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Occurrence of Microplastics across Seasonal Variations in a Municipal Wastewater Treatment Plant in Thailand

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Abstract

The behavior of microplastics (MPs) in aquatic environments is influenced by a variety of factors; however, the impact of seasonal variations and meteorological conditions on MPs remains insufficiently explored and understood. This research investigates the impact of seasonality on the presence, transfer, and removal efficiency of MPs at a wastewater treatment plant (WWTP) in Lampang, Thailand. The study monitored the fate and transport of MPs across the rainy, winter, and summer seasons of 2023 - 2024. The results indicated that the average MP concentration was highest during the rainy season, at 1.20 ± 1.27 particles/L, compared to 0.27 ± 0.50 particles/L and 0.27 ± 0.54 particles/L during the winter and summer seasons, respectively. Statistical analysis using ANOVA confirmed a statistically significant difference in MP abundance among the 3 seasons ($p < 0.05$). Across all seasons, most MPs detected in the WWTP processes were characterized by sizes of 151 - 350 µm, gray coloration, and fragment shapes. The chemical composition of MPs primarily included polyethylene terephthalate (PET), polypropylene (PP), and polyethylene (PE). Despite these findings, seasonal trends in MP abundance within the secondary treatment processes were inconsistent. These inconsistencies underscore the necessity for further investigation into the fate and transport of MPs under varying conditions, including overflow scenarios. Furthermore, the design and implementation of effective wastewater management strategies, specifically tailored to seasonal variations, are crucial for improving MPs removal efficiency and minimizing their discharge into natural bodies of water.

Keywords: FT-IR microscope, Microplastic, Microplastic removal, Seasonality, Stabilization pond, Wastewater treatment plant

Introduction

Plastic contamination has rapidly emerged as one of the most pressing environmental issues worldwide [1]. Small plastic particles, defined as microplastics (MPs) and less than 5 mm in diameter, have exacerbated this environmental challenge [2]. These particles, which originate from sources such as cosmetic products, synthetic textiles, and the degradation of larger plastic debris, have spread across nearly every ecosystem [3]. Due to their environmental persistence and potential risks to wildlife, human health, and ecosystem balance, addressing the scale of MP pollution and developing solutions to mitigate it have become increasingly urgent [4]. MPs are categorized into primary and secondary types based on their source and characteristics. Primary MPs are small plastic particles intentionally included in products like cosmetics and personal care items (e.g., facial scrubs, toothpaste) and microfibers shed from clothing and other textiles. In contrast, secondary MPs are generated through the fragmentation of larger plastic waste in the environment, such as fragments from plastic containers, food packaging, bottle caps, and disposable foam containers [5]. Human activities are the primary contributors to the presence of MPs in municipal wastewater, with industrial sources also playing a significant role. These activities include the release of MPs from clothing during laundry and the everyday use of personal care products (e.g., facial cleansers, toothpaste, shower gels) that enter wastewater treatment plants (WWTPs). The 6 most commonly identified MPs in influent and effluent wastewater are polyethylene (PE), polypropylene (PP), polyamide (PA), polyester (PES), polystyrene (PS), and polyethylene terephthalate (PET) [6-9]. Understanding the properties and composition of MPs in WWTP effluents is crucial for estimating the levels of MP pollution in nearby estuaries and aquatic environments [10]. WWTPs serve as critical points for capturing MPs before they enter aquatic environments; however, the efficiency of MPs removal in current WWTPs is incomplete, with many captured MPs ending up in the sludge phase [11]. Consequently, research into the fate and transport of MP pollutants has become increasingly important. Factors such as polymer type, shape, density, and morphology influence the behavior and removal efficiency of MPs in WWTPs [11,12]. For example, previous studies have shown that microspheres are removed more effectively than fibrous MPs, with fragments being the easiest shape to remove, followed by pellets and fibers [6]. Understanding the impact of MP shapes on removal efficiency is essential for improving WWTP performance in addressing MP pollution.

In aquatic environments, the behavior and distribution of MPs are further complicated by seasonal and weather-related variations, which have been largely overlooked in existing research. Many studies have emphasized the need for further investigation into how seasonal and temporal factors influence the extent and dispersion of MP particles in these environments [13,14]. Given that climate change is intensifying the severity and frequency of extreme weather events, it is essential to examine the migration and transformation of MPs in WWTPs under these conditions, including heavy flooding, severe droughts, and instances of combined sewer overflows driven by stormwater surges [1]. The objective of this study is to examine the concentration of MPs in a municipal WWTP with a stabilization pond in Thailand, with a focus on seasonal effects. According to 2016 data, Thailand has the highest number of stabilization ponds, with 45 out of a total of 101 used for treating municipal wastewater [15]. Therefore, this study investigates the detection, fate, and transport of MPs within the treatment system. While previous research has explored the ecotoxicity of MPs based on size categories of 100 μm, 500 μm, 1 mm, and 5 mm Wang *et al.* [16], this study specifically focuses on MPs sized 0.3 - 5.0 mm. These smaller particles exhibit behavior like that of colloidal particles, making them particularly responsive to dynamic processes within WWTPs. The goal of this study is to improve our comprehension of the pathways, dynamic behavior, and transport mechanisms of MPs. These findings are crucial for both environmental scientists and engineers [17], as well as for WWTP operators, to develop more effective strategies for addressing the impacts of seasonal variations on MP pollution.

