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Application of Radial Type Multifiber Media Filtration Process for Combined Sewer Overflow Treatment

Heejin Kim [1], Intae Shim [1], Donghyeon Lee [1], Bongchang Hong [1], Hyungjun Kim [1], Sangmin Lee [2] and Tae-Mun Hwang [3,*]

[1] Center of Research and Development, P&I HUMANKOREA, 167 Songpa-daero, Songpa-gu, Seoul 05855, Republic of Korea
[2] Department of Environmental Engineering, Kongju National University, 1223-24 Cheonan-daero, Seobuk-gu, Cheonan-si 31090, Republic of Korea
[3] The Department of Land, Water and Environment Research, Korea Institute of Civil Engineering and Building Technology, Environment Research Institute, Goyangdae-ro, Goyang-si 10223, Republic of Korea
* Correspondence: taemun@kict.re.kr

Abstract: Fiber media filtration for combined sewer overflow (CSO) treatment was evaluated in this work. Pilot-scale experiments of CSO treatment involve seven layers that form radial-type fiber media filters. The fiber media filter was characterized using analysis techniques and exhibited extremely high hydrophobicity and negative charge. The results obtained for a sewer treatment plant at Tancheon in Seoul revealed potential for suspended solid, total organic carbon, and biochemical oxygen demand removal with efficiencies of 89.6%, 56%, and 42%, respectively. The results are consistent with the sieving effects and electrostatic repulsion between fiber media and pollutants. Head loss was induced by organic pollutants and was 10.5 cm after 20 h of operation. To mitigate the head loss induced by organic pollutants on the fiber media filter, sodium hypochlorite (NaClO) was used as a chemical backwashing agent. An NaClO concentration of 2000 mg/L with a soaking time of 24 h yielded an optimal head loss recovery of 96.2% of the initial head loss obtained for the virgin fiber media filter without media filter degradation. The result of the present study will provide practical insight and act as a technical guide for CSO treatment plant engineers.

Keywords: radial multimedia-filter; combined sewer overflows; NaClO soaking; removal mechanisms; organic pollutants

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1. Introduction

Pollution from urban stormwater discharges and combined sewer overflows (CSOs) are considered two of the main factors affecting the river water quality of receiving bodies [1]. Consequently, CSO management has become central to the environmental protection strategies of municipalities around the world. The problems associated with CSOs are exacerbated by the limitations of combined sewer system infrastructure and the limited capacity of municipal wastewater treatment plants (WWTPs). Furthermore, the additional flow generated by extreme rainy weather events could lead to a bypass of WWTPs and untreated wastewater being discharged directly into rivers. As a result, oxygen-depleting matter and pathogens are discharged into the river with solid nutrients and other micropollutants (including a high concentration of organics and chemicals) [2]. Pollutants such as total suspended solids (TSS), chemical oxygen demand (COD), biochemical oxygen demand (BOD), total Kjeldahl nitrogen, and total phosphorus could occur in concentrations of 270–550 mg/L, 260–480 mg/L, 60–220 mg/L, 4–17 mg/L, and 1.2–2.8 mg/L, respectively, in CSOs [3].

Various technologies control CSOs prior to discharge into rivers or other water bodies. A vortex separator uses rotational gravity to separate large amounts of high-concentration

liquor with high treatment quantities. Chemical treatment processes (e.g., ballasted flocculation processes) have improved sedimentation time by mixing with coagulants and media and effectively removing TSS, COD, BOD, P (phosphorus), algae, and heavy metals [4]. Primary treatments, such as constructed wetlands and setting tanks, could be used to remove TSS, COD, BOD, nutrients, micropollutants, coliform bacteria, and heavy metals [5].

Over the last two decades, various studies have examined the development of CSO treatment processes. Compared with other processes, coagulation-flocculation treatments using coagulants such as polyaluminum chloride and alum exhibited higher removal efficiency for particulate matter; these form flocs when coagulants react with small particles and allow insoluble precipitates to form prior to flocculation of the solids and organic matter [6,7]. A hydrodynamic vortex separator can remove suspended solids and sediments simultaneously with lower head loss than that encountered in other CSO treatments [8]. However, the removal efficiency of vortex separators is inadequate for CSO treatments [9]. Although, compared with other treatments, flocculation processes exhibit higher removal efficiency, the operation and maintenance costs are high due to the considerable coagulant injection required and sludge treatment costs associated with the operating process [10,11]. In recent years, benefits of fiber media-based filtration over both vortex separators and coagulation and flocculation processes have been reported; compared with these processes, the fiber media filtration process has higher removal efficiency, higher biological resistance, low power consumption, and requires less land [12–14]. The development of fiber media filtration with high clogging prevention is essential for CSO treatments. During a physical backwashing, or backflush, tap water is injected in the opposite direction to that of filtration. The expectation is that this process will detach the cake layer loosely attached to the surface of the fiber media filter. Many researchers have reported that physical backwashing can improve the particulate and colloid cleaning efficiency of the filters [15–23]. However, control of organic pollutants in wastewater through physical backwashing in fiber media filters is difficult if such pollutants are attached to the surface of the media [18–23].

Chemical cleaning is effective in removing organic pollutants from the fiber media filter. Sodium hypochlorite (NaClO) was found to be the most common oxidant for controlling these pollutants, owing to its effective oxidation of organic matter and because it is less environmentally hazardous than other chlorine-based chemicals [17,18]. Intensive chemical soaking, in terms of both frequency and concentration of the chemical reagent, may enable long-term operation of the filtration processes for water and wastewater treatment [17]. Additionally, the impact of a NaClO solution on the fiber media filter depends strongly on the pH and concentration of the solution. The fiber media hydrophilicity may decrease at pH < 7 (where HOCl is dominant), owing to chlorination accompanying NaClO exposure, and may increase at pH > 7 owing to the hydrolysis effect [18].

