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Performance of Conventional Drinking Water Treatment Plants in Removing Microplastics in East Java, Indonesia

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ABSTRACT

Microplastic (MP) has been a new emerging contaminant in the municipal water supply. A water treatment process is a key to producing high-quality and safe drinking water. The performance of a conventional drinking water treatment plant (CDWTP) to remove MPs is questionable. This research aimed to investigate the performance of 2 CDWTPs in East Java in removing MPs. Full-stage treatment in two CDWTPs consisted of intake, pre-sedimentation, coagulation-flocculation, sedimentation, sand filter, and disinfection units. Five L water samples were collected with a grab sampling technique in the sampling points of intake and outlet of each water treatment unit. MP abundance and characteristics in each sample were determined using a Sunshine SZM-45T-B1 stereomicroscope and a Nicolet i10 FTIR spectrophotometer. Total MP removal efficiencies in CDWTPs I and II were 66 and 62%, respectively. The coagulation-flocculation unit performed the highest MP removal efficiencies (56%). The MP with 1–350 µm size achieved lower removal efficiencies (33–53%) than that with 351-<5,000 µm size (53–76%). The removal efficiencies of fiber, fragment, and film in the CDWTPs were 61–65%; 86–100%; and 100%, respectively.

Keywords: drinking water, microplastic, removal efficiency, water treatment.

INTRODUCTION

Plastic material has a highly persistent character in environments (Mendoza et al., 2021). The residue of plastic waste might leave microplastic (MP) particles in environments due to the aging and fragmentation process (Zha et al., 2022). MPs have been reported to distribute throughout the environments, like air, land, and water (Petersen & Hubbart, 2021). Moreover, past studies evidenced that MPs have contaminated food and drink products (Zhang et al., 2020), such as seafood (Lu et al., 2021), salt (Iniguez et al., 2017), beer (Liebezeit & Liebezeit, 2014), honey (Liebezeit & Liebezeit et al., 2015), mineral water (Obmann et al., 2018; Schymanski et al., 2018), and drinking water (Weber et al., 2021; Tong et al., 2020; Mintenig et al., 2019). Therefore, MP pollution was suspected of establishing in the food web cycle (Rochman et al., 2018).

The MP particles having less than 5 mm in size have attracted worldwide concern because of potential detrimental impacts on biota and their habitat (Li et al., 2020a). In addition, MPs could infiltrate into the human body through the food web cycle (Senathirajah et al., 2021). MP particles could harm human health, particularly those with small particle sizes (Prata et al., 2020). MP exposure to the human body could occur through mechanisms of dermal contact (Revel et al., 2018), inhalation (Dris et al., 2017), and ingestion (Galloway, 2015). Human body might experience several reactions due to MP exposure, for instance, an increase in oxidative stress, inflammation, and translocation (Prata et al., 2020). Furthermore, the adsorbed persistent organic pollutants and pathogenic organisms in the MP particles may cause toxicity in the human body (Senathirajah et al., 2021).

The MP content in drinking water has been an international interest because water ingestion has been a possible MP pathway in human bodies (Na et al., 2021). Therefore, the MP studies on drinking water have vastly evolved globally (Li et al., 2020b). Moreover, the current findings on MP pollution in raw water sources encouraged researchers to reveal the possibility of MP contamination in produced drinking water (Yuan et al., 2022). Current studies indicated that MP contamination in drinking water was tangible due to MP presence in raw water sources (Mintenig et al., 2019). In addition, water treatment plants (WTPs) could not eliminate MP pollutants in the produced water (Shen et al., 2020; Novotna et al., 2019). Most countries generally utilized conventional technology in the WTPs, which were not designed for MP pollutant removal (Shen et al., 2020). To date, the standards to limit MP abundance in produced drinking water have not yet been enacted internationally (Novotna et al., 2019). However, the performance of the CDWTPs in removing MP contaminants deserves an investigation since the MP ingested through water consumption might lead to human health risks, particularly in long-term exposure (Li et al., 2020b). Besides, the data could be a guide to improve CDWTP performance on MP removal, either to optimize the main process in conventional technology or further treat the water using advanced technology (Novotna et al., 2019).

A Water Supply Enterprise in East Java performed municipal water supply, which owned six WTPs with conventional technologies (Said and Hartaja, 2018). The total daily treatment capacity in six WTPs was 935,712 m^3, which provided water for around 98.97% of total residents (Ministry of Work and Public Housing, 2019; Lassoued, 2017). Deterioration of water quality has appeared in the river as raw water source due to illegal solid waste disposal from proximity households or industries (Natalia, 2013). Municipal solid waste generation was predicted to rise by 76% by 2025, of which 13,36% was plastic (World Bank Group, 2018). On the other hand, if the solid waste is not managed properly, the river would become the end disposal point, so using the river as the primary raw water source should be considered. Besides, the produced water quality in the three WTPs might be suspected of contamination, including MP particles.

The studies on MP removal in WTP have been broadly progressing; however, the basic information on the performance of CDWTP in removing MP was still inadequate in East Java, Indonesia. Therefore, it was urgent to carry out the investigation. In addition, a better understanding of MP fate in each treatment stage of CDWTP was proper to assess the MP removal ability of a single treatment, which contributed to overall removal efficiency (Shen et al., 2020; Enfrin et al., 2019). This study is critical because mismanaged solid waste generation tends to increase and eventually end up in rivers used as raw water sources (Yuan et al., 2022). This research focused on the MP removal performance of 2 CDWTPs in East Java. The two CDWTPs were selected to represent the actual condition of CDWTP, which used the raw water source experiencing anthropogenic contamination. The data were crucial to monitor the quality of municipal water supply in East Java.

MATERIALS AND METHODS

Sampling location and sampling approach

Sampling was conducted in CDWTPs I and II, located in East Java (Figure 1). These CDWTPs obtained raw water from river. The water treatment process in CDWTP I was the same as in CDWTP II. However, the processes were operated in quite different schemes of water treatment compartments (Figures 2 and 3). The CDWTPs I and II have daily water supply capacities of 86,400 and 151,200 m^3, respectively (Lassoued, 2017). Two replicates of 5 L water samples were collected from the points of intake and each water treatment outlet (Figures 2 and 3). The water samples were placed in glass bottles and then stored at 4 °C prior to laboratory analysis.

