Performance of rapid sand filter – single media to remove microplastics

Emenda Sembiring, Mutiara Fajar and Marisa Handajani

ABSTRACT

Microplastics (MPs) have been detected in drinking water and raw water sources. Therefore, it is important to know the performance of drinking water treatment process. The rapid sand filter (RSF) is one of the water treatments that can be an alternative treatment in removing MPs after several configuration processes (pre-sedimentation, coagulation-flocculation, and sedimentation). This study aims to determine the effectiveness of RSF to remove MPs. The artificial samples were made from plastics bags and tyre flakes, with sizes from 10 μm to more than 500 μm. Bentonite was added to represent turbidity in the water. The average removal efficiency of plastics flakes before entering the filter was 50.48% (using bentonite) and 47.78% (without bentonite). Overall, the removal efficiency for the tyre flakes was 90.72% (using bentonite) and 93.03% (without bentonite). The filtration used in this study was varied between 4 and 10 m/h. Removal efficiency using RSF for plastic flakes on which the Effective Size (ES) filter media 0.39 mm was 97.7% and on which ES 0.68 mm was 94.3%. Meanwhile, the removal efficiency of the tyre flakes for ES 0.39 mm were 90.6% and ES 0.68 mm was 85.2%. However, in this study, RSF mostly removed MPs particles greater than 200 μm in size.

Key words | drinking water treatment plant, microplastics, rapid sand filter, removal

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HIGHLIGHTS

- Mostly MPs $>=$ 200 μm can be removed by using a conventional rapid sand filter.
- Increased turbidity will not increase the efficiency of MPs removal.
- Part of the MPs can also be removed in coagulation and flocculation.
- Size of MPs is important for the surface screening mechanism.

GRAPHICAL ABSTRACT

Performance of Rapid Sand Filter- Single Media to Remove Microplastics (MPs)

Considerable fraction of MPs can be removed by Rapid Sand Filtration especially MPs >=200 μm

MPs Type	% Removal of MPs based on Effective Size (ES)	
	0.39-mm	0.68-mm
Tyre flakes	77.8 - 95.5	90.53- 96.6
Plastic-bag flakes	96.4 - 99.2	76.5 - 93.6

INTRODUCTION

At present, the occurrence of plastic waste is increasing in the aquatic environment, including oceans and water bodies. Plastic waste includes not only larger plastic debris, but also smaller plastic particles commonly referred to as microplastics (Eerkes-Medrano *et al.* 2015). Microplastics (MPs) are plastics less than 5 mm in size, which can be formed from industrial production or fragmented from larger plastics (Crawford & Quinn 2017).

Microplastics formed from manufactured plastics production are called primary MPs (Cole *et al.* 2011). Secondary MPs include fibre or fragments resulting from the breakdown of larger plastics (Browne *et al.* 2011). Recent studies show that MPs have been found in several regions (Eerkes-Medrano *et al.* 2015), such as in Asia, Europe, North America and Antarctica (Klein *et al.* 2015; Zhang *et al.* 2015; Su *et al.* 2016; Isobe *et al.* 2017; Morganaa *et al.* 2018; Alam *et al.* 2019).

The source of MPs into water bodies can be diversion from runoff water, such as from roads, or upstream agricultural, industrial and urban areas. The stormwater runoff diverts into receiving water bodies such as rivers and lakes which might be used as the main raw water sources (Browne *et al.* 2011; Eriksen *et al.* 2013; Kole *et al.* 2017).

Microplastics can be a serious threat, especially for humans because of MPs' ability to absorb organic pollutants such as poly-chlorinated bi-phenyls (PCB), dichloro-diphenyl-trichloro ethane (DDT), and hexachloro-cyclohexane (HCH) (Hidalgo-Ruz *et al.* 2012). Galloway (2015) explained that MPs can enter the human body through the digestive or respiratory system, so further studies are needed to prevent MPs spread from the waters, especially from water supply.

Detection of MPs in drinking water was initiated in 2017 (Eerkes-Medrano *et al.* 2019). The first attempt, which mentioned the presence of MPs in a drinking water treatment plant (DWTP), was conducted in Germany in 2019 (Mintenig *et al.* 2019). Some researchers showed that MPs were found in bottled water, tap water and water treatment plants (Oßmann *et al.* 2018; Pivokonsky *et al.* 2018; Schymanski *et al.* 2018; Mintenig *et al.* 2019).

