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A comparison study on the removal of suspended solids from irrigation water with pumice and sand–gravel media filters in the laboratory scale

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ABSTRACT

In this study, different bed materials in media filter systems were examined. For this purpose a laboratory experiment was established to determine the solids removal efficiency, total outlet flow volume and outlet flow velocity of pumice that has numerous open spaces, vesicles and irregular cavity, sand–gravel and combination of pumice and sand–gravel. In the experiment, two different filter column diameters (150 and 200 mm) and two different inlet flow pressures (100 and 150 kPa) were used. The results show that the total outlet flow volumes increased logarithmically as the filtration test period progressed, while the outlet flow velocities and the outlet concentrations of suspended solids decreased logarithmically for all filter types. Pumice media filters provided higher total outlet flow volumes and lower solid removal efficiency in comparison with sand–gravel media filters. However, the highest average solid removal efficiency was determined by pumice plus a sand–gravel media filter at 90.5%. The average outlet flow velocity value for this filter type was 34.2 $m^3 h^{-1} m^{-2}$, which was higher than the other filter types at the same experimental conditions. Pumice plus sand–gravel media filters increased the filtration period according to the sand–gravel media filters as well.

Keywords: Water treatment; Sediment; Media filters; Pumice; Sand–gravel; Physical clogging

1. Introduction

One of the largest problems encountered with micro-irrigation in agriculture is the clogging of emitters, sprinklers, and valves. Clogging is directly related to water quality [1–3]. In the micro-irrigation system, the small openings can be easily clogged by suspended particles including trash, algae, sand, silt, and other solid contaminants present in irrigation waters. Sand and silt particles may be carried into the irrigation water supply from wells, open channels, rivers, or lakes, and these materials must be removed in any operation. Filtration is an important operation that can help avoid physical clogging under micro-irrigation [3–5].

The media filters achieve the filtration of water through different thickness of graded particle layers. These particles can be gravel, sand, or other granular materials [6]. Many studies have examined performance of different filter materials. Pumice in sand–gravel media with non-pressure conditions was studied by Şahin et al. [7]. Another work was investigated the use of recycled glass as an alternative media to sand media filter [8]. The trickling filter system was developed by using plastic fiber media and analyzed an

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ability of water purification by Dockko et al. [9]. Remize et al. studied the granular media as a pretreatment filtration process [10]. As the filter media, pumice and sand were compared under rapid filtration and single layer conditions by Farizoğlu et al. [11]. Sand–gravel media filters are particularly suitable for water with a high suspended solid content [4,12]. Previously, the efficiency of sand media filters for the removal of suspended solids has been reported by Duran-Ros et al., Hamoda et al., and Bulancak et al. [5,13,14]. Pressure sand filters have been used as the most common sand media filter type. These closed systems contain filtering media that include different numbers of layers: single, two or much layers [7,14,15].

Among the filter bed materials, pumice has also been used as a natural source [16]. Farizoglu et al. reported that vesicular pumice has high potential as a filter bed material [11].

Pumice is a type of extrusive igneous rock that is erupted from volcanoes. It consists of a network of gas pockets, so it resembles a sponge. The pores of pumice are irregular and oval shape, which are usually not connected to each other. Vesicular pumice has long been used as an abrasive in cleaning, polishing, and scouring compounds. It is also used as a lightweight aggregate in concrete, precast masonry units, insulation and acoustic tiles, and plaster. Pumice has got large surface area and high porosity, so it is used as a biofilm support material for wastewater and water material [11].

In the applications, filter bed materials should be acquired easily. Worldwide, over 50 countries produce pumice products, with Italy ranking as the largest producer. Other major pumice producers are Greece, Chile, Spain, Turkey, and the US. Turkey's pumice reserves are estimated to be about 1.5 billion tons [17].

The suspended solids concentration in surface irrigation water is much greater than $10\,\mathrm{mg\,L^{-1}}$ and represents a tremendous amount of solids that pass through pipelines and emitters. Nakayama et al. emphasized that the emitter clogging hazard is severe if the suspended solid concentration of the water is higher than $100\,\mathrm{mg\,L^{-1}}$ [3].