A radial-type multifiber filtration (RMF) process is implemented for treating real CSOs. The goal of this study was to develop and assess the performance of the CSO treatment process and optimize its operation and maintenance conditions. The main advantage of the radial-type multifiber media filtration process is that the filtration efficiency can be maximized by minimizing the filtration time and area. For optimizing the operation and maintenance conditions of the RMF process, physical and chemical cleaning methods associated with surface morphology and water quality analysis were systematically performed to assess the impact of organic pollutants in CSOs. In addition, chemical soaking using NaClO should be optimized to minimize the negative impact of NaClO on the properties of the fiber media filter. Minimizing this impact will allow for high clogging control and maximum filtration time with low operational costs in real CSO treatment plants.

2. Materials and Methods

2.1. CSO Characterization

Prior to the beginning of the study, the characteristics of real CSOs occurring in Daegu, South Korea, were analyzed to determine the standard water quality of CSOs considered in this study. Table 1 shows the characteristics of the standard CSO concentration of CSOs

associated with a rainfall intensity of 7 mm/h. The concentrations of BOD_5, COD_{Mn}, and SS in CSOs occurring in Daegu were approximately three times higher than the concentrations in non-overflows.

Table 1. Water quality of CSOs in Daegu overflows.

Sampling Time	Concentration of Pollutant in CSOs in Daegu					Remarks
	BOD_5 (mg/L)	COD_{Mn} (mg/L)	SS (mg/L)	T-N (mg/L)	T-P (mg/L)	
15:10	39.9	25.9	31.0	16.4	1.27	-
15:40	79.4	56.3	62.1	17.2	1.27	-
16:00	141.2	72.5	120.5	18.2	1.35	Overflow
16:15	145.5	71.2	159.5	21.6	2.62	Overflow
16:30	175.8	75.4	232.5	19.5	2.11	Overflow
16:45	206.4	86.4	330.4	23.5	3.11	Overflow
17:00	210.7	85.1	305.4	22.3	3.05	Overflow
17:15	161.2	59.4	290.2	18.8	1.66	Overflow
17:30	168.5	60.2	160.4	16.9	1.61	Overflow
18:00	60.9	43.1	85.2	15.2	1.24	Overflow
18:30	51.2	45.2	49.5	13.4	1.23	Overflow
19:00	45.0	34.2	45.5	13.5	1.23	Overflow

To simulate the water quality of real CSOs, raw water was collected from a public sewer treatment facility in Seoul, South Korea. Table 2 shows the concentration of influent in a public wastewater treatment facility under different weather conditions employed in this study. During a rainy day with a rain intensity of 5 mm/h, the samplings were performed after 30 min of an initial 3 h rainy period. Under these weather conditions, the analysis was performed for TSS, Total Organic Carbon (TOC), and BOD_5. Moreover, the removal efficiencies were calculated for a total of 350 samples collected at each process (raw water, pretreatment, and RMF).

Table 2. Water quality of raw wastewater associated with different weather conditions in testbed.

Weather Condition (Sample Number)		Public Sewer Treatment Facility in Testbed					
		BOD_5 (mg/L)	TOC (mg/L)	SS (mg/L)	T-N (mg/L)	T-P (mg/L)	Remarks -
Dry Weather	Minimum	74.0	51.1	42.0	27.6	2.78	-
	Average	115.7	59.6	84.4	30.7	3.05	-
	Maximum	156.6	68.1	126.0	37.8	3.73	-
Rainy Weather	Minimum	180.0	50.4	76.0	35.7	3.38	-
	Average	224.7	60.9	130.6	38.0	3.63	-
	Maximum	279.5	66.0	174.0	40.1	3.85	-

2.2. Pilot-Scale Multifiber Media Filtration Process Units

In this study, a pilot-scale plant of radial multifiber (RMF) filtration was performed to control CSOs and was set up in a public wastewater treatment plant in Seoul, Republic of South Korea. A schematic of the RMF filtration process was performed under conditions of 480 m^3/day and a linear velocity of 20 m/h (see Figure 1) as a natural flow. The whole pilot-scale treatment process consists of 3.0 m in length, 2.3 m in width, and 2.0 m in height.

The radial multifiber media filtration process in this study involves a raw water tank, a pretreatment process, and a filtration tank. A mesh-type multilayer screen with mesh sizes of 8 mm, 5 mm, and 2 mm from the bottom of the tank was chosen to remove large particulates or debris as a pretreatment process. Fiber media filtration equipment with seven layers in radial formation and a filtration area of 1.00 m^2 was designed, and the filter area increases toward the outflows of the filtration process. From the inner to the

outer of the fiber media filter, the inner fiber media filter is densely formed to remove large pollutants, and the outer fiber media filter treats fine residual pollutants. The RMF was to test for removal of SS, TOC, and BOD in different weather conditions.

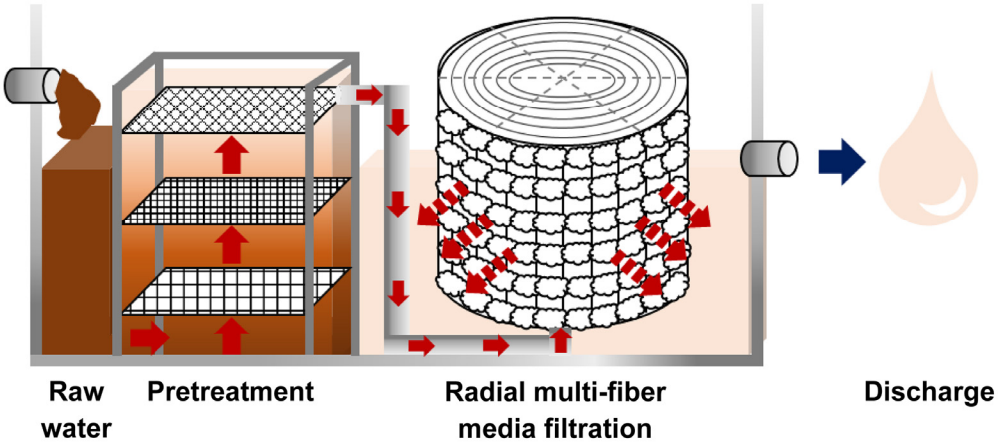


Figure 1. Schematic of the radial multifiber media filtration process for CSOs.

