



Identification and characterization of Microplastics in the Kartamantul Water Supply System, Yogyakarta, and its Potential Human Exposure

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ABSTRACT

Microplastics are emerging contaminants that can enter drinking water systems from raw water sources. This study is the first to evaluate microplastics across all treatment stages of the Kartamantul Regional Water Supply System (RWSS) in Yogyakarta. Water samples were collected from nine points along the treatment process (intake to customer taps) and analyzed using a modified NOAA method with organic matter digestion, filtration, and microscopic observation. Supporting parameters (pH, temperature, turbidity, TSS) were assessed via Spearman's correlation. Results showed the highest concentration at the intake (964 particles/100 mL), decreasing to 55 particles/100 mL at the clearwell (94.3% removal). Fragments dominated, with black microplastics being most persistent. Estimated daily exposure at household taps averaged 18.73 particles/kg body weight/day. Turbidity and pH showed strong positive correlations with microplastic abundance. These findings indicate conventional treatment effectively reduces microplastics, but additional measures are needed at final treatment stages and within distribution networks to limit consumer exposure.

1. INTRODUCTION

According to the Indonesian National Waste Management Information System (SIPSN), approximately 34 million tons of waste were generated in Indonesia, with plastic waste accounting for 19.48% and more than 6 million tons were produced in 2024. Plastic materials have become indispensable in daily life due to widespread use in personal, household, and industrial activities. Poor management of plastic waste results in extensive release into the environment. Plastic waste gradually breaks into particles ranging from 0.05 to 5 mm and is classified as MPs (Mangla et al., 2025). According to previous studies, MPs are generally categorized into physical forms: fragments, fibers, films, beads, and foams (Fox et al., 2024).

Microplastics (MPs) pollution has become a global environmental issue, occurring across various environmental compartments and affecting both ecosystems and human health. MPs have been detected in surface water, including lakes (Tian et al., 2025) and rivers (Zhao et al., 2024), as well as in groundwater (Jeon & Kim, 2024), which serve as major raw water

sources for water supply systems. Despite the crucial role of water supply systems, or Sistem Penyediaan Air Minum (SPAM), in providing safe drinking water to communities, conventional treatment processes may not fully remove MPs. Drinking water quality must comply with the physical, chemical, and microbiological standards set forth in the Ministry of Health Regulation No. 2 of 2023. Residual microplastics in treated water may lead to human exposure, posing potential health concerns. However, no maximum limit for MPs has yet been established, highlighting a research gap regarding microplastic contamination and human exposure in Indonesia's water supply systems, particularly in the Kartamantul RWSS.

Several studies on drinking water supply systems have shown that water treatment processes do not fully remove MPs. According to Wang et al. (2020), coagulation, flocculation, and sedimentation processes can reduce the concentration of MPs. In addition, the filtration process contributes to MPs removal (Barcelo & Pico, 2020). However, some microplastic particles may escape treatment processes and enter the distribution network. Pivokonsky et al. (2018) study reveals that MPs concentration in treated water

decreased by an average of 83% compared with raw water. Similarly, Firdausy et al. (2025) found that MPs' removal efficiency in a drinking water treatment plant reached approximately 80% from the intake stage.

Although drinking water treatment processes can achieve relatively high MPs removal efficiency, residual microplastics that pass through treatment units should not be ignored. Continuous exposure of MPs via drinking water may pose health hazards to humans, especially when microplastics interact with other hazardous contaminants. MPs exposure has been associated with various health concerns, including neurodegenerative diseases, immune disorders, pulmonary diseases, developmental problems, and reproductive effects (Lee et al., 2025; Prata et al., 2020). Therefore, studies investigating the occurrence of microplastics in drinking water treatment systems are urgently needed.

Despite becoming a global concern, the occurrence of MPs in Indonesian drinking water treatment systems remains poorly characterized. Available studies in Indonesia have more commonly focused on surface water, rivers, coastal environments, bottled water, or household-level drinking water, while systematic information from water treatment plants and water supply systems remains limited. In particular, little is known about how MPs abundance and characteristics change across treatment units, how many residual particles remain in finished water, and whether treated water distributed through a regional supply system may still represent a potential exposure pathway for consumers. This creates an important knowledge gap for drinking water safety assessment in Indonesia.

Another issue is the lack of evidence from RWSS. Unlike a single treatment plant serving a limited service area, an RWSS integrates raw water abstraction, centralized treatment, transmission, and distribution across multiple administrative regions. Such a system may exhibit distinct microplastic dynamics because particle abundance and characteristics can be influenced not only by raw water quality and treatment performance but also by hydraulic residence time, pipe networks, storage systems, and distribution pathways. Therefore, studying MPs in an RWSS provides broader information on potential exposure through RWSS infrastructure.