Materials and methods

Collection of wastewater samples

This research was conducted in Lampang Province, Northern Thailand. The wastewater treatment system processes wastewater from Lampang City Municipality, located in the Mueang Lampang District of Lampang Province. The system utilizes a stabilization pond (SP) treatment process, covering a total area of 334,420 m^2 and capable of handling 12,300 m^3 of wastewater per day. Incoming wastewater passes through an automatic bar screen before being collected in 3 open ponds: 1) facultative pond 1, with a capacity of 169,923 m^3; 2) facultative pond 2, with a capacity of 222,850 m^3; and 3) the maturation pond, with a capacity of 71,034 m^3 [18]. The treated water is subsequently released into the Mae Kuei stream.

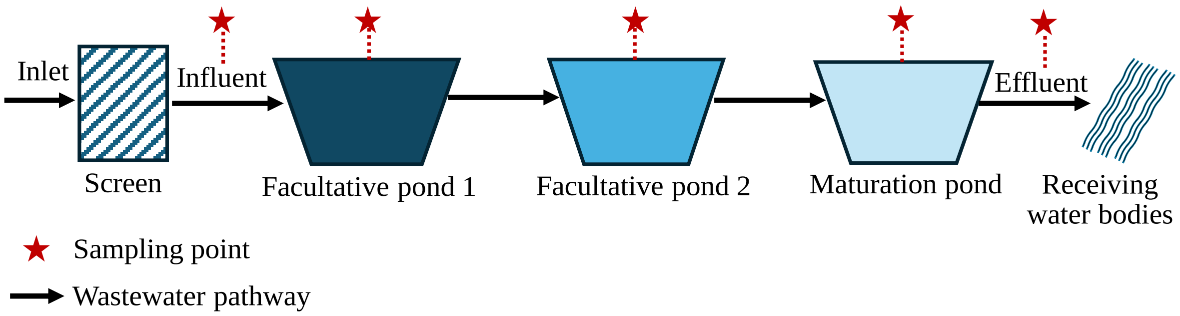

Figure 1 Wastewater sampling points.

Figure 1 presents a schematic diagram of the WWTP processes and wastewater collection points. Wastewater samples were collected using the grab sampling method, with a sample volume of 5 L taken from various stages of the WWTP: the plant's influent (raw wastewater), facultative pond 1, facultative pond 2, maturation pond, and effluent (treated wastewater). Field blank samples were also collected and analyzed using the same procedure applied to the other samples, with deionized (DI) water substituted for the wastewater samples. To assess the effect of seasonality on MPs circulation, sampling was conducted 3 times during each season: the rainy season (September - October 2023), winter (February 2024), and summer (April - May 2024). For each season, a representative sample was analyzed, with 3 replicates for MP analysis. All samples were preserved at 4 °C until pretreatment.

Sample pretreatment

To evaluate the presence of MPs in wastewater samples, a method adapted from the National Oceanic and Atmospheric Administration (NOAA) for analyzing MPs in wastewater was employed [19,20]. This method involves a multi-step separation process using a series of standard test meshes with progressively smaller apertures. In this experiment, a sieve with a mesh size of 0.3 mm was utilized. The retained solids on the 0.3 mm sieve were dried in a water bath at 90 °C overnight. Labile organic matter present in the collected solids was removed using Wet Peroxide Oxidation (WPO). Specifically, the solids retained on the sieve were transferred to a beaker, where 20 mL of a 0.05 M Fe (II) solution and 20 mL of 30 % hydrogen peroxide (H_2O_2) were added. The mixture was allowed to react at room temperature for approximately 5 min, followed by digestion at 60 °C on a hot plate until complete degradation of the organic matter was achieved. The final volume of the mixture was adjusted to 25 mL using DI water. The resulting solution was filtered through a 0.2 µm cellulose nitrate membrane filter with a diameter of 25 mm. The filter was then dried at 45 °C for approximately 2 h and stored in either a petri dish or an aluminum container. It was subsequently kept in a desiccator until analysis for microplastic content.

Identification of microplastics

The cooled-down filter papers were analyzed using a Fourier transform infrared (FT-IR) microscope (Bruker, LUMOS II) to assess the number, length, morphology, and classification of MPs. This instrument utilizes infrared wavelengths to detect and measure small MP samples. Each chemical compound produces a distinct infrared spectrum, enabling identification. The types of MPs were determined through Attenuated Total Reflection (ATR) measurements, with spectra compared against a polymer database (IR Library). Spectra exhibiting match quality below 70 % were excluded from the dataset.

Removal of MP in WWTP

The removal of MPs is evaluated by comparing their concentrations in the influent and effluent of the WWTP. As depicted in **Figure 1**, a standard combined WWTP system consists of multiple treatment stages, including facultative pond 1, facultative pond 2, and maturation ponds. MP removal in WWTPs occurs through various mechanisms. Low-density MPs often attach to suspended solids and are subsequently removed through sedimentation, settling into the sludge phase [21].