The configuration of drinking water treatment units consists of several stages such as pre-sedimentation, coagulation and flocculation, sedimentation, filtration and advanced stages, such as chlorination. There are only a few studies that explain about MPs removal efficiency from each process of the DWTP. Most studies relate to the presence and occurrence of MPs in DWTPs (Oßmann *et al.* 2018; Pivokonsky *et al.* 2018; Schymanski *et al.* 2018; Mintenig *et al.* 2019). The rapid sand filter (RSF), as one of the processing units in a series of the DWTP, is considered effective in removing MPs. However, the performance of RSF solely to remove MPs has not been investigated. Ma *et al.* (2019) investigated MPs removal in coagulation and ultrafiltration in a DWTP. As RSF is used intensively in Indonesia, this paper will investigate the performance of RSF in DWTP.

Prior to rapid sand filtration, the samples are treated in the operation unit and processes such as pre-sedimentation, coagulation and flocculation, and sedimentation. Therefore, this study also conducted a preliminary

study to show the removal of MPs in processes prior to RSF.

Talvitie *et al.*(2017) has conducted research on MPs removal efficiency from wastewater treatment plants by comparing four advanced (tertiary) treatments after primary and secondary treatment. The MPs removal efficiency of a bioreactor membrane (MBR) is about 99.9%; the rapid sand filter (RSF) is about 97%; dissolved air flotation (DAF) is about 95% and a disc filter (DF) is about 40–98.5%. In this study, the MPs removal operation used is a single-media RSF because this treatment is suspected to be effective, economical and appropriate technology for wastewater as well as for drinking water treatment.

The filter media used is silica sand because silica sand is easy to get and has a smaller porosity (Droste 1997). This study aims to analyse the effectiveness and mechanism of the RSF process in MPs removal and analyse the effect of research variables on the performance of filter media. The variables in this study were MPs type and size, filter media size, filtration time and filtration rate.

MATERIAL AND METHODS

Filter media and rapid sand filter reactor

The filter media used in this study was silica sand. Silica sand was chosen because it is common in the water supply and it is inexpensive. This study used an RSF as most of Indonesian DWTPs apply RSFs. Initially, the silica sand was screened to size 20–40 mesh and 40–70 mesh to get two variations of effective size (ES). Then, before the media was used, sieve analysis was carried out to determine the ES and uniformity coefficient (UC) of silica sand. Then, the result of sieve analysis was depicted in a distribution accumulation curve to find the ES and UC values. In addition, the values of porosity and density were also determined. Porosity and density of filter media can be calculated with the equation below:

$$\text{Porosity} \ (\varepsilon) = \frac{void \ volume}{filter \ media \ volume} \qquad (1)$$

$$\text{Density} \ (\rho) = \frac{filter \ media \ mass}{filter \ media \ volume} \qquad (2)$$

The reactor used was cylindrical, made of acrylic, 10 cm in diameter and 100 cm in height. The reactor was designed with continuous flow (downflow) using a submersible pump. The flow rate was managed by a flow meter. The filtration process scheme for the reactor is depicted in Figure 1.

Microplastics artificial sample

The microplastics samples used in this study were artificially made from plastic shopping bags and motorcycle tyres. Based on the model conducted by Siegfried *et al.* (2017), the most abundant MPs types diverted to water bodies were tyre flakes. Based on research by Pivokonsky *et al.* (2018), the type of plastic fragments is most commonly found in raw water.

The plastic shopping bags were crushed using a grater and blender, while a motorcycle tyre was shredded by using a grinder. Scouring was removed manually. Clean samples were then sieved using standard 100, 70 and 40 sieves with size openings of 150, 212 and 425 μm respectively. Size range was set based on the study by Stundt
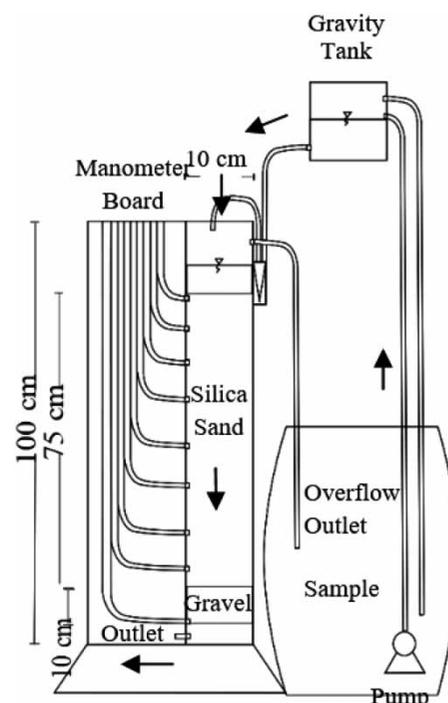

Figure 1 | Rapid-sand filter reactor scheme.

et al. (2014) and Verschoor *et al.* (2016), who reported that the size of the tyre flakes found on the road surface was between 10 and 400 μm. The artificial MPs were added to tap-water samples.