The Kartamantul RWSS is unique as an interconnected drinking water supply system serving three major urban and peri-urban areas in the Yogyakarta region: Yogyakarta City, Sleman Regency, and Bantul Regency. This system presents a strategic case for assessing the occurrence of MPs in a regional drinking water infrastructure serving a densely populated, rapidly urbanizing area. However, MPs' contamination in this system has not been sufficiently documented, particularly regarding treatment-unit performance and residual microplastics in treated water. Therefore, this study aimed to investigate the occurrence, abundance, and characteristics of microplastics across the water treatment process of the Kartamantul RWSS and to estimate potential community exposure through treated drinking water. The findings are expected to provide baseline data for

microplastic monitoring in Indonesian drinking water supply systems and to support future risk assessment and management strategies.

2. METHOD

2.1 Study location

Samples were collected at each treatment unit, namely, intake, presedimentation tank, coagulation, flocculation, sedimentation, filtration, and final storage, at the Bantar Water Treatment Plant (WTP) within the Kartamantul RWSS with coordinates 7°49'18.323 S and 110°14'4.753 E. Sampling was performed as grab samples on 25 June 2025, during the dry season. In addition, water samples were also collected from two customer households that use water from the Kartamantul RWSS (Figure 1). Although the sampling was conducted on a single day, the abundance of microplastics in each sample was analyzed in duplicate (two replicates) to ensure analytical reliability. Sampling was conducted throughout June 2025. The samples were then analyzed at the Environmental Quality Laboratory of the Faculty of Civil Engineering and Planning, Universitas Islam Indonesia.



Figure 1. Kartamantul Regional Water Supply System

2.2 Sample collection

There were nine sampling points: seven from water treatment plant units (Figure 2) and two from households. Water samples were collected according to the national standard procedure (SNI) 6989.57:2008 for surface water sampling. The collected water was then transferred into glass for MPs analysis and into HDPE bottles for turbidity and total suspended solids (TSS) analysis. While pH and temperature were measured *insitu* following SNI 06-6989.11-2004 for pH and SNI 06-6989.23-2005 for temperature. Each sample was labeled using a marker and stored in a cooler box before being transferred to a laboratory refrigerator at 4°C.

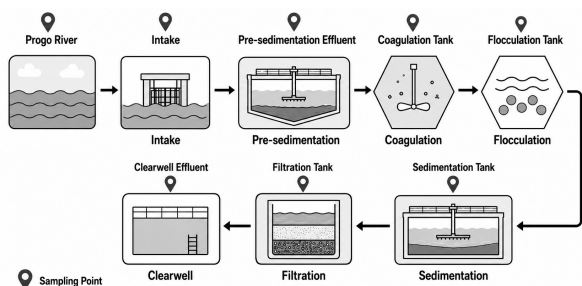


Figure 2. Bantar water treatment plant diagram and sampling points

2.2 Sample analysis

Microplastics analysis was performed following the National Oceanic and Atmospheric Administration (NOAA) method. For each 100 mL water sample, 10 mL of 10% NaCl and 20 mL of 30% H₂O₂ were added. The mixture was heated to 75 °C and stirred for 30 minutes. After cooling, the sample was filtered under vacuum using Whatman GF/B glass microfiber filter diameter 47mm. The filter papers containing suspected microplastic particles were transferred to petri dishes, dried, and observed under a trinocular Olympus BX53 microscope at 4x and 10x magnifications to examine the type and color of MPs. Analyses were conducted in duplo, and results represent the average of the two measurements. This study focuses solely on the abundance, type, and color of microplastics, without polymer composition analysis.

To ensure contamination control and analytical reliability, all laboratory surfaces and equipment were thoroughly cleaned prior to sample processing. Both procedural blanks, analysis blanks and field blanks were included in each batch of analysis. Microplastic analysis was conducted in duplicate (duplo) for each sample. All sample handling was performed in a controlled environment using nitrile gloves and lab coats, and measures were taken to minimize airborne fiber contamination. These QA/QC procedures help to reduce the risk of false positives and ensure the reproducibility and reliability of microplastic identification.

Total Suspended Solids (TSS) analysis followed SNI 6989.3:2019, which specifies the gravimetric method for suspended solids in water and wastewater. A filter paper was placed in a funnel and rinsed with 20 mL of distilled water. The filter paper was then transferred into a porcelain dish and dried in an oven at 103-105°C for one hour. After cooling in a desiccator for 10 minutes, the filter paper was weighed using an analytical balance to obtain the initial weight. The pre-weighed filter paper was then placed back in the funnel, and the filtration medium was moistened with a small amount of distilled water. A 100 mL homogenized water sample was filtered, then rinsed three times with 10 mL of distilled water. The filter paper containing the sample residue was transferred to a petri dish, dried in an oven at 103-105°C for 1 hour, and cooled in a desiccator for 10 minutes. Then the filter was weighed to obtain the final weight. TSS was calculated as the difference between the initial and final weight. Turbidity analysis was

performed using a turbidimeter. A 10 mL water sample was placed into a cuvette and measured in duplicate.

