Journal of Environmental Management 371 (2024) 123348

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Unraveling microplastic pollution patterns in sediments of a river system: The combined impacts of seasonal changes and waterway differences

Nguyen Xuan Tong [a], Vo Thi Kim Khuyen [b], Nguyen Thi Thanh Thao [a], Binh Thanh Nguyen [a,*]

[a] *Institute for Environmental Science, Engineering and Management, Industrial University of Ho Chi Minh City, 12 Nguyen Van Bao, Go Vap District, Ho Chi Minh City, Viet Nam*

[b] *Faculty of Pharmcy, University of Medicine and Pharmacy at Ho Chi Minh City, 41 Đinh Tiên Hoang, District 1, Ho Chi Minh City, Vietnam*

ARTICLE INFO

Handling Editor: Lixiao Zhang

Keywords:
Microplastics
Particle size
Pollution sources
Surface water network
Water transport

ABSTRACT

Microplastic (MP) distribution in river sediment, influenced by water regimes and pollution sources, remains understudied in the current literature. This study examines the combined impacts of seasonal variation and waterway differences on MP concentration in the sediment of the Saigon River and its tributaries, while identifying potential sources. Paired sediment samples were collected from eleven sites along the river and its tributaries during rainy and dry seasons. MPs from these 44 samples were separated, quantified, and characterized for a comprehensive assessment. The results revealed that MP concentrations in sediments ranged from 140 to 1200 items kg^{-1}, with predominant characteristics of fiber particles, white color, and particle sizes ranging from 200 to 500 μm. During the rainy season, MP concentrations were similar between the river (584 items kg^{-1}) and tributaries (553 items kg^{-1}), while during the dry season, tributaries exhibited statistically higher MP concentrations (737 items kg^{-1}) than the river (351 items kg^{-1}). Notably, the river, despite being farther from the sources, had a higher proportion of smaller MPs (<200 μm), while larger particles (>200 μm) were more prevalent in tributaries. These discrepancies are attributed to the combined impacts of water flow patterns and pollution sources, derived from residential, industrial, and agricultural activities. In brief, MP pollution in the river and tributary sediments is influenced by the interplay of seasonal variation and waterway characteristics, determined by water flow patterns and pollution sources. These findings emphasize the need for specific management strategies that account for spatial and temporal variations in MP distribution.

1. Introduction

In 2018, global plastic production reached approximately 360 million tons, with only about 7% being recycled (Ng et al., 2023; Naderi Kalali et al., 2023). Plastic waste generation is projected to reach 12 billion tons by 2050, accumulating in landfills and the environment (Corcoran et al., 2020), posing a significant threat through the formation of microplastics (MPs). These particles, typically less than 5 mm, result from the breakdown of larger plastics or are intentionally manufactured at microscopic sizes (Ziani et al., 2023; Luu et al., 2021). The pervasiveness of MPs in ecosystems worldwide is a growing concern due to their persistence, ability to absorb toxic chemicals, entry into food chains, and widespread distribution across terrestrial, freshwater, and marine environments, and challenges in removal once they've entered ecosystems (Emenike et al., 2023; Thacharodi et al., 2024; Osman et al., 2023; Sheraz et al., 2023). Although extensive research has quantified and characterized as well as examined their spatial, depth, and temporal distribution across various locations and regions, the influence of seasonal variations and waterway differences requires further investigation.

Microplastics, originating from areas with significant anthropogenic influence, are transported from pollution sources to sinks, usually river and tributary sediments, and eventually flow into the sea (He et al., 2020). MP presence and distribution in the river and tributary sediments are influenced by a few key factors including land use type, river morphology, grain size, and organic debris (Corcoran et al., 2020). Furthermore, environmental factors such as microorganisms, UV light, temperature, rainfall, river flow, and water characteristics also affect MP occurrences (Thepwilai et al., 2021; Jaubet et al., 2021). The impacts of these factors depends on pollution sources that deliver MPs to the sinks, water flow patterns to transport MP from their sources to their sinks, and waterways as MP sinks. The former can originate from various human

---

* Corresponding author.
E-mail address: nguyenbinh@iuh.edu.vn (B.T. Nguyen).

https://doi.org/10.1016/j.jenvman.2024.123348
Received 19 August 2024; Received in revised form 29 October 2024; Accepted 10 November 2024

activities, including agricultural production, industrial processes, and residential areas (Wu et al., 2023). These activities release plastic debris and primary MPs (collectively referred to as plastic materials) into the environment, which are then transported to various locations by waterway flow dynamics (Haque et al., 2023). Areas proximal to pollution sources typically exhibit higher concentrations of plastic materials compared to more distant regions (Ashrafy et al., 2023). In a typical river system, tributaries collect water from their respective basins before merging with the main river. This structure suggests that tributaries serve as initial receivers of plastic materials, subsequently conveying them to the main river or other water bodies. Additionally, the transport process of plastic materials depends on the flow of the surface water system, which is influenced by seasonal changes throughout the year. During the rainy season, increased precipitation significantly enhances water flow, facilitating rapid transport of plastic materials through tributaries and rivers towards the sea, leading to low MP concentration (Xia et al., 2021). In contrast, reduced water flow during the dry season promotes deposition of these materials in river and tributary sediments. These observations indicate a complex interplay between seasonal changes and waterway characteristics in determining MP pollution patterns in sediments. This leads to the first hypothesis of the current study: MP concentrations are greater in tributary sediments compared to river sediments, particularly during the dry season.

While in the environment, plastic debris decomposes by various mechanisms (Dimassi et al., 2022) to form secondary MPs, together with primary MPs, polluting ecosystems (Borriello et al., 2023). This process occurs during the transport of larger plastic items from their sources to sinks and within sediments, forming secondary MPs. As degradation progresses, smaller particles become more prevalent, leading to the second hypothesis that MPs with smaller particle sizes dominate in sediments. The rate and extent of this degradation can vary based on factors such as UV exposure, mechanical abrasion, and microbial activity (Kye et al., 2023), which may differ between rivers and tributaries. Additionally, smaller particles may be more easily transported by water currents, potentially traveling further from their source than larger particles, leading to size-dependent distribution of MPs in the river and tributary sediments. The combination of differential transport and ongoing degradation causes a shifting size distribution along the river system. Consequently, MP distribution in sediment can be affected by the complex interplay of seasonal changes (reflected through environmental transport patterns), pollution sources, and particle size distribution. These factors lead to the third hypothesis: Tributaries contain higher MP concentrations and larger particles than rivers, which predominantly held smaller particles. These hypotheses encapsulate the multifaceted nature of MP pollution in river systems, emphasizing the need to consider seasonal dynamics, spatial differences between tributaries and main rivers, proximity to pollution sources, and the evolving size distribution of MPs.

Therefore, this study was conducted in Saigon River and its tributaries in Ho Chi Minh City, Vietnam, to test three hypotheses regarding MP pollution. The mainstream of the Saigon River was found to contain at least 172,000 micro-fibers per cubic meter of water (Lahens et al., 2018). This may lead to high accumulation of MPs in sediment, which are limitedly studied (Trinh et al., 2021). This study aims to investigate the combined impacts of seasonal change and waterway differences on MP concentration in sediments of the Saigon River and its tributaries, while also identifying potential sources. By addressing both seasonal variations and the distinction between the main river and its tributaries, this research fills a gap in current literature and provides a more comprehensive understanding of MP distribution in river ecosystems, leading to developing effective management strategies to mitigate MP pollution in aquatic environments.

2. Materials and methods

2.1. Study area

The present study was conducted in the Saigon River and its 11 principal tributaries that flow through the urban areas of Ho Chi Minh City, Vietnam (Supplementary Fig. 1). Originating in Binh Phuoc Province, it flows through Ho Chi Minh City, receiving water from numerous tributaries before merging with the Dong Nai River and discharging into the East Sea of Vietnam. This river system is crucial for the city's water resources, serving various purposes including transportation, irrigation, and urban drainage needs. However, it faces significant environmental challenges due to rapid urbanization, industrial development, and population growth in Ho Chi Minh City. As Vietnam's largest city and on the verge of megacity status, Ho Chi Minh City is the country's economic and entertainment hub, as well as one of its two most important centers for culture and education. These factors contribute to the complex environmental pressures on the Saigon River system.