Microplastics identification

The sample was collected using a glass bottle with a volume of 500 mL. Then the sample was filtered with a Whatman GF/C paper filter using a vacuum filter. The filter paper with MPs above was transferred into a petri dish and dried in an oven at 105 °C for approximately 30 minutes to remove the moisture content on the filter paper. The dried filter paper was observed to identify the type, number, and size of MPs using a light binocular microscope (Olympus CX-21) at 100× magnification. The number of MPs observed was reported as the number of MPs per litre of samples.

In this study, no determination of the type of MPs polymer was conducted; MPs identification was limited to its shape. Horton *et al.* (2017) concluded that MPs can be identified based on their colour, which contrasts with the environment, and also their form, such as flake, fragment or fibre.

Pre-treatment

Pre-treatment aims to simulate a series of water treatment units before water enters through the filtration unit. Pre-treatment includes pre-sedimentation, coagulation-flocculation, and sedimentation. In this study, the samples were given two treatments, namely the addition of bentonite and without the addition of bentonite. In the pre-sedimentation stage, the sample was settled for two hours, then the settling MPs were counted.

The first stage in this preliminary study was pre-sedimentation. Microplastics removal at the pre-sedimentation stage was similar to the provision of particulates in the processing of raw water and wastewater utilizing gravity. Discrete particle deposition occurs in the pre sedimentation unit (Metcalf and Eddy 1991; Kawamura 2000). Deposition of particles is affected by particle size, particle shape (flat, round or irregular), density, liquid specific gravity, liquid viscosity, particle concentration in the liquid, particle properties in the suspension and temperature. The size and shape of the particles will affect the ratio of the surface to the volume of

particles. Temperature affects the viscosity and specific gravity of the liquid.

Studies related to the MPs settling process in surface water have been simulated as the same pattern as natural particles (Hoellein *et al.* 2019). If analyzed based on factors that influence the settling process, MPs generally have the same properties as discrete particles. As explained by Gregory in Chubarenko *et al.* (2016), the general movement of MPs particles in the marine environment is caused by physical forces, such as gravity, Archimedes buoyant force, and drag force, where the forces depend on the characteristics of particles. Low-density MPs tend to spend a long time at sea level. MPs settling varies depending on MPs characteristics, such as size type (Hidalgo-Ruz *et al.* 2012). MPs settling rates vary according to particle type, shape, buoyancy and the presence of biofilm in MPs in water bodies (Hoellein *et al.* 2019).

The supernatant from pre-sedimentation was then diverted to the coagulation, flocculation and sedimentation processes. Steel & McGhee (1985) explain that the coagulation process is a physical-chemical process from mixing chemicals into treated water, and then mixing rapidly in the form of a mixed solution, while flocculation is a slow stirring process to increase the contact between particles so as to increase their agglomeration. Several factors that influence the coagulation-flocculation process include temperature, coagulant form, turbidity level and agitation force (Manurung 2012).

The coagulation, flocculation and sedimentation processes were conducted in standard jar test apparatus. In coagulation, 1% alum (30 ppm) was added and the sample was rapidly mixed (120 rpm) then the mixed speed was reduced to slow mixing (40 rpm). pH was monitored to remain within the optimum range for coagulation (5.5–7.0). The sample was then allowed to stand for two hours at the sedimentation stage. Also, the settling MPs in this stage were counted to calculate the difference between initial MPs and the final stage of pre-treatment as MPs removal efficiency.

Filtration tests

The main research was conducted using a reactor as shown in Figure 1. Water from the sample tank was pumped to the storage tank using a submersible pump and was filled into the

reactor through the filter media to the outlet. The initial height of the water surface above the filter media was 5 cm. The sample flowed for 10 hours for each batch with four variations of loading rate (4; 6; 8; and 10 m/h consecutively). One litre of inlet and outlet samples was collected at the specified filtration times, which were at 0.5; 1; 5 and 10 hours. The experiment was duplicated for each variation loading rate. The objective was to find the average MPs removal efficiency after several reactors operating times, as well as the size distribution and the number of MPs that affect the performance of the filter.

RESULTS AND DISCUSSIONS

Filter media analysis

Filter media analysis consists of sieve analysis and analysis of filter media distribution. The sieve analysis was carried out using a mechanical sieve analyser and the measurement results were depicted in the accumulation curve of the filter media distribution. Based on the graph, the effective size (ES = D_{10}) and uniformity coefficient (UC = D_{60}/D_{10}) values of each filter media were obtained. The results of filter media analysis can be seen in Table 1.

