial filters [25] and falls within the range from 80 to 600 mm [22–24] heights used in other laboratory experiments. On the other hand, the filtration velocities in sand media filters for irrigation used in the scientific literature vary from 20 to 100 m h^{-1} [25,27], although the most common are limited in the 20–75 m h^{-1} interval [20,23,25]. Filter backwashing is carried out at higher velocities in order to effectively fluidize and expand the bed [10]. The minimum fluidization velocity increases with the media particle size [33], being 30 m h^{-1} for 0.75–0.85 mm silica sand [34]. Since the silica sand size used in the present experiment had smaller grain sizes, the backwashing velocities used in the present experiment (45 and 75 m h^{-1}) allowed proper bed fluidization, which was visually observed in less of 10 s of backwashing. Overall, the experimental conditions under which the present work was conducted fall within those common in similar studies.

Several authors have tackled the study of the solids retained across the sand media bed by analyzing equally thick slices of 20 [22], 87.5 [19,20], and 100 mm [23,24]. Our approach has been to take slices of different thickness, being thinner (5 mm) at the top 20 mm of the bed and thicker (20 mm) at the rest of the bed. These different slice thicknesses were set to obtain more information on the backwashing efficiency at the top of the media bed, since that is where more solids are retained [23–25] due the predominant effect of superficial filtration mechanisms [14]. The total amount of suspended solids present in each slice were determined following the van Staden and Haarhoff [32] methodology, which might not be able to detect all the particles retained in the filter bed [21], despite that here, we analyzed thinner bed layers using more media mass than in other studies [19,20]. Each slice had to be removed from the bed for analyzing the suspended solid content, according to the procedure described in Section 2.2.2. This implied that results after filtration and after backwashing were obtained in independent experiments, since the whole content of each bed slice was analyzed. Another approach would be to take sand samples [19] to determine the suspended solids, but we prioritized obtaining information on the whole slice.

The suspended solid removal efficiency achieved by backwashing can be explained by the double interactions between the type of clogging particle added and the operation velocity and the bed depth slice, respectively (Table 4). The average suspended solid removal efficiencies in the whole media bed were 64 and 63% when sand dust was added, working at 30/45 and 60/75 m h^{-1} filtration/backwashing velocities, respectively, and 70 and 86% when using the reclaimed effluent at 30/45 and 60/75 m h^{-1} velocities, respectively (Figure 4). Greater removal efficiencies of inorganic particles have been previously reported at higher filtration and backwashing velocities [20,21], but in the present experiment, the solid removal efficiencies with sand dust were around 64% at both operation velocities. Conversely to other studies [19,20,23], where filters ran for a pre-set time, in our work, the filtration mode lasted until the increase in the total head loss across the filter was 50 kPa, regarding its initial value. This means that the filter runs did not last the same time for each test. In fact, working at 60 m h^{-1}, filtration cycles were shorter, filtered volumes were smaller, and therefore, less than the half of sand dust was added (3.95 and 4.66 g in filtration and backwashing experiments, respectively, Table 3) than at 30 m h^{-1} (8.39 and 11.11 g). Consequently, these differences in the sand dose during the filtration mode allowed for less inorganic suspended solids to be retained when working at higher filtration velocities.

When the reclaimed effluent was used, the total suspended solid removal efficiency was significantly higher at 60/75 m h^{-1} (86%) than at 30/45 m h^{-1} (70%). The particle load during the experiments conducted at the WWTP could not be fixed as precisely as it was in the laboratory tests, but the filtration cycles and filtered volume were higher at 60/75 m h^{-1} than at 30/45 m h^{-1} velocities, and, consequently, the amount of solids added (Table 3) were clearly greater with the higher operation velocity (20.28 and 10.92 g vs. 7.84 and 8.61 g for filtration and backwashing experiments, respectively), although with a noticeable standard deviation due to the variable characteristics of the reclaimed effluents [6]. The more solid load at higher operation velocities may have contributed to increasing the dragging and flow shear, which are mechanisms involved in particle detachment during backwashing [35].