Few micro-irrigation systems require greater than 75 μm filtration [18]. Sand media filters provide filtration to 75 μm; however, very fine sand, silt, and clay will pass through a 75 μm screen and may settle in the emitter, micro sprinklers and lateral lines [19].

The recommended flow velocity for sand media filters is $35\,\mathrm{m^3\,h^{-1}\,m^{-2}}$–$60\,\mathrm{m^3\,h^{-1}\,m^{-2}}$ of filter surface area. If the water has $100\,\mathrm{mg\,L^{-1}}$ or more of suspended material, then the lower filter flow rates should be used. Excessive filter flow velocity can reduce the filtering ability of sand media filters [18,20].

The objective of this study was to compare the filtration capability of pumice alone, as well as pumice plus sand–gravel in media filters under different pressured filtration conditions. Additionally, the effect of filter surface area was investigated in this study.

2. Methodology

2.1. Selecting filter types and materials

The main components of the experimental system used in the filtration tests are shown in Fig. 1. In the experiment, the PVC filter columns had two different diameters (150 and 200 mm) and were 852 mm in length. The column had inlet and outlet connections, so that water could flow downwards through it.

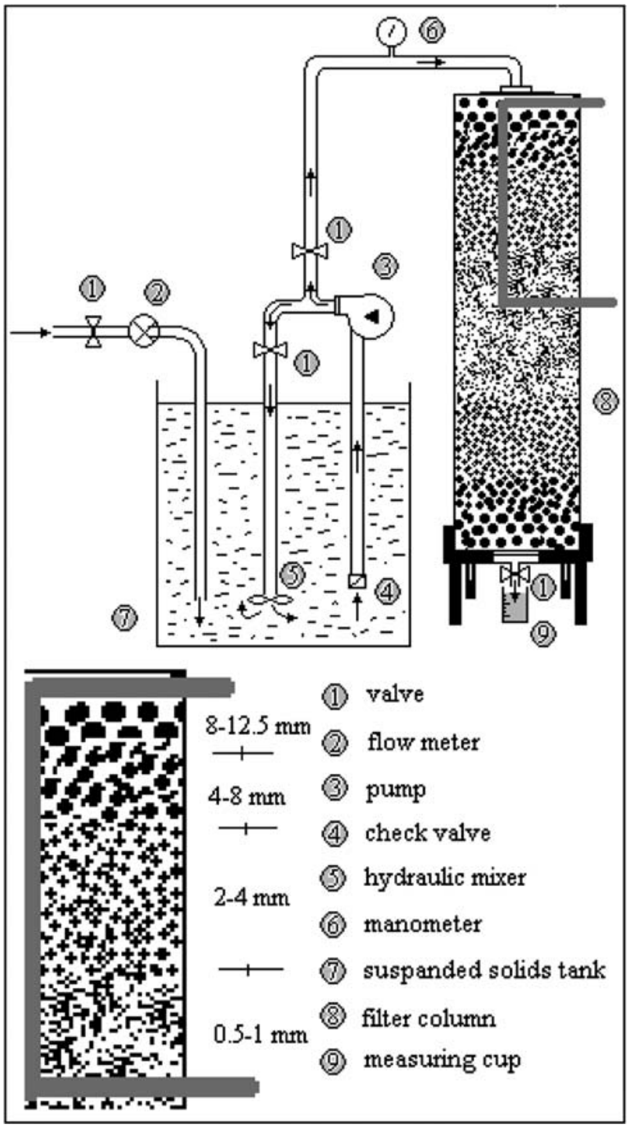

Fig. 1. The experimental system.