Spearman's correlation analysis was conducted to determine the relationships between pH, temperature, turbidity, TSS and MPs abundance. The decision to perform Spearman's correlation analysis was based on the assumption that the data likely do not follow a normal distribution; it is robust to outliers and ensures monotonicity. Spearman's correlation assesses whether the variables tend to increase or decrease together, even if the rate of change is nonlinear. The coefficient correlation interpretation is shown in Table 1.

Table 1. Coefficient correlation (r) of Spearman's correlation

r value	Interpretation
0.00 - 0.19	Very weak/no correlation
0.20 - 0.39	Weak
0.40 - 0.59	Moderate
0.60 - 0.79	Strong
0.80 - 1.00	Very strong

An Estimated Daily Intake (EDI) was conducted to estimate the amount of microplastics entering the human body through water consumption. There are three parameters to estimate exposure (Equation 1) : first, the MPs concentration, estimated from MPs concentrations in household samples; and second, the daily water consumption. According to the World Health Organization (WHO) (2017), adults consume 2 L/day of water, although actual consumption varies by climate, dietary patterns, and activity levels. Lastly, the population's body weight. The adult body weight used in this study was not intended to represent a general anthropometric average from a non-scientific database, but rather a default exposure parameter for health risk assessment. Therefore, the adult body weight was set at 55 kg following the Indonesian Environmental Health Risk Assessment Guideline issued by the Ministry of Health of the Republic of Indonesia (Direktorat Jenderal Pengendalian Penyakit dan Penyehatan Lingkungan, 2012).

$$EDI = \frac{C * IR}{BW} \quad (1)$$

Where:

EDI (Estimation Daily Intake) : EDI of MPs (particles/kg/day)

C (Concentration) : MPs concentration (particles/L)

IR (Intake Rate) : daily water consumption (L/day)

BW (Body Weight) : Average body weight of the receptor (kg)

3. RESULTS AND DISCUSSION

The Kartamantul RWSS Yogyakarta is an integrated water supply system that provides water supply to Yogyakarta City, Sleman Regency, and Bantul Regency, in accordance with the Regulation of the

Governor of the Special Region of Yogyakarta Province No. 13 of 2017. The construction is planned to have a capacity of 700 liter/s by utilizing raw water sources from the Progo River in Bantul Regency. It is expected to increase drinking water service coverage in the Yogyakarta City area by 27.6% or 56,000 household connections (Direktorat Jendral Cipta Karya, 2024).

3.1 Microplastics characteristics

The highest abundance MPs were found in the intake unit, while each water treatment unit showed a decreasing trend in accordance with the treatment sequence. The Bantar WTP intake originates from the Progo River. The Progo River is one of the largest rivers in Java. Although it is a source of irrigation water, the Progo River is also a major source of raw water for Central Java and the Special Region of Yogyakarta, Indonesia. However, the Progo River has been reported as one of the top 20 rivers globally that contributes to plastic pollution (Lebreton et al. 2017; Lestari et al. 2025). Lestari et al. (2025) research reveals that the Progo River has a microplastic abundance of 75.02-435.53 particles/m³ (Lestari et al. 2025). On the contrary, the lowest abundance of MPs was found in Household 1, which received water from the clearwell unit (Figure 3).

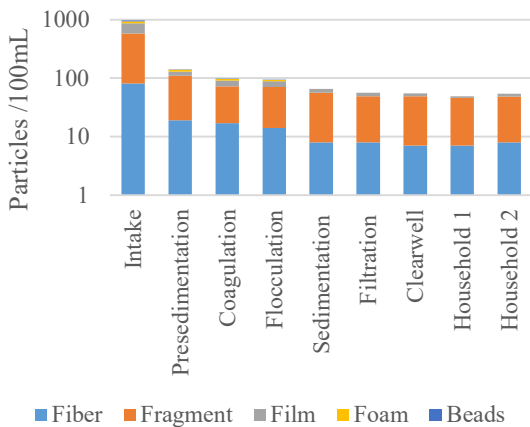


Figure 3. The abundance and type of MPs at each sampling point

Five types of MPs were identified in the intake, prasedimentation, coagulation, and flocculation units: fragments, films, fibers, foam, and beads. Foam and beads were not found in the sedimentation, filtration, clearwell units and household (Figure 3).