2.3. Characterization of the Fiber Media Filter

The fiber media filter (see Table 3 for characteristics of the filter) used in this investigation was purchased from Hyosung Green Tech (Hyosung Green Tech, Ansan, Republic of Korea), and the basic characteristics of the filter were produced. For further determination of the physiochemical properties exhibited by the filter, the inner surface morphology of the filter used in this study was analyzed via high-quality field emission scanning electron microscopy (FE-SEM; Hillsboro, OR, USA). The surface charge (zeta potential) of the filter was measured with a streaming potential instrument (SurPASS, Anton Paar, Graz, Austria) using a 10-mM NaCl solution. The water contact angle of the filter was evaluated using the sessile drop method (phoenix-300 analyzer with video capturing equipment; SEO Corporation). The results were determined as the average of at least seven tests performed on each sample.

Table 3. Characteristics of fiber media filter.

Contents	Properties
Material	1000 Denier 110 fila Polypropylene, BCF
	Diameter of 4 mm Polypropylene (PP), Rope type, Monofilament (Nylon), Polyethylene (PE) multiline
Shape	Rope type, seven stages
Porosity (%)	96.2
Diameter (mm)	40–45
Specific surface area (m^2/m)	1.78
Water permeability (cm/s)	2.47

2.4. Analysis of Pollutants in CSOs

TSS and BOD_5 were analyzed as described in Standard Test Methods for wastewater [24]. The TOC was analyzed using a TOC analyzer (TOC 4000HT, Kyoto, Shimadzu Corporation, Japan). Particle size distribution analysis was evaluated by a Laser Diffraction Particle Size Analyzer (SALD-2300, Shimadzu Corporation, Japan). In addition, the

removal efficiency under various concentrations of diluted wastewater was calculated as follows:

$$\text{Removal Efficiency } (\%) = \frac{\left(C_f - C_e\right)}{C_f} \times 100. \quad (1)$$

where C_f is the initial concentration of raw wastewater and C_e is the final concentration of effluent.

2.5. Physical and Chemical Backwashing

NaClO solution with 12% w/w freely available chloride ions was supplied by Sigma-Aldrich (St. Louis, MO, USA). The concentrations of NaClO used for soaking in this experiment were 500, 1000, 1500, and 2000 mg/L. Hydraulic backwashing was performed for 15 min with six rotational nozzles involved in the filtration process. The hydraulic backwashing water was obtained from the final discharge of a wastewater treatment plant. Each chemical soaking with different concentrations of NaClO solution was conducted for ~20 h after reaching a head loss of RMF at 16.5 cm. Both physical and chemical cleaning efficiencies under these concentrations were assessed in terms of the relative head loss recovery, which is calculated as follows:

$$\text{Head loss recovery } (HLR) = \frac{(HL_{bc} - HL_{ac})}{HL_{bc} - HL_v} \times 100. \quad (2)$$

where HLR is the relative head loss recovery, HL_{bc} is the head loss before cleaning, HL_{ac} is the head loss after cleaning, and HL_v is the initial head loss of the radial fiber-media filtration process (cm). According to various studies, NaClO is developed as an efficient chemical cleaning agent [18–23]. Therefore, different concentrations (500, 1000, and 2000 mg/L) of NaClO were tested in order to determine the optimum conditions for the CSO treatment process.

3. Result and Discussion

3.1. Characterization of Fiber Media Filter

Figure 2 shows the surface morphology, hydrophobicity, and surface charge determined via FE-SEM, water contact angle measurements, and zeta potential measurements, respectively, of the fiber media filter. FE-SEM images (Figure 2a) show that the surfaces of the filter were very rough, owing to the twisted polyethylene multilines on the monofilament loop comprising the filter. The zeta potential measurements revealed a negative charge value for the media filter over a wide pH range, and the isoelectric point of the filter occurred at pH 5.09 (Figure 2b). Additionally, the water contact angle of the fiber media filter indicated that the filter was extremely hydrophobic; an average water contact angle of 116.8° was measured. This hydrophobicity can have a significant effect on the potential for clogging, leading to an increase in hydrophobic attraction between contaminants and the filter, resulting in easy deposition of contaminants on the surface of the filter.

3.2. Removal Mechanisms of Radial-Type Multifiber Media Filtration Process

Figure 3 shows the removal efficiency of pollutants (SS, TOC, and BOD_5) for the RMF process under different weather conditions. The process removed 89.6% SS, 45.3% TOC, and 58.4% BOD_5 in dry weather and 87.4% SS, 42.8% TOC, and 48.5% BOD_5 in rainy weather.

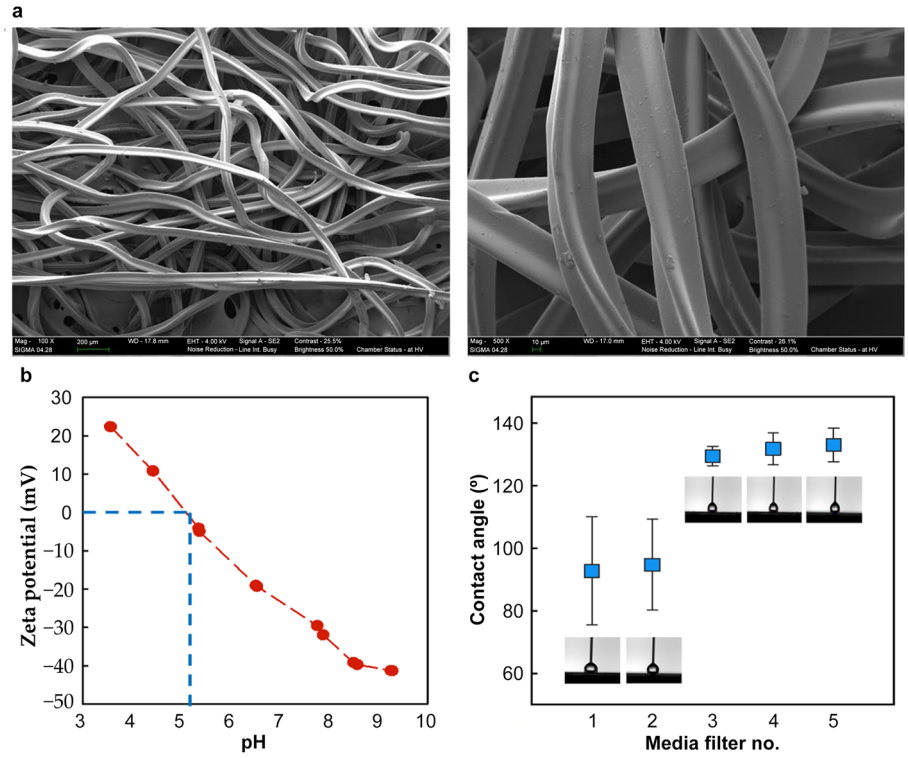


Figure 2. Characteristics of the fiber media filter as determined via (**a**) FE-SEM, (**b**) Zeta potential analysis. Blue line represents a isoelectro point of the multifiber medai filter. Isoelectro point means zeta potential equals zero when the object meets at specific pH (pH 5.09), and (**c**) water contact angle. The red line represents a zeta potential of whole multifiber media filter at different pH range.