Although the operating pressure values of commercial media filters are varying between 30 and 800 kPa, the most common values for drip irrigation applications are 100 and 150 kPa [13,21]. In this study, pressures of 100 and 150 kPa were selected as inlet flow pressures. The required pressure consisted of valves and a pump. The operating pressure was increase because of solid accumulation in filter media. In order to reduce the pressure, the inlet flow volume into the filter was decreased, and the return flow volume into the suspended solid tank was increased via valves. So the operating pressure was remained stable through the experiment. The flow volumes into both the suspended solids tank and filter column were adjusted according to the outlet flow volume. So, the water level maintained constant in the suspended solids tank, and system pressure was not affected from the accumulation of solids in the filter media through the experiment. Sand–gravel and pumice materials were used in the experiments as filter bed materials. The types of media filters tested in the experiment are shown in Table 1.

Sand-gravel and pumice were prepared as four different grain-sized filtration materials by sieving (0.5–1 mm, 2–4 mm, 4–8 mm, and 8–12.5 mm). Also, soil particles was sieved with 75 μm and used as a suspended solid material. The pumice was supplied from Ercis region in Turkey. Sieved materials at different sizes were washed with tap water. The material was filled into the filter column as seven layers. The filling form of layers was same for each filter type (Fig. 1). In this study, thickness of layers were arranged as 40% (L-4), 30% (L-3, L-5), 15% (L-2, L-6), and 15% (L-1, L-4) of total length of filter column. The size of layers was selected so as not to mix with following layer. The properties of different filter layers were given in Table 2.

Table 1
Media filter types tested in the experiment

Filter type	Column diameter (mm)	Bed material	Inlet flow pressure (kPa)
F-1	200	Sand–gravel	100
F-2	200	Sand–gravel	150
F-3	200	Pumice	100
F-4	200	Pumice	150
F-5	200	Pumice plus sand–gravel	150
F-6	150	Sand–gravel	100
F-7	150	Sand–gravel	150
F-8	150	Pumice	100
F-9	150	Pumice	150

The filter bed material was sand–gravel for F-1, F-2, F-6 and F-7 filter types, while pumice was used for the F-3, F-4, F-8, and F-9 filter types (Table 1). In F-5 type, pumice was used in the half of the filter column and first media in which the water flows. Because the pumice was thought as a pretreatment material, the filter bed material was pumice for L-1, L-2, and L-3, while sand-gravel was used for L-5, L-6, and L-7. The filter bed material in L-4 of the F-5 filter type was pumice for the top 170 mm of this layer, while sand–gravel was used for the bottom 170 mm. In F-5 filter type, the latest filtration step was completed with sand-gravel. The highest pressure and the largest column diameter were tested on the F-5 filter type.

2.2. *Operating of experiment systems and measurements*

Porosity of granular medium is formed by pores with different sizes. Pore sizes have traditionally been divided into macropores (> 100 μm diameter), mesopores (100–30 μm diameter), micropores (30–3 μm diameter), and ultramicropores (< 3 μm diameter).

Total porosity for pumice was estimated according to Danielson and Sutherland by using bulk and particle densities of materials before the experiment [22].

$$n = \left(1 - \frac{D_b}{D_p}\right) * 100 \tag{1}$$

where n: total porosity (% by volume); D_b: bulk density (g cm^{-3}); D_p: particle density (g cm^{-3}).

Bulk and particle densities were determined using the cylinder and pycnometer methods, respectively [23,24]. Stainless cylinders (50 mm in diameter and 51 mm in height) were used for bulk densities. The solid and pore size distribution of pumice is given in Fig. 2 [25].

After installation of bed materials, water with suspended solids was provided by a polyethylene tank from a pump that was applied from the top of the filter column. A hydraulic mixer was used in the suspended solids tank for the continuous mixing of solids into the water during the filtration test period (Fig. 1). The solid concentration for the inlet flow was selected to be 250 mg L^{-1}. The grain size of the suspended solid particles for the inlet flow was smaller than 75 μm. Through the experiment, 2.5 mg solids were added continually into the tank in response to reading of per liter from the flowmeter. The temperature of the inlet flow was 12 ± 1˚C, and the electrical conductivity of the inlet flow was 0.26 dS m^{-1}. There was not any intermixing between different layers through the experiment. It was studied with parallel two systems.