Prevention of contaminants and data quality assurance

Possible contamination during sample handling might derive from the air, laboratory glasswares, and equipment (Lu et al., 2021; Dris et al., 2017). Water sample contamination prevention was subject to reliable data (Lu et al., 2021). For laboratory analysis, cotton clothing was used to avoid fiber contamination (Tong et al., 2020). Before laboratory analysis, all glass wares and equipment were cleaned with distilled water

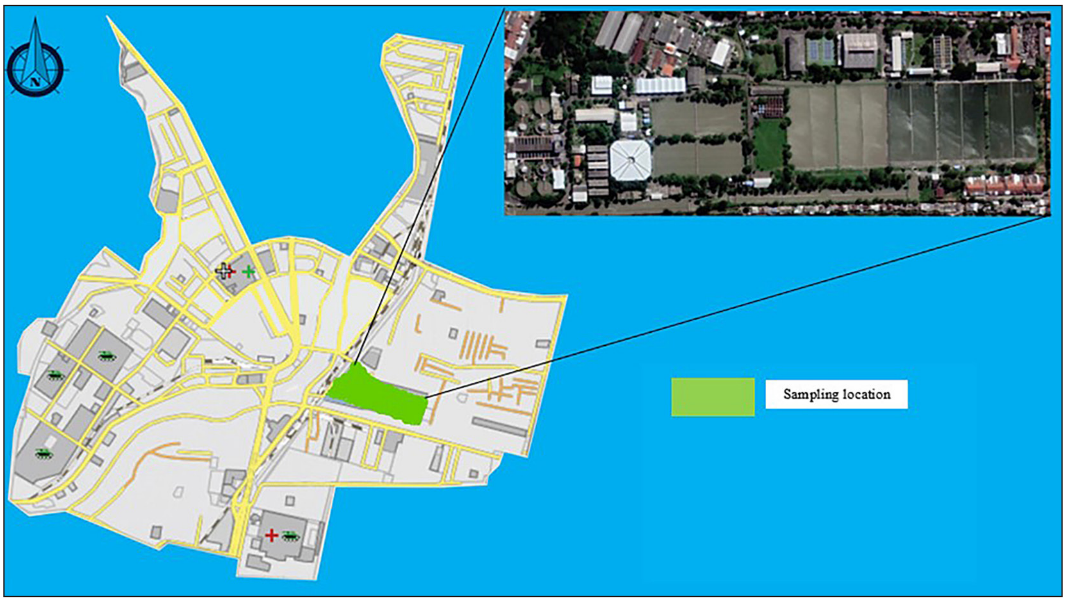

Figure 1. Map of sampling location

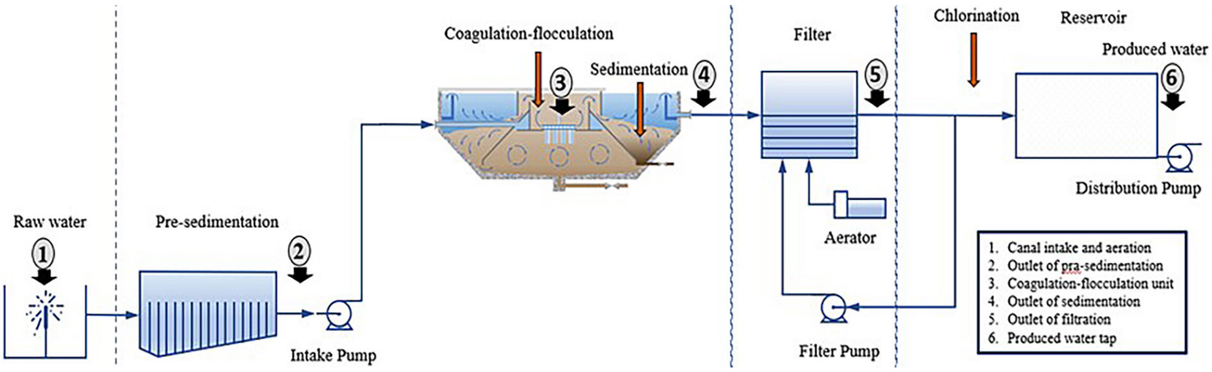

Figure 2. Scheme of water treatment compartments in CDWTP I

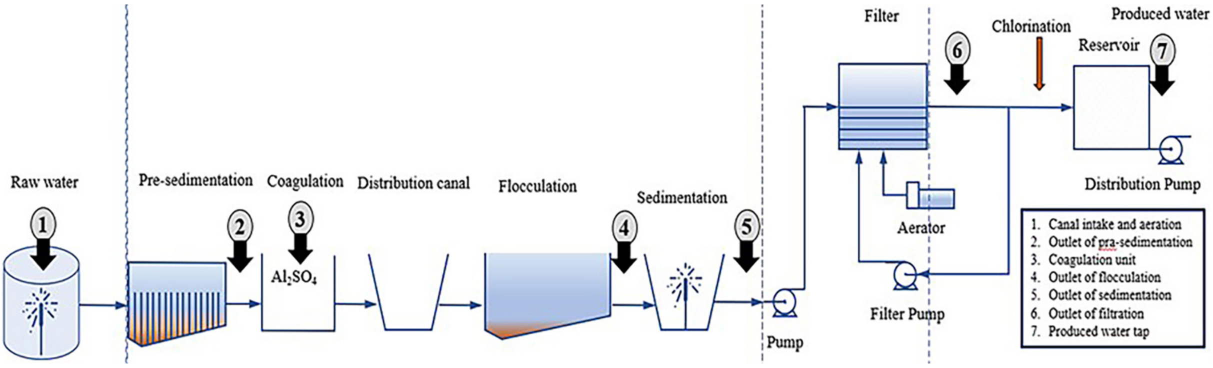

Figure 3. Scheme of water treatment compartments in CDWTP II

(Kankanige & Babel, 2020). Plastic-made material was minimized during sample handling and laboratory work (Wu et al., 2022a; Sarkar et al., 2021). In addition, a blank procedure was applied to this experiment. Five L distilled water was used as blank and treated the same as water samples. The blanks were prepared in duplicate for each sample set. One set sample referred to the samples taken from all sampling points in one CDWTP. MP particles in the blanks were considered contaminants; therefore, the abundance was deducted from that in water samples regarding the same classification of size, shape, and color (Yuan et al., 2022).