When the results of sieve analysis were compared to RSF design criteria from Reynolds & Richards (1996), Droste (1997) and Tchobanoglous et al. (2003), ES, UC values and sand porosity, this study has met the requirements for RSF. The ES value (D_{10}) is the size of the upper filter media that is considered to be the most effective in separating the impurities that pass through the filter media, and the UC value is the filter media uniformity value expressed by the ratio D_{60}/D_{10}. Reynolds & Richards (1996) described design criteria for RSF r; ES values ranges 0.35–0.70 mm while the UC value is <1.7. Based on design criteria, the results of sieves analysis indicate that silica sand can be used as the filter medium in this study.

The filter media porosity design criterion for RSF is 0.42–0.47 (AWWA 1990), so based on Table 1, the two variations of sand media fulfilled the filter media category for RSF . The filter media porosity greatly influences the efficiency of particle removal in sand filters. Crittenden et al. (2012) explain the arrangement between filter media will cause strain when the ratio of particle diameter to filter media diameter is greater than 0.15. The effective size of the smallest media specified in an RSF is usually around 0.5 mm, where at that size the filter media is unable to hold particles smaller than 30–80 μm.

Identification of artificial microplastics samples

Microplastics from plastics flakes are generally like fragments and films (sheets). This type is one of the secondary MPs formed from the process of fragmentation of larger plastics (Cole et al. 2011). The average size of artificial MPs from the microscope observation ranged from 10 to 800 μm. Microscope observations on each type of sample can be seen in Figure 2.

Pre-treatment

The pre-treatment process consists of pre-sedimentation, coagulation, flocculation and sedimentation. The pre-treatment

Table 1 │ Filter media analysis

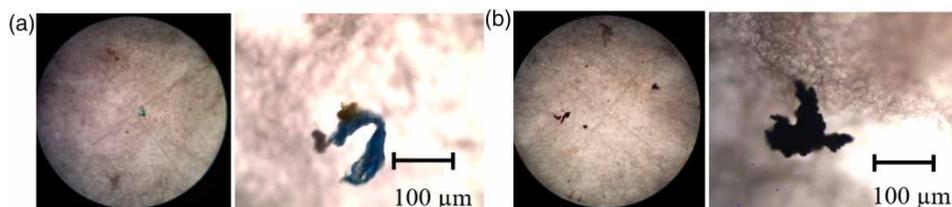| Variation of sand	ES (mm)	UC	Density (g/cm³)	Porosity
1	0.68	1.617	2.542	0.451
2	0.39	1.692	2.491	0.431

Figure 2 │ Results of microscope observations for artificial samples. (a) plastics flakes (b) tyre flakes.

proceses was conducted in a standard jar test apparatus. The artificial MPs were added to tap water. All experiments were conducted using the tap water despite the possibility of MPs being sourced from tap water. The possible MPs bias from tap water remains constant. The addition of bentonite in the sample represents the total suspended solid (TSS) of rainwater runoff. Based on the analysis of runoff water characteristics, the average concentration of TSS was 42 mg/L.

Pre sedimentation

Based on the results (Figure 3), the removal of tyre flakes was greater than plastic bag flakes. This could be caused by differences in shape, size and specific gravity. Tyre flakes were irregular and thicker than plastics flakes. However, thickness measurements were not carried out for both types of MPs, so comparison cannot be made based on thickness.

In addition to the MPs forms, differences in the percentage of removal can also be caused by differences in density. Based on the literature, the specific gravity of tyres was 1.9–$2.5\ g/cm^3$ while the density of plastics (plastics bags were made of the widely used polyethylene, LDPE), was 0.92–$0.94\ g/cm^3$ (Crawford & Quinn 2017). The tyre flakes have a greater specific gravity so more tyre debris settles in the pre-sedimentation process, up to 89%.

Coagulation and flocculation

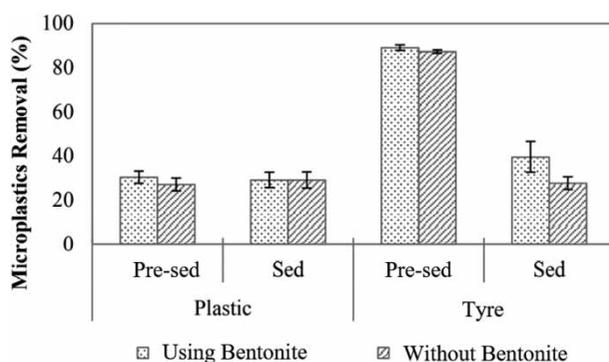Alum is used as a coagulant in this study. Alum is easily soluble in water and easily forms Al^{3+} and sulfate (SO_4^-) ions.