Table 2
The properties of different filter layers

Layer numbers	Layer dept (mm)	Material sizes (mm)	Effective diameter (mm) D_{10}		Uniformity coefficient D_{10}/D_{60}		Porosity values of granular medium (%)	
			Pumice	Sand–gravel	Pumice	Sand–gravel	Pumice	Sand–gravel
1—7	64	8–12.5	8.80	8.60	0.92	0.90	80.3	41.1
2—6	64	4–8	5.03	5.00	0.83	0.83	77.4	43.6
3—5	128	2–4	2.42	2.45	0.81	0.82	74.6	45.0
4	340	0.5–1	0.58	0.61	0.97	0.85	71.7	46.4

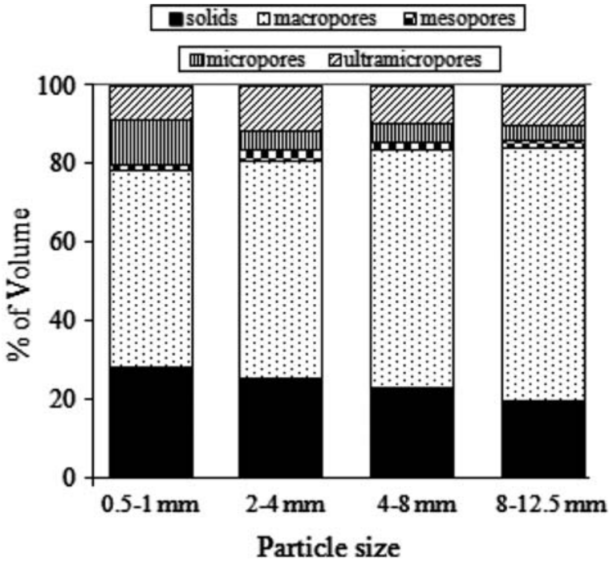

Fig. 2. The solid and pore size distribution of pumice granular medium.

Filtration tests were performed at 4 h continuously for each day, and all experiments took about four months. After the filtration system was stopped, every valve was closed. Before the starting experiment, suspended solid tank was mixed, and then the valves were opened. There is not varying at the inlet and outlet filter pressure between different days.

Outlet flow volumes and outlet concentrations of the suspended solids were recorded during filtration test periods for each filter type. Measurements for each filter type were continued down to an outlet flow velocity of 100 L h^{-1}. The outlet concentrations of suspended solids during the tests were determined by gravimetric analysis after drying at 105℃ of outlet flow samples in an oven. After the filtration tests, a liter volume of each layer in bed material was washed and accumulation of solid amounts was determined by gravimetric analysis after drying at 105℃ of layer samples in an oven.

Removal efficiency was calculated with the following equation [6].

$$E_r = \left(1 - \frac{S_{\text{outflow}}}{S_{\text{inflow}}}\right) \times 100 \tag{2}$$

where E_r: removal efficiency (%); S_{outflow}: Outlet concentration of suspended solids (mg L^{-1}); S_{inflow}: Inlet concentration of suspended solids (mg L^{-1}).

The equations of relationships between the filtration test period and total outlet flow volume, outlet flow velocity, and outlet concentration of the suspended solids were determined by a regression analysis.

3. Results and discussion

3.1. The total outlet volumes

The total outlet flow volumes during the filtration test periods for different filter types are shown in Fig. 3. The total outlet flow volumes increased logarithmically with the increase in filtration test periods (Table 3). In general, larger filter surface areas and higher inlet flow pressures produced higher outlet flow volumes during the filtration test period. The total outlet flow volumes and filtration test periods for pumice and pumice plus sand–gravel media filters were higher than sand–gravel media filters for the same experimental conditions. In the F-4 filter type, total outlet flow volume and total filtration test period were the highest (Fig. 3). However, the F-5 filter type caused the highest outlet flow volumes during its filtration test period in comparison with the other filter types (Fig. 3). The later clogging, and higher total outlet flow volumes determined for the pumice media filters, may have explained the higher porosity and macro pores ratio of the pumice granular medium compared with sand-gravel granular medium [25,26]. As mentioned before in the material and methods description, the total porosity values for the granular medium of tested bed materials were determined at between 71.7 and 80.3% for pumice bed material and between 41.1 and 46.4% for sand–gravel bed material.

