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The Effect of Filter Media Size and Loading Rate to Filter Performance of Removing Microplastics using Rapid Sand Filter

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Highlights:

- Plastic bags and torn tires were used as artificial MP samples.
- RSF can remove MP up to 96.6%.
- A smaller filter media size allows a higher head loss increment.
- An increased loading rate will cut short the duration of the filtration cycles.

Abstract. Microplastics (MP) can pose a serious threat to the environment and human health because of their tiny size and ability to spread easily in water. One of the alternative treatments to remove MP from water is the rapid sand filter (RSF). The objective of this study was to analyze the effects of filter media size and loading rate on RSF performance in removing MP. The applied filter media was silica sand with effective sizes (ES) of 0.39 and 0.68 mm. The loading rates of filtration were 4; 6; 8 and 10 m^3/m^2-h. The MP samples were made from plastic bags and torn tires (artificial samples: 10 to 800 µm). This study showed that the MP removal percentage was up to 96.6% (MP size larger than 200 µm). The head loss increment for loading rates 4; 6; 8; 10 m^3/m^2-h was 0.16; 0.35; 0.34; 0.25 m (ES 0.39 m) and 0.10; 0.18; 0.18; 0.19 m (ES 0.68 m)), respectively. Meanwhile, the filtration cycle for loading rates 4; 6; 8; and 10 m^3/m^2-h was 5, 2, 2, and 1 days (ES 0.39 mm) and 9, 4, 3, and 3 days (ES 0.68 mm), respectively. The result of this study showed that the smaller the filter media size, the higher the head loss of the filter media bed. Furthermore, there is an increased head loss of the filter media bed when the loading rate is greater.

Keywords: *effective size; filtration cycle; head loss; loading rate; microplastics removal; rapid sand filter.*

1 Introduction

Currently, products made from plastic can be found everywhere. People cannot do without things made of plastic in their daily life. Daily products containing

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plastic are for example household appliances, clothing, footwear, food packagings, vehicles, electrical and electronic equipment, and personal cleaning products (Bouchet & Friot [1]). Microplastics have become a serious issue that is increasingly studied and discussed by scientists and environmentalists around the world. Microplastics (< 5 mm) have been found in all marine environments, including oceans, rivers, and streams [2]. Based on their type, microplastics can be classified into primary and secondary groups. Primary microplastics are intentionally made with microscopic sizes and secondary microplastics are derived from the fragmentation of macro-plastics.

Microplastics spread easily into water bodies. Elgarahy, *et al.* [3] state that microplastics in water bodies source from: (i) human use; microbeads in textile, cosmetics, laundry, and personal care products; (ii) domestic and industrial wastewater treatment plants; and (iii) aquaculture activities like broken crop nets, fishing nets and lines. Meanwhile, runoff water flows into water bodies that is used as the source for drinking water and agriculture irrigation as well as direct flow to the ocean.

Pivokonzky, *et al.* [4] state that MP have been found in tap water, bottled water, and water treatment plants. Wright, *et al.* [5] explain that MP can be harmful to human health due to their property of absorbing organic pollutants, such as dichloro-diphenyl-trichloroethane (DDT) and poly-chlorinated-biphenyls (PCB). Zhao, *et al.* [6] states that microplastics can adsorb and concentrate on hazardous pollutants from aquatic and soil environments. Likewise, microplastics are able to enter the human respiratory and digestive systems through the air or the water cycle. Hence, future studies are needed to investigate and formulate strategies to prevent microplastics dispersion, especially into water supply systems.

Talvitie, *et al.* [7] discovered that some treatment plants can remove microplastics from wastewater. The removal efficiency of microplastics for bioreactor membranes (MBR) is about 99.9%, for rapid sand filters it is approximately 97%, for disc filters it is around 40 to 98.5%, and for dissolved air flotation it is roughly 95%. Sembiring, *et al.* [8] concluded that pre-treatment of the water followed by RSF (ES 0.39 mm and 0.68 mm) could remove about 85 to 97 % of microplastics that are greater than 200 µm in size. The use of RSF as an alternative method to remove microplastics still requires further research. This can be assessed from the parameters affecting the MP removal performance of RSF. This study was conducted to analyze the relationship between filter media size parameters and loading rate on the performance of RSF. The ultimate goal of this research was to determine the filtration cycle and the best time to wash the filter media. Thus, the results of this study can be implemented as initial data in designing RSF performance to be more effective in removing microplastics.