Results and discussion

Total quantities of MPs in the WWTP

Wastewater samples demonstrated significantly higher MP concentrations during the rainy season compared to both the winter and summer seasons. As presented in **Table 1**, the average concentration of MPs during the rainy season was 1.20 ± 1.27 particles/L, whereas the concentrations during the winter and summer seasons were both 0.27 ± 0.50 particles/L and 0.27 ± 0.54 particles/L, respectively. These findings are consistent with prior research, which reported elevated MP concentrations in the sediments of the Mvudi River in South Africa during the hot-wet season, compared to the cooler dry and hot-dry seasons [22]. However, they contrast with other studies, which observed higher MP concentrations in harbor sediments in Taiwan and in wastewater samples from Nonthaburi City, Thailand, during the dry season rather than the wet season [1,23]. The authors observed that variations in the number of MPs found in different wastewater treatment systems may be attributed to differences in the observation period, regional factors, and specific treatment system configurations [1].

Table 1 Number of MPs across each WWTP process during the rainy, winter, and summer seasons.

WWTP process	Number of MPs* (Particles/L)			
	Rainy	**Winter**	**Summer**	**Average**
Influent	3.22 ± 1.20	0.22 ± 0.44	0.44 ± 0.73	1.30 ± 1.61
Secondary treatment				
Facultative pond 1	0.22 ± 0.44	0.44 ± 0.53	0.44 ± 0.73	0.37 ± 0.56
Facultative pond 2	1.00 ± 0.00	0.44 ± 0.73	0.00 ± 0.00	0.48 ± 0.58
Maturation pond	1.00 ± 0.87	0.22 ± 0.44	0.33 ± 0.50	0.52 ± 0.70
Effluent	0.56 ± 0.53	0.00 ± 0.00	0.11 ± 0.33	0.22 ± 0.42
Average	1.20 ± 1.27	0.27 ± 0.50	0.27 ± 0.54	0.58 ± 0.95

*Average ± standard deviation.

The average MP concentration in the Lampang WWTP was lower than that reported in several other studies investigating MPs of similar sizes (0.05 - 5.0 mm). For instance, influent samples from 3 municipal WWTPs in the Bangkok metropolitan area of Thailand exhibited an average MP concentration of 12.2 particles/L, which is higher than the results observed in this study [24]. In the Nonthaburi WWTP (Thailand), MP concentrations ranged from 76 - 192 particles/L during the dry season and 36 - 68 particles/L during the wet season in 2019 and 2020, respectively [1]. Conversely, 4 WWTPs in Bandung, Indonesia, reported significantly higher concentrations, with an average of 537.50 ± 35.21 particles/L [25]. These results underscore notable temporal and regional variations in MP concentrations across different WWTPs.

MP characteristics

MP sizes

Figure 2(a) illustrates the distribution of MP sizes at various stages of the WWTP in Lampang Province. Among the influent samples, MPs in the range of 351 - 650 μm were the least frequently detected, and no MPs ranging from 351 - 5000 μm were observed in the effluent. The most frequently detected MPs in both influent and effluent were within the 151 - 350 μm range. This pattern indicates that larger MPs are predominantly removed during the treatment process. Similarly, a study of a municipal WWTP system in Bandung City, Indonesia, found that the most frequently detected MPs were in the 151 - 350 μm range [25]. However, this contrasts with findings from downstream WWTPs in the United States, where MPs in the 125 - 500 μm range showed a significant increase [5]. Additionally, in Los Angeles, MPs detected across 4 WWTPs primarily ranged in size from 45 - 400 μm [17].

The average size distribution of MPs in the WWTP influent was 17.14 % (50 - 150 μm), 31.43 % (151 - 350 μm), 14.29 % (351 - 650 μm), 20.00 % (651 - 1000 μm), and 17.14 % (1001 - 5000 μm). In the effluent, the detected MP sizes were slightly different, with 33.33 % in the 50 - 150 μm range and 66.67 % in the 151 - 350 μm range. These findings suggest that MPs smaller than 350 μm are more challenging to remove during the treatment process, whereas MPs larger than 351 μm are effectively removed by the WWTP system.

MP shapes

As shown in **Figure 2(b)**, MPs in fragment shape are more prevalent than those in fiber shape. In the WWTP influent, MPs consisted of 54.29 % fibers and 45.71 % fragments. However, the effluent composition differed significantly, consisting entirely of fragments (100.00 %), with no fiber detected. These findings contrast with previous studies, which reported that approximately 70 % of MPs in WWTPs were fibers Talvitie *et al.* [26], and that fibers accounted for 51.91 % of MPs in influent and 43.37 % in effluent [25]. The authors observed that a previous study investigated MPs in anaerobic digestion-based wastewater treatment systems Fauzi *et al.* [25], which may have contributed to the presence of fiber-shaped MPs in the effluent. This phenomenon can be attributed to the characteristics of anaerobic systems, including short retention times, mixing effects, and the absence of ultraviolet exposure, all of which limit the removal of fiber-shaped MPs. In contrast, the present study focuses on stabilization ponds, where the absence of fiber-shaped MPs in the effluent may be due to enhanced sedimentation, biofilm trapping, reduced turbulence, and potential degradation under sunlight. Therefore, different wastewater treatment systems can influence the types and shapes of MPs found in the effluent.

