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Occurrence, fate, and an outlook on management strategies in Asia

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DOI
10.1016/B978-0-443-23775-1.00001-1

Publication date
2024

Document Version
Final published version

Published in
Solid Waste Management for Resource-Efficient Systems

Citation (APA)
Zhang, Z., Mohapatra, S., & Jong, M. C. (2024). The flow of microplastics from wastewater to the urban aquatic environment: Occurrence, fate, and an outlook on management strategies in Asia. In R. Singh, S. Mohapatra, & M.-C. Jong (Eds.), *Solid Waste Management for Resource-Efficient Systems: Circularity in Action* (pp. 115-142). Elsevier. https://doi.org/10.1016/B978-0-443-23775-1.00001-1

CHAPTER

6

The flow of microplastics from wastewater to the urban aquatic environment: Occurrence, fate, and an outlook on management strategies in Asia

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OUTLINE

Solid Waste Management for Resource-Efficient Systems
https://doi.org/10.1016/B978-0-443-23775-1.00001-1

1 Introduction

1.1 Plastic pollution burden

We currently live in the "plastic epoch." As a typical organic polymer, plastic production is growing at an exponential rate in the contemporary economy (Drummond et al., 2022), whereby vast reliance on plastic products has resulted in their imprudent use, especially in single-use plastics, causing imminent environmental pollution due to unsustainable management of plastic resources (Geyer et al., 2017; Walker et al., 2021). According to statistics, humanity produces over 430 million tons of plastic every year, two-thirds of which soon become waste and are improperly disposed of in landfills and/or in the natural surroundings (UNEP, 2023), forming "white pollution" in the land, ocean, plateau, and even glaciers (Lusher et al., 2015; Wang and Zhou, 2023).

Plastics typically have stable-long polymer chains that exhibit remarkable persistence in the environment (expected centuries), where they gradually break down into small debris through processes involving photo-, bio-, and physical degradation (Kubowicz and Booth, 2017). Among them, microsized plastic particles smaller than 5 mm are called microplastics (MPs) (Thompson et al., 2004), consisting of (i) primary MPs produced directly for added in personal care products and cosmetics (Alimi et al., 2018; Rochman et al., 2015) and (ii) secondary MPs derived from fragmentation of larger plastics via environmental weathering and degradation processes including ultraviolet aging, mechanical abrasion, and wave impact (Andrady, 2017; Bao et al., 2022). MPs pollution has become an urgent global environmental issue in the 21st century because they are ubiquitous and poses complex ecological hazard risks (Kershaw et al., 2011). The significant sources of MPs contamination in the environment arise from urban, industrial, and agriculture discharges, including plastic microbeads from scrubs, the breakdown of plastic products, washing of synthetic fiber clothing, abrasion of tire rubber, wastewater discharge, agricultural plastic crushing, and shipping/fishery emissions (Hale et al., 2020).

1.2 Plastics, especially MPs is a serious problem

MPs pollution deserves heightened attention. Based on their small size and durability, MPs continue to persist for ages and migrate across various large-scale compartments, including the air (Liu et al., 2019), terrestrial (Rillig and Lehmann, 2020), water sources (Schymanski et al., 2018), food (Kwon et al., 2020), and even within human/animal bodies (Ragusa et al., 2021; Wright and Kelly, 2017), where they have potential to cross the intestinal mucosal and the blood-brain barrier, causing inflammation, neurological disorders, and neurotoxicity (Kopatz et al., 2023). Apart from their physical presence, MPs act as a "planet" of pollutants:

on the one hand, MPs release chemical additives manufactured in plastic products to enhance material performance; on the other hand, MPs also adsorb pollutants from the environment owing to their considerable hydrophobic surface area (Gunaalan et al., 2020). Furthermore, as organic compounds, MPs readily attract microbial colonization, forming plastisphere comprising diverse microbial communities, which may potentially harbor pathogenic bacteria such as antibiotic-resistant bacteria and associated resistance genes (Amaral-Zettler et al., 2020; Wu et al., 2019). Thereby, MPs aggregates facilitate the spread of contaminants.

1.3 Urban aquatic environment is a hotspot for MPs

About 80% of oceanic plastics originate from land-based sources, entering marine realms via the water flow (Malli et al., 2022). Urban areas are the primary consumption hubs for plastic products and therefore the most serious areas of plastics/MPs pollution, where the dense population and intense industrial activity in urban regions, as well as the challenges of waste recycling and disposal, lead to a higher concentration of mismanaged wastes (Baldwin et al., 2016). Being the direct interface between human activities and the natural environment, and due to their higher mobility, urban aquatic compartments have become significant reservoirs for environmental MPs (Fig. 1). MPs originating from domestic and industrial sources spread with wastewater, rainwater, and surface runoff, as well as precipitation of airborne MPs by rainwater adds to MPs loads in water flow (Sun et al., 2022). Therefore, as a vital resource for life and economic activities (e.g., drinking water, recreational, and manufacturing), the urban

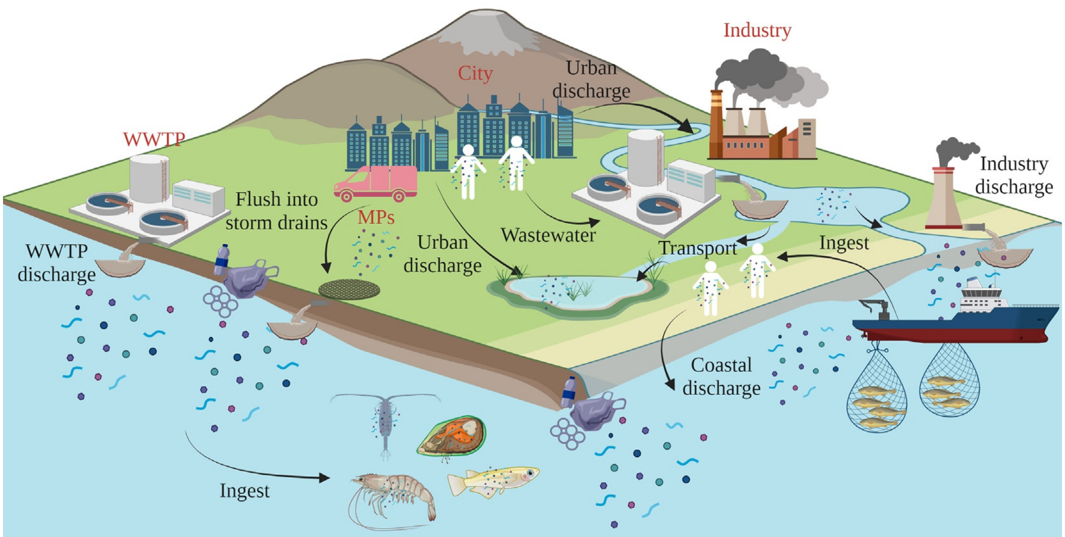

FIG. 1 Source and transport of land-based MPs in urban aquatic compartments through major water flow (WWTP, river, lake, and estuary).

aquatic environment is critical for human exposure to MPs, for which MPs have been found to be transported into the human body through the water and food based on their small size and lack of effective retention technologies, increasing the risk of MPs toxicity (Zhang et al., 2022b).

1.4 Outline of this chapter

As research on MPs pollution in aquatic environment progresses, quantifying and exploring the transport of MPs are crucial for contamination control. This chapter discusses the contamination of MPs in the urban aquatic environment, specifying the effect of wastewater treatment plants (WWTPs), rivers, lakes, and estuaries on MPs migration. WWTPs and estuaries offer potential control sites for the spread of MPs, where water-borne MPs converge and accumulate, allowing mitigation measures such as interception to take place. Influenced by physical properties, hydraulic dynamics, and biological influences, MPs would also settle, aggregate, break, and resuspend with water flow. These processes disturb the transport flux of MPs into the ocean. Finally, this chapter discusses the management strategies for MPs pollution control, including policy management, retention technologies in WWTPs, and the use of biodegradable MPs, with increasing mitigation efforts against MPs pollution crisis.