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2 Material and Methods

2.1 Preparation of Filter Media and Reactor

In this study, the applied material was silica sand as the filter media with a size of 20-40 and 40-70 mesh. The sand was cleaned before a sieve analysis and a granular analysis were carried out. The sieve analysis was conducted using a mechanical sieve analyzer to determine the filter media size distribution, uniformity coefficient (UC), and effective size (ES). The granular analysis was performed to measure the density and porosity of the filter media. The supporting media used in the reactor was gravel with a diameter of 0.5 to 1 cm. The reactor utilized was made from acrylic with a cylindrical shape (diameter 10 cm and height 100 cm). This RSF reactor was operated by a submersible pump with a continuous down-flow. The reactor scheme can be seen in Figure 1.

Figure 1 Picture of RSF reactor scheme.

2.2 Artificial Samples Preparation

The artificial microplastics samples were made from plastic bags and tires that had been mashed and sieved with mesh sizes of 100; 70; and 40, and then mixed with tap water. The samples were used in the preliminary and the primary research. The average dimension of the artificial MP was 10 to 800 µm. There were 9 pipes on the manometer board to measure the head loss of RSF. Additionally, its function was to analyze the effect of filter media size and loading rate on filter performance.

2.3 Preliminary Research

The preliminary research of this study concerned pre-sedimentation, coagulation-flocculation and sedimentation. The purpose of the preliminary study was to determine the final MP concentration used in the main experiment (filtration).
In the pre-sedimentation procedure, the artificial sample was settled for two hours. This was continued with coagulation by adding 1% alum as much as 30 ppm, while performing rapid stirring (120 rpm 1 minute) and slow stirring (60 rpm; 45 rpm; 30 rpm respectively for 5 minutes), based on the study performed by Az-zahra and Wardhani [9].

2.4 Main Research

The main research using the RSF reactor is shown in Figure 1. The process was started by turning on the submersible pump to create a continuous down-flow on the reactor. The water flowed into the reactor by passing through the storage tank and moving to the reactor column. The water then passed the filter media and streamed to the outlet pipe. The water level above the media filter was 5 cm and the reactor was operated for 10 hours to complete one filtration cycle. The filtration rates applied were 4; 6; 8; and 10 m^3/m^2-hour.

During the filtration process, the head loss at the manometer board (9 points at 10 cm in height) was measured every hour. A total of one 1000 ml of inlet and 500 ml of outlet were collected at the specified filtration times (0.5; 1; 5; and 10 hours) to count the average amount of MP removal. The effects of filter media size and loading rate on filter performance were also identified.

2.5 Microplastics Identification

With the assistance of a vacuum filter pump, 500 ml of sample was collected in a glass bottle and then filtered by Whatmann GF/C filter paper (1.2 µm glass microfiber filter). Subsequently, the filter paper was placed on a petri dish and heated in the oven (temperature at 105 °C for 30 minutes). Then, the microplastics in the filter paper were observed by using a light binocular microscope (100 times total magnification). The microplastics were measured and counted manually by identifying the colors and shapes.

2.6 Filtration Cycle

The filtration cycle is the period of filtration operation between washing the filter media (backwash). According to Crittenden, *et al.* [10], the filtration cycle can be determined by recording the turbidity in the effluent and the head loss of the filter that occurs during filter operation based on Eqs. (1) and (2):

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$$k_{HL} = \frac{(h_{L,t} - h_{L,0})L}{v_F(C_0 - C_E)t} \quad (1)$$

$$t_{HL} = \frac{(H_T - h_{L,0})L}{k_{HL} v_F (C_0 - C_E)} \quad (2)$$

where k_{HL} is the constant rate of the head loss increase (liter.m/particle) and t_{HL} is the limiting head time (hour). The filtration cycle can be defined by limiting the available head. Crittenden, *et al.* [11] states that the commonly used maximum head limit for RSF is 1.8 to 3 m and the filtration cycle duration is 1 to 4 days. Thus, based on the filter cycle calculation, the applied maximum head was 2.4 m.