MP-type fragments dominate in every unit and household. The Abundance by type from the intake to flocculation units is fragment > film > fiber > foam > beads, which corresponds to the total abundance of MP types. Meanwhile, for the sedimentation unit, only three types of MPs were found, in the order fragment > film > fiber, and from the filtration unit, to the household, the order is fragment > fiber > film. The percentage composition of total MPs and each unit is shown in Figures 4 and 5, respectively. Fragment has a percentage composition of 51.14% to 79%; film, 6.12% to 30.19%; and fiber, 8.40% to 17.35%.

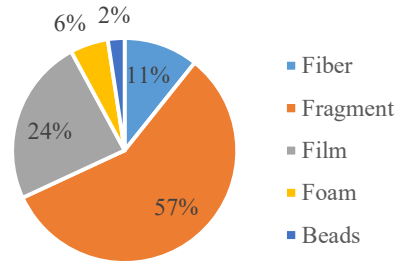


Figure 4. Relative percentage of microplastics based on particle type in all analyzed samples

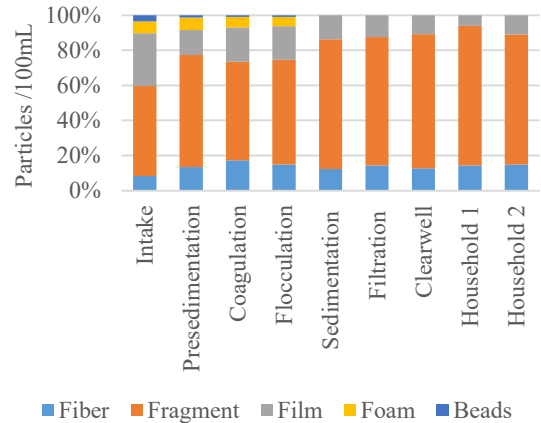


Figure 5. Distribution of microplastic types at each sampling point

The dominance of fragment-type MPs in this study is consistent with similar studies throughout various water treatment systems, where fragments are the most commonly observed type of MPs in fresh water and drinking water because they are stable and difficult to degrade compared to other types (Koelmans et al. 2019; Hartmann et al. 2019). The percentage of film-type MPs is the second-highest after fragments, indicating that plastic packaging or plastic bags are a source of MP contamination in raw water. Meanwhile, fiber-type MPs may originate from fabric fibers or laundry activities carried by drainage channels stemming from domestic activities. Fibers may originate from fishing activities (Sulistyo et al. 2020; Sulaiman et al. 2023). Foam and beads have lower percentages compared to other types of MPs. Beads come from personal care products, while foams come from polystyrene foam packaging. Based on the MP study in the Progo River, beads and foam have lower percentages than fragments, film, and fibers (Lestari et al. 2025).

Microplastics are removed to a significant extent in the intake and pre-sedimentation units, representing about 85%. The initial sedimentation process can remove most large microplastic particles due to natural settling and gravitational sedimentation. MPs entering the system were relatively large or aggregated with other particles, making them easier to settle by gravity (Ziajahromi et al. 2017; Iyare et al. 2020). This unit contains four sedimentation tanks, each equipped with a screen, gutter, and water gate.

Microplastic removal from the pre-sedimentation and coagulation units is approximately 30%, while coagulation-flocculation removal is only about 4%. Removal in the sedimentation unit reaches 30% (the unit is equipped with a plate settler). The formation of flocs allowed smaller microplastic particles to aggregate and settle together with other suspended particles (Ma et al. 2019). After filtration, the removal efficiency was only 14%, indicating that the remaining microplastics after sedimentation had characteristics that made them more difficult to remove through conventional processes.

Smaller MPs or MPs with densities close to water tend to remain stable in suspension. Therefore, it is difficult to aggregate during coagulation-flocculation. In addition, microplastics with smooth or hydrophobic surfaces may pass through conventional filter media (Koelmans et al. 2019; Lapointe et al. 2020; Tang et al. 2022). Nevertheless, the 94% total removal efficiency indicates that conventional water treatment systems remain relatively effective at reducing microplastic loads. However, the remains of MPs that passed through the treatment system and entered the distribution network become a concern because of potential exposure to customers (households) (Pivokonsky et al. 2018; Wang et al. 2020; Dalmau-Soler et al. 2021; Cao et al. 2024).

Fragments remained dominant after the final treatment stage (76.36% of total MPs in the clearwell), although the removal efficiency from the intake unit was 91.48%. The dominance of fragments in the final stages of treatment may be attributed to their compact physical structure and relatively high density, which make them less likely to aggregate with coagulants and more likely to pass through sedimentation and filtration processes (Enfrin et al. 2019). This result is consistent with Dalmau-Soler et al. (2021), who reported that 40% of residual microplastics after drinking water treatment consisted of fragments measuring 20-500 μm .