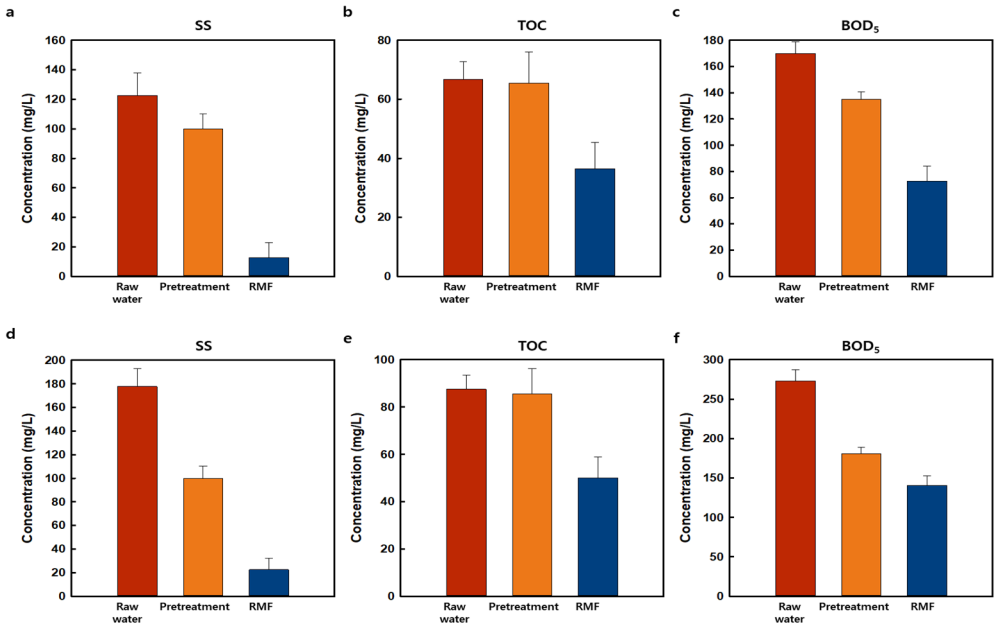


Figure 3. Removal of contaminants in combined sewer overflows (**a**) SS (Suspended Solids), (**b**) TOC (Total Organic Carbon), (**c**) BOD_5 (Biochemical Oxygen Demand) in dry weather condition, (**d**) SS in rainy weather condition, (**e**) TOC in rainy weather condition, and (**f**) BOD_5 in rainy weather condition. Operating condition: Initial velocity = 20.0 m^3/h, temperature = 23 °C, and raining intensity = 5 mm/h.

The main mechanisms for removing SS and TOC in this filtration process are the sieving effect (size exclusion) and hydrophobic adsorption. Furthermore, the mechanism

operating in the roof fiber media filter may be electrostatic repulsion between the contaminants and the negatively charged surface of the RMF. Regarding the observed charge differences, the fiber media had a negative charge (−28.84 mV) at pH 7. This may lead to a reduction in the electrostatic repulsion between the fiber media and negatively charged contaminants (NOM; organics), resulting in acceptable removal efficiency [25–27]. In addition, the roof-type fiber media filter is characterized by a high hydrophobicity value (Figure 2c), due to hydrophobic-hydrophobic interactions between the filter and hydrophobic contaminants. Hydrophobic pollutants can therefore be easily adsorbed into hydrophobic material filters [28–31]. Hence, large particles, such as suspended solids and large organic matter, were then filtered into the fiber media filter, leading to an increase in the removal efficiency.

Previous studies have shown that the SS, TOC, and BOD_5 concentrations are significantly higher in rainy weather than in dry weather [32]. The SS and TOC concentrations of pollutants increased by more than 25% in rainy weather compared to dry weather, whereas the BOD_5 concentration increased by approximately 36.5%. Precisely, the SS, TOC, and BOD_5 concentrations in dry (rainy) weather were 122.5 (177.6), 66.8 (87.5), and 174.6 (273.3) mg/L, respectively. These results can be explained in terms of the properties of CSOs in urban areas. For most urban areas, a combined sewer is usually used to transport sewage into wastewater with a very slow flow in dry weather. The sewage accumulated under a sewer pipe forms a high concentration of pollutants. During a rainfall period, accumulated sewage may be overflowed from the combined sewer pipe with a high concentration of pollutants and mixed with municipal wastewater. These CSOs increase the concentration of pollutants.

The RMF process exhibited stable SS removal efficiency in both weather types. Although the removal efficiencies of BOD_5 differed and TOC rejection showed stability in both weather types, the concentration of organic matter in CSOs can contaminate an ecosystem when untreated water discharges into rivers. Hence, it is necessary to develop the pretreatment or posttreatment process of RMF.

3.3. Particle Size Analysis of Radial Fiber Media Filtration Process

In this study, particle size analysis was performed to determine the characteristics of particulate matter treatment throughout the fiber media filter. Figure 4 shows that the particle size range was 2.18–143.4 μm (average 21.4 μm) for raw water, 2.73–148.4 μm (average 24.8 μm) after pretreatment, and 1.08–19.8 μm (average 4.45 μm) after the RMF process. Particle sizes up to 20.0 μm can be removed using the fiber media filter. In addition, the particle size distribution after pretreatment was slightly higher than that of raw water, as its lower retention time reduced the sedimentation effect for micro -substances with sizes less than 150 μm in the pretreatment process.