Figure 3 | Microplastics percentage removal.

Al^{3+} ions in water are hydrolyzed to $Al(OH)_3$ in colloidal form. According to Manurung (2012), the mechanism of coagulation is categorized into chemical and physical processes. A chemical process states that colloids obtain an electric charge on their surface by chemical ionized group and coagulation occurs because of the chemical interaction between colloidal particles and coagulants.

The charge of colloidal particles that cause turbidity in water is the same, therefore if the ionic strength in water is low, the colloids will remain stable. In theory, coagulation occurs through reduction of force.

Plastics and several other types of materials such as cloth and glass are insulators. Insulators are materials that do not easily release electrons. In this study, the zeta potential test on MPs was not carried out, so the mechanism of why the addition of coagulant (alum) did not affect MPs removal in this study is still unknown.

During the flocculation process, MPs did not agglomerate, so MPs flocs were not formed. Floc formation only occurs in bentonite because it has a negative charge Churchman *et al.* (2013).

Sedimentation

The supernatant of the coagulation-flocculation process was filtered to identify the number of MPs that were settled and which were still floating in the sample. The settling process was carried out for two hours. The sedimentation process for plastics flake removal with additional bentonite was 29.03%, whereas removal without bentonite was 29.01%. The removal rate for tyre flakes with additional bentonite was 39.55% and without bentonite was 27.60%. The t-test was conducted to determine the effect of the addition of bentonite on MPs removal. The results of the t-test for the type of plastic flakes ($p > 0.05$), so that H_0 is accepted. This means that there are no differences in the mean values of MPs removal with or without additional bentonite. Likewise for the tyre flakes, with a value of t count ($p > 0.05$), there is no difference in the average MPs removal of tyre flakes with or without bentonite. It is suspected that MPs samples in this study and bentonite have the same surface charge. So, no floc formation occurs during the flocculation process.

Observations on MPs removal and size distribution and MPs number in the preliminary study can be seen in
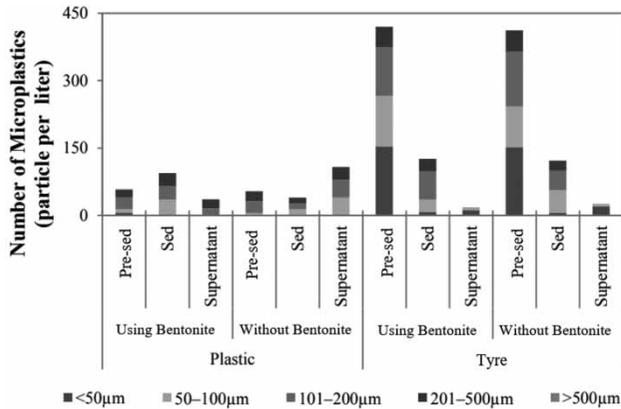
Figure 4 │ Size distribution and number of microplastics.

Figures 3 and 4. The addition of bentonite resulted in higher MPs removal than without bentonite. But it was not significant. The results of the t-test ($\alpha = 0.05$) for both MPs types showed a *p*-value >0.05. It means that there was no difference in the average MPs removal with or without additional bentonite. So, the presence of TSS did not significantly affect MPs removal in the preliminary study.

Initial MPs concentration was 1.0 mg/L for both plastic bag and tyre samples. On average, the initial number of MPs was 256 particles/L and 588 particles/L for plastic bag and tyre samples respectively. Initial size of particles in the plastic bag sample was dominated by the 50–100 μm range, whereas particles for the tyre sample were predominantly smaller than 50 μm.

Rapid sand filtration

Filter media ES 0.39 mm

Similar to MPs removal in preliminary treatment, the percentage of MPs is obtained from the comparison of the number of incoming MPs (inlet) and those that diverted after the filtration process (outlet). The results of the observation of MPs removal of plastics flakes can be seen in Figure 5 and for tyre flakes can be seen in Figure 6.

Based on Figure 5, the MPs removal of plastic flakes using silica sand with ES 0.39 mm ranged from 96.4 to 99.2%. The highest removal occurs at a filtration rate of 8 m/h, which was equal to 99.2% after the operation of the reactor for 1 hour. Whereas, the lowest removal was at the filtration rate of 8 m/h of 96.4% after operation of the reactor for 30 minutes.
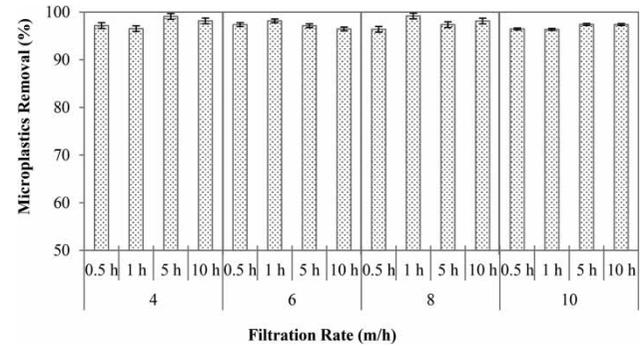