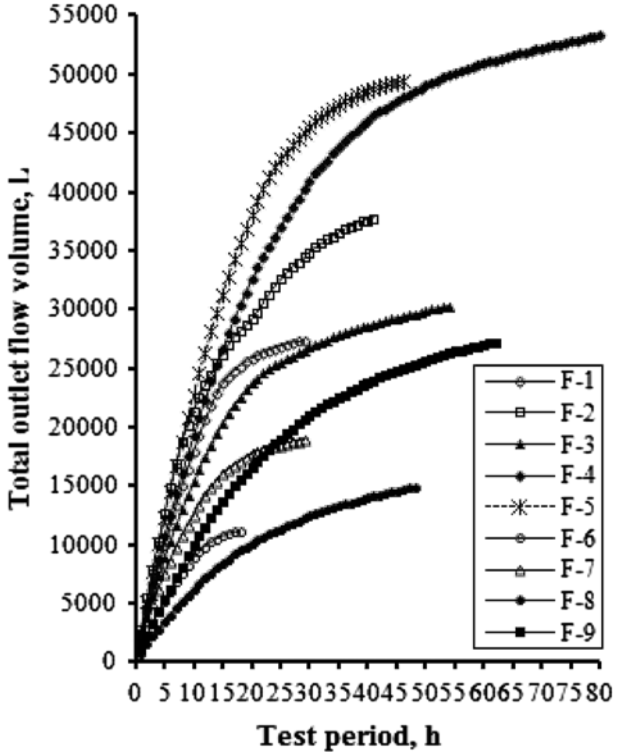

Fig. 3. The total outlet flow volumes for different filter types.

3.2. The outlet flow velocities

The outlet flow velocities during the filtration test periods for different filter types are shown in Fig. 4. Outlet flow velocities for all media filters reduced logarithmically with time (Table 3). The flow velocity gets lower as the pore size smaller. Therefore, the filter bed resistance increases with decreasing in pore size of filter material [11]. In general, larger filter surface area and higher inlet flow pressure produced higher outlet flow velocities. The F-5 filter type caused the highest outlet flow velocities in the first half of its test period in comparison with the other filter types. In the beginning hours of the filtration test period, the outlet flow velocities of pumice media filters were lower than sand–gravel media filters. This is because pumice is a material with very rough grains that increase resistance to flow, and after the first few hours of the test period, the outlet flow velocities of the pumice media filters were higher than sand–gravel media filters because of its highly porous nature [11,16].

3.3. The outlet concentrations of suspended solids

Fig. 5 shows the outlet concentrations of suspended solids during the filtration test periods for different filter types. The outlet concentration of the suspended solids for all media filters decreased

Table 3
The equations of the relationships between the filtration time (x) and total outlet flow volume (Y_1), outlet flow velocity (Y_2) and outlet concentration of suspended solids (Y_3)