Table 4 summarizes the average particle size in each process for CSO treatment and the cumulative distribution according to the standard deviation. Ninety percentage of the cumulative particle size distributions for raw water, after pretreatment, and after the RMS process were 140.8, 148.4, and 19.7 μm, respectively; 60% of the cumulative particle size distributions for raw water, after pretreatment, and after the RMS process were 37.9, 44.1, and 5.79 μm, respectively. Meanwhile, 10% of the cumulative particle size distributions for raw water, after pretreatment, and after the RMS process were 2.19, 2.73, and 1.08 μm, respectively. These results indicate that particle size shows a decreasing trend for the RMF process.

Table 4. Particle size distribution of each process.

Process	Particle Size (Diameter, μm)								
	D10	**D20**	**D30**	**D40**	**D50**	**D60**	**D70**	**D80**	**D90**
Raw water	2.18	5.20	10.8	17.9	26.2	37.9	56.2	87.9	140.8
Pretreatment	2.73	6.51	12.9	20.6	30.6	44.1	64.4	96.8	148.4
RMF	1.08	1.57	2.21	3.08	4.22	5.79	8.13	12.1	19.8

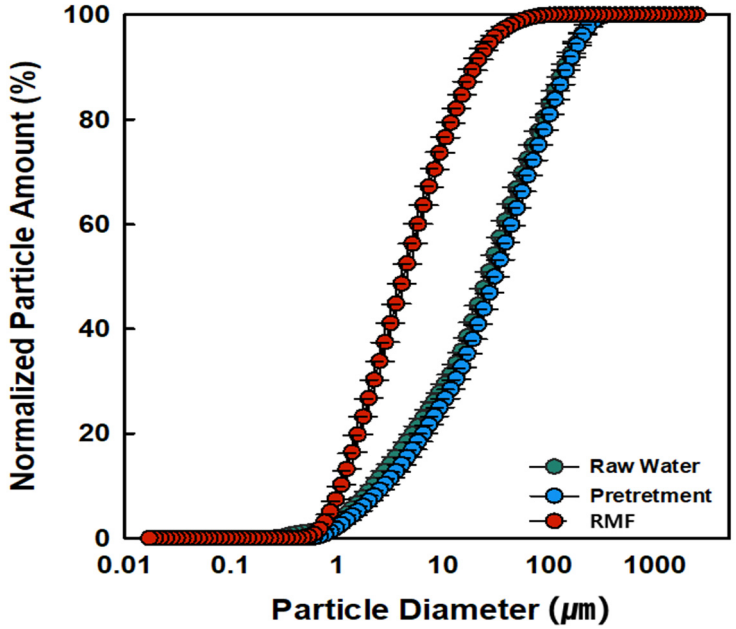


Figure 4. Particle size analysis of multifiber media filtration.

3.4. Head Loss Recovery Rate after Physical Backwashing in the Radial Fiber Media Filtration Process

In this investigation, physical backwashing was commonly performed to remove adhesive contaminants from the surface of a fiber media filter. Figure 5 shows the head loss recovery in a radial-type multifiber media filtration process after physical backwashing. The head loss recovered by 40.5% after filtration. No improvement in the head loss recovery efficiency of the multimedia was achieved because the organic material in the CSOs formed a gel-like sticky layer on the surface of the media [33,34].

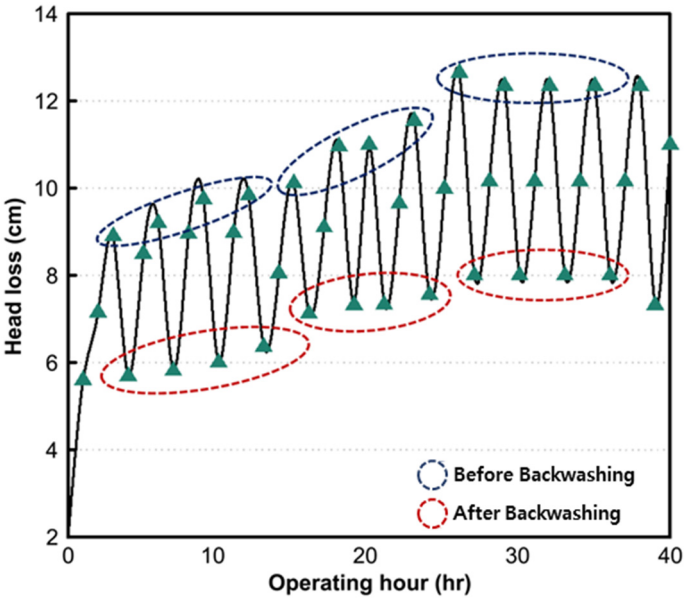


Figure 5. Head loss recovery in radial-type multifiber media filtration process after physical backwashing every 2.5 h.

An average head loss of 8.5 cm occurred after every 2.5 h of the filtration process. The optimal backwashing period was determined at a head loss of 8.8 cm and a backwashing time of 15 min. These kinds of adhesive pollutants on the surface of the fiber media filter can increase the head loss of the RMF; additional force would be necessary to remove

adhesive pollutants from this surface. Therefore, physical backwashing showed a weakened backwashing effect, and thus, the head loss of the radial multimedia filtration process was only partly recovered after filter clogging by pollutants.

3.5. Chemical Backwashing for Radial Fiber Media Filtration Process

Chemical backwashing was evaluated for the radial multifiber media filtration process because physical backwashing was ineffective in restoring the head loss of the organically contaminated fiber media filter [16]. Previous studies found that sodium hypochlorite solutions may have a negative impact on the properties of the fiber media filter or may lead to the deterioration of the filter [19,35–38]. A sodium hypochlorite (NaClO) solution with optimal concentration was used during chemical soaking to achieve optimal head loss recovery with a minimum impact on the properties of a fiber-type filter.