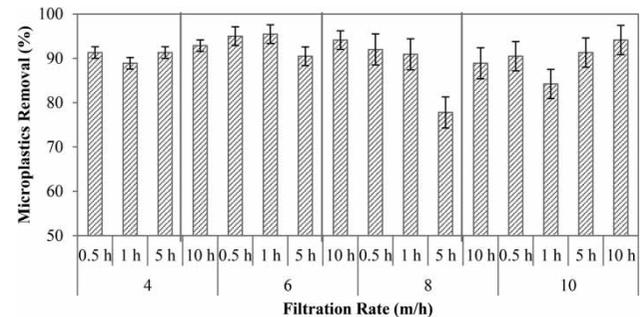**Figure 5** │ Microplastics removal (plastic flakes) using filter media ES 0.39 mm.

Figure 6 │ Microplastics removal (tyre flakes) using filter media ES 0.39 mm.

The percentage of plastic flakes removal tends to fluctuate at each measurement; that is, at 0.5; 1; 5 and 10 hours. Fluctuations in measurements occur at each filtration rate. However, the trend shows that the removal percentage tends to decrease with increasing filtration rate.

Similar to the plastic flake removal, the percentage of MPs removal from tyre flakes also fluctuated (Figure 6). The percentage of removal ranged from 77.8 to 95.5%. The highest removal occurs at a filtration rate of 6 m/h after reactor operation for 1 hour, which is 95.5%, while the lowest removal occurs at a filtration rate of 8 m/h after operation of the reactor for 5 hours, which is equal to 77.8%. By looking solely at the trend, the removal of tyre flakes decreases with increasing filtration rate.

The percentage of MPs removal of plastic flakes (96.4%–99.2%) is higher than that of tyre flakes (77.8%–95.5%). The MPs particles of plastics flakes were bigger than that of tyre flakes so it is more likely that plastic flakes removal is higher.

Research on the relationship between filtration rate and the efficiency of MPs removal has not been found, so the

results of this study are compared with the results of TSS removal using sand filters. TSS is the total solid strain by a filter with a maximum colloidal particle size of 2 μm or greater than the size of colloidal particles (Tanata *et al.* 2013). The results showed that the average percentage of removal in both types of MPs decreased with increasing filtration rate. This is in line with the research conducted by Fitri *et al.* (2013). Based on the results of their research, it was concluded that the variation of filtration rates had an effect on the efficiency of TSS reduction. Where the discharge gets slower, the efficiency of the TSS removal is higher, and vice versa.

According to Edahwati & Suprihatin (2010), a discharge that is too fast will cause the filter to malfunction. This means the filtering process cannot perform perfectly due to the flow of water, which passes through the cavity between the grains of the filter media too fast. This results in reduced contact time between the surface of the filter media grains and the filtered water. Wegelin (1996), Mahvi *et al.* (2001), and Fitri *et al.* (2013) explained that the discharge value is proportional to the rate of filtration: the smaller the filtration rate, the smaller the discharge and vice versa. With a low filtration rate, this will help to hold particles by gravity at the top of the filter media.

Filter media ES 0.68 mm

Similar to MPs removal in filter media ES 0.39 mm, the percentage of MPs is obtained from the comparison of the number of incoming MPs (inlet) and those that are diverted after the filtration process (outlet). The results of observations of MPs removal with filter media with ES 0.68 can be seen in Figures 7 and 8.

The percentage of MPs removal for plastic flakes is around 90.53%–96.58% (Figure 7). The highest removal
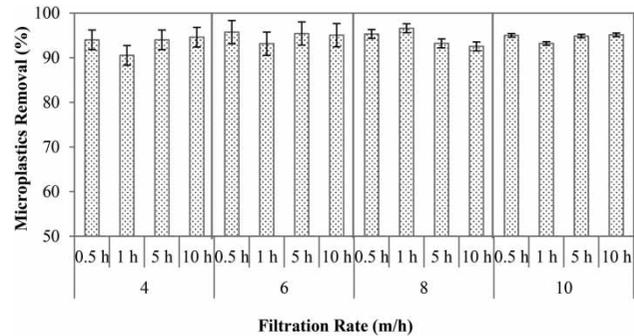