Ho Chi Minh City is located in a tropical monsoon zone, characterized by consistently high temperatures year-round (an average annual temperature of 28.4 °C) and two distinct seasons - wet and dry - which profoundly influence the local environment and landscape. The wet season extends from May to November, while the dry season lasts from December to April of the following year (Nguyen et al., 2023). Rainfall patterns are highly seasonal, with the dry period receiving minimal precipitation. In contrast, the rainy season accounts for approximately 80–90% of the total annual rainfall, which averages around 2100 mm (Nguyen et al., 2023).

2.2. Sampling strategies, sample preparation, and sediment analysis

The current study analyzed a subset of sediment samples collected from a previous study (Nguyen et al., 2019). Sediment samples were obtained from 11 key sampling sites, located at the confluences of the Saigon River and its main tributaries (Supplementary Fig. 1). At each pre-identified river junction, samples were collected in pairs: one from the main river and a corresponding sample from the tributary. This paired sampling approach enables direct comparison between the main river and its tributaries at each confluence point. The sampling was conducted in two distinct seasons to capture seasonal variations in the rainy season (September 2018) and dry season (April 2019). This seasonal sampling approach allows for the assessment of temporal variations in MP concentrations and distributions between the rainy and dry seasons.

The sediment sampling was implemented using Petersen grabs to collect the 0–10 cm surface layer of sediments. For each sample, eight grabs were taken from both sides of the river or its associated tributary. Sediment from these grabs was collected in a plastic bucket and thoroughly mixed. Approximately 5 kg of this homogenized sediment was then transferred to a polybag, which was immediately stored in an ice chest maintained at 4 °C to preserve sample integrity during transport to the laboratory. Once in the laboratory, the sediment samples were spread out and allowed to dry at room temperature and the dried samples were passed through a 2-mm sieve to remove plant debris and gravel, ensuring a uniform particle size for analysis.

A total of 44 (11 sites x 2 waterways x 2 seasons) sediment samples were subjected to analyses for some selected parameters, including particle size distribution, pH, electrical conductivity (EC), and organic carbon content. Particle size distribution was determined using a Mastersizer 2000 laser diffraction analyzer (Malvern Instruments, UK), with three measurements averaged per sample to quantify percentages of coarse sand, fine sand, silt, and clay. Organic carbon (OC) content was measured using the Walkley – Black method. For pH measurement, a 1:1 sediment-to-water suspension was prepared, stirred intermittently for over 30 min, allowed to settle for an hour, and then measured using a glass electrode. The filtered suspension from the pH analysis was subsequently used to determine EC following the method described by Ryan, Estefan (Ryan et al., 2007). These analyses provide crucial information about the physical and chemical properties of sediments.

2.3. Extraction, quantification, and characterization of microplastics in the sediment

The MP extraction technique for sediments was adapted from Nuelle, Dekiff (Nuelle et al., 2014) and Wang, Song (Wang et al., 2018), with modifications to suit study conditions. The process began by mixing 100 g of dry sediment with 250 mL of NaCl solution (density ≈ 1.2 g L^{-1}), stirring for 2 min with a clean glass rod, and setting for 24 h. Subsequently, the suspension was treated with 30% H_2O_2 (1:3 w/v) at 65 °C for 24 h to decompose organic matter. After vacuum filtration and rinsing with distilled water, the filter papers were dried at 50 °C for 24 h in clean Petri dishes, preparing the samples for microscopic observation (Wang et al., 2017).

The current study used three techniques to characterize MP items extracted from the sediment samples, including stereomicroscopy, fluorescent microscopy, and Fourier-Transform Infrared (FTIR) to ensure a comprehensive analysis of the extracted MP particles. Primarily, a 40X magnification stereomicroscope was used for the observation and classification of MP particles. This technique allowed for categorization based on shape (fiber, pellet, fragments, and others), color (white, blue, green, red, and others), and size (<200 μm, 200–500 μm, 500–1000 μm, 1000–1500 μm, 1500–2000 μm, and 2000–5000 μm), following methods described by Kalaronis, Ainali (Kalaronis et al., 2022) and Alam, Sembiring (Alam et al., 2019). Nile Red staining and fluorescent microscopy were employed to separate, visualize, and initially characterize extracted MPs (Wen et al., 2024). The diluted Nile Red solution was applied to filter paper containing MPs, which was allowed to dry for 30 min at room temperature. Stained samples were observed under an Olympus BX 53 fluorescence microscope at 40X magnification in three wavelength ranges: DAPI (430–470 nm), FITC (515–560 nm), and SPO (650–670 nm) using a 12V/100W halogen lamp for optimal brightness. Items exhibiting fluorescent signals were identified as plastics. Additionally, FTIR spectroscopy (FTIR Spectrum Spectrometer 100, PerkinElmer) was used to determine the chemical composition of MPs, following the procedure by Campanale, Savino (Campanale et al., 2023). FTIR analysis recorded percentage transmission in the 500-4000 cm^{-1} range with a 4 cm^{-1} resolution, enabling the identification of MP materials.

2.4. Quality control

Following principles summarized by Nayebi, Khurana (Nayebi et al., 2023), the research team implemented rigorous protocols including thorough equipment cleaning, appropriate covering, and maintaining a clean workspace with laminar airflow when possible. Researchers adhered to strict protocols, wearing cotton clothes and latex gloves to minimize contamination. All solutions were pre-filtered, and procedural blanks were conducted at various stages of the analysis. Sampling equipment was carefully selected to reduce secondary contamination, following recommendations by Saad, Ndlovu (Saad et al., 2024) for specific materials such as aluminum frames and stainless-steel components. Notably, no MP particles were detected in any of the procedural blanks, validating the effectiveness of these measures. Proper preparation of laboratory instruments before sampling and analysis was also rigorously maintained throughout the study.

2.5. Statistical analyses

The study quantified MPs as the number of items per kilogram of dry sediment (items kg^{-1}). Percentages of MPs were calculated for each category (shape, color, and size) relative to the total number of MP items identified. To assess the combined effects of seasonal change and waterway differences on measured parameters, a two-way analysis of variance (ANOVA) was employed (Fig. 1b). Additionally, three-way ANOVAs were conducted to analyze the percentages of MP categorized by shape (Fig. 3a), color (Fig. 4a), and size (Fig. 5a). Tukey's Honest Significant Difference (HSD) test was used to identify statistically significant differences ($p < 0.05$) between various factors affecting the analyzed parameters.

3. Results

3.1. Microplastic (MP) abundance

The numeric concentration of MPs in sediment samples ranged from 140 to 1200 items kg^{-1} dry sediment, varying with sampling sites, seasons, and waterways (Fig. 1). On average, sampling site 5 had the highest MP concentration, 710 and 1075 items kg^{-1} in river and tributaries, respectively. Sediment collected from the tributaries exhibited statistically higher MP content, varying from 260 to 770 items kg^{-1}, than from the river, ranging from 450 to 1075 items kg^{-1}. A significant correlation ($R^2 = 0.43$, $P = 0.02$) was observed between MP concentrations in these two waterways. The MP abundance was also dependent on the seasons and the waterways. During the rainy season, MP concentrations were statistically similar between the river (583.6 items kg^{-1}) and the tributaries (552.7 items kg^{-1}), while during the dry season, the tributaries had statistically higher MP concentration (737.3 items kg^{-1}) than the river (350.9 items kg^{-1}). These findings highlight the complex interplay between seasonal change and waterway differences influencing MP distribution in the Saigon River system.

3.2. The morphology of isolated microplastics (MPs)

A stereomicroscope (Fig. 2a, b, and 2c) and fluorescence microscopy (Fig. 2d, e, and 2f) were employed to capture representative images of MPs isolated from sediment samples. MPs had three main shapes: fibers, pellets, and fragments, along with the others. MPs also appeared in various colors such as white, blue, green, red, and others, in different sizes. While the MPs ranged widely in size, the images in Fig. 2 specifically showcased particles between approximately 50 to 160 μm. The top row (Fig. 2a, b, and 2c) depicted MPs under normal light, while the bottom row (Fig. 2d, e, and 2f) represented fluorescence microscopy images, enabling more precise identification and measurement of MP particles. This dual imaging approach effectively illustrated the various shapes, sizes, and types of MPs found in sediment samples in the current study.