Filter type	Equations		
	Y_1	Y_2	Y_3
F-1	$Y_1 = 9{,}111 \ln(x) - 2{,}399$ (3) $R^2 = 0.964$	$Y_2 = -25.2 \ln(x) + 92.16$ (12) $R^2 = 0.855$	$Y_3 = -22.6 \ln(x) + 76.18$ (21) $R^2 = 0.898$
F-2	$Y_1 = 10{,}932 \ln(x) - 3{,}017$ (4) $R^2 = 0.984$	$Y_2 = -27.3 \ln(x) + 105.2$ (13) $R^2 = 0.939$	$Y_3 = -22.5 \ln(x) + 96.75$ (22) $R^2 = 0.819$
F-3	$Y_1 = 847 \ln(x) - 2{,}758$ (5) $R^2 = 0.978$	$Y_2 = -19.1 \ln(x) + 76.16$ (14) $R^2 = 0.954$	$Y_3 = -35.5 \ln(x) + 139.0$ (23) $R^2 = 0.897$
F-4	$Y_1 = 14{,}959 \ln(x) - 10{,}886$ (6) $R^2 = 0.970$	$Y_2 = -21.4 \ln(x) + 94.73$ (15) $R^2 = 0.963$	$Y_3 = -19.3 \ln(x) + 117.3$ (24) $R^2 = 0.930$
F-5	$Y_1 = 15{,}575 \ln(x) - 9{,}221$ (7) $R^2 = 0.961$	$Y_2 = -27.8 \ln(x) + 114.6$ (16) $R^2 = 0.890$	$Y_3 = -14.2 \ln(x) + 57.64$ (25) $R^2 = 0.559$
F-6	$Y_1 = 3{,}965 \ln(x) - 356.4$ (8) $R^2 = 0.968$	$Y_2 = -23.1 \ln(x) + 81.99$ (17) $R^2 = 0.874$	$Y_3 = -3.642 \ln(x) + 61.46$ (26) $R^2 = 0.919$
F-7	$Y_1 = 6{,}036 \ln(x) - 942.4$ (9) $R^2 = 0.975$	$Y_2 = -33.4 \ln(x) + 119.2$ (18) $R^2 = 0.954$	$Y_3 = -22.1 \ln(x) + 76.75$ (27) $R^2 = 0.938$
F-8	$Y_1 = 4{,}471 \ln(x) - 2{,}993$ (10) $R^2 = 0.958$	$Y_2 = -12.0 \ln(x) + 52.77$ (19) $R^2 = 0.956$	$Y_3 = -24.9 \ln(x) + 96.75$ (28) $R^2 = 0.795$
F-9	$Y_1 = 8{,}021 \ln(x) - 6{,}427$ (11) $R^2 = 0.961$	$Y_2 = -18.9 \ln(x) + 84.80$ (20) $R^2 = 0.943$	$Y_3 = -21 \ln(x) + 94.18$ (29) $R^2 = 0.771$

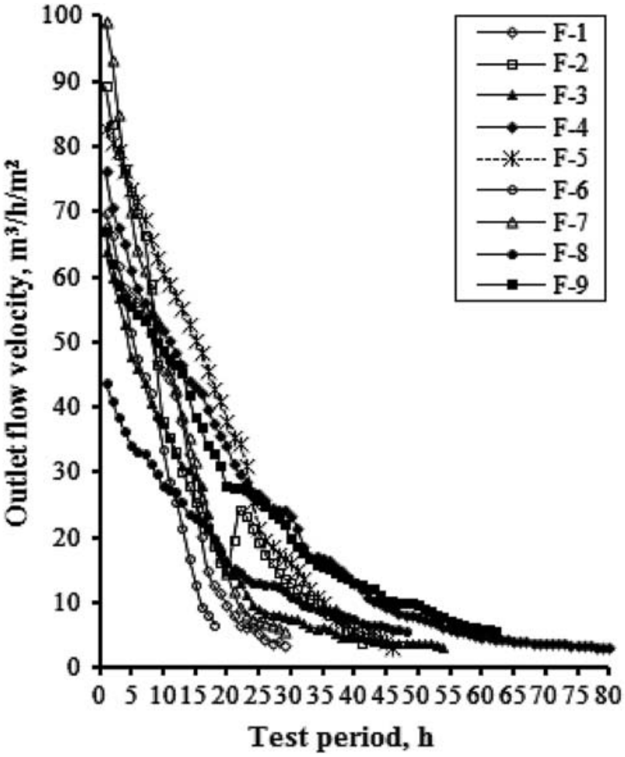

Fig. 4. The outlet flow velocities for different filter types.