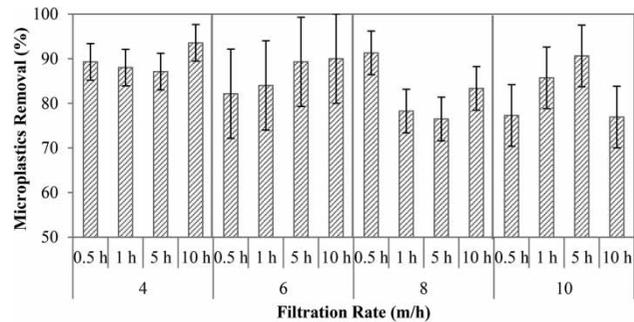**Figure 7** | Microplastics removal (plastic flakes) using filter media ES 0.68 mm.

Figure 8 | Microplastics removal (tyre flakes) using filter media ES 0.68 mm.

occurs at a filtration rate of 8 m/h after reactor operation for 1 hour, which is 96.58%, while the lowest removal occurs at a filtration rate of 4 m/h after 1-minute reactor operation, which is equal to 90. 53%. The One-Sample Wilcoxon test was conducted to determine the uniformity of the removal data at each contact time in Table 2. All Wilcoxon test results show ($p > 0.05$), meaning that at each filtration rate, the contact time does not affect the yield of MPs removal. Likewise with the results of the Kruskal-Wallis test to see the effect of the filtration rate on the MPs removal. The test results showed ($p > 0.05$), meaning that there was no effect of filtration rate on MPs removal.

Table 2 | Wilcoxon test and *Kruskal-Wallis test*

| | *Wilcoxon test* | | | | | |
| | *Filtration rate (m/h)* | | | | | |
Microplastics type	4	6	8	10	*Kruskal-Wallis test*	Significant level
Plastic flakes	0.098	0.100	0.100	0.100	0.468	0.005
Tyre flakes	0.100	0.100	0.100	0.100	0.385	

Similar to the plastic flakes removal, the percentage of MPs removal of tyre flakes also fluctuates (Figure 8). The percentage of removal ranges from 76.47 to 93.55%. The highest removal occurs at the filtration rate of 4 m/h after the operation of the reactor for 10 hours, which is 93.55%, while the lowest removal occurs at the filtration rate of 8 m/h after the operation of the reactor for 5 hours, which is equal to 76.47%.

Similar to MPs removal in filter media ES 0.39 mm, the percentage of MPs removal of plastic flakes (90.53%–96.58%) is higher than that of tyre flakes (76.47%–93.55%). The MPs particles of plastics flakes were bigger than those of tyre flakes, so it was more likely that plastic flakes removal would be higher. It seems like the size is an important parameter for the surface screening mechanism.

Mechanism of microplastics removal process using rapid sand filter

Three process are involved in removing particulates using granulated media, namely transportation, which includes the process of Brownian motion; sedimentation and attraction between particles; sticking ability, including mechanical straining, adsorption (physical-chemical) and biological processes and ability to resist, including collisions between particles and repelling forces. The results of these experiments show mainly the mechanical straining. Attraction, collisions and repelling force have not yet been proven from this study.

In the rapid sand filter process, particle removal is mostly caused by physical processes, although there is still a possibility of the occurrence of physical-chemical processes due to the presence of van der Waals forces (Twort *et al.* 2006). As also explained by Schmitt & Shinault (1996), the screening process is determined by two basic physical principles. First, relatively large suspended particles are trapped between grains of sand when passing through filter media (mechanical straining). Second, smaller particles are attached to the surface of the sand grains caused by the effects of Van der Waals forces (physical adsorption). A chemical filter aid (i.e. a coagulant or flocculant) can be added to increase the additional adhesion force.

In this study, two variations in the size of filter media were used. After sieving analysis, it was found that the ES (Effective Size) value was 0.39 mm and 0.68 mm with a porosity of 0.431 and 0.451 respectively. The microplastics used in this study originated from artificial samples, namely from plastic flakes and tyre flakes with variations in size <50 μm, (50–100 μm), (100–200 μm), (200–300 μm), (300–400 μm), (400–500 μm) and >500 μm. Four variations of filtration rate are tested for 10 hours.