The results of this study suggest that fiber-shaped MPs are more effectively removed during the WWTP process, likely due to their larger average size compared to fragment-shaped MPs. Fragment-shaped MPs are commonly produced through the breakdown of larger plastic materials, a process referred to as secondary MP formation. In contrast, fiber-shaped MPs often originate from clothing fibers released during washing processes [27].

MP colors

As shown in **Figure 2(c)**, transparent and blue MPs are the most abundant colors found in the influent and effluent, respectively. Previous studies investigating MPs in WWTPs have reported that transparent MPs are the most predominant in wastewater [25,28]. In addition to transparent MPs, other colors, including blue, red, green, brown, purple, and various shades, have also been identified [1,25]. These color variations are believed to be influenced by the different polymer types and sources of MPs [25].

The percentage distribution of MP colors in the WWTP influent was 31.43 % transparent, 25.71 % gray, 17.14 % blue, 17.14 % black, and 8.57 % red. In contrast, the composition of MPs in the effluent differed, consisting of 50.00 % blue, 33.33 % brown, and 16.67 % gray. The majority of MPs identified throughout the WWTP processes during the rainy, winter, and summer seasons predominantly exhibited a gray coloration. The authors believe that the gray coloration of MPs found in stabilization ponds during different seasons is likely due to a combination of polymer degradation, biofilm formation, sediment attachment, and the inherent properties of the plastic materials. These factors contribute to the observed gray appearance in the wastewater.

Polymer types

Figure 2(d) illustrates the different MP polymer types identified in the communal WWTP under investigation. The WWTP influent contained the following MP polymers: PET at 71.43 %, PP at 14.29 %, polyethylene PE at 11.43 %, and cellulose acetate (CA) at 2.86 %. In the effluent, the distribution of polymers shifted, with PP accounting for 50.00 %, PET for 33.33 %, and styrene-ethylene-butylene-styrene (SEBS) comprising 16.67 %. The FT-IR spectra of these MP polymers are presented in **Figures 3** and **4** depicts the shapes and colors of MP samples observed under a microscope. **Table 2** provides an overview of the density and typical application areas of plastics commonly identified in WWTPs. These MPs predominantly originate from polymer-based textiles that degrade during laundering processes. Additionally, MPs are derived from household products, such as detergents, shampoos, bath soaps, and hand soaps.