2 Occurrence of MPs in urban aquatic compartments

MPs are released directly or indirectly into the aquatic systems through both point and diffuse sources. Among them, MPs from land-based anthropogenic activities are being transported to WWTPs via the urban sewerage network (Napper and Thompson, 2016; Rochman et al., 2015). Through wastewater treatment processes and depending on the technology applied, 50%–95% of MPs would settle into sludge (Cydzik-Kwiatkowska et al., 2022; Lares et al., 2018), while others are released with the effluent into rivers or coastal oceans (Murphy et al., 2016; Woodward et al., 2021). Based on the huge effluent volume, WWTPs are considered to be an important point source of MPs discharge (Carr et al., 2016; Schmidt et al., 2020). MPs discharged into rivers navigate through water flow into inland lakes, reservoirs, and coastal cities to the oceans (Baldwin et al., 2016; Zhao et al., 2019). Once MPs reach the ocean, they further disperse with seawater and accumulate across coastal shallow seas and deep seas (Kane et al., 2020). As such, urban aquatic environments present opportunities for pollution intervention. In this chapter, we focus on the MPs contamination in three connected urban aquatic compartments (wastewater, freshwater, and estuaries) and their role in MPs pollution control.

2.1 Wastewater

Wastewater discharge is a prominent point source of MPs to the natural water (Murphy et al., 2016). Large amounts of MPs released during household and personal washing or industrial cleaning operations, as well as the wear of car tires and paint particles contained in urban stormwater runoff, are transported through sewers to WWTPs (Cheung and Fok, 2017;

Hale et al., 2020). Through conventional wastewater treatment process, more than 80% of MPs could be captured in sludge while others are released with the bulk effluent into receiving waters such as rivers and oceans (Lares et al., 2018; Talvitie et al., 2017b). However, even with advanced unit processes with high removal efficiencies (i.e., membrane filtration), the large quantities of effluent would eventually introduce considerable amounts of MPs to natural aquatic compartments (Alvim et al., 2020; Parashar and Hait, 2023). For example, an Italian WWTP with a wastewater treatment capacity of 4.0×10^8 L wastewater per day could release approximately 1.6×10^8 MPs in total via the daily outflow, with treated effluent containing 0.4 ± 0.1 MP particles/L (Magni et al., 2019). Likewise, a WWTP located in Finland (averaged effluent concentration $= 1.0 \pm 0.4$ MP particles/L) could contribute to daily loading of 1.0×10^7–4.6×10^8 MPs per day (Lares et al., 2018). Table 1 summarizes the discharge of MPs from typical WWTP effluents worldwide, ranging from 4.19×10^4 to 1.5×10^9 particles/day.

It is worth noting that most published studies focused on MPs discharges in advanced WWTPs, while there are still many areas where wastewater treatment facilities are inadequate, especially across some developing countries in South America and Southeast Asia (Woodward et al., 2021). Even in developed countries like the United States and Canada, some sewage with primary-only treatment is permitted to be discharged into open marine areas (Hale et al., 2020; Johannessen et al., 2015). However, untreated wastewater outflow like these poses a higher MPs burden to the aquatic environment.

2.2 Freshwater

2.2.1 Rivers

As the direct discharge site for wastewater effluents, freshwater systems receive major input of MPs from WWTPs (Woodward et al., 2021; Zhang et al., 2022c), and other MPs from land-based anthropogenic activities that are flushed into waterways through runoffs (Talbot and Chang, 2022). As such, rivers are important transport pathways for MPs, particularly to the marine environments (Zhao et al., 2019). It was estimated that the annual influx of plastic waste into marine was 0.8–2.7 million metric tons (Meijer et al., 2021), further complicating mitigation efforts for MPs contamination due to the wide-scale riverine input and efficient distribution through the running water medium (Table 2) (Malli et al., 2022). Inland rivers contribute to MPs pollution in lakes and reservoirs, even in remote areas such as lakes on the Tibetan plateau (Lenaker et al., 2019; Liang et al., 2022).

MPs contamination in rivers is usually influenced by the proximity of the stream to urban or industrial sites, or the effluents of WWTPs (Alimi et al., 2018), and is often positively correlated with population density (Talbot and Chang, 2022). Present studies of MPs pollution in rivers have mostly concentrated in large or major watersheds (Table 2). The abundance of MPs at the surface of the Rhine (one of the largest European rivers) was 8.93×10^5 particles/km^2 on average (Mani et al., 2015). In the Yangtze River, the world's third-largest river, the average abundance of MPs in surface water and sediments across the basin was 1.27 particles/L and 286.20 particles/kg, respectively (Yuan et al., 2022).

Despite the larger watersheds have attracted more attention, a study by Meijer et al. (2021) found that the size of the river itself does not determine how much plastic debris is transported into the ocean. The study concluded other factors including the environmental

TABLE 1 Global studies on the abundance of MPs in WWTPs.

Region	Country	Treatment processes	Sampling method	Minimum mesh size	Detection method	Influent (particles/L)	Effluent (particles/L)	Discharge (particles /day)	Ref.
Asia	China	Primary, secondary, tertiary	Grab sampling	50 μm	Microscope, FTIR	12.03 ± 1.29	0.59 ± 0.22	$5.9 \pm 2.2 \times 10^8$	Yang et al. (2019a)
	China	Primary, secondary	Pump	43 μm	Microscope, Raman	1.57–13.69	0.20–1.73	6.5×10^8	Long et al. (2019)
	China	Primary, secondary	Grab sampling	13 μm	Microscope, Raman	18–890	6–26	/	Wang et al. (2020)
	Iran	Primary, secondary	Grab sampling	25 μm	Microscope	9.2	0.84	2.4×10^7	Takdastan et al. (2021)
	Vietnam	Primary, secondary	Grab sampling	1.6 μm	Microscope, FTIR	183–443	138–340	$3.8 \times 10^7 - 1.5 \times 10^9$	Do et al. (2022)
	Turkey	Primary, secondary	Grab sampling	55 μm	Microscope, Raman	26.5	7.0	1.2×10^6	Gundogdu et al. (2018)
	Turkey	Primary, secondary	Grab sampling	55 μm	Microscope, Raman	23.4	4.1	3.5×10^5	Gundogdu et al. (2018)
Europe	France	Primary, secondary	Autosampler	100 μm	Microscope	293	35	8.40×10^9	Dris et al. (2015)
	Scotland	Primary, secondary	Grab sampling	65 μm	Microscope	15.7	0.25	6.52×10^7	Murphy et al. (2016)
	Italian	Primary, secondary, tertiary	Grab sampling	63 μm	Microscope, FTIR	2.5 ± 0.3	0.4 ± 0.1	1.60×10^8	Magni et al. (2019)
	Sweden	Primary, secondary	Pump	300 μm	Microscope, FTIR	15.1	0.00825	4.25×10^4	Magnusson and Norén (2014)

	Germany	Primary, secondary	Pump	10 µm	FTIR	/	0.08–7.52	4.19×10^4–1.24×10^7	Mintenig et al. (2017)
	Finland	Primary, secondary	Grab sampling	250 µm	Microscope, FTIR, Raman	57.6	1	1.00×10^7	Lares et al. (2018)
	Finland	Primary, secondary, tertiary	Pump	20 µm	Microscope	610	13.5	3.65×10^9	Talvitie et al. (2017b)
	Finland	Primary, secondary, tertiary	Pump	20 µm	Microscope, FTIR	/	0.02–0.3	1.26×10^6–6.59×10^7	Talvitie et al. (2017a)
North America	United States	Primary, secondary	Pump	125 µm	Microscope	/	0.004–0.195	5.28×10^4–1.49×10^7	Mason et al. (2016)
	United States	Primary, secondary, tertiary	Pump	125 µm	Microscope	/	0.009–0.127	1.01×10^5–9.63×10^6	Mason et al. (2016)
	United States	Primary, secondary	Pump	100 µm	Microscope, FTIR	1	8.8×10^{-4}	9.30×10^5	Carr et al. (2016)
Oceania	Australia	Primary	Pump	25 µm	Microscope, FTIR	/	1.5	4.60×10^8	Ziajahromi et al. (2017)
	Australia	Primary, secondary	Pump	25 µm	Microscope, FTIR	/	0.4	8.16×10^6	Ziajahromi et al. (2017)
	Australia	Primary, secondary, tertiary	Pump	25 µm	Microscope, FTIR	/	0.21–0.28	$3.60 \times 10^6 - 1.00 \times 10^7$	Ziajahromi et al. (2017)

Note: FTIR, Fourier transformed infrared.

TABLE 2 Global studies on the abundance of MPs in freshwater.