Sample treatment

Each sample was treated with Wet Peroxide Oxidation (WPO) to remove organic contaminants and then was vacuum filtered (Masura et al., 2015). One L water sample was added with 10 mL of 30% Merck hydrogen peroxide and 10 mL of Fe (II) 0.05 M. Then, the mixture was heated at 75 °C. Once the hydrogen peroxide evaporated entirely, the samples were filtered using vacuum filtration equipment with the Hawach Scientific membrane. Afterwards, the membrane was stored in a Petri dish and loosely covered with aluminum foil while air-dried for about 24 hours. The membrane specification was PTFE material- made with a pore size of 0.2 μm and 47 mm diameter.

Microplastic quantification and characterization

MP particles in the PTFE membranes were observed under a Sunshine SZM-45T-B1 stereo microscope with 40-60 x magnifications to identify MP abundance and characteristics (size, shape, and color). MP abundance was determined according to the MP particle number per L sample, which was enumerated during manual sortation under microscopic observation (Radityaningrum et al., 2021). The MP particle was also separated based on classifications of MP characteristics. The MP size class was divided into 1–100 μm, 101–350 μm, 351–1000 μm, and 1001-<5000 μm (Frias & Nash, 2019; Radityaningrum et al., 2021). The categories of MP shape were fiber, fragment, film, and pellet (Lestari et al., 2020). The color classifications were black, blue, red, yellow, and transparent (Peng et al., 2017). The polymer type was characterized using the Nicolet i10 FTIR spectrophotometer. About eight MP particles from each sample were selected for the FTIR test for polymer characterization (Radityaningrum et al., 2021). The FTIR test employed The Hummel Polymer Sample Library's polymer reference to match the tested MP particle's spectra. The particle chosen for the FTIR test was the particle with 351–5000 μm size. The reason was the accuracy of MP particle detection using the FTIR spectrophotometer (Wu et al., 2022a). The MP particle size <100 μm was more unstable than that of >100 μm.

Statistical analyses

A one-way ANOVA statistic test aimed to identify the difference of MP removal efficiency in each water treatment stage. If the *p-value* < 0.05, the MP removal efficiency in each water treatment unit was significant.

RESULTS AND DISCUSSION

Microplastic abundance, size, morphology in the raw and produced water

The average MP abundance of 0.4 particles/L was found in the blanks. The presence of MPs in the blanks illustrated that the external contamination possibly occurred during sample handling and laboratory analysis. The 351–1000 μm in size dominated the MP particle. The main shape of contaminants was fiber with black color. Woodall et al. (2015) stated that fiber contamination commonly existed in the process of sample handling and laboratory analyses. The abundance of MPs in the raw and produced water varied in size, shape, and color (Table 1).

Table 1 shows that the average MP abundance in the produced water decreased in both CDWTPs I and II. This condition highlighted that MP pollutants underwent removal in the CDWTPs. Compared with CDWTPs of other countries, CDWTP I (5.45±0.28 particles/L) and II (3.75±2.83 particles/L) showed higher MP of produced water than in Thailand (609.1±84.7 particles/L) (Kankanige and Babel, 2020); Cambodia (521±61 particles/L) (Babel and Dork, 2021); Changsha-China (352±15 particles/L) (Shen et al., 2021); Tehran-Iran (971±103 particles/L) (Adib et al., 2021); Czech Republic (369-485 particles/L) (Pivokonsky et al., 2018); Canada (20±8 particles/L) (Cherniak et al., 2022). These CDWTPs in other countries employed similar treatment stages to CDWTPs I and II; however, the MP abundance in the produced water differed. This condition was possibly due to the different quality of raw water sources and the performance of each treatment unit to remove MP (Cherniak et al., 2022; Novotna et al., 2019).

Regarding the particle size groups, small MP particles (1–1000 μm) were dominant in the raw water, which reached up to 55.3%. This condition was probably due to the existing water dam, which was located before the water intake of CDWTPs I and II. According to Wu et al. (2022b), dam construction could reduce the MP distribution in the downstream area, mainly of which particle size was 501 μm-<5 mm. These groups

Table 1. MP abundance in raw and produced water and removal efficiency

MP characteristics	CDWTP I			CDWTP II		
	Raw water (particles/L)	Produced water (particles/L)	Removal efficiency (%)	Raw water (particles/L)	Produced water (particles/L)	Removal efficiency (%)
Size						
1–100 µm	0.0 ± 0.0	0.0 ± 0.0	-	0.20 ± 0.28	0.10 ± 0.0	50
101–350 µm	0.60 ± 0.49	0.40 ± 0.14	33	0.85 ± 1.20	0.40 ± 0.35	53
351–1000 µm	8.88 ± 4.70	2.10 ± 0.50	76	2.33 ± 1.95	0.88 ± 1.17	62
1001 µm – < 5 mm	6.58 ± 2.23	3.10 ± 0.64	53	6.53 ± 1.73	2.40 ± 1.31	63
Shape						
Fiber	15.6 ± 6.29	5.43 ± 0.32	65	9.50 ± 4.60	3.7 ± 2.76	61
Fragment	0.18 ± 0.11	0.03 ± 0.03	86	0.20 ± 0.28	0.0 ± 0.0	100
Film	0.28 ± 0.0	0.0 ± 0.0	100	0.20 ± 0.28	0.0 ± 0.0	100
Pellet	0.0 ± 0.0	0.0 ± 0.0	-	0.0 ± 0.0	0.05 ± 0.0	-100
Color						
Black	2.55 ± 0.70	1.43 ± 0.60	44	1.7 ± 1.06	0.70 ± 0.92	59
Blue	0.78 ± 0.18	0.53 ± 0.25	32	0.15 ± 0.21	0.10 ± 0.0	33
Red	0.70 ± 0.78	0.15 ± 0.07	79	0.05 ± 0.07	0.0 ± 0.0	100
Yellow	1.78 ± 2.29	0.0 ± 0.0	100	0.0 ± 0.0	0.0 ± 0.0	100
Transparent	10.25 ± 3.89	3.35 ± 0.28	67	8.0 ± 3.82	2.95 ± 1.91	63
Total	16.05 ± 6.43	5.45 ± 0.28	66	9.90 ± 5.16	3.75 ± 2.83	62

of MPs tended to settle. On the other hand, MP particles of 1–500 µm quickly migrated to downstream areas, leading to the domination of small MP particles. Concerning MP removal efficiency, Table 1 also indicates that MP particles of 1–350 µm experienced lower removal efficiency (33–53%) than that of 351 µm-<5 mm (53–76%). This phenomenon happened because MP fragmentation might occur during water treatment (Wu et al., 2022a; Na et al., 2021; Shen et al., 2021). MP fragmentation would ultimately increase the abundance of small-size MP. In addition, the small-size class of MPs was released in effluent water because the small particles were difficult to settle in the sedimentation unit and retain in filter media (Enfrin et al., 2019). Therefore, the MP removal efficiency of the small-size group appeared to be low. This result was similar to a previous study in other CDWTPs in East Java which reported that the CDWTPs achieved higher MP removal efficiency of 351 µm-<5 mm MP size class (up to 84%) than that of 1–350 µm class (up to 53%) (Radityaningrum et al., 2021).