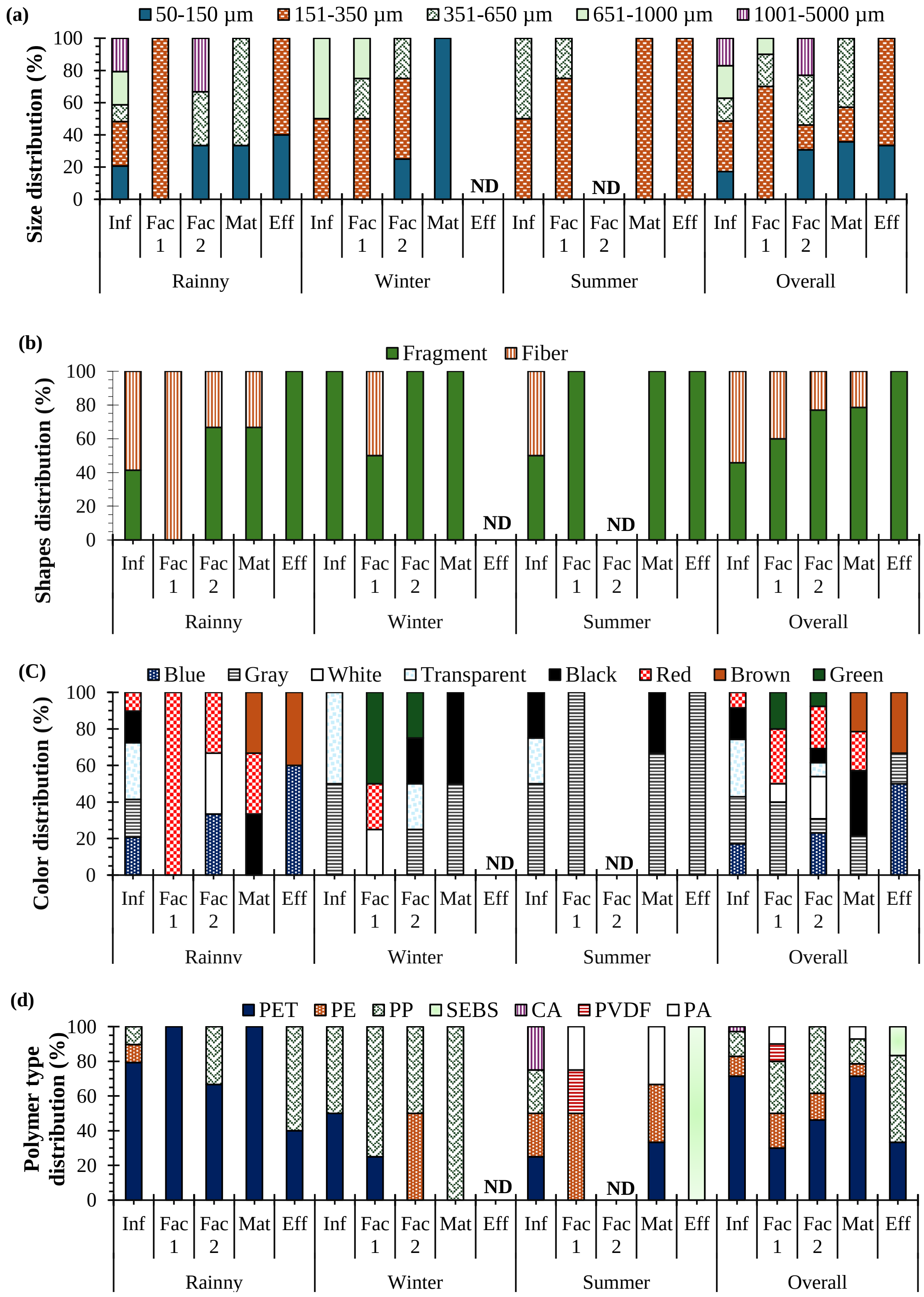

Figure 2 Distribution of (a) size, (b) shape, (c) color, and (d) polymer type of MP in municipal wastewater treatment plant in Thailand (Inf = Influent, Fac 1 = Facultative pond 1, Fac 2 = Facultative pond 2, Mat = Maturation pond, Eff = Effluent).

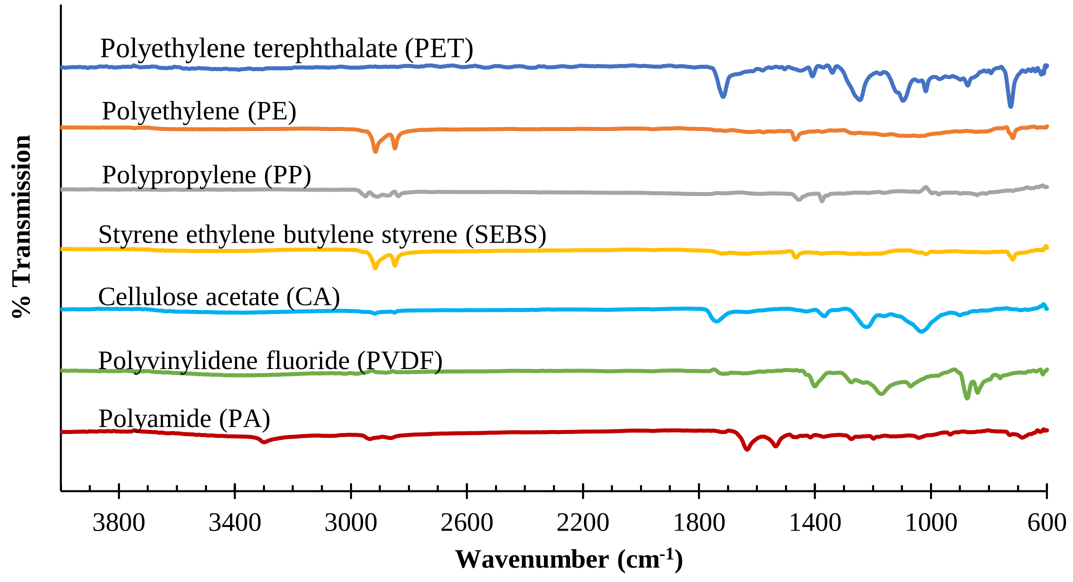

Figure 3 FT-IR spectra of MP in WWTPs.