Region	Country	Location	Sample	Sampling method	Minimum mesh size	Detection method	Abundance	Ref.
Asia	China	The Yangtze River	Surface water	Steel sampler	48 µm	Microscope, Raman	1.27 particles/L	Yuan et al. (2022)
	China	The Yangtze River	Sediment	Steel sampler	/	Microscope, Raman	286.20 particles/kg	Yuan et al. (2022)
	China	Pearl River	Surface water	Plankton net	160 µm	Microscope, FTIR	Spring: 0.14 ± 0.01 to 0.37 ± 0.05 particles/L Summer: 0.14 ± 0.01–0.35 ± 0.08 particles/L Winter: 0.36 ± 0.01 to 1.96 ± 0.90 particles/L	Fan et al. (2019)
	China	Pearl River along Guangzhou City, China	Surface water	Water sampler	50 µm	Microscope, FTIR, SEM/EDS	19.86 particles/L	Yan et al. (2019)
	China	Taihu Lake	Surface water	Plankton net	333 µm	Microscope, FTIR, SEM	3.4–25.8 particles/L	Su et al. (2016)
	China	The Three Gorges Reservoir	Surface water	Pump	48 µm	Microscope, Raman	1.60–12.6 particles/L	Di and Wang, 2018)
	China	The Three Gorges Reservoir	Sediment	Van Veen Grab	48 µm	Microscope, Raman	25–300 particles/kg wet weight	Di and Wang, 2018)
	Thailand	Chao Phraya River	Surface water	Manta trawl	300 µm	Microscope, FTIR	0.042 particles/L	Ta and Babel, 2019)
	Malaysia	Dungun River	Surface water	Stainless steel bucket	60 µm	Microscope, FTIR	0.0228–0.300 particles/L	Tee et al. (2020)
	Vietnam	Saigon River	Surface water	Plankton net	300 µm	Microscope, FTIR	0.01–519.22 particles/L	Lahens et al. (2018)
	India	Vembanad Lake	Sediment	Van Veen grab	/	Microscope, Raman	252.80 ± 25.76 particles/m^2	Sruthy and Ramasamy (2017)

Europe	Germany	Rhine River	Surface water	Manta net	300 μm	Microscope, FTIR	8.93×10^5 particles/km^2	Mani et al. (2015)
	France	Seine River	Surface water	Plankton net and manta trawl	80 μm (Plankton net) and 330 μm (Manta trawl)	Microscope	0.003–0.106 (Plankton net) and 0.00028–0.00045 (Manta trawl) particles/L	Dris et al. (2015)
	Finland	Kallavesi Lake	Surface water	Manta trawl and pump	333 μm (Manta trawl) and 20 μm (Pump)	Microscope, FTIR	$(2.70 \pm 1.80) \times 10^{-4}$ (Manta trawl) and 0.17 ± 0.09 (Pump) particles/L	Uurasjarvi et al. (2020)
	The United Kingdom	Kelvin River	Sediment	Grab	11 μm	Microscope, SEM/EDS	161–432 particles/kg dry weight	Blair et al. (2019)
	Italy	Bolsena Lake	Surface water	Manta trawl	300 μm	Microscope, SEM	0.00082–0.00442 particles/L	Fischer et al. (2016)
	Italy	Bolsena Lake	Sediment	Grab	/	Microscope, SEM	112 particles/kg dry weight	Fischer et al. (2016)
	Italy	Chiusi Lake	Surface water	Manta trawl	300 μm	Microscope, SEM	0.00268–0.00336 particles/L	Fischer et al. (2016)
	Italy	Chiusi Lake	Sediment	Grab	/	Microscope, SEM	234 particles/kg dry weight	Fischer et al. (2016)
North America	The United States	Milwaukee River Basin to Lake Michigan	Surface water	Neuston net	355 μm	Microscope, FTIR	0.00021–0.0191 particles/L	Lenaker et al. (2019)
	Canada	Ottawa River	Surface water	Manta trawl	100 μm	Microscope	0.71–1.99 particles/L	Vermaire et al. (2017)
	Canada	Ottawa River	Sediment	Grab	100 μm	Microscope	220 particles/kg dry weight	Vermaire et al. (2017)
	Canada	Winnipeg Lake	Surface water	Manta trawl	333 μm	SEM/EDS	2014: $(5.25–74.80) \times 10^4$ particles/km^2	Anderson et al. (2017)

Continued

TABLE 2 Global studies on the abundance of MPs in freshwater—cont'd

Region	Country	Location	Sample	Sampling method	Minimum mesh size	Detection method	Abundance	Ref.
							2015: (6.92–26.60) × 10^4 particles/km^2 2016: (6.68–29.34) × 10^4 particles/km^2	
South America	Brazil	Jurujuba Cove	Surface water	Plankton net	150 μm	Microscope, FTIR	0.0164 particles/L	Castro et al. (2016)
Africa	South Africa	Durban Harbor	Surface water	Zooplankton net	300 μm	Microscope, FTIR	0.00703 ± 0.01193 particles/L	Naidoo et al. (2015)
	South Africa	Durban Harbor	Sediment	Corer	20 μm	Microscope, FTIR	1490.8 ± 259.4 particles/L	Naidoo et al. (2015)
	South Africa	Bloukrans River	Sediment	Grab	63 μm	Microscope	Summer: 6.3 ± 4.3 particles/kg Winter: 160.1 ± 139.5 particles/kg	Nel et al. (2018)

Note: SEM, scanning electron microscopy; EDS, energy dispersive spectroscopy.

pathways of plastics transport (such as water flow and wind effects), geographical features of watershed (such as distance to the ocean), and the retention of plastics within river basins may be more important, since some smaller rivers were discovered to transport more plastics than large river basins. The study further stated that rivers located in areas with small land surface areas and high precipitation rates are more likely to emit marine plastics compared to the length of their coastline. Therefore, it is necessary to forecast MPs emissions from rivers globally, with a focus on controlling higher MPs emission in rivers. Overall, Asian rivers are responsible for the majority (86%) of global plastic emissions.

2.2.2 *Lakes, ponds, and reservoirs*

Compared to rivers with continuous flow (i.e., higher mobility), lakes, ponds, and reservoirs usually serve as temporary or long-term sinks for MPs (Table 2) (Vivekanand et al., 2021). The average abundance of plastic debris in Lake Baikal, the world's largest freshwater lake, is around 4.2×10^4 particles/km^2, among which 91.6% were classed as MPs (Il'ina et al., 2021). The highest abundance of plastic particles detected in the study (around 7.5×10^4 particles/km^2) was similar to the average values for ocean "garbage patches" in the subtropics (Cozar et al., 2017). In the Three Gorges Reservoir, China, the average concentration of MPs in surface waters was 4703 ± 2816 particles/m^3, ranging from 1597 to 12611 particles/m^3, and 25 to 300 particles/kg wet weight in sediments (Di and Wang, 2018). As a dam located upstream of the Yangtze Estuary, it forms a barrier that traps MPs, thus behaving as a potential reservoir (He et al., 2021). It is noteworthy that the majority of inland aquatic systems serve as sources of drinking water for the local population, which increases the probability of MPs entering the human body (Sarijan et al., 2021). Furthermore, influenced by atmospheric deposition, runoff, and snowfall, even the remote locations with minimal human disturbance, such as the Antarctic (Waller et al., 2017), Arctic (Gonzalez-Pleiter et al., 2020), and Tibetan plateau lakes (Dong et al., 2021), have been contaminated with MPs.

2.3 Estuarine

Estuaries are the passage and transition regions connecting freshwater and marine realms. The bi-directional flow of freshwater and seawater forms heterogeneous boundaries where MPs flowing toward the ocean may be temporarily retained here (Malli et al., 2022). Some of the MPs come from the upstream rivers while others originate from the direct discharge of anthropogenic-induced wastes near the estuary, such as tourism, fishery, and industrial facilities (Gray et al., 2018). Concentrations of MPs in estuaries are often reported to be higher than in the open ocean (Wessel et al., 2016). Comparing the samples from the Yangtze Estuary and the East China Sea, the abundance of MPs was 4137.3 ± 2461.5 and 0.167 ± 0.138 particles/m^3, respectively (Zhao et al., 2014). The significant reduction in abundance is attributed to oceanic dilution. Therefore, estuaries provide distinctive possibilities to mitigate MPs contamination in rivers and prevent the transport of MPs into the ocean (Wang et al., 2022).

The distribution of MPs in estuaries is complicated by the effects of salinity, rainfall, tides, turbulence, and windage (Cohen et al., 2019; Pinheiro et al., 2021). The relative concentration of MPs increases upstream during tidal influx and then rises seawards when river flows disrupt this gradient (Lebreton et al., 2017). Density properties, bioaccumulation, aggregation, and salinity result in varied spatial distribution, whereas wind direction and intensity affect the spatiotemporal distribution in the water column (Miao et al., 2021; Wang et al., 2022). Daily versus monthly tides as well as seasonal flows were found to vary the concentration of MPs temporally (Malli et al., 2022). Therefore, the sampling locations and time significantly impact the concentration of MPs. Compounding these effects, several researchers also reported higher MPs concentration in sediments than in the water, which hinders the migration of MPs from rivers to the seawater (Gray et al., 2018; Wu et al., 2020a). The low water flows decrease turbulence and promote the deposition of MPs into sediments, as well as geophysical disturbances such as dredging and earthworks, or bioturbation may enhance the burial of MPs within the sediments (Diaz-Jaramillo et al., 2021; Waldschlager et al., 2020). Therefore, it is hypothesized that estuarine sediments may act as the repository for MPs (McEachern et al., 2019). Table 3 shows studies relating MPs concentrations in the estuarine water column and sediment.