Figure 6 shows the result of the experiments performed once a week using different NaClO concentrations. Increasing the concentration of NaClO increased the cleaning efficiency at 500, 1000, and 2000 mg/L after 24 h of chemical soaking following 20 h of operation. The head loss of the radial multifiber media filtration process was efficiently restored through chemical soaking at a concentration of 2000 mg/L. The head loss recovery efficiency was 96.2% at 2000 mg/L of NaClO but was restored by only 65.2% and 84.5% at 500 and 1000 mg/L, respectively (Figure 6a). Compared to the removal efficiencies of virgin media filters (Figure 6b), the radial-type multifiber media filter exhibited stable removal efficiency after soaking at the highest NaClO concentration (2000 mg/L). The removal efficiencies after soaking at a concentration of 2000 mg/L were 88.5% for TSS, 59.4% for TOC, and 42.3% for BOD_5.

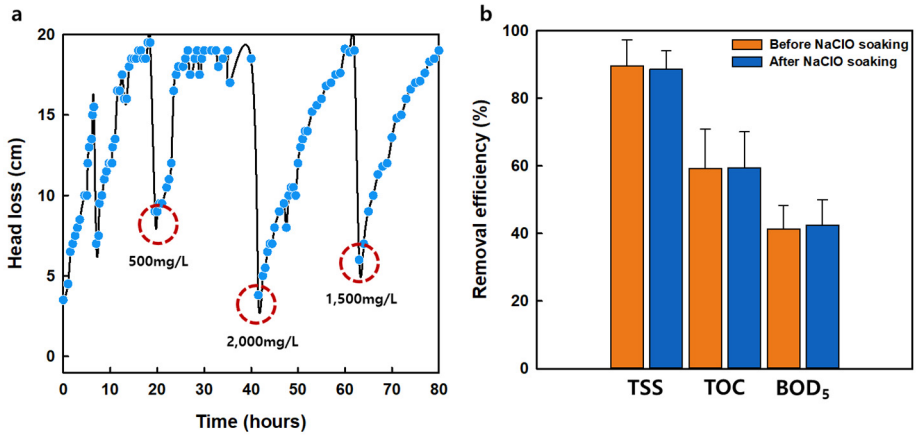


Figure 6. (**a**) Head loss recovery of the fiber media filter after chemical soaking with different concentrations of NaClO solution and (**b**) removal efficiencies of TSS, TOC, and BOD_5 from radial-type multifiber media filtration after chemical soaking with 2000 mg/L of NaClO solution.

Although NaClO consists of functional groups such as aldehyde (CHO), carboxyl (COOH), and keto (C=O), these functional groups can degrade the mechanical properties of organic-based fiber media filters [39]. As shown in Figure 7, NaClO soaking of the fiber media in this experiment provided relatively good recovery of head loss due to the oxidation and removal of organic contaminants on the surface. The NaClO solution may damage the surface of the fiber media filter due to oxidation of the media surface. However, the solution increased the negative charge on the surface, thereby leading to an increase in electrostatic repulsion between negative charges on the filter and negatively charged contaminants [40]. This may increase the interaction between contaminants and the filter, resulting in stable removal efficiencies after NaClO soaking.

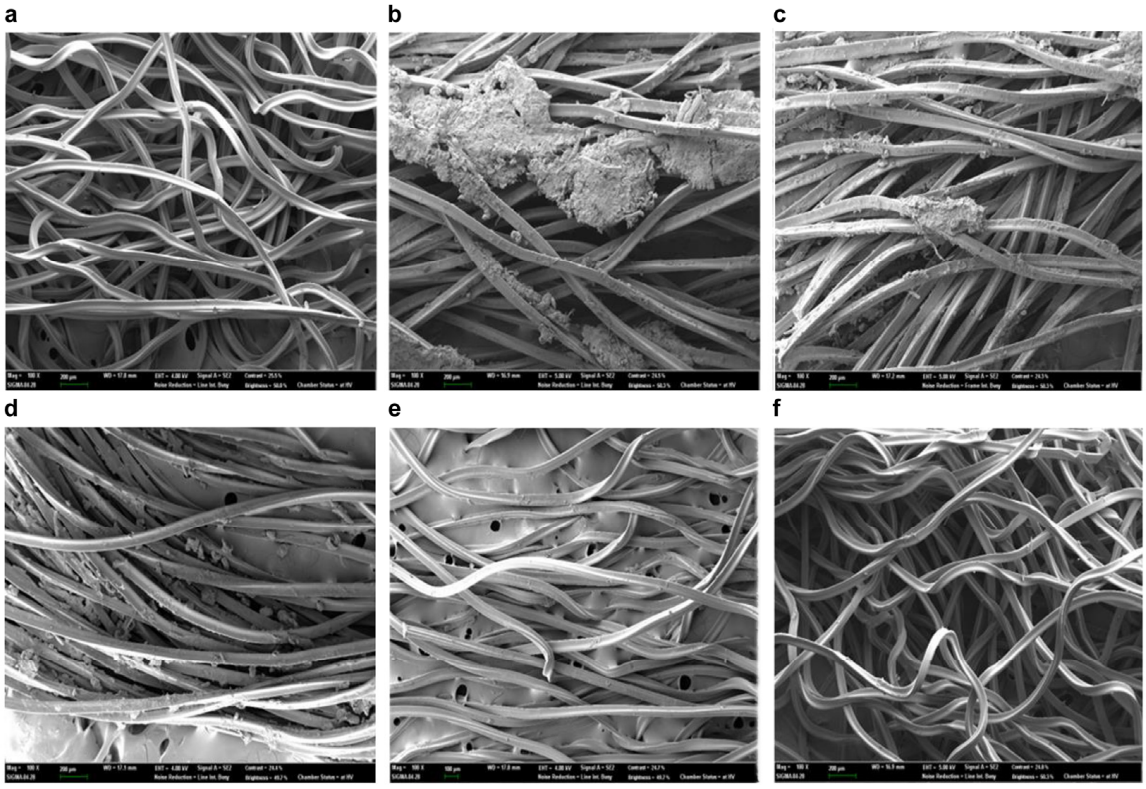


Figure 7. Scanning electron microscopy (SEM) images of the (**a**) virgin fiber media filter and fiber media filter after (**b**) 20 h of operation, (**c**) physical backwashing, (**d**) chemical soaking with 500 mg/L of NaClO, (**e**) chemical soaking with 1000 mg/L of NaClO, and (**f**) chemical soaking with 2000 mg/L of NaClO.