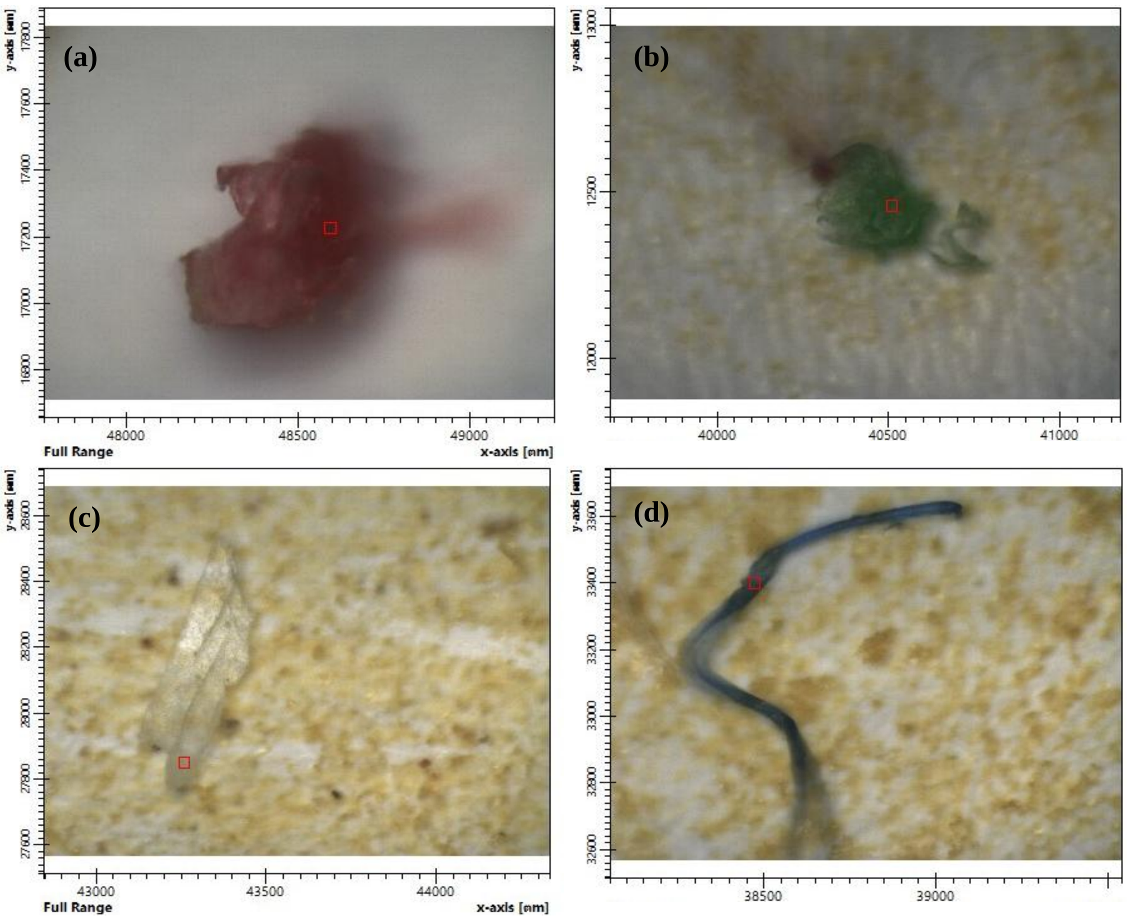

Figure 4 Visualization of the MP morphology observed at the studied WWTPs includes the following types: (a) red fragment, (b) green fragment, (c) transparent fragment, and (d) blue fiber. For interpretation of the references to color in this figure legend, readers are directed to the web version of this article.

Table 2 Density and application areas of commonly used plastics.

Polymer type	Density (g/cm^3)	Application
Cellulose acetate (CA)	1.31	Applications in textiles, photographic films, filters, plastic products, and packaging
Polyamide (PA)	1.02 - 1.16	Synthetic textiles and plastic bags a
Polypropylene (PP)	0.83 - 0.92	Food packaging, chip bags, pipes, and automotive parts
Polyethylene (PE)	0.89 - 0.98	Food wrapping materials, water bottles, and personal care items
Polyethylene terephthalate (PET)	0.96 - 1.45	Bottles of water, juice, and cleansers
Polyvinylidene fluoride (PVDF)	1.78 - 1.79	Pharmaceuticals and packaging, gaseous substances barriers and coatings for the inner layers of pipes, storage tanks, valves, membrane filters, pumps, and bearings
Styrene ethylene butylene styrene (SEBS)	0.91	Car interiors, home furnishings, domestic electrical appliances, flippers and other diving equipment. Food grades and medicine: tops for containers and bottles. Toys.

Source: Fauzi *et al.* [25]; Acarer [29]; Scientific Polymer Products [30]; Silva *et al.* [31]; Teixeira *et al.* [32]; CJP sales [33].

Previous studies have reported the presence of PE, PP, PA, PS, and PET in WWTPs, with respective proportions of 64.07, 32.92, 10.34, 24.17, and 28.09 % [7,9,26]. In a WWTP in Sydney, PE and PET constituted 42 and 36 % of the total influent and effluent concentrations, respectively [9]. PE and PP were the most frequently detected polymers in WWTP influents, comprising 3 - 32 % and 11 - 42 % of the total, respectively. These polymers are ubiquitous in WWTPs owing to their extensive use in industrial and household products, including personal care items and packaging materials [11].

Fate and transfer of MPs in WWTP

Influent and primary treatment

Relatively low concentrations of MPs were observed in the wastewater influent, with an average of 1.30 ± 1.61 particles/L (**Table 1**). It is hypothesized that during the skimming process, MPs with a tendency to settle are likely removed [34]. However, due to their buoyant properties, the remaining particles are expected to resist primary removal. Sedimentation and flotation are techniques used to isolate substances with a lower density than water by utilizing gas bubbles to lift them to the surface, where they can then be removed through skimming [35]. MPs with low densities generally float, while those with higher densities settle at the bottom. Therefore, it is plausible that higher-density MPs, such as PET, can be removed from wastewater through precipitation. Flotation, on the other hand, is a more appropriate method for removing low- or medium-density MPs that cannot be easily precipitated [34].

Secondary treatment

As summarized in **Table 1**, the predominant MP particles were detected during the secondary treatment process, with concentrations ranging from 0.22 - 1.00 particles/L, 0.22 - 0.44 particles/L, and 0.00 - 0.44 particles/L during the rainy, winter, and summer seasons, respectively. These findings align with previous research, which reported elevated concentrations of MP fibers following the secondary treatment stage [36].

MPs detected in the aeration tank were primarily composed of PP, copolymers, PE, and materials from toothpaste formulations. Similarly, MPs identified in the activated sludge predominantly consisted of PP, PE, PET, and copolymers, with fragmented shapes being the most common morphology [36].