3 Fate and accumulation of MPs in the aquatic compartments

Similar to other natural substances, MPs experience intricate migration and modification processes in the natural aquatic compartments. However, owing to their resistance to natural degradation, MPs tend to endure in diverse forms and properties within aquatic ecosystems for prolonged durations. This section discusses the intricate dynamics of MPs migration, accumulation, and transformation in aquatic environments within the influence of natural factors and biological interactions, as well as the implications of special interface "estuarine front."

3.1 Transport and transformation of MPs in water system

The transport of MPs is a complex process, heavily influenced by hydraulic conditions, rainfall, river morphology, dams, vegetation, etc. (Yan et al., 2021). During the wet season, rainfall usually leads to an increase in surface runoff, resulting in significant quantities of MPs transported downstream (Cheung et al., 2016; Zhao et al., 2020). Higher river flow intensities would also resuspend MPs from sediments into the water column, further increasing the MPs transport flow (Lima et al., 2015). While during the dry season, the decreased turbulences are expected to increase the deposition of MPs in sediments (Malli et al., 2022). Considering the morphology of the river, inner outer bends tend to trap more MPs than straight river channels (Corcoran et al., 2020). Furthermore, dams can trap and retain MPs, as well as riparian vegetation has the potential to decelerate flow velocity and settle MPs from the water column, thereby reducing the downstream migration (Di and Wang, 2018; Wu et al., 2020a).

Apart from the hydrodynamic fields, factors including the particles' physical properties (density, shape, size), biofouling, and aggregation would also affect MPs movement (Wang et al., 2022). For example, MPs with larger sizes and higher densities, such as polyvinyl chloride (PVC, 1.30–1.58 g/cm^3) and polyethylene terephthalate (PET, 1.29–1.40 g/cm^3), are more prone to deposition from the water column (Horton and Dixon, 2018). While there

TABLE 3 Global studies on the abundance of MPs in estuaries.

Region	Country	Location	Sample	Sampling method	Minimum mesh size	Detection method	Abundance	Ref.
Asia	China	The Yangtze Estuary	Surface water	Pump	32 μm	Microscope	4.14 ± 2.46 particles/L	Zhao et al. (2014)
	China	The lower Yellow River near the estuary	Surface water	Stainless steel bucket	50 μm	Microscope/ FTIR	Dry season: 623–1392 particles/L; Wet season: 380–582 particles/L	Han et al. (2020)
	China	Hong Kong coastline (the Pearl River Estuary)	Beaches	Grab	315 μm	Microscope	520 ± 688 particles/m^2	Fok and Cheung, 2015)
	Malaysia	Lukut Estuary	Surface water	Van Dorn	25 μm	Microscope/ FTIR	4.17 particles/L	Zainuddin et al. (2022)
	Indonesia	Jagir Estuary	Sediment	Grab	300 μm	Microscope/ FTIR	92–590 particles/kg dry weight	Firdaus et al. (2020)
	India	Kayamkulam Estuary	Sediment	Grab	/	Microscope/ FTIR	433 particles/kg dry weight	Radhakrishnan et al. (2021)
Europe	Spain	Ebro River Estuary	Surface water	Neuston net	5 μm	Microscope/ FTIR	0.0035 ± 0.0014 particles/L	Simon-Sanchez et al. (2019)
	Spain	Ebro River Estuary	Sediment	Grab	/	Microscope/ FTIR	2050 ± 746 particles/kg dry weight	Simon-Sanchez et al. (2019)
	Spain	Ebro River Estuary	Beaches	Stainless-steel spoon	/	Microscope/ FTIR	422 ± 119 particles/kg dry weight	Simon-Sanchez et al. (2019)
	France	Bay of Brest	Surface water	Manta trawl	335 μm	Microscope/ Raman	0.00024 ± 0.00035 particles/L	Frere et al. (2017)
	France	Bay of Brest	Sediment	Grab	/	Microscope/ Raman	0.97 ± 2.08 particles/kg dry weight	Frere et al. (2017)
North America	The United States	Chesapeake Bay	Surface water	Manta net	300 μm	Microscope/ Raman	<1.0–563 particles/km^2	Yonkos et al. (2014)

Continued

TABLE 3 Global studies on the abundance of MPs in estuaries—cont'd

Region	Country	Location	Sample	Sampling method	Minimum mesh size	Detection method	Abundance	Ref.
	The United States	Winyah Bay	Sediment	Grab	63 μm	Microscope/FTIR	221.0 ± 25.6 particles/m^2	Gray et al. (2018)
	The United States	Charleston Harbor	Sediment	Grab	63 μm	Microscope/FTIR	413.8 ± 76.7 particles/m^2	Gray et al. (2018)
	Mexico	Mobile Bay northern Gulf of Mexico Estuary)	Sandy sediment	Grab	200 μm	Microscope/FTIR	5–117 particles/m^2	Wessel et al. (2016)
South America	Brazil	Jurujuba Cove	Surface water	Plankton net	150 μm	Microscope/FTIR	0.0164 particles/L	Castro et al. (2016)
	Argentina	Río de la Plata Estuary	Surface water	Bucket	36 μm	Microscope	0.139 particles/L	Pazos et al. (2018)
	Argentina	Río de la Plata Estuary	Surface water	Plankton mesh	36 μm	Microscope/FTIR	0.005–0.11 particles/L	Pazos et al. (2021)
	Argentina	Río de la Plata Estuary	Sediment	Grab	250 μm	Microscope/FTIR	154 particles/m^2	Pazos et al. (2021)
	Argentina	SW Atlantic Estuaries	Sediment	Aluminum tube core	100 μm	Microscope/FTIR	0–1030 ± 657 particles/kg dry weight	Diaz-Jaramillo et al. (2021)
Africa	South Africa	Durban Harbor	Surface water	Zooplankton net	300 μm	Microscope/FTIR	0.00703 ± 0.01193 particles/L	Naidoo et al. (2015)
	South Africa	Durban Harbor	Sediment	Corer	20 μm	Microscope/FTIR	1490.8 ± 259.4 particles/L	Naidoo et al. (2015)

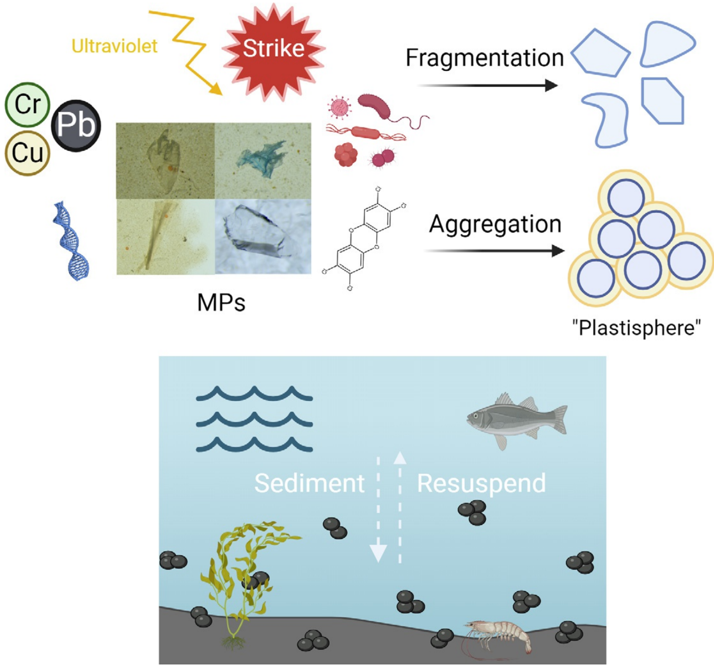

FIG. 2 Transformations of waterborne MPs.

are also some buoyant MPs including polyethylene (PE) and polypropylene (PP) being detected in sediments, which could be explained by the aggregation of MPs. Aggregation is a crucial process that dominates both vertical and horizontal transport of MPs in water systems, involving the interaction between MPs themselves (Song et al., 2019) or MPs with other contaminants such as metals, minerals, sediments, organism, and so on (Wang et al., 2021) (Fig. 2). For instance, aggregation with microorganisms, i.e., growth of microorganisms would alter the surface properties of MPs, forming plastisphere that influence the density of particles (Kaiser et al., 2017; Wu et al., 2020b). When the overall density surpasses that of the water, the biofouled MPs would deposit (Kooi et al., 2017). The hydrophobic and high surface area features of MPs enable them to serve as carriers to transport organic pollutants, pathogens, heavy metals and resistance genes, etc., promoting spread of these pollutants (Rochman et al., 2014; Wu et al., 2019; Yang et al., 2019b).