On the other hand, film-type MPs showed high removal performance (97.98%) from the intake unit to the clearwell, with a composition percentage of 10.90% from total MPs in the clearwell. The high removal efficiency due to the high surface area to volume ratio of films, which allows better interaction with coagulants and facilitates floc formation, enhances gravitational settling (Ma et al. 2019; Lapointe et al. 2020; Tang et al. 2022).

Fibers decreased significantly, with a removal efficiency of 91.36%; the composition percentage in the clearwell was 12.72% due to the complete elimination of other microplastic types (foam and beads. Foam and beads showed the most optimal removal, with elimination rates reaching 100% after sedimentation. This can be ascribed to physical properties. Foam has low density (<1.0 g/cm^3), which makes it float and facilitates removal in the early stages, while beads have spherical shapes that promote efficient gravitational settling according to Stokes' law (Koelmans et al., 2019).

The abundance of microplastics by color is shown in Figure 6. The abundance and percentage of MPs by color at each sampling point are shown in Figures 7 and 8, respectively. Black microplastics dominated, with

percentage 35% of the total, followed by transparent (20%), blue (11%), red (8%), orange (8%), brown (7%), yellow (6%), and others (green, purple, and pink) are 5%.

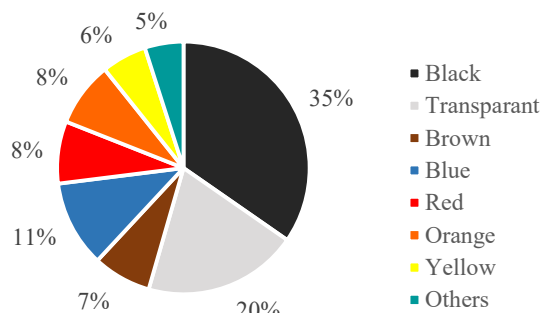


Figure 6. Relative abundance of microplastics by color category in the analyzed samples

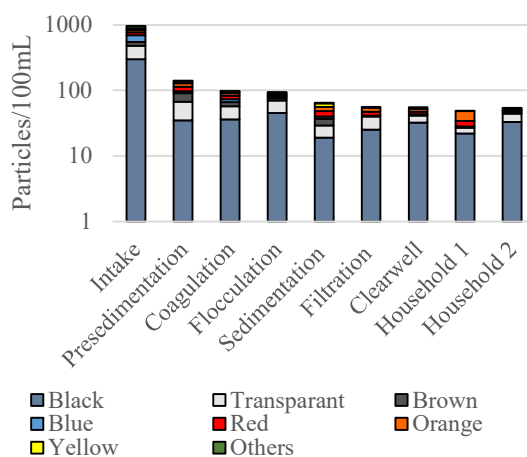


Figure 7. Abundance of microplastics by color category at each sampling point

Black MPs can originate from primary microplastics, such as microbeads or synthetic tire rubber, transported by surface runoff into the raw water source (Kole et al., 2017). They can also come from secondary microplastics resulting from the fragmentation of black plastic items, such as plastic bags, or from UV-absorbing pigments used in manufacturing processes. The transparent MPs could come from plastic bottles, transparent food packaging, and other clear plastic materials widely used in daily activities (Mason et al. 2018; Schwaferts et al. 2019; Ragusa et al. 2021). The dominance of black and transparent colors of MPs indicates major contributions from transportation-related sources and food and beverage packaging (Dris et al. 2016).

Other colored MPs, such as orange, red, and brown, indicate contributions from various plastic products, such as toys, household items, and colored packaging materials (Wang et al., 2020). The wide variation in color suggests that microplastic contamination originated from multiple sources, including domestic waste, industrial activities, and urban runoff (Mason et al., 2016).

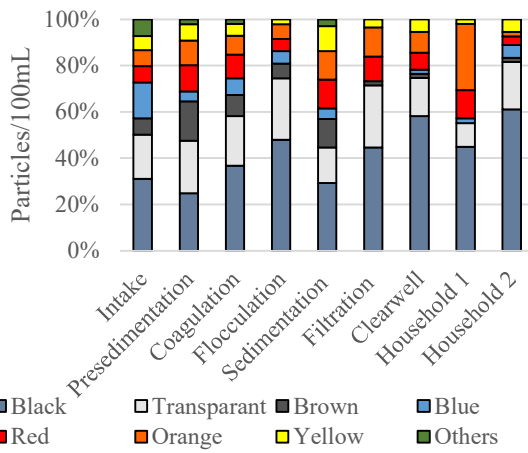


Figure 8. Relative percentage of microplastics by color category at each sampling point

The purple and pink MPs showed the lowest abundance throughout the system and were not detected in several treatment phases, indicating that these colored particles were either more readily removed or present in limited quantities in the raw water source (Koelmans et al., 2019). Furthermore, these colors made a limited contribution to microplastic contamination or may be more readily degraded in aquatic environments in this study (Hartmann et al., 2019).