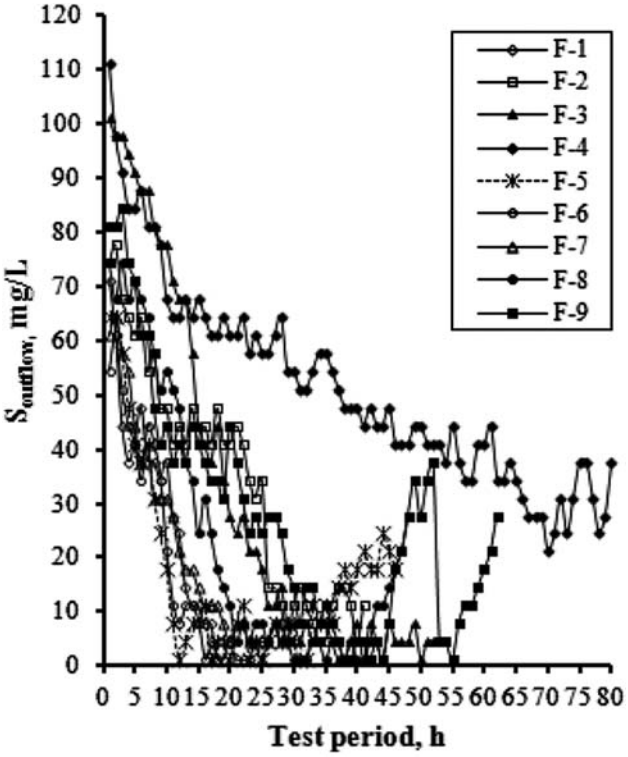

Fig. 5. The outlet concentrations of suspended solids ($S_{outflow}$) for different filter types.

logarithmically with the increase in the filtration test period (Table 3). We can conclude that the solid accumulation in the filter beds increased logarithmically as the filtration test period progressed. A larger filter surface area and higher inlet flow pressure produced higher outlet concentration of suspended solids (Fig. 5). Hanson et al. and James also reported higher flow velocities that reduced the filtering ability [20,27]. The suspended solid concentration in the outlet flow of pumice media filters was higher than that of sand-gravel media filters during the filtration test period. The pressure flow conditions could increase the outlet concentration of the suspended solid because pumice is a material with abundant macro pores [25,26]. When the pumice media was subjected to pressure, suspense solids retained in irregular cavities went out at higher concentration than the sand–gravel media. On the other hand, Şahin et al. also determined that the outlet concentration of suspended solids for pumice media filters was lower than that of sand–gravel media filters without pressure flow conditions [7]. The F-5 filter type caused the lowest outlet concentration of suspended solids throughout the filtration test period among the other filter types, except the final concentration at the end of the test period (Fig. 5).

3.4. The average removal efficiencies

The average removal efficiencies of the different filter types were calculated at 86.1% for F-1, 80.1% for F-2, 74.9% for F-3, 73.0% for F-4, 90.5% for F-5, 85.1% for F-6, 85.3% for F-7, 85.0% for F-8, and 83.8% for F-9. Because F-5 filter type has got positive properties of pumice and sand-gravel bed materials, the highest average removal efficiency obtained in this filter among all the filter types. This can be explained by the different porosity and pore size distribution of the bed materials granular medium.

3.5. Solid accumulations for layers

At the finish of the experiment, solid accumulations were determined separately for each layer of each filter type, and the highest solid accumulations were observed in L-4 for all filter types (Fig. 6). Solid accumulations from L-1 to L-4 increased and then decreased from L-4 to L-7. It is well known that sediment retention in filtration systems is a function of media particle size [28]. Total accumulated solid amounts in the filter beds of F-1, F-2, F-3, F-4, F-5, F-6, F-7, F-8, and F-9 filter types were 5.89, 7.55, 5.67, 9.74, 11.19, 2.38, 4.04, 3.16, and 5.69 kg, respectively. Solid