As such, transformations of MPs within aquatic environments can be ascribed to physicochemical and biological alterations. Affected by photodegradation, biodegradation, hydraulic shock, and weathering processes, MPs tend to age, become brittle, and fragment into smaller pieces during transport (Fig. 2). Photodegradation leads to the autocatalytic thermal oxidation of plastic polymers, resulting in the weaken and breakage of MPs (Song et al., 2017). Mechanical forces such as sand abrasion, wave and wind action, and interactions with biological particles can wear and separate the weathered surface layer into micro/nanoplastics (Ter Halle et al., 2016). This fragmentation is responsible for the generation of most secondary MPs in the environment, exacerbating the difficulty of MPs pollution control.

The aging process further impacts the surface properties of MPs, increasing the roughness and content of oxygen-containing functional groups, causing changes in the polarity, hydrophilicity, and charge of the MPs surface, which further disturb the environmental behavior of MPs and may lead to synergistic effects of their transportation (Zha et al., 2022). The further decrease in particle size will weaken the van der Waals force between aged MPs and porous medium, thus the deposition of MPs in the porous medium will be weakened and the migration ability will be enhanced (Yan et al., 2020). The increase of oxygen-containing functional groups enhances the surface charge negativity and the hydrophilicity of MPs, which is a key factor facilitating the transport of MPs (Fei et al., 2022). Furthermore, aging of MPs also improves their adsorption capacity to organic pollutants and microorganisms, which alters their surface characteristics and affected the migration of MPs (Bhagat et al., 2022; Luo et al., 2022). Therefore, the transport of MPs is influenced by their properties and interaction with the surrounding aquatic environment, and the mobility of aged MPs is generally greater compared to their pristine counterparts (Fei et al., 2022).

3.2 Convergence of MPs at estuarine fronts

The interaction between buoyant freshwater and high-density seawater propels significant fluctuations in salinity, forming robust density fronts in estuaries (Giddings et al., 2012; Wang et al., 2022). In comparison with ambient waters, estuarine fronts are typically accompanied by strong horizontal convergence, vertical velocities, and turbulent mixing, where MPs transported into estuaries are more likely to amass (Fig. 3) (van Sebille et al., 2020). Significantly higher concentrations of MPs at estuarine fronts (0.089–2.20 particles/L; 0.3–5.0 mm) were found compared to those detected in the open-ocean sites (0.0014–0.12 particles/L) (Wang et al., 2022). Therefore, as recurring transition zones between land-based plastics sources and the open-ocean, estuarine fronts possess the capacity to accumulate high loads

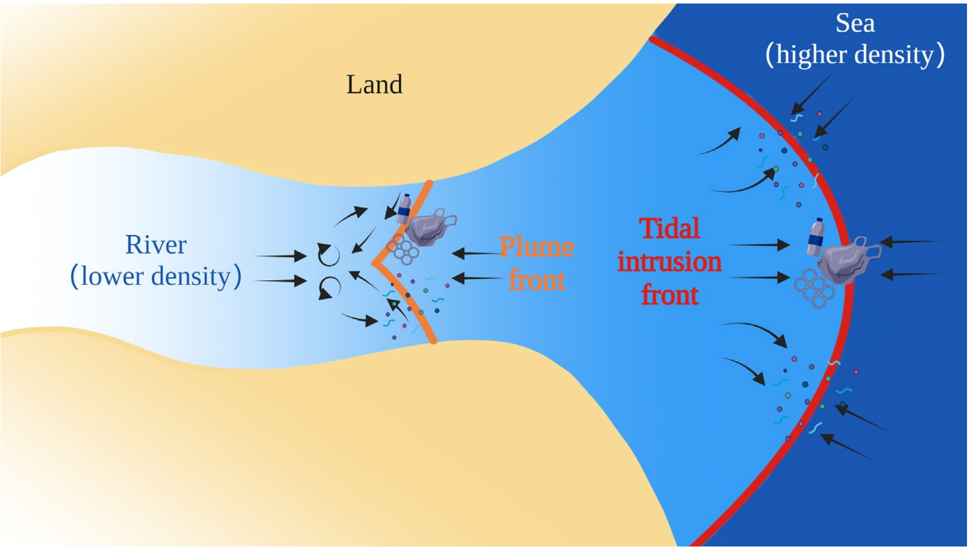

FIG. 3 Convergence of MPs at estuarine fronts (plume/tidal intrusion).

of MPs (Malli et al., 2022). Due to the strong hydrodynamics and biological enrichment, MPs in the fronts will also undergo processes of fragmentation, aggregation, biofouling, and sinking (McWilliams, 2021; Taylor, 2018; Zhao et al., 2015). In future studies, estuarine fronts can act as potential sites for MPs pollution control.

3.3 Accumulation and transfer of MPs in aquatic biota

Owing to their small size, especially those smaller than 1 mm, MPs are easily ingested by aquatic biotas (Zhu et al., 2019). Currently, aquatic organisms such as zooplanktons, mussels, fishes, crabs, and shrimps have been reported to be polluted with MPs (Gong et al., 2021; Rashid et al., 2021; Wang et al., 2023). The average retention of MPs in the eastern Arabian Sea's faunas was 0.03 ± 0.01 particles/individual for copepods, 0.14 ± 0.06 particles/individual for decapods, and 0.57 ± 0.18 particles/individual for fish larvae (Rashid et al., 2021). In the rivers of Chongming Island, the average abundances of MPs in the shrimps were 1.92 ± 0.52 particles/g and 1.49 ± 0.30 particles/g wet weight, respectively (Wang et al., 2023).

Ingested MPs move with the organisms, some of which would be excreted in feces and subsequently returned to the ambient environment (Yin et al., 2018). The feces of many aquatic biotas typically possess mucus binding, which could trap particles and promote the aggregation of MPs (Arlinghaus et al., 2021; Zhao et al., 2018). MPs that are not excreted from the biotas will accumulate in the body or translocated to different tissues/organs, thereby moving with the food chain and ultimately entering the human body through seafood consumption (Lehel and Murphy, 2021; Mamun et al., 2023). MPs are also found accumulated in seabirds following the ingestion of contaminated fishes or shrimps (Suhring et al., 2022). More than ingestion, MPs can also adhere to the surface of some organisms. High concentrations of MPs were detected in the feet of mussels and the proportion of adherent MPs accounted for 42%–59% of the total MPs in the tissue of mussels (Kolandhasamy et al., 2018). Thus, the movement and seasonal migration of aquatic biotas promote the spread of MPs pollution.

4 Management strategies for MPs pollution control

Implementation of a concerted plan is promptly needed to ameliorate plastics and MPs pollution. At a global scale, the United Nations is instigating multinational joint commitment (175 nations have signed up) to mitigate plastic contamination, with the aim to forge an international legally binding agreement, by the end of 2024 (UNEP, 2022). Scientific understanding through research programs is important and basal knowledge support to provide policy and management recommendations for addressing global plastics issue. In this section, we delineate existing management approaches to reduce levels of MPs contamination in the aquatic environment.

4.1 Approaches for plastic waste treatment

In recent years, increasing biodegradable polymers have been developed as an eco-friendly alternative to traditional plastics, which commonly harbor an ester bond formed during polymerization and would be degraded by microorganisms into less hazardous metabolites such as water, carbon dioxide, methane, and biomass (Samir et al., 2022). Nowadays, biodegradable plastics gradually replacing nonbiodegradable plastics in several uses such as plastic bags and packaging. In healthcare systems, biodegradable polymers are also employed in vital applications such as soft tissue engineering and gene therapy (Samir et al., 2022). However, due to the fast but incomplete degradation of biodegradable plastics in nature, biodegradable plastics seem to break down into MPs more quickly. Emissions of chemicals from biodegradable plastics during natural degradation (Qin et al., 2021), and their co-exposure with emerging contaminants warrant further investigations (Eregowda and Mohapatra, 2020; Mohapatra et al., 2021, 2022, 2023).