MPs' removal based on their color reveals an interesting pattern throughout the water treatment process. The black color of MPs showed the lowest removal rate from the intake unit to the clearwell (89.30%), compared with other colors, which ranged from 92.54% to 100%. This phenomenon indicates that black MPs are more difficult to remove than microplastics of other colors in conventional treatment processes (Koelmans et al., 2019). The blue color of MPs has an efficiency of 99.33% in removal, while the other colors (green, purple, and pink) have 100% efficiency during the sedimentation stage. According to Ma et al. (2019), the coagulation-flocculation and sedimentation processes are effective in removing blue-colored MPs. The distribution pattern of MPs' colors indicates that the effectiveness of microplastic removal in water treatment systems depends not only upon particle size and shape but also on color characteristics that may be related to the polymers and additives present in the microplastics (Schwaferts et al., 2019).

The comparison with the previous study can be shown in Table 2. The highest abundance of MPs was observed in this study compared with other locations. Both the Kartamantul and Kamijoro RWSS intake water from the Progo River, which is one of the 20 rivers with the highest plastic waste input in the world 12,800 ton/year and has the highest MPs in the downstream area (Utami et al., 2021). Although the location of the Kartamantul intake is in the upstream section of the Progo River compared to the Kamijoro intake location, the abundance of MPs in the Kartamantul intake water is higher than in the Kamijoro intake water. Kartamantul is situated in an urban/suburban area with high residential density and heavy traffic, while Kamijoro is in a rural, agrotourism area. These factors are suspected to contribute to higher MPs concentrations at Kartamantul, in addition to its larger intake capacity 400 l/s compared to 50 l/s at the Kamijoro RWSS.

Furthermore, the efficiency of MPs removal at the Kartamantul RWSS is also higher, reaching 94%, compared to 58% at Kamijoro. This efficiency is influenced by the presence of flocculation and sedimentation processes within the treatment system, which help bind MPs, particularly those in fiber form and with low density (Rizkia & Hendrasarie, 2023). The efficiency of MP removal at Kartamantul RWSS is also higher than in other studies of WSE facilities in Surabaya, including the Karangpilang III WSE (76% efficiency), the Surabaya WSE I & II (11-88% efficiency), and the Padasan Tirtamarta WSE (78%). This may be due to differences in the characteristics of the MPs in the water intake. The Progo River is characterized by MPs dominated by films and fragments, which are believed to originate from domestic activities (Lestari et al., 2025). Meanwhile, in the Surabaya River, fiber was by far the most dominant MPs type (Radityaningrum et al., 2021).

Conventional water treatment units (coagulation-flocculation and sedimentation-filtration) are effective for particles that form clumps (flocs) or are spherical (fragments). However, they are not very effective for fiber-type MPs. In other words, these fibers are too long to be filtered out but too thin to settle; therefore, most of them still pass into the production water. This is why the total removal efficiency is only 54 - 76%, and the fiber type of MPs still dominates (84 - 100%) in the final treated water (Radityaningrum et al., 2021).

Table 2. Comparison with others studies

Location	Intake	Intake	Product	Efficiency	Reference
Kamijoro RWSS	Progo River	3372	1416	58	Safitri et al. (2022)
Karangpilang III WSE	Surabaya River	54.4	13	76	Mar'atusholihah et al. (2023)
Surabaya WSE I	Surabaya River	26.8 - 35	8.5 - 12.3	11-71	Radityaningrum et al. (2024)
Surabaya WSE II	Surabaya River	8.5	1	88	Radityaningrum et al. (2024)
Padasan Tirtamarta WSE	Bedoyo well and Kuning River	180	40	78	Firdausy (2025)
Kartamantul RWSS	Progo River	9640	550	94	This study (2025)

WSE : Water Supply Enterprise

3.2 Temperature, pH, Turbidity, and TSS parameters

The results of the pH, temperature, turbidity, and TSS measurements are shown in Table 3 and Figure 9. Two regulations are referenced: the first, water quality standards for raw water at intake units; and the second, drinking water quality standards for treated water at the clearwell before the water distribution process. The raw water quality standards refer to Indonesian Government Regulation No. 22 of 2021 on the Implementation of Environmental Protection and Management for River Water Quality Class 1, while the standards for treated water refer to Ministry of Health Regulation No. 2 of 2023 on drinking water quality.

Table 3. pH and temperature of each sampling point

No	Sampel	pH	Temperature (°C)
	Standard ¹	6.0-9.0	dev 3
	Standard ²	6.5-8.5	±3 °C
1	Intake	8.08	28.10
2	Pre-sedimentation	8.10	32.39
3	Coagulation	7.80	31.18
4	Flocculation	7.79	31.15
5	Sedimentation	7.80	31.21
6	Filtration	7.86	31.44
7	Clearwell	7.91	31.62
8	Household 1	7.52	30.06
9	Household 2	7.61	30.42

¹Indonesian Government Regulation No. 22 of 2021 regarding the Implementation of Environmental Protection and Management for River Water Quality Class 1

²Drinking water quality standard based on Minister of Health Regulation No. 2 of 2023.