This study revealed that the water samples contained fiber, fragments, film, and pellets (Figure 4). The fiber was identified as the major MP form in both the raw waters of CDWTPs I (97.20%) and II (95.96%) and the produced waters of CDWTPs I (99.63%) and II (98.67%). The fragment was presented in the raw water in CDWTPs I and II, while the film was only found in CDWTP II. The pellet form appeared in the produced water in CDWTP II. Regarding the removal, fiber was not completely removed during the water treatment process (61–65%), whereas the removal efficiencies of fragments in CDWTPs I and II were 86 and 100%, respectively. In contrast, film-shaped MP was eliminated in the produced water in CDWTPs I (100%) and II (100%). The occurrence of fiber in the raw water was predicted from clothing fibers like cotton, nylon, and viscose fabric (Sulistyo et al., 2020). Fishing appliances, such as rope and nets, were also suggested as a fiber source in raw surface water (Buwono et al., 2021). Meanwhile, the fragment-shaped MP originated from more oversized plastic products and plastic litter broken in the environments (Wu et al., 2019; Horton et al., 2017; Zhang et al., 2015). The film was forecasted from the weathering of plastic wrap and packaging materials (Li et al., 2020a; Wang et al., 2017).

On the basis of MP color, transparent was the dominant MP color, both in the raw and produced water in CDWTPs I and II. The raw water in CDWTPs I and II contained transparent MPs of 63.9 and 80.8%, respectively. Meanwhile, transparent MPs in the produced water in CDWTPs I and II were 61.5 and 78.7%. In terms of MP polymer,

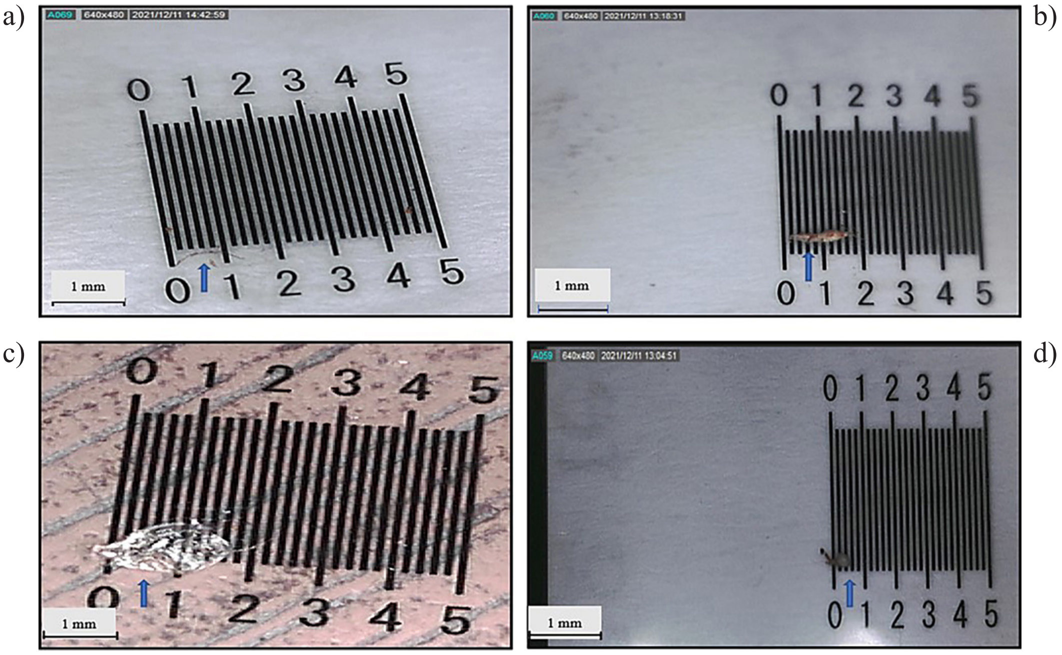

Figure 4. Photograph of MP shapes in the water samples: a) Fiber; b) Fragment; c) Film; d) Pellet

the FTIR test indicated that polymer types in the raw water in CDWTPs I and II were polyethylene (PE). This result was in line to the finding on MP distribution in the Surabaya River as raw water source, which highlighted that the major polymer types were PE and PP (Lestari et al., 2020). PE and PP polymer types were commonly detected in surface water because these plastics were categorized as commodity polymers (Koelmans et al., 2019; Crawford & Quinn, 2017). In addition, packaging materials often use PE and PP materials, potentially polluting rivers as raw water if the plastic waste is unmanaged properly (Koelmans et al., 2019; Novotna et al., 2019; Manalu et al., 2017).

Performance of the full-stage units to remove microplastic

Each water treatment unit performed a different capability in removing MP, which depended on the design criteria (Xue et al., 2022; Novotna et al., 2019). CDWTPs I and II achieved various MP removal efficiencies in each treatment unit (Figure 5). The average MP abundance in effluents of water treatment units in CDWTPs I and II fluctuated (Figure 6).

The fluctuation of MP abundance was in line with former studies in CDWTP in Thailand (Kankanige & Babel, 2020); Cambodia (Babel & Dork, 2021), India (Sarkar et al., 2021); China (Shen et al., 2021), Iran (Adib et al., 2021); the Czech Republic (Pivokonsky et al., 2018); and Canada (Cherniak et al., 2022). Meanwhile, Figure 5 indicates that MP abundance increased in sedimentation units in CDWTPs I and II by 35 and 9%, respectively. Besides, in the filter unit of CDWTP II, MP abundance was raised by 3%. The rise in MP abundance led to negative MP removal efficiency in a particular treatment unit which caused a slight difference in overall MP removal efficiency in produced water of CDWTPs I and II. In terms of MP characteristics, the size and shape distribution of MP abundance was illustrated in Figures 7 and 8.