4. Conclusions

In this study, a radial-type fiber media filtration process was developed to control CSO treatments for urban areas in different weather conditions. The physicochemical properties of the media were characterized in order to obtain an average water contact angle of 116.8° and a negatively charged value of −28.84 at pH 7. The removal efficiencies of SS, TOC, and BOD_5 in dry weather are 87.4%, 42.8%, and 48.5%, respectively, while they are 89.6% for SS, 45.3% for TOC, and 58.4% for BOD_5 in rainy weather. In addition, the RMF process has rejected 20 μm of particulate and organic matter due to its size exclusion, large negative charge, and hydrophobicity adsorption. Due to the high concentration of organic pollutants in CSOs from urban areas, organic pollutants can be easily adsorbed onto the surface of the highly hydrophobic fiber media filter. Chemical backwashing was then applied to control the organic pollutants on the surface of the fiber media filter.

NaClO soaking can oxidize the most particulates, colloids, and organics and overcome the problems involved in removing pollutants deposited on the surface of fiber media filters. Compared with the initial head loss of the radial-type multimedia filtration process, the optimal head loss recovery after 2000 mg/L of NaClO soaking was 96.2%. Removal efficiencies of 88.5%, 59.4%, and 42.3% were realized for TSS, TOC, and BOD_5, respectively. Therefore, chemical soaking with a concentration of 2000 mg/L for the NaClO solution can be selected as the optimal condition in actual CSO treatments involving fiber media filter applications. We expect that the accumulation of field data on CSO treatment using fiber media-based filtration will efficiently contribute to the development of operational guidelines for such treatment processes and their operations. Furthermore, the RMF process is a physical treatment process that comprises seven fiber media filters and easily treats insoluble matter such as SS; however, RMF hardly treats dissolved pollutants or fine pollutants such as soluble BOD and micropollutants in CSOs (e.g., pharmaceuticals

and microplastics) that need more advanced treatment technology. The process can be improved by incorporating an advanced water treatment process as a post-treatment for CSO, such as ozonation, granular activated carbon, and membrane technology. Such a development of the RMF process should be necessary for future research to protect the river bodies by satisfying the next-generation river quality standards.

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References

1. Botturi, A.; Daneshgar, S.; Cordioli, A.; Foglia, A.; Eusebi, A.L.; Fatone, F. An innovative compact system for advanced treatment of combined sewer overflows (CSOs) discharged into large lakes: Pilot-scale validation. *J. Environ. Manag.* **2020**, *256*, 109937. [CrossRef] [PubMed]
2. US Environmental Protection Agency (EPA). Report to congress on impacts and control of combined sewer overflows and sanitary sewer overflows. *Water* **2004**, *1*, e680. [CrossRef]
3. Inc. Metcalf & Eddy; Tchobanoglous, G.; Stensel, H.; Tsuchihashi, R.; Burton, F. *Wastewater Engineering: Treatment and Resource Recovery*, 5th ed.; McGraw-Hill Education: New York, NY, USA, 2014.
4. Zukovs, G.; Marsalek, J. Planning and design of combined sewer overflow treatment. *Water Qual. Res. J. Can.* **2004**, *4*, 439–448. [CrossRef]
5. Krebs, P.; Holzer, P.; Huisman, J.L.; Rauch, W. First flush of dissolved compounds. *Water Sci. Technol.* **1999**, *39*, 55–62. [CrossRef]
6. Bolto, B.; Dixon, D.; Eldridge, R.O.B.; King, S. Cationic Polymer and clay or metal oxide combinations for natural organic matter removal. *Water Res.* **2001**, *35*, 2669–2676. [CrossRef]
7. Scherrenberg, S.M. Treatment Techniques for Combined Sewer Overflows. *Techniques* **2006**, *170*, 115328.
8. Han, J.K.; Joo, J.Y.; Lee, B.J.; Na, J.H.; Park, C.H. Optimal operating condition of vortex separator for combined sewer overflows treatment. *J. Korean Soc. Water Wastewater* **2009**, *23*, 557–564.
9. Bum-joon, L.; Ji-hoon, N.; Jin-sung, K.; Jae-young, J.; Yoon-sun, B.; In-ho, J.; Chul-hwi, P. A study on treatment of CSOs by vortex separator and continuous fiber-filter system. *J. Korean Soc. Water Wastewater* **2010**, *24*, 443–451.
10. Flaten, T.P. Alumnium as a risk factor in Alzheimer's disease, with emphasis on drinking Water. *Brain Res. Bull.* **2001**, *55*, 187–196. [CrossRef]
11. Geiger, W.F. Combined sewer overflow treatment: Knowledge or speculation. *Water Sci. Technol.* **1998**, *38*, 1–8. [CrossRef]
12. Caliskaner, O.; Tchobanoglous, G.; Carolan, A. High-rate filtration with a synthetic compressible media. *Water Environ. Res.* **1999**, *71*, 1171–1177. [CrossRef]
13. Jimenez, B.; Chavez, A.; Leyva, A.; Tchobanoglous, G. Sand and synthetic medium filtration of advanced primary treatment effluent from Mexico city. *Water Res.* **2000**, *34*, 473–480. [CrossRef]
14. Judd, S. *The MBR Book, Principles and Applications of Membrane Bioreactors in Water and Wastewater Treatment*; Elsevier: Amsterdam, The Netherlands, 2010.
15. Chang, H.; Liang, H.; Qu, F.; Liu, B.; Yu, H.; Du, X.; Li, G.; Snyder, S.A. Hydraulic backwashing for low-pressure membranes in drinking water treatment: A review. *J. Membr. Sci.* **2017**, *540*, 362–380. [CrossRef]
16. Liang, H.; Gong, W.; Chen, J.; Li, G. Cleaning of Fouled Ultrafiltration (UF) membrane by algae during reservoir water treatment. *Desalination* **2008**, *220*, 267–272. [CrossRef]
17. Kweon, J.H.; Jung, J.H.; Lee, S.R.; Hur, H.W.; Shin, Y.; Choi, Y.H. Effects of consecutive chemical cleaning on membrane performance and surface properties of microfiltration. *Desalination* **2012**, *286*, 324–331. [CrossRef]
18. Bogati, R.; Goodwin, C.; Marshall, K.; Leung, K.T.; Liao, B.Q. Optimization of chemical cleaning for improvement of membrane performance and fouling control in drinking water treatment. *Sep. Sci. Technol.* **2015**, *50*, 1835–1845. [CrossRef]