Based on average classification of size in the inlet and outlet, the dominant size in inlet is 101–200 μm, whereas in the outlet the dominant size for plastic flakes is 50–100 μm

Table 3 | Size distribution in inlet and outlet for both ES 0.39 and ES 0.68

Microplastics from plastic flakes

Size μm	Filtration rate (m/h)							
	4		**6**		**8**		**10**	
	Inlet (%)	Outlet (%)	Inlet (%)	Outlet (%)	Inlet (%)	Outlet (%)	Inlet (%)	Outlet (%)
<50	2.7	50	6.4	83.4	4.4	70	4.6	35.7
50–100	23.7	40	25.9	8.3	29	20	23.8	42.9
101–200	29.4	10	27.7	8.3	30.1	10	30	21.4
201–300	24.1	0	21.6	0	23.5	0	24.2	0
301–400	11.8	0	10.7	0	5.5	0	12.1	0
401–500	5	0	4.1	0	4.2	0	2.2	0
>500	3.2	0	3.6	0	3.3	0	3,1	0
Total	100	100	100	100	100	100	100	100

(Table 3). It can be seen that the average MPs size that still passes through the filter media is ≤200 µm. It is also evident that small particles break through the filter more easily under the whole range of filtration rate. When compared with the Talvitie *et al.* (2017) study, the MPs size that still passes through the filter media is <100 µm. The size of sand filter media on the WWTP Talvitie *et al.* (2017) studied is 0.1–0.5 mm with a depth of 50 cm. Whereas in the Pivokonsky *et al.* (2018) for the three DWTPs studied, the average MPs still surviving was <50 µm. But the specifications of sand used as filter media are not explained. Both Talvitie *et al.* (2017) and Pivokonsky *et al.* (2018) studied a full-scale treatment plant with the capacity to remove smaller MP particles in comparison with a rapid sand filter. The full-scale study can remove smaller MPs particles better than solely a rapid sand filter.

The process of mechanical straining that occurs in MPs removal using RSF is influenced by the size of the ES, porosity and MPs size. This is basically because the process of mechanical straining occurs by utilizing the pore size of the filter media so that MPs of a larger size will be strained. Crittenden *et al.* (2012) explained that if particles have a size greater than the size of the voids in the filter, the particles will be removed through straining, but if the particle size is smaller, then the particles will be set aside when contacted and attached to the filter media due to Van der Waals forces. The diameter of the opening between the filter media pores can be determined mathematically in reference to Huisman and Wood (1974) in Figure 9.

It is known that e is the diameter of the opening in the filter media, which can be used as the basis for the size of particles that can be retained or which can still pass through the pores of the filter media, while d is the diameter of the filter media grain. The value of e can be determined by
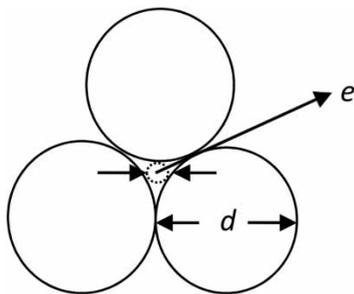

Figure 9 │ The diameter of the opening between the filter media pores (Huisman & Wood 1974).

Table 4 │ Prediction of microplastics size that pass through the filter

ES (mm)	Porosity	Huisman and Wood (1974) mm	µm	Crittenden *et al.* (2012) mm	µm
		The opening diameter of filter media (e)			
0.39	0.431	0.060	60.37	0.0585	58.5
0.68	0.451	0.105	105.26	0.102	102

looking for a comparison of the valued with 6.46. Crittenden *et al.* (2012) also explained that for round filter media, a tightly closed arrangement would cause strain when the ratio of particle diameter to grain diameter was greater than 0.15, meaning that smaller particles would pass through the filter media.

However, this does not apply to all conditions. So, based on this explanation, the MPs size that can pass through the filter media can be determined. The calculation results can be seen in Table 4.

Based on the results of calculations in Table 4, it can be seen that the diameter of filter media openings for ES filter media 0.39 using the equation of Huisman and Wood is 60.37 µm and using the equation of Crittenden *et al.* is 58.5 µm. This means that the filtration process using 0.39 mm ES filter media is able to screen particles that have a size of ≥58.5–60.37 µm. Likewise, with ES 0.68 mm, filter media is able to screen particles 102–105 µm (Table 4). But in this study, the ES of the 0.39 mm and 0.68 filter media was mostly only able to hold MPs that had a size of ≥200 µm.

The difference in the results of mathematical calculations and the results of the study can be caused by the measured MPs dimensions being the longest part of the MPs, not the diameter. So even though the MPs has a size of 200 µm, this is not necessarily a diameter of 200 µm. However, by carrying out theoretical calculations, estimation of filter performance can be predicted.

CONCLUSIONS

Microplastics removal in conventional water treatment processes consisting of sedimentation, coagulation and flocculation, sedimentation and followed by filtration, were

considered capable of removing certain size of MPs. Pre-treated water followed by the rapid silica sand filter process with ES 0.39 mm and 0.68 mm can remove 85% to 97% MPs that are mostly greater than 200 μm in size.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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