Three primary shapes of MPs - fiber, pellets, and fragments - along with a combination of the other shapes were identified, with their percentages by waterway, season, and locations shown in Fig. 3. Out of the total MP items identified in the current study (2447 items 100 g^{-1} equal to 24,470 items kg^{-1} of dry sediment), fiber-like MPs were most prevalent, comprising 7–18.7% of the total, depending on season and waterway. The combination of other shapes was the least common, while pellets and fragments showed similar proportions. The percentages of these four MP shapes varied based on the combination interaction between the waterway and season. Fiber-like items were most abundant in tributary sediments during the dry season (17.7%), while the lowest percentage was found in river sediments during the dry season. The percentages of pellets and fragments were statistically similar across all four combinations of two reasons and two waterways. Among the four main MP shapes, fiber items consistently showed the highest percentages across all 11 sampling sites (Fig. 3b), with sites 5 and 10 exhibiting the highest proportions (8.1% and 7.8%, respectively) and site 6 the lowest (2.6%). The combined other shapes showed the lowest percentages, while pellets and fragments had medium and similar percentages across all sampling sites.

The percentages of MP items in four primary colors and other combination colors are shown in Fig. 4. White MPs occupied the highest

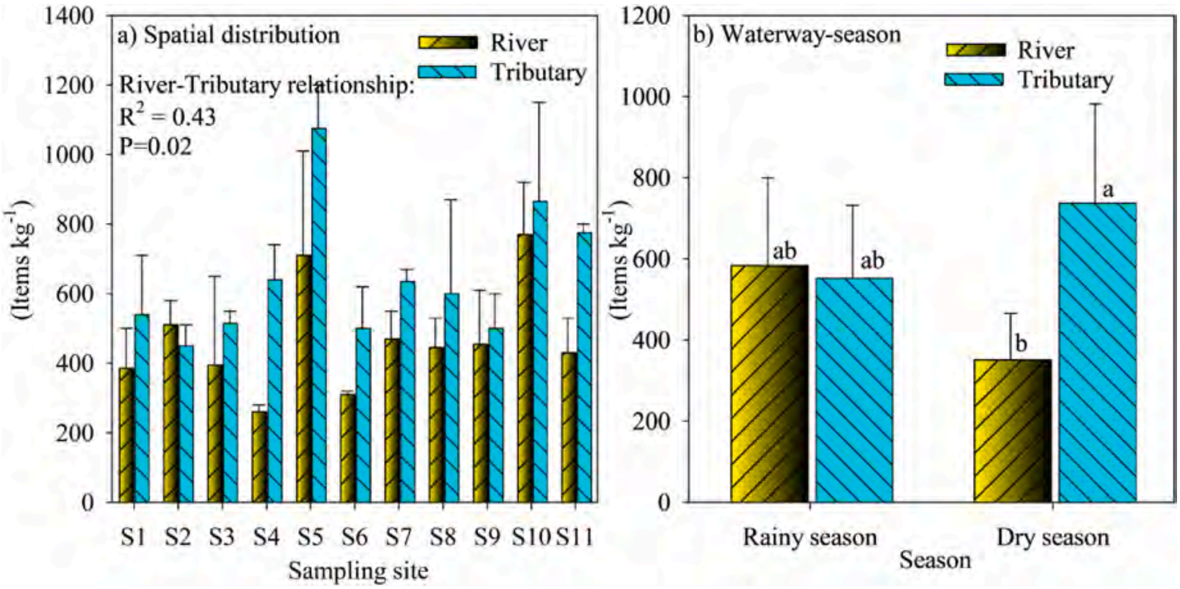

Fig. 1. Spatial variation of microplastic quantity in sediments in two waterways of river and its tributary (a) and the interaction between waterway and season on microplastic quantity. The vertical bars represent the standard error (SE) of the mean. Within panel b, bars attached with different lowercase letters were significantly different from each other with $P \leq 0.05$.

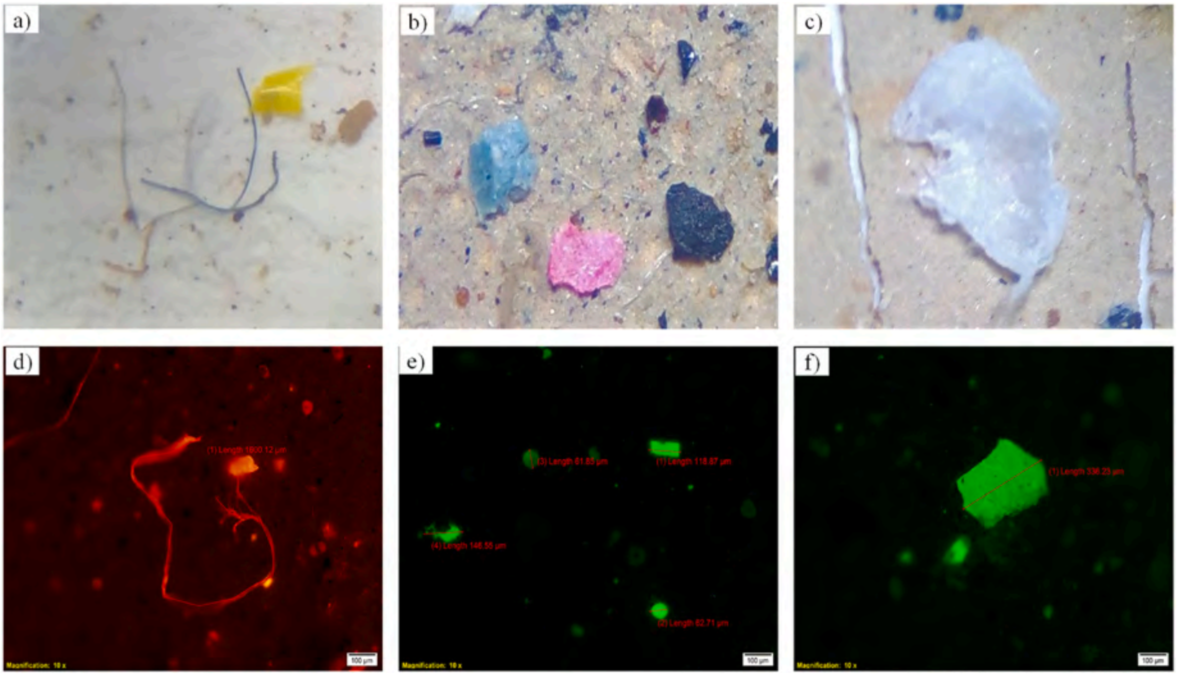

Fig. 2. The image of representative microplastics in sediment under a stereomicroscope (a, b, c) and fluorescence microscopy (d, e, f).

proportion, ranging from 6.6% to 16.8% of the total, depending on the waterway and season, while other combination colors had the lowest percentages. Statistically significant differences were observed only for white MP particles among the four combinations of waterways and seasons, with the highest percentages found in tributaries during the dry season and the lowest in the river during the dry season. Blue, green, red, and other colors did not show significant variations across these combinations. Across all 11 sampling sites, white MP particles consistently showed the highest percentages, followed by blue, green, red, and other colors. Sites 5 and 10 exhibited the highest percentages of white particles, while particles of other colors showed statistically similar proportions across all sampling sites.