According to Table 3, pH at all sampling points ranged from 7.52 to 8.10. The highest pH value was recorded at the pre-sedimentation unit, while the lowest was observed at household 1 (7.52). pH at the intake unit meets the first standard, while pH at the clearwell is within the second standard.

Temperature measurements have ranged from 28.10°C to 32.39°C. The lowest temperature, 28.10°C, was recorded at the intake, which may be attributed to the river water's temperature. In contrast, higher temperatures were observed in other treatment units due to sampling time in midday. Water temperature can affect the effectiveness of treatment processes, such as flocculation, by influencing floc size, strength, and the ability of flocs to reform after being disrupted by shear forces. Warmer temperatures generally produce larger flocs that are more easily broken and less able to reform than those formed at lower temperatures (Fitzpatrick et al., 2004).

Figure 9 shows the turbidity and TSS measurements at each sampling point. The highest turbidity was found in the presedimentation units (34.08 NTU), while the lowest was found at household 2 (1.18 NTU). There is no maximum limit for the raw water quality standard. However, the water quality before the distribution

process should be below 3 NTU. According to the measurement, the turbidity at the clearwell unit (2.56 NTU) and both households (1.91 and 1.18 NTU) meet the drinking water quality standard. In the case of TSS, the intake unit value (172 mg/L) exceeds the raw water quality standard of 40 mg/L. TSS concentration decreases throughout the treatment process, reaching 87 mg/L in the clearwell unit before distribution. However, there is no maximum TSS concentration limit according to the drinking water quality standard.

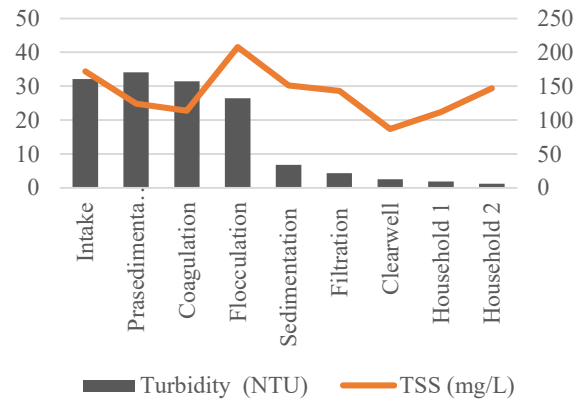


Figure 9. Turbidity and TSS measurement

3.3 pH, temperature, turbidity, and TSS correlation with MPs.

Before conducting the correlation analysis, a normality test was performed on the data. Since not all data follow a normal distribution, the correlation analysis was performed using Spearman's correlation. The results of the analysis are shown in Table 4 below.

Table 4. Correlation analysis

	r	p value (<0.05)	significant
Turbidity	0.97	0.0000216	significant
pH	0.67	0.05	significant
Temperature	0.08	0.83	not significant
TSS	0.43	0.24	not significant

The correlation analysis showed a significant, very strong positive ($r=0.97$) correlation between turbidity and MPs (p -value < 0.05). A strong positive correlation ($r = 0.67$) was observed between pH and MPs ($p = 0.05$). However, the correlation between temperature and MPs ($r = 0.08$) was not significant (p -value was much greater than 0.05), indicating that temperature does not have a strong or significant relationship with the number of microplastics. Although TSS shows a moderate positive correlation with MPs ($r = 0.43$), the p -value was not significant (> 0.05). This study shows that pH and MPs, as well as turbidity and MPs, showed notable correlations. However, neither the correlation between temperature and MPs nor the correlation between TSS and MPs was significant.

Turbidity reflects the presence of suspended particles in water, including MPs. Higher turbidity indicates a greater abundance of suspended particles, which may

include microplastics or other particles that interact with them (Pivokonsky et al., 2018). Furthermore, pH was associated with higher microplastic abundance. This phenomenon can be explained by electrostatic mechanisms, in which more alkaline conditions affect the surface charge of microplastics and their interaction with other suspended particles. This thereby increases the stability of microplastics in suspension and reduces their tendency to settle (Ma et al. 2019).

3.4 Ratio of Microplastics to TSS

The ratio of MPs (particles/L) to TSS concentration (mg/L) was used to assess the influence of MPs on TSS (Figure 10). This ratio could indicate whether microplastics are an important element of suspended solids or only a minor fraction of the total suspended solids. The high ratio at the intake unit indicated that MPs were abundant in raw water from the Progo River. In addition, the high ratio reveals that microplastic contamination in the source water was relatively dominant compared with other suspended particles, possibly because microplastics with less density can remain suspended in the water column (Kooi et al., 2017).