Breaking down plastics with enzymes represents another option, applicable to both biodegradable and traditional nonbiodegradable plastics. Enzymatic degradation splits polymers into their constituent components or monomers, which can then be repurposed in the new plastic products. This approach offers a promising solution to mitigate plastic waste and its environmental impact, fostering the development of more sustainable waste management and recycling practices (Kwon, 2023). However, despite its potential to reduce plastic and MPs pollution, enzyme-based recycling still faces certain limitations. In one respect, the technology remains costly. Based on estimation, enzymatic recycling of PET costs about twice as much as the virgin product, and up to four times higher than mechanical recycling; it also consumes more energy and releases more greenhouse gases (Uekert et al., 2023). Additionally, it is highly selective. So far, the enzyme approach seems to be exclusively applied to PET and polyurethane (PU), the polymers which might be more readily degraded due to they are not composed exclusively of carbon-carbon bonds. In contrast, other plastics, such as PE, PP, and polystyrene (PS), which are linked together by carbon–carbon bonds, pose greater challenges to tackle (Zhang et al., 2022a).

In further researches, interdisciplinary technologies need to be developed to alleviate the pressure of global plastic contamination. For example, organisms such as waxworms and mealworms, as well as associated microorganisms can accelerate the biodegradation of plastics through mechanisms including biodeterioration, depolymerization, assimilation, and mineralization (Brandon et al., 2018; Yang et al., 2014).

4.2 WWTP as critical control points

WWTPs represent major point-source discharge, which can serve as the site for MPs interception. Untreated wastewater loaded with MPs has been discharged into rivers, resulting in significant MPs contamination of riverbed (Woodward et al., 2021). Therefore, removing MPs from wastewater is one crucial step in reducing their contamination in the natural environment. Typically, physical processes during the primary treatment step can remove a major proportion of MPs (40%–60%), thereafter biological and physicochemical processes in secondary and tertiary treatments further capture the remaining MPs (70%–90%) (Magni et al., 2019; Parashar and Hait, 2023).

Among the treatment technologies commonly employed in WWTPs, filter and biofilter, settling, grit tank, coagulation, and membrane bioreactor achieved better performance in MPs removal (Liu et al., 2021; Parashar and Hait, 2023). Anaerobic-anoxic-oxic (A^2O), the most commonly used process in WWTPs, is not suitable for MPs removal because the returned sludge would carry MPs back (Liu et al., 2021). But it promotes the aggregation of MPs and activated sludge that is further removed in the sedimentation tank. Advanced treatment techniques like membrane disc filter, rapid sand filter, reverse osmosis, and ultrafiltration could also remove over 90% of MPs from secondary-treated effluent (Parashar and Hait, 2023). However, the use of filters requires frequent maintenance because MPs may clog the filters and reduce the effectiveness of wastewater treatment. The retention of MPs should be balanced with the effectiveness of wastewater treatment.

However, wastewater treatment facilities are still inadequate in some countries in Asia. In Cambodia, only 5% of urban wastewater can be treated by the centralized WWTPs, while other wastewater is predominantly treated by septic tanks before being discharged. A similar situation also occurs in Nepal, where only around 7% of the collected wastewater can be treated while 93% is disposed of untreated. Inadequate wastewater treatment significantly exacerbates MPs contamination in natural aquatic bodies (WEPA, 2021). Overflows from wastewater facilities during wet weather cause MPs bypass from the retention systems. MPs emissions from a single overflow event are approximately 4–5 times higher than daily effluent discharge (Zhou et al., 2023). Therefore, wastewater-bound MPs pollution control in Asia remains a pressing challenge.

4.3 Management strategies in Asia

Asia accounts for 30% of the world's land area and possesses 30% of the world's freshwater resources, supporting approximately 60% of the global population (WEPA, 2021). With the expand of regional populations and economies, Asia experiences challenges related to water pollution, leading to the deterioration of the living environment, decreasing water resources, and degradation of ecosystem services. It was reported that Asian rivers were highly polluted and contributed approximately 86% of global plastic emissions, with the top 10 polluted rivers located in the Philippines, India, and Malaysia (Meijer et al., 2021). Therefore, the task of plastic control in Asia is urgent.

Considering the difficulty of removing MPs due to their small size, mitigating at source, such as reducing emissions of plastic tends to be an option. In 2023, the United Nations Environmental Programme reported "Turning off the Tap: How the world can end plastic pollution and create a circular economy," proposing to accelerate three key shifts—reuse, recycle, and reorient and diversify—along with actions to address the legacy of plastic pollution. In Asia, some countries are taking proactive solution-focused measures to combat pollution.

(i) Plastic import ban. Developing countries, especially in Southeast Asia, have imported large amounts of waste plastic for decades (Wen et al., 2021). Responding to the severe plastic pollution crisis, in 2017, the Chinese government established an import ban on importing plastic waste, before which China was the world's largest importer of plastic waste, annually receiving an average of 8 million tons of plastic from over 90 nations globally (Isarin, 2023). It was anticipated that the ban in China would displace around 111 million metric tons of plastic waste by 2030 (Brooks et al., 2018). In 2023, the Thai government announced the ban on all plastic waste imports by 2025. Only 14 waste-based manufacturers in the free trade zone are allowed to import plastic waste this year, but with no more than the total production capacity of these companies (equivalent to approximately 372,000 all plastic waste imports by 2025); by 2024, inflows will be halved before the total ban on importing plastic waste (Isarin, 2023).

(ii) Roadmap toward zero single-use plastics. Single-use plastic products epitomize convenience, but with the pollution they cause during production, consumption, and litter, a critical finding is that "single-use" is more problematic than "plastic" (UNEP, 2021). Most of these plastics are designed to be used only once and disposed of subsequently, which leads to rapid accumulation of disposable plastic waste. It was estimated that only 9% of the nine billion tons of plastic the world has ever produced has been recycled (Parker, 2018; WWF, 2022). In response to this issue, Malaysia has deployed a roadmap toward zero single-use plastics from 2018 leading up to 2030 (MESTECC, 2018), including encouraging customers to bring their own food containers, no straws by default, and expanding the use of biodegradable and compostable products, etc. In the roadmap, the responsibility of Government, manufacturers, suppliers, business operators, nongovernmental organizations, and publics also be considered and Malaysia will ban all plastic bags by 2025. Similarly, Indonesia also declared a total ban on single-use plastic products, including PS foam used for food, single-use plastic straws, plastic cutlery, and plastic shopping bags, by the end of 2029. At present, a number of Asian countries, including China, Malaysia, Thailand, Indonesia, and India, have restricted the manufacture and use of single-use plastics through various policies.

(iii) Plastic interceptor. To clean up plastic pollution in the environment, some governments have organized plastic salvaging from lakes and rivers as downstream solution. Besides governmental efforts, nongovernmental organizations also actively involved in providing educational and scalable technological solutions to help reduce plastic pollution. As a highlight, plastic interception was introduced as a physical method to prevent the release of plastics downstream through setting up U-shaped floating barriers (Gramling, 2018). Indonesia, Malaysia, and Vietnam have installed plastic interceptors to close the "plastics tap" in rivers. Nevertheless, the efficiency and ecological impact of the interceptors are under explored. The nature of the interceptor is still being optimized to achieve plastic interception through a more automatic, efficient, and cost-effective method.

(vi) Precise polices and increase of public awareness in the future. In China, plastic pollution regulations began in the early 1990s, but there were only four plastic-pertinent policies until 2000 (Fuerst and Feng, 2022). During the 13th Five-Year Plan (2016–2020), the efforts of plastic pollution control have been greatly accelerated with the policy awakening of the government, including the ban on imports of plastic waste, establish of a plastic recycling system, etc. Public opinion advances political leaders to act to draft regulations. Also, the government's efforts have raised public awareness for the use of plastic alternatives and waste sorting. People are educated from young to protect the environment and take away rubbish. Since 2016, the growth trend of plastic products production and consumption has decelerated while the recycling rate has risen, exceeding 30% in 2021 (Liu and Liu, 2023). Therefore, the establishment of regulations and polices, as well as increase in public awareness and educating citizens would help for reduction in the production of plastics waste and environmental plastic pollution. However, there are still some limitations on the efficacy of the restrictions' policy impacts. For example, the production, sale, and use of plastic bags have been eliminated, while in practical implementation more attention has been focused on the consumer side without effective control at the source; restricting the use of plastic microbeads in personal care products is merely the initial stage of MPs management (Liu and Liu, 2023; Yu and Ma, 2022). Therefore, regulations should be more precise to incentivize both plastic pollution mitigation and technological innovation in the future work. Furthermore, wider and sound education system help public in comprehending the source and fate processes, ecological risks, and health hazards of plastics/MPs, as well as the impact of plastic production and pollution on the environmental sustainability and the energy consumption, in order to strengthen the fight against plastic/MPs pollution.