The abundance of microplastics in the sediments was classified into six size groups, with their percentages shown in Fig. 5. MP particles in the 200–500 μm range were most prevalent, constituting approximately 43.4% of the total. This was followed by particles below 200 μm (26.7%), 500–1000 μm (20.31%), 1000–1500 μm (8.1%), 1500–2000 μm (1.1%), and 2000–5000 μm (0.3%). MP particles smaller than 200 μm were most abundant in the river during both dry and rainy seasons. In contrast, particles in the 200–500 μm range dominated in tributaries across both seasons. The most significant variation in size distribution was observed for the 200–500 μm range at site 5, where these particles reached their highest proportion of 9.97%. Other sites and size groups showed lower proportions, with the next highest being 5.8% for the

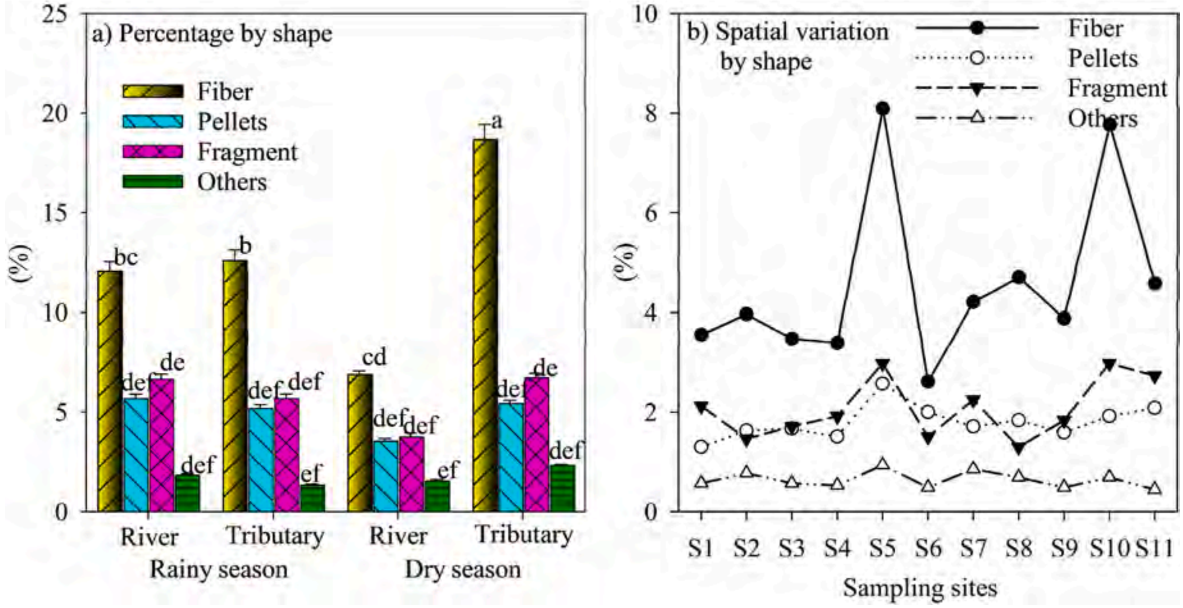

Fig. 3. Percentage by shape of microplastic items based on season and waterway (a) and space (b). The vertical bars represent the standard error (SE) of the mean. Within panel a, bars attached with different lowercase letters were significantly different from each other with $P \leq 0.05$.

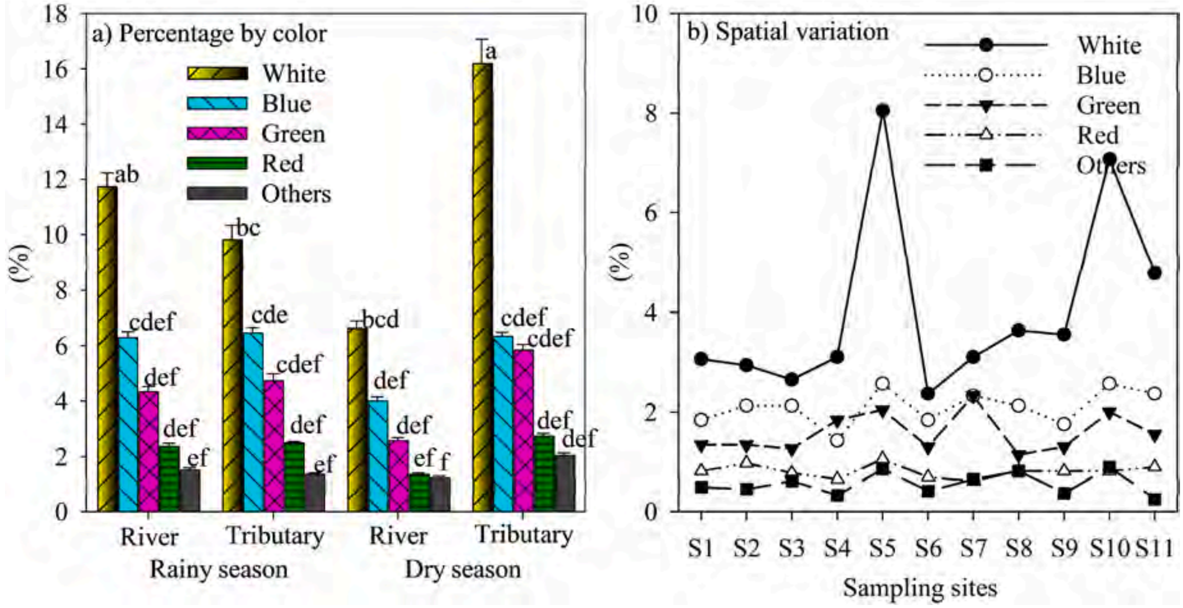

Fig. 4. Percentage by color of microplastic items based on season and waterway (a) and space (b). The vertical bars represent the standard error (SE) of the mean. Within panel a, bars attached with different lowercase letters were significantly different from each other with $P \leq 0.05$.

500–1000 μm group at site 11.

3.3. *Microplastic characterization by fourier transform infrared spectroscopy (FTIR)*

FTIR was used to identify functional characteristics and MP materials by analyzing their unique spectral fingerprints. Fig. 6 presented four representative spectra of the primary MP materials identified in the study: high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS), and polyamide (PA). HDPE exhibited characteristic peaks 2915 cm^{-1} and 2848 cm^{-1} (strong C-H stretching vibrations from CH_2 groups), and 730 cm^{-1} and 720 cm^{-1} (rocking vibrations of CH_2). PP spectra showed peaks at 2950 cm^{-1} and 2870 cm^{-1} (asymmetric and symmetric C-H stretching vibrations of CH_3 groups), 1450 cm^{-1} (CH_3 bending), 1375 cm^{-1} (symmetric deformation of CH_3), and 1167 cm^{-1} (C-C stretching). PS materials displayed peaks at 1601 cm^{-1} and 1493 cm^{-1} (C=C stretching in the aromatic ring), 1452 cm^{-1} (CH_2 bending), and 756 cm^{-1} and 698 cm^{-1} (C-H out-of-plane bending in the aromatic ring). PA showed characteristic peaks at 1640 cm^{-1} (amide I band: C=O stretching), 1540 cm^{-1} (amide II band: N-H bending and C-N stretching), and 1260 cm^{-1} (amide III band: C-N stretching and N-H bending).

3.4. *Selected physicochemical properties of the sediments*

Table 1 summarizes the distribution of particle size, pH, electrical conductivity (EC), and total organic carbon (TOC) in the sediment samples. Particle size analysis revealed that coarse sand content ranged from 1.8 to 3.0%, while fine sand content varied from 20.0 to 21.1%. Silt