As shown in Figure 7, MP particles of 351–1000 µm size class were dominant in effluents of water treatment units (38.5–63.5%). This dominance of MP size was different from the findings in CDWTP in the Czech Republic (Pivokonsky et al., 2018; Pivokonsky et al., 2020) and the Changsha-China Region (Shen et al., 2021), of which the abundant particle size was 1–100 µm. On the basis of MP size, large-size class particles (1001 µm -<5 mm) experienced the highest removal in produced water. This condition was possible because the more prominent MP might deposit due to MP fouling (Wu et al., 2022b). In addition, in the coagulation-flocculation and sedimentation processes, the removal of more prominent MP tended to be easier than that of smaller size (Lapointe et al., 2020; Zhou et al., 2021). Following Na et al. (2021), in the coagulation-flocculation unit,

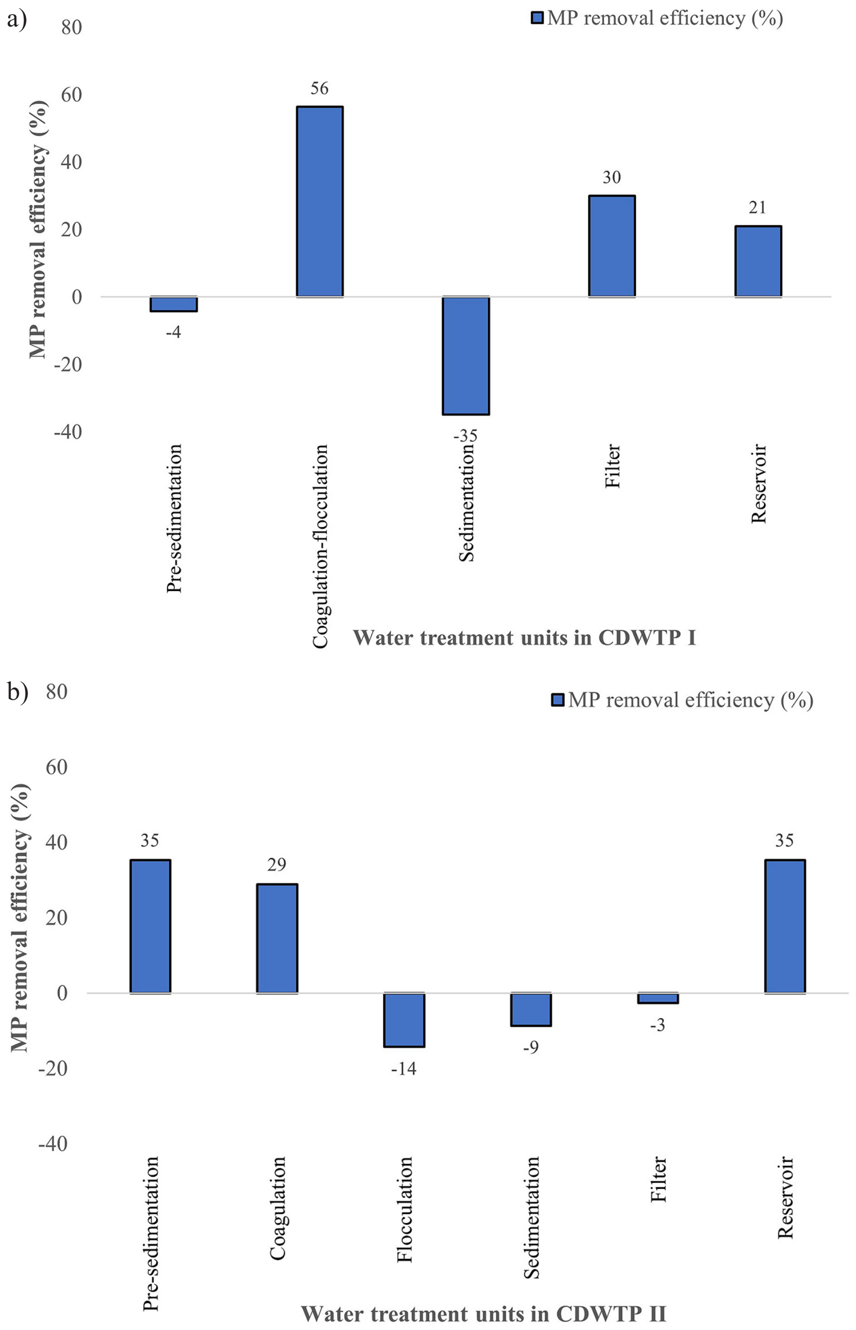

Figure 5. MP removal efficiency in treatment units: a. CDWTP I; b. CDWTP II

removal efficiency for MP particle size of 20–90 µm was 77.4–95.3%, whereas, that of 10 µm was only 33.0–41.1%.

In terms of MP shape (Figure 8), fiber was the dominant MP particle (90–100%) in the effluent of each treatment unit. Meanwhile, fragments were presented in most treatment unit effluents, which only accounted for 0.5–10%. Film-shaped MP was only found in a small percentage in CDWTPs I and II, 0.3–1.7% and 2–6.6%, respectively. Pellet-shaped MP was only detected as 0.1 particles/L in produced water in CDWTP II. These results were consistent with several studies in other countries. Cherniak et al. (2021) reported >89% fiber in each treatment unit in CDWTP in Canada. Besides, Wang et al. (2020) also identified fiber as the significant MP shape in overall treatment units in a WTP in China.

Fate of MPs in the water treatment stages

MP fate in each treatment unit in WTPs, which depended on MP behavior, presumably determined the MP removal in produced water (Shen et al., 2021). The MP behavior in WTPs was influenced by the operational of treatment