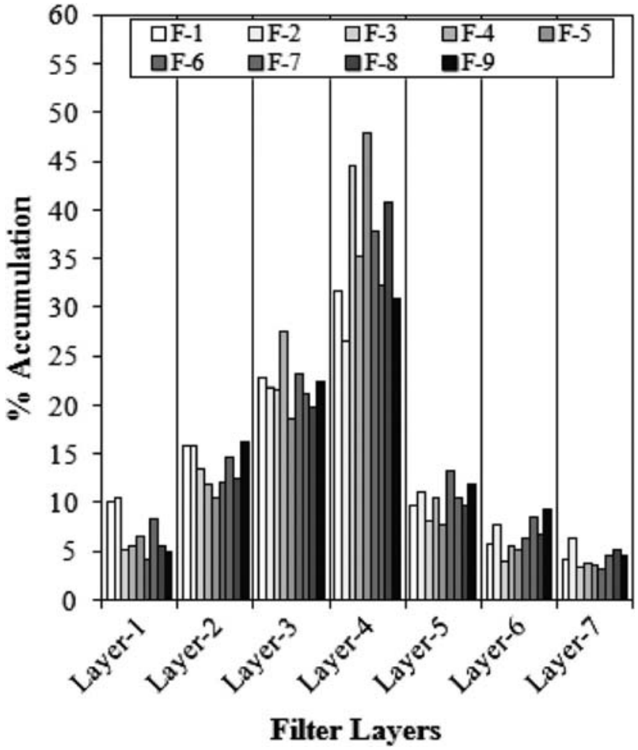

Fig. 6. Solids accumulations in filter layers for different filter types.

accumulation in L-4 of the pumice and sand–gravel media filters in the lower inlet flow pressure conditions were higher than in the higher inlet flow pressure conditions (Fig. 6). Additionally, accumulation in layers with finer grain sizes for pumice media filters was generally higher than for sand-gravel media filters. Şahin et al. determined that using the pumice material with a finer grain size in the filter bed increased the deposition of solids in comparison with sand–gravel material due to the higher porosity of the pumice granular medium [7]. In addition, accumulation in L-4 was the highest for the F-5 filter type in comparison to the other media filter types. The change in total porosity and pore size distribution using two materials in L-4 of the F-5 filter type could increase the accumulation capacity of this layer. The change in total porosity and pore size distribution in L-4 of the F-5 filter type could increase the accumulation capacity of this layer.

Conclusions

- The highest total outlet flow volume was observed in pumice media filters. Total outlet flow volume in F-5 filter type was higher than in the sand–gravel media filters at the same experimental conditions.
- Filter column diameter affects on the amount of solids removed from irrigation water. Higher amounts of solid removal were accomplished using 200 mm diameter filter column as compared to that of 150 mm filter column. It can be explained that the surface velocity was smaller in 200 mm diameter filters than the others. The highest average solid removal efficiency was observed in F-5 filter type. The solid removal efficiency values of pumice media are closer to the sand–gravel media filter values.
- Higher average outlet velocities were determined for filter types with an inlet flow pressure of 150 kPa in comparison with an inlet flow pressure of 100 kPa. The highest average outlet flow velocity was observed in F-5 filter type. These values of pumice media filters were lower than the sand–gravel media filter values.
- The pumice media filter, due to its higher total outlet flow volumes, can be used for the filtration of waters with a high suspended solid concentration. The use of pumice media filters with a small surface area can cause higher solid removal efficiency. Additionally, pumice media filters, due to their higher solid deposition capacity, can be used as a pre-filtering unit before sand–gravel filters.
- The pumice plus sand–gravel media filters, due to their higher outlet flow volume, higher solid removal efficiency, and higher flow velocity, can firstly be used for solid removal of waters with a high concentration of suspended solid. The use of combined filters of sand–gravel and pumice may increase the water quality delivery and durability of the micro-irrigation system. The results of this study clearly showed that using pumice plus sand–gravel filters is important for avoiding the need for frequent back-washing.
- The operating pressure and required flow velocity are taken into consideration, both pumice and pumice plus sand–gravel media filters are suitable for lower pressure micro-irrigation types such as surface and subsurface drip irrigation systems and low pressure dripper stakes, etc. on the small field applications and greenhouses.

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