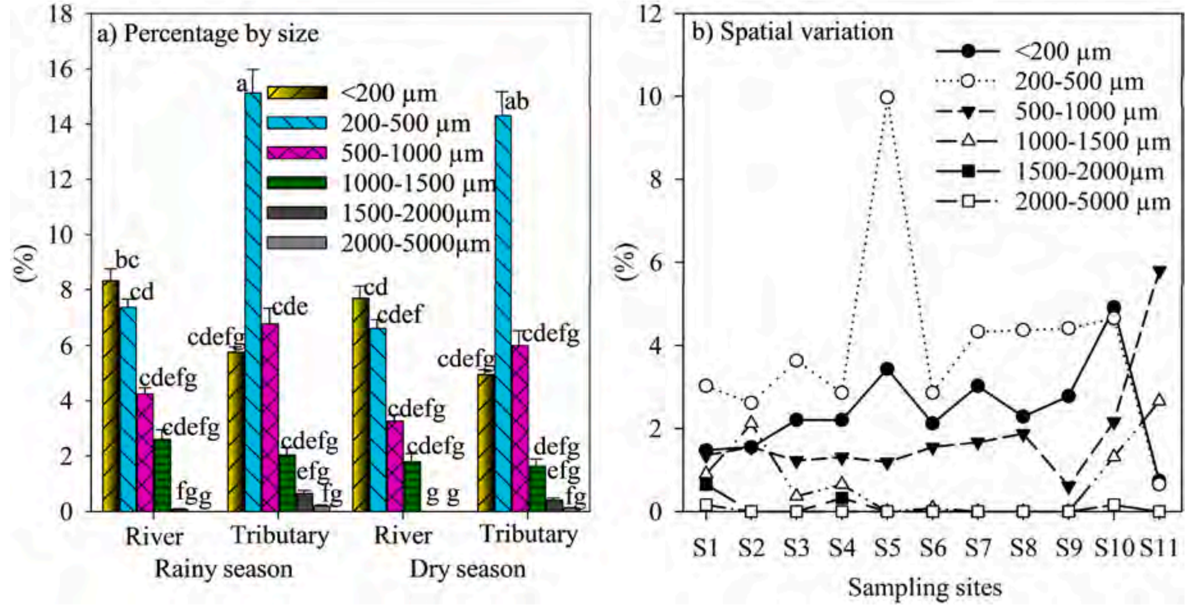

Fig. 5. Percentage by size of microplastic items based on season and waterway (a) and space (b). The vertical bars represent the standard error (SE) of the mean. Within panel a, bars attached with different lowercase letters were significantly different from each other with $P \leq 0.05$.

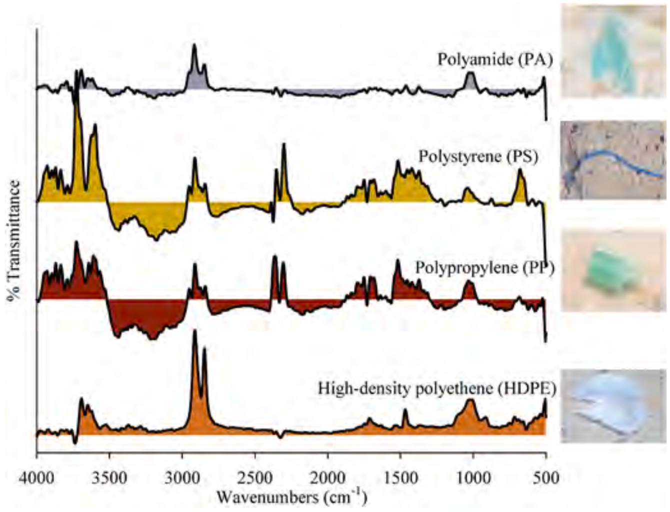

Fig. 6. The FTIR spectrum of representative microplastics in the sediments of the Saigon River.

particles were the most prevalent, comprising 65.4–68.9% of the samples. The pH levels of the sediments ranged from 4.3 to 4.9, indicating acidic conditions, while EC values varied from 1.48 to 1.7 µS cm^{-1}. Organic carbon (OC) content showed seasonal and spatial variations, with the lowest value observed in tributaries during the dry season (3.2 %) and the highest in the river during the dry season (5.3 %). These sediment characteristics provide important context for understanding the distribution and behavior of microplastics in the Saigon River system.

4. Discussion

The numeric concentration of microplastics (MPs) in the sediment of the Saigon River and its tributaries varied from 140 to 1200 items kg^{-1} (Fig. 1). These levels are comparable to those reported from other locations, such as from Guanabara Bay, Southeast Brazil (160–1000 items kg^{-1}) (Alves et al., 2019), Wuliangsuhai lake, northern China (16.5–72.4 items 100 g^{-1}) (Mao et al., 2021), and the Red River delta and Tien Yen Bay, Northern Vietnam (0–4941 items kg^{-1}) (Luu et al., 2021). However, the MP abundance observed in this study exceeded levels found in Edgbaston lakeside, the UK (25–30 items 100 g^{-1}) (Vaughan et al., 2017), the Yangtze River, China (2–34 items 100 g^{-1}) (Peng et al., 2017), and the Swat River, Pakistan (202 items kg^{-1}) (Khan et al., 2022). These comparisons indicate that MP concentrations in the sediments in the Saigon River system fall within the global range but tend towards the higher end of the spectrum observed worldwide. This finding underscores the potential environmental and ecological risks associated with MP pollution in the study area.

The MP concentration in the current study was highly influenced by the combined impacts of season changes and waterway differences (Fig. 1). During the rainy season, high rainfall generates strong currents

Table 1
Selected physicochemical characteristics of sediment samples. SE is the standard deviation of the mean, EC is electrical conductivity, and OC is organic carbon.

Season	Waterway	Statistics	Particle size distribution (%)				pH	EC (µS/cm)	OC (%)
			Coarse sand	Fine sand	Silt	Clay			
Rainy season	River	Mean	2.18	20.02	67.80	9.99	4.27	1.51	4.18
		SE	2.31	5.08	5.76	2.23	0.50	0.28	0.96
	Tributary	Mean	1.81	21.06	68.88	8.25	4.31	1.67	4.77
		SE	2.14	6.67	4.83	2.98	1.06	0.55	0.76
Dry season	River	Mean	2.97	20.94	65.44	10.64	4.90	1.38	5.27
		SE	1.67	2.08	2.54	1.94	0.75	0.32	1.34
	Tributary	Mean	2.24	20.19	66.83	10.73	4.48	1.70	3.18
		SE	2.71	7.64	7.38	2.80	0.84	0.40	0.67

that rapidly transport sediments and MP particles from their sources through the river and its tributaries, ultimately depositing them in the sea. This process may also erode, disturb, resuspend, and redistribute MPs already present in river and tributary sediments. Consequently, the rainy season results in a more balanced MP concentration between the main river and its tributaries. Conversely, the dry season's low rainfall leads to slower flow rates, causing MPs to accumulate closer to their sources, particularly in tributaries connected to urban areas where plastic waste is generated. The main Saigon River, influenced by tidal forces and water from the upper basin, maintains a relatively stronger flow compared to its tributaries. This phenomenon leads to higher MP concentrations in the tributaries and lower levels in the river during the dry season, as observed in Fig. 1. These findings support the study's first hypothesis that MP concentrations are greater in tributary sediments than in river sediments, particularly during the dry season. This seasonal and spatial variation in MP distribution highlights the complex dynamics of MP pollution in urban river systems and emphasizes the need for season-specific management strategies.

The size, color, and shape of MPs significantly influence their environmental impact and can serve as indicators of pollution levels and associated ecological risks (Saeedi, 2024). Smaller MPs pose a greater threat due to their increased bioavailability and potential for environmental harm as these tiny particles are readily ingested by organisms and can enter various organs, potentially causing toxicity to the host (Ziani et al., 2023). In the current study, 26.7 %, 43.4 %, and 20.3 % of the total MP items belonged to the size groups below 200 μm, 200–500 μm, and 500–1000 μm, respectively. The prevalence of these smaller sizes suggests a higher level of MP pollution in the study waterways. Additionally, the predominance of smaller MP particles indicates strong decomposition processes occurring in the river and its tributaries, suggesting extensive environmental processing. In the meantime, MP color can reflect their ability to absorb pollutants. While multiple factors influence the coloration of MPs, darker colors might suggest the adsorption of persistent organic pollutants and heavy metals (Rafa et al., 2024), whereas whiter colors might suggest relatively uncontaminated MPs that are either newly formed or recently deposited in the sediment. Regarding shape, the current study found the highest percentage of fiber-like particles, consistent with findings from a similar river study but in a water environment (Khuyen et al., 2022). MP shapes can indicate their origins and determine their properties and environmental impacts, which are discussed in more detail in the following sections.