3 Results and Discussion

3.1 Sieve and Filter Media Distribution Analysis

To perform the distribution analysis of the sieve and filter media, two sizes of silica sand were applied. The purpose was to compare both filter media and determine the best performing one. Additionally, to analyze the sieve of the filter media, a mechanical sieve analyzer was employed. Then, the effective size (ES) and uniformity coefficient (UC) were detected by the results depicted in curves and graphs. A granular analysis (density and porosity) of the filter media was carried out with reference to Notodarmojo [12]. The results can be seen in Table 1.

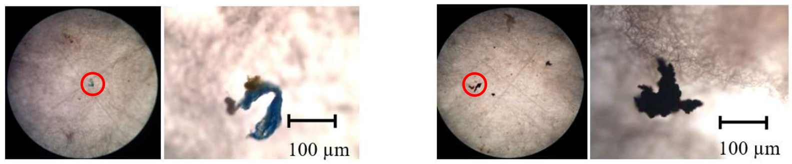
Table 1 ES and UC of the filter media sieve analysis.

Variation	ES (cm)	UC	Density (g/cm^3)	Porosity
1	0.68	1.617	2.542	0.451
2	0.39	1.692	2.491	0.431

Based on the conventional RSF design criteria from Reynolds and Richards [13] and Droste [11], the applied variation of silica sand was suitable in this study.

3.2 Identification of Artificial Microplastics Sample

The results of the artificial plastic (shopping bag and tire samples) identification can be seen in Figures 2(a) and (b). The size of the microplastics ranged from 10 to 800 μm.



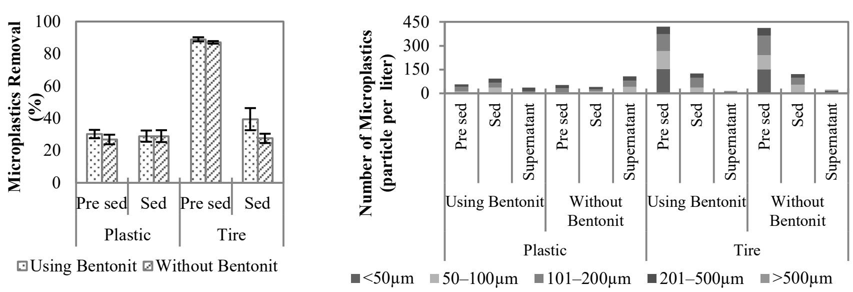
(a) (b)

Figure 2 (a) Artificial plastic flakes, (b) artificial tire flakes.

3.3 Preliminary Research

The result of microplastics removal, the number of microplastics, and the size distribution of the identified microplastics are shown in Figures 3(a) and 3(b). The process steps administered were pre-sedimentation, coagulation, flocculation, and sedimentation. This stage was carried out referring to the processing process before filtration. The percentages of removal in the pre-sedimentation stage were 30.31% for plastic debris and 89% for tire debris; both used bentonite. The difference in removal percentage occurred due to the difference in specific gravity of the two types of MP [14], where the tire flakes had a greater specific gravity (1.9 to 2.5 g/cm^3) than the plastic flakes (0.92 the 0.94 g/cm^3). Hence, the MP removal for tire debris was greater than for plastic.

In the coagulation-flocculation-sedimentation stage, by using bentonite, the MP removed was 29.03% for plastic flakes and 39.55% for tire flakes. Furthermore, the research conducted by Hidayaturrahman & Lee [15] using PAC had a percentage range from 53.8 to 81.6%. The addition of bentonite served to alter the sample into a shape close to its original form (river water) [8].



(a) (b)

Figure 3 Results of preliminary research observation: (a) microplastics removal, (b) size distribution and number of microplastics.

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3.4 Main Research

3.4.1 Microplastics Removal Process

The amount of microplastics observed in the main study (RSF) was a combination of 0.0522 g of plastic flakes and 0.0093 g of torn tires, which were mixed in 100 L of distilled water. This amount was adjusted to the volume of the utilized sample container, which was 150 L. Furthermore, the sample was continuously flowed from the sample container to the gravity tank as described in Section 2.1. The samples containing microplastics would thus be trapped in the grains of the filter media. The percentage of removal was calculated by counting the number of microplastics entering the system and the number of microplastics coming out after the filtering process. In addition, the data published in Ref. [8] suggest that an RSF with ES 0.39 mm and ES 0.68 mm is capable of removing microplastics up to 96.6% for sizes larger than 200 μm.