5 Conclusion and future outlook

The aquatic environment is a crucial medium for the dissemination of MPs contamination, once in which MPs will undergo a complex process. This section summarized the occurrence, transport, aggregation, and transformation of MPs in the urbanized aquatic compartments (including wastewater, freshwater, and estuarine); discussed the management strategies as well as policies for MPs pollution control with Asia as an example. Currently, the aquatic environment has been extensively polluted by MPs. Among them, WWTPs not only retain MPs pollution from domestic wastewater but also act as the significant point source of MPs discharge into the water system. Rivers are important transport pathways for MPs, and lakes, ponds, and reservoirs usually serve as sinks. As for estuarine fronts, due to the unique density differentials that form the "marine garbage belt," which can be important site for the retention and salvaging of MPs. The application of biodegradable polymers has alleviated the pressure of plastic contamination to a certain extent. The improvement of public awareness and the establishment of governmental management policies are the keys to defeating MPs contamination in addition to technological intervention. At present, the widespread environmental problems caused by MPs still deserve attention; drawing upon current research, the following recommendations are proposed for future work:

(1) At present, many studies have investigated MPs contamination in urban aquatic environments. The lack of standardized experimental methods (including sampling protocols, MPs extraction, and identification), nonetheless, has created challenges in data comparisons. In addition, the limitations of existing quantitative and qualitative techniques make experiments time-consuming. Therefore, efficient techniques such in situ detection could facilitate the development of MPs research.

(2) Studies on the migration of MPs are primarily based on model simulations, during which researchers should analyze and discuss the retention of MPs and the factors that influence their transport, rather than assessing solely on the number of plastic products manufactured or the population. In addition, multiple interrelated aquatic environments should be conducted on a continuous basis, to form a research model of SLA (spot-line-area).

(3) Influenced by local economic and infrastructural constraints, not all countries can achieve a better outcome on plastic and MPs pollution control. While MPs pollution is a global issue, feasible solutions should be tailored to local and/or regional conditions. Regionally, a joint strategy could be culminated to catalyze, collaborate, and apply long-tern solutions relating to plastic usage and plastic resource management from a regional scale, especially through emission containment.

Acknowledgments

This work was supported by the Guangdong Higher Education Institutions Innovative Research Team of Urban Water Cycle and Ecological Safety (2023KCXTD053).

References

Alimi, O.S., Budarz, J.F., Hernandez, L.M., Tufenkji, N., 2018. Microplastics and nanoplastics in aquatic environments: aggregation, deposition, and enhanced contaminant transport. Environ. Sci. Technol. 52, 1704–1724.

Alvim, C.B., Mendoza-Roca, J.A., Bes-Pia, A., 2020. Wastewater treatment plant as microplastics release source—quantification and identification techniques. J. Environ. Manage. 255.

Amaral-Zettler, L.A., Zettler, E.R., Mincer, T.J., 2020. Ecology of the plastisphere. Nat. Rev. Microbiol. 18, 139–151.

Anderson, P.J., Warrack, S., Langen, V., Challis, J.K., Hanson, M.L., Rennie, M.D., 2017. Microplastic contamination in Lake Winnipeg, Canada. Environ. Pollut. 225, 223–231.

Andrady, A.L., 2017. The plastic in microplastics: a review. Mar. Pollut. Bull. 119, 12–22.

Arlinghaus, P., Zhang, W.Y., Wrede, A., Schrum, C., Neumann, A., 2021. Impact of benthos on morphodynamics from a modeling perspective. Earth-Sci. Rev. 221.

Baldwin, A.K., Corsi, S.R., Mason, S.A., 2016. Plastic debris in 29 great lakes tributaries: relations to watershed attributes and hydrology. Environ. Sci. Technol. 50, 10377–10385.

Bao, R.Q., Cheng, Z.R., Hou, Y.P., Xie, C.L., Pu, J.R., Peng, L.C., et al., 2022. Secondary microplastics formation and colonized microorganisms on the surface of conventional and degradable plastic granules during long-term UV aging in various environmental media. J. Hazard. Mater. 439.

Bhagat, K., Barrios, A.C., Rajwade, K., Kumar, A., Oswald, J., Apul, O., et al., 2022. Aging of microplastics increases their adsorption affinity towards organic contaminants. Chemosphere 298.

Blair, R.M., Waldron, S., Phoenix, V.R., Gauchotte-Lindsay, C., 2019. Microscopy and elemental analysis characterisation of microplastics in sediment of a freshwater urban river in Scotland, UK. Environ. Sci. Pollut. R 26, 12491–12504.

Brandon, A.M., Gao, S.H., Tian, R.M., Ning, D.L., Yang, S.S., Zhou, J.Z., et al., 2018. Biodegradation of polyethylene and plastic mixtures in mealworms (Larvae of Tenebrio molitor) and effects on the gut microbiome. Environ. Sci. Technol. 52, 6526–6533.

Brooks, A.L., Wang, S.L., Jambeck, J.R., 2018. The Chinese import ban and its impact on global plastic waste trade. Sci. Adv. 4.

Carr, S.A., Liu, J., Tesoro, A.G., 2016. Transport and fate of microplastic particles in wastewater treatment plants. Water Res. 91, 174–182.

Castro, R.O., Silva, M.L., Marques, M.R.C., de Araujo, F.V., 2016. Evaluation of microplastics in Jurujuba Cove, Niteroi, RJ, Brazil, an area of mussels farming. Mar. Pollut. Bull. 110, 555–558.

Cheung, P.K., Fok, L., 2017. Characterisation of plastic microbeads in facial scrubs and their estimated emissions in Mainland China. Water Res. 122, 53–61.

Cheung, P.K., Cheung, L.T.O., Fok, L., 2016. Seasonal variation in the abundance of marine plastic debris in the estuary of a subtropical macro-scale drainage basin in South China. Sci. Total Environ. 562, 658–665.

Cohen, J.H., Internicola, A.M., Mason, R.A., Kukulka, T., 2019. Observations and simulations of microplastic debris in a tide, wind, and freshwater-driven estuarine environment: the Delaware Bay. Environ. Sci. Technol. 53, 14204–14211.

Corcoran, P.L., Belontz, S.L., Ryan, K., Walzak, M.J., 2020. Factors controlling the distribution of microplastic particles in benthic sediment of the Thames River, Canada. Environ. Sci. Technol. 54, 818–825.

Cozar, A., Marti, E., Duarte, C.M., Garcia-de-Lomas, J., van Sebille, E., Ballatore, T.J., et al., 2017. The Arctic ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. Sci. Adv. 3, 8.

Cydzik-Kwiatkowska, A., Milojevic, N., Jachimowicz, P., 2022. The fate of microplastic in sludge management systems. Sci. Total Environ. 848, 157466.

Di, M., Wang, J., 2018. Microplastics in surface waters and sediments of the Three Gorges Reservoir, China. Sci. Total Environ. 616–617, 1620–1627.

Diaz-Jaramillo, M., Islas, M.S., Gonzalez, M., 2021. Spatial distribution patterns and identification of microplastics on intertidal sediments from urban and natural SW Atlantic estuaries. Environ. Pollut. 273.

Do, M.V., Le, T.X.T., Vu, N.D., Dang, T.T., 2022. Distribution and occurrence of microplastics in wastewater treatment plants. Environ. Technol. Innov. 26.

Dong, H., Wang, L., Wang, X., Xu, L., Chen, M., Gong, P., et al., 2021. Microplastics in a remote lake basin of the Tibetan Plateau: impacts of atmospheric transport and glacial melting. Environ. Sci. Technol. 55, 12951–12960.

Dris, R., Gasperi, J., Rocher, V., Saad, M., Renault, N., Tassin, B., 2015. Microplastic contamination in an urban area: a case study in Greater Paris. Environ. Chem. 12, 592–599.

Drummond, J.D., Schneidewind, U., Li, A.G., Hoellein, T.J., Krause, S., Packman, A.I., 2022. Microplastic accumulation in riverbed sediment via hyporheic exchange from headwaters to mainstems. Sci. Adv. 8.

Eregowda, T., Mohapatra, S., 2020. Fate of micropollutants in engineered and natural environment. In: Resilience, Response, and Risk in Water Systems: Shifting Management and Natural Forcings Paradigms, pp. 283–301.

Fan, Y.J., Zheng, K., Zhu, Z.W., Chen, G.S., Peng, X.Z., 2019. Distribution, sedimentary record, and persistence of microplastics in the Pearl River catchment, China. Environ. Pollut. 251, 862–870.