Additionally, the type of biological treatment process (anaerobic or aerobic) and the specific operational conditions of the treatment system, such as hydraulic retention time and aeration intensity, are critical factors influencing MP removal efficiency. In anaerobic processes, sedimentation effectively removes larger MPs (0.1 - 5 mm) due to their higher settling velocities compared to smaller MPs (< 0.1 mm) [37]. In contrast, aerobic processes primarily rely on interception and sludge adsorption mechanisms to remove smaller MPs (< 0.1 mm), with turbulence induced by aeration further enhancing these removal efficiencies [37]. Furthermore, studies on MP degradation by microorganisms have demonstrated that plastic materials require several weeks to months to undergo significant microbial degradation [38].

Effluent

As shown in **Table 3**, the concentrations of MPs detected in the effluent were 0.56 particles/L during the rainy season and 0.11 particles/L during the summer season. Notably, no MPs were detected in the effluent during the winter season. These findings are consistent with previous studies, which reported MP concentrations ranging from 0 - 2.8 particles/L in the effluents of various WWTPs [1,7,8,39,40]. **Table 3** summarizes the MP removal efficiencies of different WWTPs. Prior research has also documented minimal or absent MP particles in the effluents of WWTPs located in Vancouver, Canada [41].

Table 3 MP concentration and removal efficiency in WWTPs across various countries.

Location	Treatment process	Concentration (Particles/L)		Removal efficiency (%)	References
		Influent	Effluent		
China (Wuhan)	Primary, secondary (activated sludge), and chlorination	79.90	28.40	64.40	[21]
China (Beijing)	Primary, secondary, and series of advanced treatments	12.03	0.59	95	[40]
China (Xiamen)	Secondary	1.57 - 13.69	0.20 - 1.73	79.30 - 97.80	[6]
Canada (Vancouver)	Primary and secondary	31.10	0.50	97.10 - 99.10	[41]
Scotland (Glasgow)	Primary and secondary	15.70	0.25	98.41	[43]
Indonesia (Bandung)	Secondary (anaerobic system)	793.33 - 573.33	80.00 - 133.33	76.74 - 83.78	[25]
Thailand (Udon Thani)	Primary and secondary (stabilization pond)	8.50	1.92	77	[44]
Thailand (Khon Kaen)	Primary and secondary (aeration lagoon)	9.58	1.50	84.35	[44]
Thailand (Nonthaburi)	Primary and secondary (activated sludge)	4 - 12 (Dry) 6 - 33 (Wet)	0 - 2 (Dry) 0 - 6 (Wet)	75 - 86 (Dry) 16 - 75 (Wet)	[1]
Thailand (Lampang)	Primary and secondary (stabilization pond)	3.22 (Rainy) 0.22 (Winter) 0.44 (Summer)	0.56 (Rainy) 0.00 (Winter) 0.11 (Summer)	82.76 (Rainy) 100.00 (Winter) 75.00 (Summer)	This study

Furthermore, it was observed that tertiary treatment processes in WWTPs are not substantial sources of MPs, as primary treatment stages effectively remove the majority of MPs. Mechanisms such as the skimming of lightweight MP fragments and the sedimentation of heavier MPs during grit removal play a pivotal role in this process [17]. Tertiary treatment processes can further enhance MP removal efficiency. For example, a study conducted in the Netherlands reported MP removal efficiencies of 88 % for WWTPs without tertiary treatment and 97 % for those with tertiary treatment [42].

The density of MP particles also plays a critical role in their removal, as it determines their buoyancy and sedimentation potential [34]. While PP and PE are among the most commonly identified MP types, these materials were not present in the effluent, likely owing to their low densities, which facilitate removal through air flotation processes [11]. In this study, the MP removal efficiencies for the WWTPs were 75.00, 82.76, and 100.00 % during the summer, rainy, and winter seasons, respectively. These results align with previous findings, which reported MP removal efficiencies of approximately 77 and 84.35 % for primary and secondary treatment processes, including stabilization ponds and aeration lagoons, in Thailand [44].

Seasonal distribution

Abundance, fate and transport of MPs

Seasonal variation analysis indicated a greater abundance of MPs in the WWTP during the dry seasons compared to the wet seasons. Notable fluctuations in MP concentrations were observed at the Lampang WWTP across the rainy, winter, and summer seasons. ANOVA statistical analysis revealed a significant difference in MP abundance among the 3 seasons ($p < 0.05$). Further pairwise t-tests identified significant differences in MP concentrations between the rainy and winter seasons ($p < 0.05$), as well as between the rainy and summer seasons ($p < 0.05$). However, no significant difference was found between the winter and summer seasons ($p > 0.05$). These findings suggest that MP concentrations were notably higher during the rainy season compared to the winter and summer seasons. This aligns with prior research, such as a study along a subtropical river system in South Africa, which found that MP densities and diversities peaked during the hot-wet season compared to the cool-dry and hot-dry seasons [22]. The results point to diverse sources of MPs in river catchments, which may vary within and across catchment areas [45]. External factors, including river flow, water depth, substrate type, and the physical characteristics of plastics, likely contribute to the increased MP concentrations upstream of WWTPs [46,47].