This study found that approximately 90.4 % of identified MPs were smaller than 1000 μm, supporting the second research hypothesis predicting a predominance of smaller MP particles. These small MPs likely originate from the plastic particles being initially produced in small sizes, such as clothing fibers, cosmetic ingredients, road paints, and microbeads, or the breakdown of larger plastic debris over time (Chen et al., 2023). A considerable proportion of the small-sized MPs could be derived from the broken large particles in the current study. The aged plastic debris in sediment is more likely broken down, forming new ones with lighter colors. In addition, the current study found that white-colored MPs were predominant, occupying more than 44 % of the total MPs identified, which is in agreement with the other study (Sarkar et al., 2023). High percentages of lighter-colored MPs could be the consequence of the more rapid decomposition of darker-colored MPs compared to their white counterparts. The underlying mechanism for this difference likely stems from the high sensitivity to UV light decomposition of MPs (Alavian Petroody et al., 2023) and the greater UV absorption capacity of darker-colored plastics. This leads to a low proportion of darker-colored MPs in the current study, compared to white-colored MPs. These findings highlight the presence of significant MP pollution in the studied waterway, dominated by smaller and lighter-colored particles. These findings also suggest potential sources of both primary and secondary microplastics and emphasize the need for further research to fully understand the mechanisms of microplastic degradation and the ecological impacts of these tiny plastic particles.

Identifying the pollution sources of MPs in the current study is crucial for developing effective mitigation strategies and improving waste management practices. The study revealed significantly higher MP concentrations in tributaries compared to the main Saigon River at most sampling sites, with a strong correlation between river and tributary sediment MP levels. The finding suggests that there should be a linkage in MP concentrations between the two waterways and that MPs may primarily originate from urban areas within the city rather than from the upper basin of the Saigon River. Land-based plastic waste in riparian areas has been identified as a significant contributor to marine pollution (Sadri et al., 2014). Residential houses were identified as a major point source of MP pollution through the discharge of municipal wastewater from residential areas (Jessieleena et al., 2023).

In general, MPs in the environment can come from two main sources: primary and secondary MPs (Ziani et al., 2023). This study's findings suggest that the observed MPs are primarily secondary in nature, based on the predominance of fiber MPs and the significant proportion of fragment MPs. The fiber shape, comprising 50.2 % of the total MPs, likely originates from the breakdown of synthetic textiles, laundry lint, carpets, and synthetic upholstery (Acharya et al., 2021). Likewise, filament-shaped MPs are thought to derive mainly from decomposed agricultural equipment and municipal wastewater containing clothing fibers (Claessens et al., 2011). In addition, fishing gear, atmospheric deposition, and surface runoff are potential sources of MP fibers (Browne et al., 2011). MP fibers can be made from various polymer types, including polyamide, polystyrene, and polyethylene (Sarkar et al., 2023; Cole, 2016), which are also shown in the IR spectra in Fig. 6. In addition to the fibrous form, plastic fragments in the sediment might come from the decomposition of plastic waste such as agricultural implements, plastic packaging materials, and plastic bags (Antunes et al., 2013). Personal care products and manufactured plastic products can be broken down gradually into secondary plastic particles. Therefore, industrial production, agricultural production, and domestic wastewater can be potential sources of MPs in the current study.

This study's findings suggest that residential, industrial, and agricultural activities in Ho Chi Minh City's urban areas are the primary sources of MP pollution affecting the Saigon River and its tributaries. Among the eleven sampling sites, sites 5 and 10 exhibited the highest MP concentrations. Site 5, located at the confluence of the Saigon River and the Nhieu Loc - Thi Nghe canal, is characterized by densely populated residential areas and concentrated community services. Site 10, situated at the junction of the Saigon River and the Vam Thuat River 2, features significant agricultural activities, industrial facilities, and horticultural production. These diverse land use patterns and activities serve as the primary sources of MP contamination in the sediments of both the Saigon River and its tributaries, particularly the Nhieu Loc - Thi Nghe Canal and Vam Thuat River 2. The high MP concentrations at sites 5 and 10 likely reflect the cumulative impact of these pollution sources. This spatial variation in MP concentrations highlights the complex interplay between urban development, land use, and MP pollution.

This study revealed higher overall MP concentrations in tributary sediments compared to river sediments, with smaller MPs (<200 μm) more prevalent in river sediments and larger MPs (200–1000 μm) more common in tributary sediments across both seasons (Fig. 5). These findings support the third hypothesis that tributaries contain higher MP concentrations and larger particles than rivers, which predominantly held smaller particles. Pollution source and water flow in the river system may explain the finding. Urban areas, particularly residential, industrial, and agricultural activities, are identified as primary MP pollution sources. Areas closer to these pollution sources typically exhibit higher total MP content, while more distant regions show a greater proportion of smaller MP particles. This patten explains the higher MP concentration observed in the tributaries compared to the river. In addition, stronger flows in rivers may reduce MP levels, whereas slower currents in tributaries may enhance MP accumulation. However, these factors alone cannot explain why the proportion of smaller MPs is higher in the main river than in the tributaries. To address this discrepancy, theories regarding MP transport and decomposition mechanisms were proposed.

Given that the majority of observed MPs are secondary in nature and presumably originate from urban areas, the following theory of MP transport and decomposition is proposed for future investigation: At pollution sources, larger plastic debris is initially deposited in sediments. Rain and water flow gradually transport these plastic-containing sediments towards tributary mouths and the Saigon River as a main flow. This process results in MP loss and reduces overall MP content while increasing the proportion of small MPs due to degradation during transport. This theory explains the higher total MP concentrations in tributaries but the higher proportion of small MPs in the river. The degradation of plastics along with their transport from sources to sinks in tributaries and the river, plays a crucial role in this theory. An alternative theory suggesting that small MP particles are transported farther from their source compared to larger particles seems less plausible, given our earlier discussion that MPs in the study area are primarily of secondary origin. Moreover, both large and small MPs, as defined in this study, would be easily carried by the flow of the river or tributaries, making it difficult to distinguish transport distances based on size. These suggest that the second theory is less robust, leaving the first hypothesis as the more likely explanation. While these hypotheses are based on observed results and current knowledge, they require further verification through additional field studies to fully understand the complex dynamics of MP transport and degradation in urban river systems.

Overall, the finding from the current study emphasizes the need for season-specific management strategies, as MP distribution patterns vary between dry and rainy seasons. Effective management should consider both spatial (river vs. tributary) and temporal (seasonal) variations in MP distribution. More specific management strategies should be more targeted, focusing on source-specific interventions, seasonally adapted measures, size-based treatments, and location-specific controls. Additionally, the findings, based on MPs in sediments being primarily of secondary origin, highlight the importance of addressing the entire lifecycle of plastics, from production to disposal and environmental degradation. The study underscores the need for comprehensive solutions, including regulatory measures, improved waste management practices, public education, and continued research to mitigate MP pollution's impact on aquatic ecosystems and human health.

5. Conclusions

The current study revealed that the microplastic (MP) concentration in the sediment of the Saigon River and its tributaries ranged from 140 to 1200 items kg^{-1}. The predominant characteristics of MPs in this study were fiber particles, white color, and particle sizes ranging from 200 to 500 μm. During the rainy season, MP concentrations were statistically similar between the river and tributaries, while during the dry season, tributaries exhibited statistically higher MP concentrations than the river. This indicates that the MP concentrations were significantly influenced by the interplay of seasonal variation and waterway differences. This interplay can be attributed to water flow patterns and pollution sources, primarily originating from urban residential, industrial, and agricultural activities. High rainfall and increased water flow during the rainy season facilitate MP transport from their sources to their sinks through the river and its tributaries, resulting in more balanced MP concentrations across these waterways. Conversely, low rainfall and slower water flow during the dry season led to MP accumulation closer to their sources, resulting in higher MP concentrations in tributaries compared to the river. Interestingly, the river, despite being farther from the sources, had a higher proportion of smaller MPs (less than 200 μm). In contrast, larger MPs ($>$200 μm) were more prevalent in tributaries. This distribution pattern suggests a potential size-dependent transport mechanism for MPs in the water system. These findings highlight the complex dynamics of MP pollution in river systems and emphasize the importance of considering seasonal variations, water flow patterns, and proximity to pollution sources in developing effective strategies for MP management and mitigation.