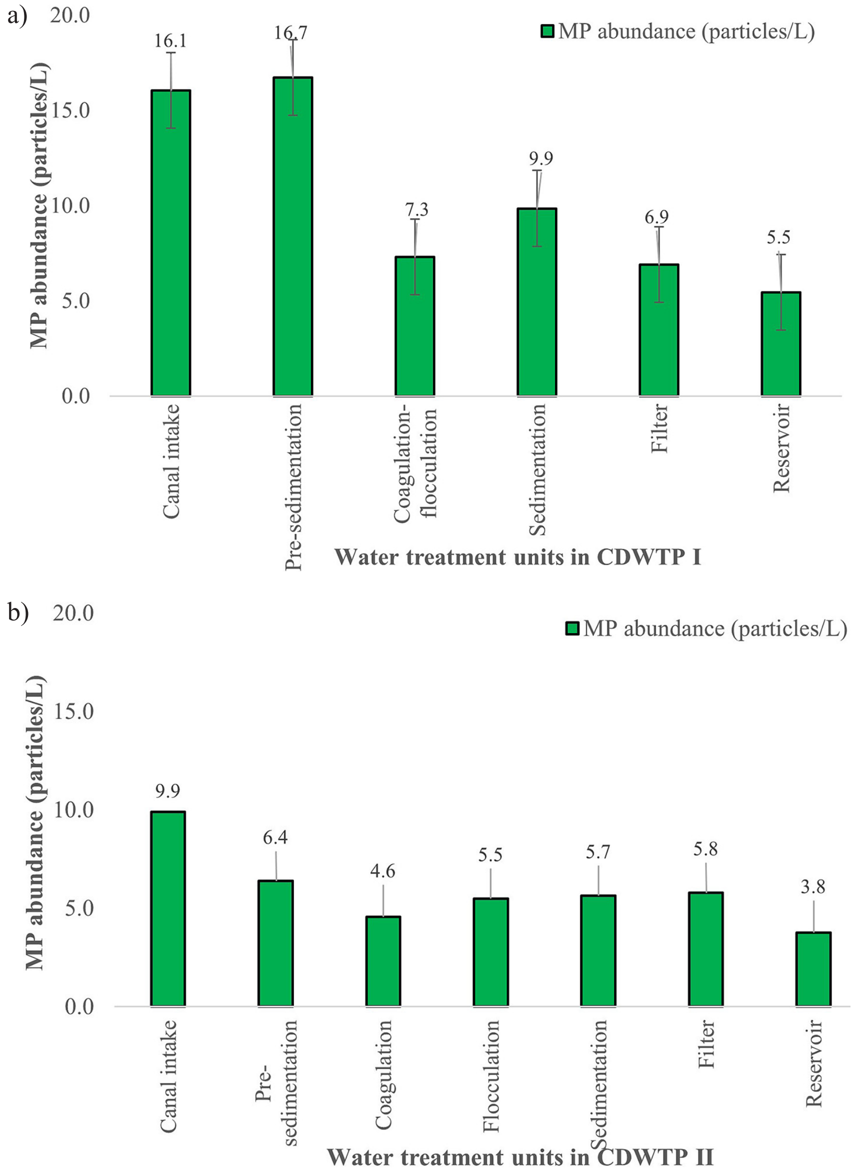

Figure 6. Average MP abundance in effluents of water treatment units: a. CDWTP I; b. CDWTP II

units (Novotna et al., 2019). The MP fate in the mechanism of water treatment in CDWTPs I and II differed in each treatment unit, as presented below.

Pre-sedimentation unit

The raw water from the river was captured in canals as intakes in CDWTPs I and II. Mechanical aeration using an aerator was applied in the canals (Lassoued, 2017). Subsequently, the raw water was treated in the pre-sedimentation unit as the first treatment unit. As presented in Table 1, MPs in the raw water mainly comprise the small particle size class. The value of MP removal efficiency in the pre-sedimentation unit was not significant. The negative removal efficiency value (-4%) occurred in CDWTP I.

Meanwhile, only 35% of removal efficiency was accomplished in CDWTP II. The reason was probably due to the MP particle challenge to settle. Dominant small-size MP particles entered the pre-sedimentation unit. Smaller MP particles were estimated to quickly escape along with the effluent water, which then entered the following water treatment unit (Di & Wang, 2018). On the basis of the MP shape, the fragment removal efficiency was higher (50%) than the fiber removal efficiency (35%) in pre-sedimentation units. The main pollutant removal in the pre-sedimentation unit was through the settling mechanism (Ziajahromi et al., 2021). Fragment owned a larger surface area than fiber because the morphology of the fragment had irregular shape (Su et al., 2016). This characteristic enabled more fouling, making

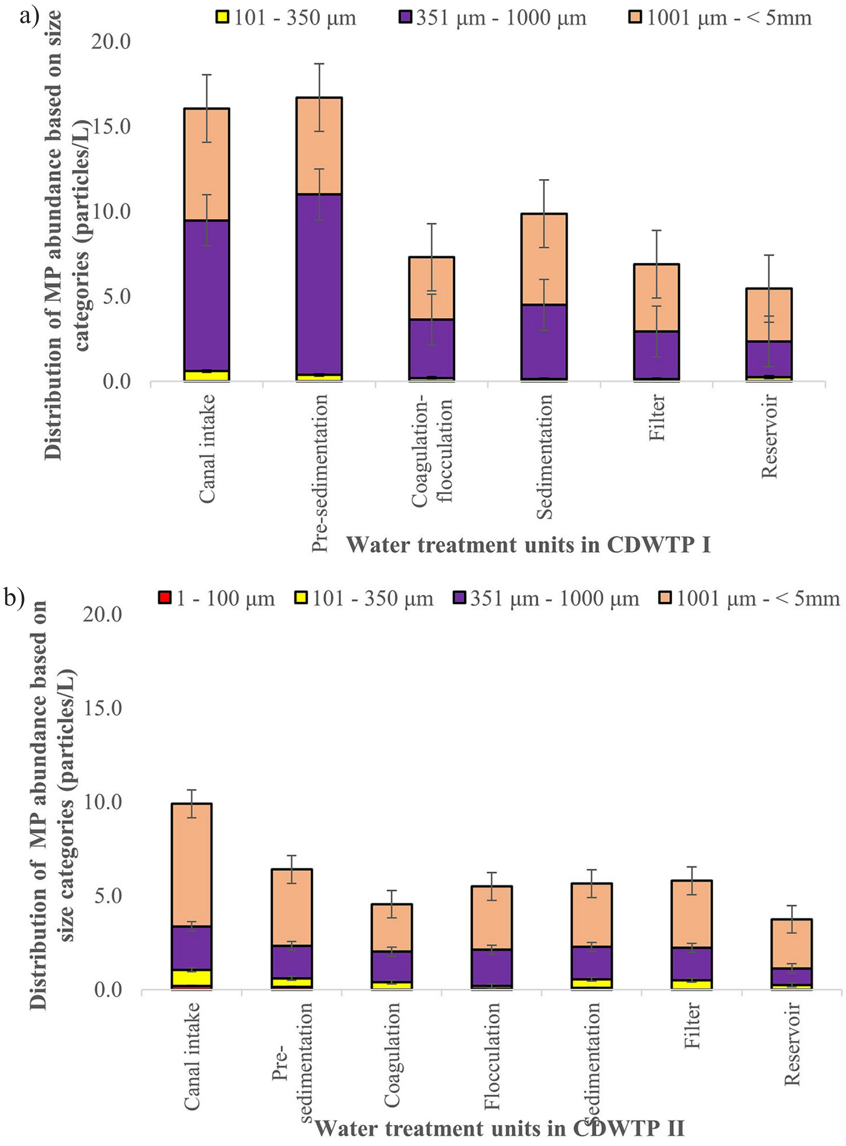

Figure 7. Distribution of MP abundance based on size categories in effluents of water treatment units: a. CDWTP I; b. CDWTP II

the fragments easier to settle than the fibers. Therefore, fragments were anticipated to pose more extensive removal in the pre-sedimentation unit than fibers.