Overall, greater solid removal efficiencies were observed with the reclaimed effluent (78% on average) than with sand dust (64% on average), but they were only significantly higher ($p < 0.05$) at filtration/backwashing velocities of 60/75 m h^{-1}. As far as the authors know, there are no published studies analyzing differences in backwashing efficiency regarding the type of irrigation water. Higher removal efficiencies with reclaimed effluents might be attributed to the fact that organic particles might be easier to fluidize and, therefore, easier to release from the filter bed during backwashing, but this hypothesis should be further confirmed.

There were some differences in the solid removal efficiencies achieved by backwashing across the filter bed (Figure 5). Removal efficiencies were significantly ($p < 0.05$) higher in the 5–15 mm bed depth (84% on average) than at both 60–160 and 180–200 mm depths (54% on average).

The suspended solids per slice mass were significantly higher ($p < 0.05$) in the top 5 mm of the media bed, whatever the operation velocity and the type of clogging particle was. This higher solid retention in the shallow silica sand bed layers was also observed by Song et al. [23], who also found that this superficial retention was reduced when the media bed was changed to modified glass and glass beads, and coarser media were used. The greater mass of solids retained at the top of the media bed achieved by silica sand is attributed to the narrower migration space of the quartz particles of the silica sand as well as their micropores, which increase the surface filtration. Despite having the maximum amount of solids retained, removal efficiencies achieved with backwashing (71 and 68% with sand dust and reclaimed effluent, respectively) in the first 5 mm of bed were not the best, although they were not significantly different ($p > 0.05$) than the highest removal efficiencies observed with each clogging particle.

The minimum solid removal efficiency with sand dust was observed in the 160–180 mm depth slice (40%), being significantly smaller ($p < 0.05$) than those efficiencies achieved in the slices above. When the reclaimed effluent was used, differences between slices were smoother, being only significantly higher ($p < 0.05$) in the 5–20 mm bed depth (87% on average) than in the deepest slice, from 180 to 200 mm (62% on average). The irregular flow distribution that is usually observed near the filter underdrain reduces the effective area for fluidizing the bed [36], and therefore, the removal efficiencies are lower. Conversely, at the top of the filter bed, the backwash flow is fully developed through all the media surface, and, consequently, the solid removal efficiencies are better.

The solid removal efficiencies observed were higher than those found in previous studies, which for a media bed with sand with $D_{10} = 0.55$ mm ranged from 60% in the top 87.5 mm to 20% in the bottom 87.5 mm at filtration velocities of 40 and 60 m h^{-1} [19,20]. On the other hand, removal differences between the type of clogging particle were only significantly higher ($p < 0.05$), with reclaimed effluents at the slices of depths 120–140 and 160–180 mm, the latter being the layer where the solid removal efficiency reached its minimum when sand dust was added.

Compared to sand dust, the removal efficiencies with the reclaimed effluent were more uniform across the filter bed, probably due to the higher presence of organic suspended solids at higher depths [21], which could be effectively removed when the bed was fluidized. Since the principal purpose of these filters is removing those solids that may clog the emitters, media heights should not be reduced when using effluents to the benefit of all the filter solid removal capacities. Media bed reductions have been suggested for reducing both filtration energy requirements and environmental impact [37], but they should only be considered when the particles carried by the irrigation water are mainly inorganic.

It should also be pointed out that results were obtained in a scaled experimental filter, and they might be affected by its specific hydrodynamic conditions. Thus, further research is needed using commercial filters which allow for assessing the effect of solids retention and removal, considering different media heights, media grain sizes, alternative materials, filter designs, filtration, and backwashing velocities, as well as long term operation.

5. Conclusions

The average total suspended solid backwashing efficiencies were greater (73% on average) using the reclaimed effluent than when sand dust was added to water (64% on average). The higher backwashing efficiencies were achieved at the filtration/backwashing velocities of 60/75 m h^{-1} with reclaimed effluents.

The highest removal efficiencies were observed at depths of 5–15 mm and 5–20 mm when sand dust and reclaimed effluents were used, respectively. The solid removal efficiency was more constant across the media bed height when the reclaimed effluent was filtered, but it decreased more at the deepest filter layers when sand dust was added. These results suggest that sand media bed depth should not be reduced when filtering reclaiming effluents, since all the filter beds remove solids effectively.

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