The size of the filter media and loading rate also affect the microplastics removal. The percentage of microplastics removal for each variation can be seen in Figures 4 and 5.

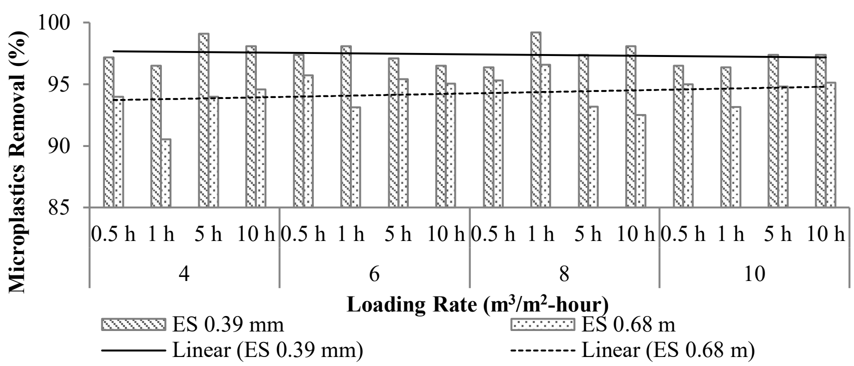

Figure 4 Plastic flake microplastics removal percentage.

The microplastics removal of plastic flakes (ES 0.39 mm) was 96.4% to 99.2%, while for ES of 0.68 mm it was 90.53% to 96.58%, respectively. Figure 4 shows the overall microplastics removal for an ES of 0.39 mm was higher than for an ES of 0.68 mm. One of the causes is the size difference of the porosity of the filter media, where the porosity of silica sand (ES of 0.39 mm) is 0.432, while it is 0.493 for ES of 0.68 mm. The microplastics size detected at the outlet ranged from <50 to 200 μm.

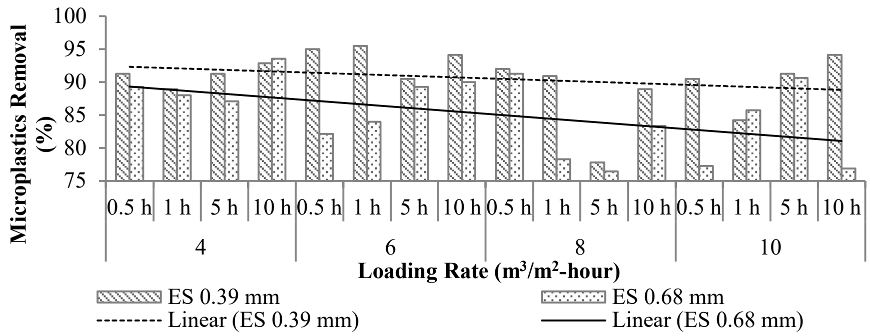

Figure 5 Torn tire microplastics removal percentage.

Microplastics were trapped between the porous filter media. The porosity of the filter media applied in this study ranged from 0.431 to 0.451. Crittenden, *et al.* [10] describes that tight arrangement of the filter media will cause strain when the ratio of particle diameter to filter media diameter is greater than 0.15. Besides, as explained by Pivokonsky, *et al.* [4], it is estimated that there is a relationship between the shape of microplastics and their removal ability in applying various water treatment technologies. Microplastics retained over time will cause blockages in the filter media and influence the performance of the RSF. Therefore, the effect of filter media size and filtration speed on RSF performance should be discussed as well.

3.4.2 Effect of Filter Media Size and Loading Rate on Filter Performance

The decrease of filtration performance can be observed in the quality of the processed water and the state of the filter media [10]. If the water level starts to increase, then it should be concluded that the filter media is blocked, so backwashing is necessary. Furthermore, deficiency of filter performance is recognized by escalation of the head loss during the filtration process (for 10 hours). Determination of the operating time at 10 hours was based on preliminary experiments. This operating time also refers to the saturation time in this study. The head loss measurements are shown in Table 2.

Table 2 Head loss measurements.