Coagulation-flocculation unit

Coagulation-flocculation constituted one of the significant stages in conventional water treatment, of which processes could be conducted in one or a separate compartment (Hendricks, 2011). The pollutant removal mechanism in the coagulation-flocculation unit consisted of destabilizing ions of pollutant particles, neutralizing ionic charge, and agglomeration of micro-flocs into macro-flocs (Ma et al., 2019a; Ma et al., 2019b). Coagulation-flocculation unit in CDWTP I only involved one compartment (Figure 2); meanwhile, CDWTP II comprised two separated compartments (Figure 3). The MP removal efficiency differed from the overall process of coagulation-flocculation in CDWTPs I and II. As depicted in Figure 6, the MP abundance in one compartment of coagulation-flocculation in CDWTP I was 7.3 particles/L. In contrast, those in CDWTP II were 4.6 particles/L in the coagulation compartment and 5.5 particles/L in the flocculation compartment. Therefore, the MP removal efficiencies in the coagulation-flocculation process were 56% in CDWTP I and 14% in CDWTP II. These values were close to another study in China DWTP, which showed the value of MP removal efficiency in coagulation-flocculation as 50% (Wang et al., 2020). However, the CDWTPs I and II attained slightly lower values of MP removal

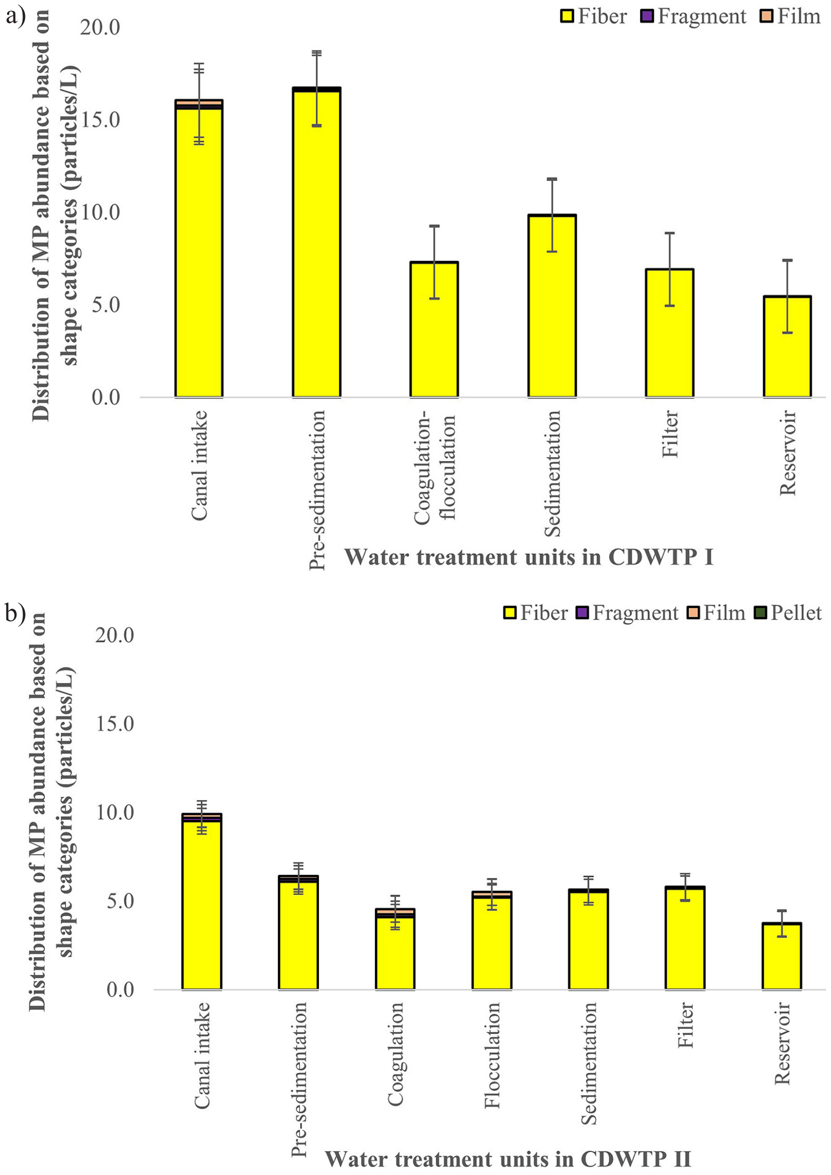

Figure 8. Distribution of MP abundance based on shape categories in effluents of water treatment units: a. CDWTP I; b. CDWTP II

efficiencies in coagulation flocculation than the Indian CDWTP at 60,9% (Sarkar et al., 2021).

Small particle size (1–100 µm, 101–350 µm, 351–1000 µm) experienced higher MP removal efficiency than that of large particle size (1001-<5000 µm). The removal efficiencies of 1–100 µm, 101–350 µm, and 351–1000 µm MP class were 50%, 50–60%, and 12–68%, respectively. Meanwhile, particles of 1001-<5000 µm were removed in 17–35%. Smaller MP particles have larger specific area, potentially increasing the possibility of being absorbed in the micro-floc surface (Ma et al., 2019b). Further, the MP particle formed a macro-floc with a coagulant particle. This MP fate in the CDWTPs I and II coagulation-flocculation unit was like the study performed on a laboratory scale (Skaf et al., 2020). Regarding MP shape, the coagulation-flocculation unit in CDWTPs I and II reached significant removal efficiencies of the fragment (up to 100%) and film (up to 100%). Fiber removal efficiency (15–56%) was lower than those of fragments and films. Fragment and film were supposed to have a larger surface area, allowing more particle adsorption into micro-floc. This mechanism probably caused the higher removal efficiency of fragments and films than that of fibers.

Sedimentation unit

The sedimentation process in CDWTP I was performed together with the coagulation-flocculation process in one compartment (Figure 2).