To understand the fate and transport of MPs from their sources to their eventual discharge as treatment effluent, it is essential to examine MP behavior during the rainy season. It is hypothesized that MP concentrations are significantly higher during the rainy (wet) season due to 2 main factors: 1) the deposition of airborne MPs via precipitation and 2) the increased mobility of MPs under wet conditions. First, previous studies have shown that the deposition of MPs is higher during periods of wet deposition compared to dry deposition, underscoring the important role of rainfall in removing MPs from the atmosphere [48]. Second, rainfall during the wet season likely enhances the mobility of MP particles, particularly those from road runoff and other transport-related sources, such as plastic particles from tire wear. These particles are then transported into combined sewer systems. Notably, the current study found that most MP fragments detected in the WWTP were composed of PET, PP, and PE. Additionally, prior research has demonstrated that rainfall can increase MP concentrations in WWTPs connected to combined sewer systems, as rain events wash small anthropogenic litter into these systems [49]. However, the effects of rainfall on the movement and accumulation of pollutants within WWTPs remain inadequately understood. Factors such as wastewater influent characteristics, treatment efficiency, and other environmental conditions all interact to influence the fate of pollutants alongside rainfall.

MPs removal in WWTPs

The occurrence and variation of specific MP types within WWTP processes may be influenced by diurnal fluctuations in wastewater flow and hydraulic retention time associated with different treatment stages [50]. Typically, influent flow patterns exhibit peaks during periods of high water usage, such as in the mornings and early evenings. However, these patterns can be disrupted by stormwater inflows, which alter the hydraulic retention times across various treatment units. Seasonal differences in secondary treatment processes during the rainy, winter, and summer periods may further contribute to variations in the types of MPs observed.

The WWTP examined in this study employs a stabilization pond system across all 3 seasons—rainy, winter, and summer. However, the seasonal trends in the abundance of MPs identified within the secondary treatment processes were found to be inconsistent. This observation contrasts with findings from previous research, which reported a consistent decrease in MP quantities across secondary treatment stages [44]. A possible explanation for this discrepancy lies in the operational characteristics of the stabilization pond system. The extended retention time of approximately 15 days allows for the settling of MPs, a process driven by factors such as gravitational forces and the polymer density of MPs. This prolonged retention promotes sedimentation, resulting in a statistically significant reduction in MP concentrations [44]. Additionally, variations in the hydraulic retention times of the stabilization pond system across different seasons may also influence the efficiency of MP removal. These seasonal differences in retention time could play a role in determining removal rates, necessitating further investigation to substantiate or refute their impact on MP removal efficiency.

Limitations of the research and further studies

The number of wastewater grab samples collected in this study may introduce biases, highlighting the need for future research to incorporate continuous or composite sampling methods to enhance the reliability and accuracy of the findings. Additionally, this study did not examine the abundance of MPs in sediments, which represents a key limitation. Future research should address this gap to gain a better understanding of the role of sedimentation in the MP removal process within WWTPs. Several other factors influencing the quantity of MPs in wastewater influents were not thoroughly explored, such as land use patterns (e.g., residential, commercial, or industrial areas), housing and population densities, urban density and proximity to urban centers, sewage overflow volumes, WWTP types, and the nature of solid waste management systems in surrounding areas [44]. These factors should be investigated in future studies to offer deeper insights into strategies for reducing MP discharges into WWTPs and the broader environment. Previous studies have emphasized the importance of examining MP contamination comprehensively across all components of the municipal ecosystem, including WWTPs, surface water, and atmospheric fallout from both wet and dry depositions [51]. Additionally, further research is necessary to assess the potential harmful effects of MPs released from WWTPs on aquatic ecosystems and human livelihoods. Such investigations will be essential for understanding and mitigating the risks associated with MP pollution.

Conclusions

MPs are increasingly recognized as a significant aquatic contaminant. This study provides important insights into the seasonal variations in MP detection, fate, and transport, focusing on the samples and data collected from the Lampang WWTP in Thailand. The key findings of this research are as follows: First, a higher abundance of MPs was detected in the WWTP during the rainy season compared to the winter and summer seasons. The average MP concentration during the rainy season was 1.20 ± 1.27 particles/L, while the average concentrations during the winter and summer seasons were 0.27 ± 0.50 particles/L and 0.27 ± 0.54 particles/L, respectively. Statistical analysis through ANOVA indicated a statistically significant difference in MP abundance across the 3 seasons ($p < 0.05$). Secondly, this study corroborates previous research suggesting that the deposition of airborne MPs through precipitation and the increased mobility of MPs under wet conditions contribute to the elevated MP quantities observed in WWTPs during the rainy season. Thirdly, most MPs detected across the rainy, winter, and summer seasons within the WWTP processes were characterized by sizes of 151–350 µm, gray coloration, and fragment shapes. Additionally, MPs composed of PET, PP, and PE were identified. These findings emphasize the need to optimize the stabilization pond system employed by the Lampang WWTP, which showed inconsistent performance across different seasons. Developing seasonally adaptive strategies is essential to better understand MP trends and enhance the efficiency of wastewater treatment systems. Further research should focus on the fate and transport of MPs during overflow conditions and the implementation of effective water management strategies tailored to the rainy, winter, and summer seasons. Such measures are crucial to minimizing the release of MPs into natural water bodies, thereby mitigating their environmental impact.

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