CRediT authorship contribution statement

Nguyen Xuan Tong: Writing – original draft, Supervision, Resources, Methodology, Investigation, Data curation. **Vo Thi Kim Khuyen:** Writing – original draft, Validation, Software, Methodology, Formal analysis. **Nguyen Thi Thanh Thao:** Writing – original draft, Methodology, Formal analysis. **Binh Thanh Nguyen:** Writing – review & editing, Writing – original draft, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This research is supported by the Industrial University of Ho Chi Minh City (IUH) under grant number 108/HD-DHCN. The authors would like to thank the Industrial University of Ho Chi Minh City (IUH), colleagues, and students at the Institute of Environmental Science, Engineering and Management (IESEM-IUH) for providing support for this research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.123348.

Data availability

The authors do not have permission to share the data.

References

Acharya, S., Rumi, S., Hu, M., Abidi, N., 2021. Microfibers from synthetic textiles as a major source of microplastics in the environment: a review. Textil. Res. J. 91. https://doi.org/10.1177/0040517521991244.

Alam, F.C., Sembiring, E., Muntalif, B.S., Suendo, V., 2019. Microplastic distribution in surface water and sediment river around slum and industrial area (case study: ciwalengke River, Majalaya district, Indonesia). Chemosphere 224, 637–645. https://doi.org/10.1016/j.chemosphere.2019.02.188.

Alavian Petroody, S.S., Hashemi, S.H., Škrlep, L., Mušič, B., van Gestel, C.A.M., Sever Škapin, A., 2023. UV light causes structural changes in microplastics exposed in biosolids. Polymers 15 (21), 4322. https://doi.org/10.3390/polym15214322.

Alves, V.E.N., Figueiredo, G.M., 2019. Microplastic in the sediments of a highly eutrophic tropical estuary. Mar. Pollut. Bull. 146, 326–335. https://doi.org/10.1016/j.marpolbul.2019.06.042.

Antunes, J.C., Frias, J.G.L., Micaelo, A.C., Sobral, P., 2013. Resin pellets from beaches of the Portuguese coast and adsorbed persistent organic pollutants. Estuar. Coast Shelf Sci. 130, 62–69. https://doi.org/10.1016/j.ecss.2013.06.016.

Ashrafy, A., Liza, A.A., Islam, M.N., Billah, M.M., Arafat, S.T., Rahman, M.M., Rahman, S.M., 2023. Microplastics pollution: a brief review of its source and abundance in different aquatic ecosystems. Journal of Hazardous Materials Advances 9, 100215. https://doi.org/10.1016/j.hazadv.2022.100215.

Borriello, L., Scivicco, M., Cacciola, N.A., Esposito, F., Severino, L., Cirillo, T., 2023. Microplastics, a global issue: human exposure through environmental and dietary sources. Foods 12 (18). https://doi.org/10.3390/foods12183396.

Browne, M.A., Crump, P., Niven, S.J., Teuten, E., Tonkin, A., Galloway, T., 2011. Accumulation of microplastic on shorelines woldwide: sources and sinks. Environ. Sci. Technol. 45, 9175–9179. https://doi.org/10.1021/es201811s.

Campanale, C., Savino, I., Massarelli, C., Uricchio, V.F., 2023. Fourier Transform infrared spectroscopy to assess the degree of alteration of artificially aged and environmentally weathered microplastics. Polymers 15 (4). https://doi.org/10.3390/polym15040911.

Chen, Y.-N., Rani, A., Chiang, C.-Y., Kim, H., Pan, S.-Y., 2023. Monitoring, control and assessment of microplastics in bioenvironmental systems. Environ. Technol. Innovat. 32, 103250. https://doi.org/10.1016/j.eti.2023.103250.

Claessens, M., Meester, S.D., Landuyt, L.V., Clerck, K.D., Janssen, C.R., 2011. Occurrence and distribution of microplastics in marine sediments along the Belgian coast. Mar. Pollut. Bull. 62, 2199–2204. https://doi.org/10.1016/j.marpolbul.2011.06.030.

Cole, M., 2016. A novel method for preparing microplastic fibers. Sci. Rep. 6 (1), 34519. https://doi.org/10.1038/srep34519.

Corcoran, P., Belontz, S., Ryan, K., Walzak, M., 2020. Factors controlling the distribution of microplastic particles in benthic sediment of the Thames River, Canada. Environ. Sci. Technol. 54, 818–825. https://doi.org/10.1021/acs.est.9b04896.

Dimassi, S.N., Hahladakis, J.N., Yahia, M.N.D., Ahmad, M.I., Sayadi, S., Al-Ghouti, M.A., 2022. Degradation-fragmentation of marine plastic waste and their environmental implications: a critical review. Arab. J. Chem. 15 (11), 104262. https://doi.org/10.1016/j.arabjc.2022.104262.

Emenike, E.C., Okorie, C.J., Ojeyemi, T., Egbemhenghe, A., Iwuozor, K.O., Saliu, O.D., Okoro, H.K., Adeniyi, A.G., 2023. From oceans to dinner plates: the impact of microplastics on human health. Heliyon 9 (10), e20440. https://doi.org/10.1016/j.heliyon.2023.e20440.

Haque, F., Fan, C., 2023. Fate and impacts of microplastics in the environment: hydrosphere, pedosphere, and atmosphere. Environments 10 (5), 70.

He, B., Wijesiri, B., Ayoko, G.A., Egodawatta, P., Rintoul, L., Goonetilleke, A., 2020. Influential factors on microplastics occurrence in river sediments. Sci. Total Environ. 738, 139901. https://doi.org/10.1016/j.scitotenv.2020.139901.

Jaubet, M.L., Hines, E., Elías, R., Garaffo, G.V., 2021. Factors driving the abundance and distribution of microplastics on sandy beaches in a Southwest Atlantic seaside resort. Mar. Environ. Res. 171, 105472. https://doi.org/10.1016/j.marenvres.2021.105472.

Jessieleena, A., Rathinavelu, S., Velmaiel, K.E., John, A.A., Nambi, I.M., 2023. Residential houses — a major point source of microplastic pollution: insights on the various sources, their transport, transformation, and toxicity behaviour. Environ. Sci. Pollut. Control Ser. 30 (26), 67919–67940. https://doi.org/10.1007/s11356-023-26918-1.

Kalaronis, D., Ainali, N.M., Evgenidou, E., Kyzas, G.Z., Yang, X., Bikiaris, D.N., Lambropoulou, D.A., 2022. Microscopic techniques as means for the determination of microplastics and nanoplastics in the aquatic environment: a concise review. Green Analytical Chemistry 3, 100036. https://doi.org/10.1016/j.greeac.2022.100036.

Khan, L., Ghias, S., Zafar, M.I., Alhodaib, A., Fatima, H., Ur-Rehman, T., Waseem, A., Howari, H., 2022. Exploration of microplastic pollution with particular focus on source identification and spatial patterns in riverine water, sediment and fish of the Swat River, Pakistan. RSC Adv. 12 (16), 9556–9566. https://doi.org/10.1039/D2RA00319H.

Khuyen, V.T.K., Le, D.V., Anh, L.H., Fischer, A.R., Dornack, C., 2022. Assessing microplastic dispersion from saigon urban canals via can gio mangrove reserve to East Sea in Vietnam by Raman scattering microscopy. MDPI Microplastics 1 (3), 536–553. https://doi.org/10.3390/microplastics1030038.

Kye, H., Kim, J., Ju, S., Lee, J., Lim, C., Yoon, Y., 2023. Microplastics in water systems: a review of their impacts on the environment and their potential hazards. Heliyon 9 (3), e14359. https://doi.org/10.1016/j.heliyon.2023.e14359.

Lahens, L., Strady, E., Le, K., Dris, R., Boukerma, K., Rinnert, E., Gasperi, J., Tassin, B., 2018. Macroplastic and microplastic contamination assessment of a tropical river (Saigon River, Vietnam) transversed by a developing megacity. Environ. Pollut. 236, 661–671. https://doi.org/10.1016/j.envpol.2018.02.005. DOI.

Luu, V.D., Huu Duc, T., Thi Khanh Linh, L., Thi Dieu Ly, T., Anh Duong, H., Thi My Hao, N., 2021. Depth profiles of microplastics in sediment cores from two mangrove forests in Northern Vietnam. J. Mar. Sci. Eng. 9 (12), 1381. https://doi.org/10.3390/jmse9121381.