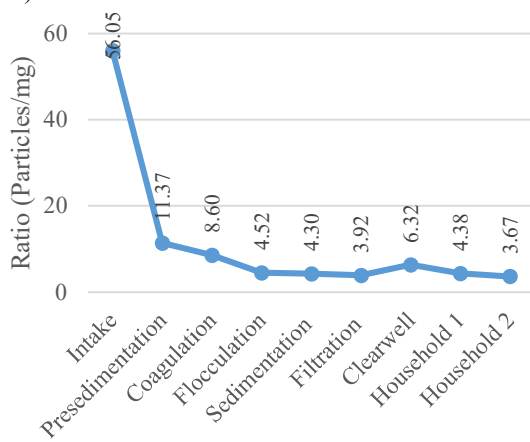


Figure 10 Ratio of microplastics to TSS

The treatment process substantially reduced this ratio, from 56.05 at the intake unit to 6.32 at the clearwell. This decreasing ratio indicates that the treatment process was effective in removing MPs and suspended particles. Each treatment unit has different removal mechanisms for microplastics and TSS. The ratio from the flocculation unit (4.52) to the sedimentation unit (4.30) decreased, due to floc aggregation and gravitational settling, which efficiently captured and removed microplastics together with other particles (Ma et al. 2019). The ratio was slightly increased at the clearwell unit (6.32), suggesting the re-release of MPs from biofilms or sediments accumulated in the reservoir, or the introduction of new microplastics from the distribution system (Koelmans et al., 2019). The ratios at households 1 and 2 are relatively low (4.38 and 3.67). It is probably due to the minimal cross-contamination in the distribution network, although variations among customers may be caused by distribution distance, pipe age, or local conditions within the piping system (Tong et al., 2020).

3.5 Estimated Daily Intake (EDI)

EDI calculation can be shown in Table 5. Based on the EDI calculation, the households were exposed to MPs 17.82 and 19.64 particles/kgbw/day, with an average of 18.73 particles/kgbw/day. Although there is currently no established threshold for microplastic exposure in drinking water, these data indicate that MPs should be considered in water quality assessment.

It should be noted that the EDI estimates presented in this study are only rough approximations of microplastic exposure due to several limitations. Factors such as variability in water consumption across age groups, particularly among children, and potential differences in microplastic polymer types and their associated toxicities were not considered. In addition, the study employed single-grab sampling and included only two households, which may not fully capture temporal and spatial variability. Therefore, future studies with larger sample sizes, repeated sampling, polymer-specific analysis, and consideration of age-specific exposure are recommended to provide a more comprehensive assessment of microplastic exposure through drinking water.

Table 5. EDI calculation results

Sample	C (particles/L)	EDI (MPs/kgbw/day)
Household 1	490	17.82
Household 2	540	19.64
Average	515	18.73

4. CONCLUSION

Based on the research findings, MPs were detected at all stages of drinking water treatment at the Kartamantul Regional Water Supply System, from the intake unit to the customer tap. The highest microplastic concentration was found in the raw water at the intake unit, at 964 particles/100 mL, and then gradually decreased to 55 particles/100 mL at the clearwell unit. This decrease indicates that the conventional drinking water treatment system, comprising presedimentation, coagulation, flocculation, sedimentation, filtration, and the clearwell, can achieve 94.29% reduction in MPs abundance. The presedimentation stage contributed the greatest removal, settling most of the larger microplastic particles and those associated with other suspended particles.

The microplastics found were dominated by fragments, followed by films and fibers, while foam and beads were no longer detected after the sedimentation stage. Based on color, black microplastics were the most dominant type and were relatively more persistent than those of other colors. This indicates that the effectiveness of microplastic removal is influenced not only by particle count but also by microplastic physical characteristics, such as shape, color, density, and potential constituent polymer type.

Analysis of water quality parameters showed that turbidity had a very strong and significant positive correlation with microplastic abundance, while pH showed a strong positive correlation. Meanwhile, temperature and TSS did not show a significant relationship with microplastic abundance. The results indicate that turbidity can serve as a relevant supporting parameter in evaluating the presence of microplastics in drinking water treatment systems, although it cannot be used as a standalone indicator.

Although microplastic removal efficiency is relatively high, microplastics were still detected in the clearwell unit and at household tap water points at levels of 49–54 particles/100 mL. Daily exposure estimates indicate that consumers are potentially exposed to an average of 18.73 microplastic particles per kilogram of body weight per day through water consumption. Therefore, it is necessary to optimize treatment processes, enhance periodic monitoring of microplastics, and control potential secondary contamination in clearwells and distribution networks to improve drinking water safety and reduce the public's risk of exposure to microplastics.

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