Loading rate	ES 0.39 mm		ES 0.68 mm	
	Overflow duration	Head loss increment	Overflow duration	Head loss increment
(m^3/m^2-h)	(h)	(m)	(h)	(m)
4	10	0.16	10	0.10
6		0.35		0.18
8		0.34		0.18
10		0.25		0.19

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The head loss was affected by the size of the filter media. The head loss of the filter media with ES 0.68 mm was lower than that of ES 0.39 mm. This is due to the influence of porosity size. According to Cescon & Jian [16], porosity alters the physical characteristics of the granular media in removing solids. Based on the data presented in Table 2 show the correlation between filter media size, loading rate and head loss increase, and the filtration time to reach the reactor overflow limit. The filtration process using 0.39-mm ES filter media at a loading rate of 4 m^3/m^2-hour led to 0.16 m of head loss increment. Meanwhile, a filtration speed of 10 m^3/m^2-hour led to 0.25 m of head loss increment. This means that increasing the loading rate generates an elevated head loss. Thus, the duration of the filtration cycle is shorter.

The increase of head loss is caused by a reduction of the effective area of the filter surface because the particles are deposited on the filter surface or lodged between the filter pores. The ES porosity of 0.68 mm is 0.465 greater than the porosity of the 0.39 mm ES filter media, which is 0.432. Thus, with the same filtration time and filtration speed, the increase of head loss is faster in filter media with smaller porosity.

3.4.3 Effect of Filter Loading Rate on Backwash Frequency Time

The filtration cycle is the period of filtration operating time between washing the filter media (backwash). It can be determined by recording the head loss that occurs during filter operation. According to Crittenden [10], several factors force the end of the filtration cycle, making it mandatory to perform backwash. Firstly, when the filter reaches its saturation period, and secondly, when the head loss increases beyond the available head. In this research, the filtration cycle was calculated based on the specified maximum head loss value. An RSF that is typically operated by gravity flow is designed with available head at 1.8 to 3 m and filtration cycle lengths of 1 to 4 days. If the head loss exceeds the available head, filter backwash is required. The calculated values of kHL and tHL using Eqs. (1) and (2) are presented in Tabel 3.

Table 3 Duration of filtration cycle.

Loading Rate	ES 0.39 mm		ES 0.68 mm	
	k_{HL}	t_{HL}	k_{HL}	t_{HL}
(m^3/m^2-h)	(L.m/particel)	(days)	(L.m/particle)	(days)
4	1.30×10^{-5}	5	$1,04 \times 10^{-5}$	9
6	1.68×10^{-5}	2	$1,17 \times 10^{-5}$	4
8	1.11×10^{-5}	2	$1,04 \times 10^{-5}$	3
10	0.71×10^{-5}	1	$1,00 \times 10^{-5}$	3

The greater the filtration speed, the less time it takes to reach the maximum head. It can be seen in Table 3 that the time to reach the predetermined head limit (2.4 m) for 0.39 mm ES filter media with a filtration speed of 4 m^3/m^2-hour was 5 days. This means that with an average microplastic inlet of 265.5 ± 5.7 particles per liter, a fast sand filter with an ES of 0.39 mm and a filtration speed of 4 m^3/m^2-hour can carry out the filtration process for 5 days continuously, with the head loss reaching 2.4 m. The average microplastic effluent is 9 ± 2.6 particles per liter with a removal percentage of 97.7%. After filtration for 5 days, the filter media is cleaned by backwash. Overall, it can be concluded that the higher the filtration speed, the less time it takes to reach the maximum head. This indicates that an increased filtration speed will result in a shorter filtration cycle and more frequent backwash to clean the filter media from microplastics.

4 Conclusion

The RSF media filter applied was silica sand with effective sizes of 0.39 mm and 0.68 mm. This RSF was considered to be relatively effective in removing microplastics that are larger than 200 µm. The average MP removal percentage reached 96.6% after passing through the pre-treatment processes (pre-sedimentation, coagulation-flocculation, and sedimentation). The filter performance was analyzed from head loss measurement. Furthermore, the loading rates applied were 4; 6; 8; 10 m^3/m^2-h. The head loss for each filter media size and loading rate was 0.16; 0.35; 0.34; 0.25 m (ES 0.39 m) and 0.10; 0.18; 0.18; 0.19 m (ES 0.68 m), respectively. Based on the measurement of the head loss, the determined filtration cycles were 5; 2; 2; and 1 days (ES 0.39 mm) and 9; 4; 3; and 3 days (ES 0.68 mm). By performing this research, the best time to wash the filter media was defined. Additionally, further research on studying the effect of residence time and media filter amount on the MP removal process is required.

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