Mao, R., Song, J., Yan, P., Ouyang, Z., Wu, R., Liu, S., Guo, X., 2021. Horizontal and vertical distribution of microplastics in the Wuliangsuhai Lake sediment, northern China. Sci. Total Environ. 754, 142426. https://doi.org/10.1016/j.scitotenv.2020.142426.

Naderi Kalali, E., Lotfian, S., Entezar Shabestari, M., Khayatzadeh, S., Zhao, C., Yazdani Nezhad, H., 2023. A critical review of the current progress of plastic waste recycling technology in structural materials. Curr. Opin. Green Sustainable Chem. 40, 100763. https://doi.org/10.1016/j.cogsc.2023.100763.

Nayebi, B., Khurana, P., Pulicharla, R., Karimpour, S., Brar, S.K., 2023. Preservation, storage, and sample preparation methods for freshwater microplastics – a comprehensive review. Environmental Science: Advances 2 (8), 1060–1081. https://doi.org/10.1039/D3VA00043E.

Ng, C.H., Mistoh, M.A., Teo, S.H., Galassi, A., Ibrahim, A., Sipaut, C.S., Foo, J., Seay, J., Taufiq-Yap, Y.H., Janaun, J., 2023. Plastic waste and microplastic issues in Southeast Asia. Front. Environ. Sci. 11. https://doi.org/10.3389/fenvs.2023.1142071.

Nguyen, B.T., Do, D.D., Nguyen, T.X., Nguyen, V.N., Phuc Nguyen, D.T., Nguyen, M.H., Thi Truong, H.T., Dong, H.P., Le, A.H., Bach, Q.-V., 2019. Seasonal, spatial variation, and pollution sources of heavy metals in the sediment of the Saigon River, Vietnam. Environ. Pollut., 113412 https://doi.org/10.1016/j.envpol.2019.113412.

Nguyen, T.N.T., Du, N.X., Hoa, N.T., 2023. Emission source areas of fine particulate matter (PM2.5) in Ho Chi Minh City, Vietnam. Atmosphere 14 (3), 579. https://doi.org/10.3390/atmos14030579.

Nuelle, M.T., Dekiff, J.H., Remy, D., Fries, E., 2014. A new analytical approach for monitoring microplastics in marine sediments. Environ. Pollut. 184, 161–169. https://doi.org/10.1016/j.envpol.2013.07.027.

Osman, A.I., Hosny, M., Eltaweil, A.S., Omar, S., Elgarahy, A.M., Farghali, M., Yap, P.-S., Wu, Y.-S., Nagandran, S., Batumalaie, K., Gopinath, S.C.B., John, O.D., Sekar, M., Saikia, T., Karunanithi, P., Hatta, M.H.M., Akinyede, K.A., 2023. Microplastic sources, formation, toxicity and remediation: a review. Environ. Chem. Lett. 21 (4), 2129–2169. https://doi.org/10.1007/s10311-023-01593-3.

Peng, G.Y., Zhu, B.S., Yang, D.Q., Su, L., Shi, H.H., Li, D.J., 2017. Microplastics in sediments of the changjiang estuary, China. Environ. Pollut. 225, 283–290. https://doi.org/10.1016/j.envpol.2016.12.064.

Rafa, N., Ahmed, B., Zohora, F., Bakya, J., Ahmed, S., Ahmed, S.F., Mofijur, M., Chowdhury, A.A., Almomani, F., 2024. Microplastics as carriers of toxic pollutants: source, transport, and toxicological effects. Environ. Pollut. 343, 123190. https://doi.org/10.1016/j.envpol.2023.123190.

Ryan, J., Estefan, G., Rashid, A., 2007. Soil and Plant Analysis Laboratory Manual. ICARDA.

Saad, D., Ndlovu, M., Ramaremisa, G., Tutu, H., Sillanpää, M., 2024. Characteristics of microplastics in sediment of the Vaal River, South Africa: implications on bioavailability and toxicity. Int. J. Environ. Sci. Technol. 21 (1), 43–50. https://doi.org/10.1007/s13762-023-05168-1.

Sadri, S., Thompson, R.C., 2014. On the quantity and composition of floating plastic debris entering and leaving the Tamar Estuary, Southwest England. Mar. Pollut. Bull. 81, 55–60. https://doi.org/10.1016/j.marpolbul.2014.02.020.

Saeedi, M., 2024. How microplastics interact with food chain: a short overview of fate and impacts. J. Food Sci. Technol. 61 (3), 403–413. https://doi.org/10.1007/s13197-023-05720-4.

Sarkar, S., Diab, H., Thompson, J., 2023. Microplastic pollution: chemical characterization and impact on wildlife. Int. J. Environ. Res. Publ. Health 20 (3). https://doi.org/10.3390/ijerph20031745.

Sheraz, M., Kim, J., Kim, J., 2023. Nano/microplastics in indoor air: a critical review of synthesis routes for toxicity testing and preventative measure strategies. Process Saf. Environ. Protect. 180, 274–304. https://doi.org/10.1016/j.psep.2023.10.002.

Thacharodi, A., Meenatchi, R., Hassan, S., Hussain, N., Bhat, M.A., Arockiaraj, J., Ngo, H. H., Le, Q.H., Pugazhendhi, A., 2024. Microplastics in the environment: a critical overview on its fate, toxicity, implications, management, and bioremediation strategies. J. Environ. Manag. 349, 119433. https://doi.org/10.1016/j.jenvman.2023.119433.

Thepwilai, S., Wangritthikraikul, K., Chawchai, S., Bissen, R., 2021. Testing the factors controlling the numbers of microplastics on beaches along the western Gulf of Thailand. Mar. Pollut. Bull. 168, 112467. https://doi.org/10.1016/j.marpolbul.2021.112467.

Trinh, B.-S., Vu, D.N., Luyen, P.T.B., Huy, P.C., 2021. A separation of plastic debris in Saigon river sediment using a microplastic sediment separator. Science & Technology Development Journal – Science of The Earth & Environment 5 (SI1), SI137–SI146. https://doi.org/10.32508/stdjsee.v5iSI1.588.

Vaughan, R., Turner, S.D., Rose, N.L., 2017. Microplastics in the sediments of a UK urban lake. Environ. Pollut. 229, 10–18. https://doi.org/10.1016/j.envpol.2017.05.057.

Wang, W.F., Ndungu, A.W., Li, Z., Wang, J., 2017. Microplastics pollution in inland freshwaters of China: a case study in urban surface waters of Wuhan, China. Sci. Total Environ. 575, 1369–1374. https://doi.org/10.1016/j.scitotenv.2016.09.213.

Wang, W.Z., Song, J.X., Zhang, G.T., Liu, Q., Guo, W.Q., Tang, B., 2018. The influence of hyporheic upwelling fluxes on inorganic nitrogen concentrations in the pore water of the Weihe River. Ecol. Eng. 112, 105–115. https://doi.org/10.1016/j.ecoleng.2017.12.012.

Wen, H., Xu, H., Ma, Y., Zhang, C., Zhang, D., Wang, X., 2024. Diverse and high pollution of microplastics in seasonal snow across Northeastern China. Sci. Total Environ. 907, 167923. https://doi.org/10.1016/j.scitotenv.2023.167923.

Wu, H., Hou, J., Wang, X., 2023. A review of microplastic pollution in aquaculture: sources, effects, removal strategies and prospects. Ecotoxicol. Environ. Saf. 252, 114567. https://doi.org/10.1016/j.ecoenv.2023.114567.

Xia, F., Yao, Q., Zhang, J., Wang, D., 2021. Effects of seasonal variation and resuspension on microplastics in river sediments. Environ. Pollut. 286, 117403. https://doi.org/10.1016/j.envpol.2021.117403.

Ziani, K., Ioniță-Mîndrican, C.B., Mititelu, M., Neacşu, S.M., Negrei, C., Moroşan, E., Drăgănescu, D., Preda, O.T., 2023. Microplastics: a real global threat for environment and food safety: a state of the art review. Nutrients 15 (3). https://doi.org/10.3390/nu15030617.