Meanwhile, in CDWTP II, the sedimentation process was conducted in a separate compartment after 1 compartment of coagulation and flocculation, respectively (Figure 3). The macro-floc from the coagulation-flocculation process was separated in the sedimentation unit through the settling mechanism (Hendricks, 2011). Therefore, the MP particles bound to the floc were removed through a deposition mechanism. The factors that influenced the settling process of macro-floc included floc characteristics, detention time, and velocity gradient (Na et al., 2021). MP removal efficiency in CDWTPs I and II sedimentation units underwent negative values. It meant that the MP particles in the sedimentation unit were more abundant than in the previous treatment unit. This situation was possibly due to the macro-floc inability to settle well. In addition, the macro-floc was suspected of breaking due to external forces, such as the shearing force of water flow in the sedimentation unit, which resulted in a more abundant MP small-size class (Corcoran et al., 2022). This phenomenon was the same as the findings of Wu et al. (2022) in Chinese CDWTP. In terms of MP size, the highest increase of abundance occurred in the MP size class of 351–1000 μm (29–60%), which meant the lowest MP removal efficiency achievement in this particle size class. Regarding MP shape, fiber abundance values were identified in CDWTPs I and II as 9.8 and 5.5 particles/L, respectively. The fragment was only detected in a limited number of 0.2 particles/L in CDWTP II, whereas the film was also observed in a low value of 0.1 particles/L in CDWTP I. There was a rise of fiber abundance in both in CDWTPs I and II at 34% and 6%, respectively.

Filter unit

The type of filter unit in CDWTPs I and II was a rapid sand filter (RSF) (Lassoued, 2017). RSF enabled to remove aggregates >10 μm (Hendricks, 2011). The MP removal mechanisms in the RSF unit involved filtration and adsorption process. The MP particles and aggregates larger than the filter media pore would be retained (Carr et al., 2016). MP removal mechanism in the RSF unit was influenced by many factors, such as the type, size, and structure of media and MP particle size (Cai et al., 2020). As described in Figure 5, the MP removal efficiencies were 30% in CDWTP I and negative 3% in CDWTP II. The negative removal efficiency value described an increase in MP abundance. This condition was consistent with a previous study in China which revealed the phenomenon of fragmentation (Wu et al., 2022a). The friction between surfaces of MP particles and RSF media was suspected of causing fragmentation which increased smaller MP abundance. Small MP particles were prone to escape through pores between RSF media.

On the basis of MP size, only the extensive range of MP particles (1001-<5000 μm) was removed (3-25%). Meanwhile, the smaller MP size range did not undergo removal. The prominent MPs behaved to retain in the top layer of filter media. In addition, large MP removal was also possible through the attachment mechanism of MP particles into the surface of the filter media (Na et al., 2021; Cai et al., 2014). This situation could narrow the pore gaps in filter media. MP shape also affected the MP removal efficiency value in the RSF unit (Talvitie et al., 2017a). The fiber-shape MP performed the lowest RE, which was 30% in CDWTP I and negative 4% in CDWTP II. Fragment and film were removed by 50 and 100%, respectively. This finding was in contrast with other studies which were conducted in wastewater. Talvitie et al. (2017b) investigated fiber removal in wastewater using RSF, which resulted in a fiber removal efficiency of around 57%. In addition, another study on wastewater resulted in better fiber removal efficiency than other particles, reaching up to 99.1% (Lares et al., 2018).

Reservoir unit

Produced water was stored in the reservoir unit for certain time detention. The occurrences of MP removal in reservoir unit in CDWTPs I and II were 21 and 35%, respectively. MP removal efficiency of 101–350 μm, 351–1000 μm MP size range were 20%; 25–46%; 23–31%, respectively. MPs were possibly eliminated through the settling mechanism in the reservoir unit (Cerniak et al., 2021). These results contrasted with the study in Canadian CDWTP, which indicated considerable values of MP removal efficiency (Cerniak et al, 2021). The removal efficiency values of 0–100 μm and 101–350 μm size range MPs were 57–59% and 94%. The produced water of CDWTPs I and II still contained the MP particles with a small size range (1–1000 μm) which accounted for 0.1–3.1 particles/L. This situation requires a critical concern, because the small size range MPs can potentially harm human health if ingested through drinking water (Shen et al., 2021; Amereh et al., 2020).

Statistical analyses of CDWTP performance on MP removal

The result of one-way ANOVA test indicated the significant MP removal efficiency value in each water treatment unit with the *p*-value of 0.018 (< 0.05). The most significant MP removal efficiency was achieved in coagulation-flocculation unit. When comparing CDWTPs I and II, the overall MP removal efficiency values were not significantly different (*p*-value = 0.26).

Further research

This study showed that MPs were not eliminated using conventional technology during water treatment. MP still presented in the produced water, with a considerable abundance of small size range MPs (1–1000 μm), which reached up to 55.3%. Besides, the overall MP removal efficiency of the small size MP, particularly of < 350 μm, was not significant (33–53%). Furthermore, fiber remained in the produced water. The CDWTP capability in removing MP still left MPs in the produced water. The small MPs and fiber-shaped MP appeared resistant to the produced water. The small-sized MP particle removal could be improved by applying advanced technology using membrane technology, such as microfiltration, ultrafiltration, nanofiltration, and reverse osmosis (Shen et al., 2021; Wang et al., 2020). Wang et al. (2020) investigated the MP removal efficiency in an advanced drinking water treatment plant (ADWTP) in China, confirming better MP removal. That ADWTP utilized a full-stage conventional technology prior to the advance (Wang et al., 2020). MP studies in drinking water have just developed. Additional research should be conducted to improve the knowledge of MP in drinking water. Further studies on the removal of MP in the water treatment process using membrane technology are of great significance to minimize MP in drinking water.

CONCLUSIONS

CDWTPs I and II performed the MP removal efficiency at 66 and 62%, respectively. A small MP of 351–1000 size range existed as the dominant MP in each treatment unit (38.5–63.5%). Fiber is also presented as the major MP in effluents of water treatment unit (90–100%). However, the removal efficiency value of small size range MP and fiber did not significantly minimize these MP characteristics in the produced water. Membrane technology was proven to eliminate small size MP. Further research on removing MP, particularly of that small size and fiber-shaped MP, should be thoroughly investigated to enhance the high produced water quality. Studies on applying membrane technology to remove MP in the water treatment process are essential to solve the MP issues in conventional drinking water.

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