19. Regula, C.; Carretier, E.; Wyart, Y.; Gésan-Guiziou, G.; Vincent, A.; Boudot, D.; Moulin, P. chemical cleaning/disinfection and ageing of organic uf membranes: A review. *Water Res.* **2014**, *56*, 325–365. [CrossRef] [PubMed]
20. Lateef, S.K.; Soh, B.Z.; Kimura, K. Direct membrane filtration of municipal wastewater with chemically enhanced backwash for recovery of organic matter. *Bioresour. Technol.* **2013**, *150*, 149–155. [CrossRef] [PubMed]
21. Do, V.T.; Tang, C.Y.Y.; Reinhard, M.; Leckie, J.O. Degradation of polyamide nanofiltration and reverse osmosis membranes by hypochlorite. *Environ. Sci. Technol.* **2012**, *46*, 852–859. [CrossRef]
22. Donose, B.C.; Sukumar, S.; Pidou, M.; Poussade, Y.; Keller, J.; Gernjak, W. Effect of pH on the ageing of reverse osmosis membranes upon exposure to hypochlorite. *Desalination* **2013**, *309*, 97–105. [CrossRef]
23. Kim, H.J.; Shim, I.T.; Zhan, M. Chemical enhanced backwashing for controlling organic fouling in drinking water treatment using a novel hollow-fiber polyacrylonitrile nanofiltration membrane. *Appl. Sci.* **2021**, *11*, 6764. [CrossRef]
24. American Public Health Association (APHA). *Standard Methods for the Examination of Water and Wastewater, a Joint Publication of the American Public Health Association (APHA)*, 20th ed.; American Water Works Association: Washington, DC, USA, 1998.
25. Hobbs, C.; Taylor, J.; Hong, S. Effect of Surface Roughness on Fouling of RO and NF membranes during filtration of a high organic surficial groundwater. *J. Water Supply Res. Technol. AQUA* **2006**, *55*, 559–570. [CrossRef]
26. Chang, E.-E.; Yang, S.-Y.; Huang, C.-P.; Liang, C.-H.; Chiang, P.-C. Assessing the fouling mechanisms of high-pressure nanofiltration membrane using the modified hermia model and the resistance-in-series model. *Sep. Purif. Technol.* **2011**, *79*, 329–336. [CrossRef]
27. Lee, S.; Kim, S.; Cho, J.; Hoek, E.M.V. Natural organic matter fouling due to foulant–membrane physicochemical interactions. *Desalination* **2007**, *202*, 377–384. [CrossRef]
28. Ghosh, A.K.; Jeong, B.-H.; Huang, X.; Hoek, E.M.V. Impacts of reaction and curing conditions on polyamide composite reverse osmosis membrane properties. *J. Membr. Sci.* **2008**, *311*, 34–45. [CrossRef]
29. Vrijenhoek, E.M.; Hong, S.; Elimelech, M. Influence of membrane surface properties on initial rate of colloidal fouling of reverse osmosis and nanofiltration membranes. *J. Membr. Sci.* **2001**, *188*, 115–128. [CrossRef]
30. Hong, S.; Elimelech, M. Chemical and physical aspects of natural organic matter (NOM) fouling of nanofiltration membranes. *J. Membr. Sci.* **1997**, *132*, 159–181. [CrossRef]
31. Nyström, M.; Kaipia, L.; Luque, S. Fouling and retention of nanofiltration membranes. *J. Membr. Sci.* **1995**, *98*, 249–262. [CrossRef]
32. Chen, Y.; Shi, X.; Jin, X.; Jin, P. Characteristics of overflow pollutant from combined sewer sediment: Formatiom, contribution and regulation. *Chemosphere* **2022**, *298*, 134254. [CrossRef]
33. Pontié, M.; Thekkedath, A.; Kecili, K.; Habarou, H.; Suty, H.; Croué, J.P. Membrane autopsy as a sustainable management of fouling phenomena occurring in MF, UF and NF processes. *Desalination* **2007**, *204*, 155–169. [CrossRef]
34. Meng, F.; Chae, S.R.; Drews, A.; Kraume, M.; Shin, H.S.; Yang, F. Recent advances in membrane bioreactors (MBRs): Membrane fouling and membrane material. *Water Res.* **2009**, *43*, 1489–1512. [CrossRef] [PubMed]
35. Arkhangelsky, E.; Kuzmenko, D.; Gitis, N.V.; Vinogradov, M.; Kuiry, S.; Gitis, V. Hypochlorite cleaning causes degradation of polymer membranes. *Tribol. Lett.* **2007**, *28*, 109–116. [CrossRef]
36. He, Y.; Sharma, J.; Bogati, R.; Liao, B.Q.; Goodwin, C.; Marshall, K. Impacts of aging and chemical cleaning on the properties and performance of ultrafiltration membranes in potable water treatment. *Sep. Sci. Technol.* **2014**, *49*, 1317–1325. [CrossRef]
37. Porcelli, N.; Judd, S. Effect of cleaning protocol on membrane permeability recovery: A sensitivity analysis. *J. Am. Water Works Assoc.* **2010**, *102*, 78–86. [CrossRef]
38. Ding, J.; Wang, S.; Xie, P.; Zou, Y.; Wan, Y.; Chen, Y.; Wiesner, M.R. Chemical cleaning of algae-fouled ultrafiltration (UF) membrane by sodium hypochlorite (NaClO): Characterization of membrane and formation of halogenated by-products. *J. Membr. Sci.* **2020**, *598*, 117662. [CrossRef]
39. Wolff, S.H.; Zydney, A.L. Effect of bleach on the transport characteristics of polysulfone hemodialyzers. *J. Membr. Sci.* **2004**, *243*, 389–399. [CrossRef]
40. Schafer, A. *Natural Organics Removal Using Membranes: Principles, Performance, and Cost*; CRC Press: Boca Raton, FL, USA, 2001.

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