Fei, J., Xie, H., Zhao, Y., Zhou, X., Sun, H., Wang, N., et al., 2022. Transport of degradable/nondegradable and aged microplastics in porous media: effects of physicochemical factors. Sci. Total Environ. 851, 158099.

Firdaus, M., Trihadiningrum, Y., Lestari, P., 2020. Microplastic pollution in the sediment of Jagir Estuary, Surabaya City, Indonesia. Mar. Pollut. Bull. 150.

Fischer, E.K., Paglialonga, L., Czech, E., Tamminga, M., 2016. Microplastic pollution in lakes and lake shoreline sediments—a case study on Lake Bolsena and Lake Chiusi (central Italy). Environ. Pollut. 213, 648–657.

Fok, L., Cheung, P.K., 2015. Hong Kong at the Pearl River Estuary: A hotspot of microplastic pollution. Mar. Pollut. Bull. 99, 112–118.

Frere, L., Paul-Pont, I., Rinnert, E., Petton, S., Jaffre, J., Bihannic, I., et al., 2017. Influence of environmental and anthropogenic factors on the composition, concentration and spatial distribution of microplastics: a case study of the Bay of Brest (Brittany, France). Environ. Pollut. 225, 211–222.

Fuerst, K., Feng, Y.D., 2022. China's regulatory respond to plastic pollution: trends and trajectories. Front Mar Sci 9.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv., 3.

Giddings, S.N., Fong, D.A., Monismith, S.G., Chickadel, C.C., Edwards, K.A., Plant, W.J., et al., 2012. Frontogenesis and frontal progression of a trapping-generated estuarine convergence front and its influence on mixing and stratification. Estuar. Coast. 35, 665–681.

Gong, Y., Wang, Y.X., Chen, L., Li, Y.K., Chen, X.J., Liu, B.L., 2021. Microplastics in different tissues of a pelagic squid (Dosidicus gigas) in the northern Humboldt Current ecosystem. Mar. Pollut. Bull. 169.

Gonzalez-Pleiter, M., Velazquez, D., Edo, C., Carretero, O., Gago, J., Baron-Sola, A., et al., 2020. Fibers spreading worldwide: microplastics and other anthropogenic litter in an Arctic freshwater lake. Sci. Total Environ. 722, 137904.

Gramling, C., 2018. Enormous floating barrier will corral ocean trash. Science News Explores. https://www.snexplores.org/article.

Gray, A.D., Wertz, H., Leads, R.R., Weinstein, J.E., 2018. Microplastic in two South Carolina Estuaries: occurrence, distribution, and composition. Mar. Pollut. Bull. 128, 223–233.

Gunaalan, K., Fabbri, E., Capolupo, M., 2020. The hidden threat of plastic leachates: a critical review on their impacts on aquatic organisms. Water Res. 184.

Gundogdu, S., Cevik, C., Guzel, E., Kilercioglu, S., 2018. Microplastics in municipal wastewater treatment plants in Turkey: a comparison of the influent and secondary effluent concentrations. Environ. Monit. Assess. 190.

Hale, R.C., Seeley, M.E., La Guardia, M.J., Mai, L., Zeng, E.Y., 2020. A global perspective on microplastics. J Geophys. Res. Oceans 125.

Han, M., Niu, X.R., Tang, M., Zhang, B.T., Wang, G.Q., Yue, W.F., et al., 2020. Distribution of microplastics in surface water of the lower Yellow River near estuary. Sci. Total Environ. 707.

He, D., Chen, X.J., Zhao, W., Zhu, Z.Q., Qi, X.J., Zhou, L.F., et al., 2021. Microplastics contamination in the surface water of the Yangtze River from upstream to estuary based on different sampling methods. Environ. Res. 196.

Horton, A.A., Dixon, S.J., 2018. Microplastics: an introduction to environmental transport processes. Wires Water 5.

Il'ina, O.V., Kolobov, M.Y., Il'inskii, V.V., 2021. Plastic pollution of the coastal surface water in the middle and southern Baikal. Water Resour. 48, 56–64.

Isarin, N., 2023. Thailand Sets 2025 Target for Import Ban on Plastic Waste. SWEAP. https://www.sweap.eu/.

Johannessen, S.C., Macdonald, R.W., Burd, B., van Roodselaar, A., Bertold, S., 2015. Local environmental conditions determine the footprint of municipal effluent in coastal waters: a case study in the Strait of Georgia, British Columbia. Sci. Total Environ. 508, 228–239.

Kaiser, D., Kowalski, N., Waniek, J.J., 2017. Effects of biofouling on the sinking behavior of microplastics. Environ. Res. Lett. 12.

Kane, I.A., Clare, M.A., Miramontes, E., Wogelius, R., Rothwell, J.J., Garreau, P., et al., 2020. Seafloor microplastic hotspots controlled by deep-sea circulation. Science 368, 1140.

Kershaw, P., Katsuhiko, S., Lee, S., Samseth, J., Woodring, D., 2011. Plastic debris in the ocean. In: UNEP Yearbook Emerging Issues in our Global Environment. United Nations Environment Programme, Nairobi, Kenya.

Kolandhasamy, P., Su, L., Li, J.N., Qu, X.Y., Jabeen, K., Shi, H.H., 2018. Adherence of microplastics to soft tissue of mussels: a novel way to uptake microplastics beyond ingestion. Sci. Total Environ. 610, 635–640.

Kooi, M., van Nes, E.H., Scheffer, M., Koelmans, A.A., 2017. Ups and downs in the ocean: effects of biofouling on vertical transport of microplastics. Environ. Sci. Technol. 51, 7963–7971.

Kopatz, V., Wen, K.V., Kovacs, T., Keimowitz, A.S., Pichler, V., Widder, J., et al., 2023. Micro- and nanoplastics breach the blood-brain barrier (BBB): biomolecular Corona's role revealed. Nanomater.-Basel 13.

Kubowicz, S., Booth, A.M., 2017. Biodegradability of plastics: challenges and misconceptions. Environ. Sci. Technol. 51, 12058–12060.

Kwon, D., 2023. Three ways to solve the plastics pollution crisis. Nature 616, 234–237.

Kwon, J.H., Kim, J.W., Pham, T.D., Tarafdar, A., Hong, S., Chun, S.H., et al., 2020. Microplastics in food: a review on analytical methods and challenges. Int. J. Environ. Res. Publ. Health 17.

Lahens, L., Strady, E., Kieu-Le, T.C., Dris, R., Boukerma, K., Rinnert, E., et al., 2018. Macroplastic and microplastic contamination assessment of a tropical river (Saigon River, Vietnam) transversed by a developing megacity. Environ. Pollut. 236, 661–671.

Lares, M., Ncibi, M.C., Sillanpaa, M., Sillanpaa, M., 2018. Occurrence, identification and removal of microplastic particles and fibers in conventional activated sludge process and advanced MBR technology. Water Res. 133, 236–246.

Lebreton, L.C.M., Van der Zwet, J., Damsteeg, J.W., Slat, B., Andrady, A., Reisser, J., 2017. River plastic emissions to the world's oceans. Nat. Commun. 8.

Lehel, J., Murphy, S., 2021. Microplastics in the food chain: food safety and environmental aspects. Rev. Environ. Contam. Toxicol. 259, 1–49.

Lenaker, P.L., Baldwin, A.K., Corsi, S.R., Mason, S.A., Reneau, P.C., Scott, J.W., 2019. Vertical distribution of microplastics in the water column and surficial sediment from the milwaukee river basin to Lake Michigan. Environ. Sci. Technol. 53, 12227–12237.

Liang, T., Lei, Z.Y., Fuad, M.T.I., Wang, Q., Sun, S.C., Fang, J.K.H., et al., 2022. Distribution and potential sources of microplastics in sediments in remote lakes of Tibet, China. Sci. Total Environ. 806.

Lima, A.R.A., Barletta, M., Costa, M.F., 2015. Seasonal distribution and interactions between plankton and microplastics in a tropical estuary. Estuar. Coast. Shelf Sci. 165, 213–225.

Liu, C., Liu, C., 2023. Exploring plastic-management policy in china: status, challenges and policy insights. Sustainability 15.

Liu, K., Wu, T.N., Wang, X.H., Song, Z.Y., Zong, C.X., Wei, N.A., et al., 2019. Consistent transport of terrestrial microplastics to the ocean through atmosphere. Environ. Sci. Technol. 53, 10612–10619.

Liu, W.Y., Zhang, J.L., Liu, H., Guo, X.N., Zhang, X.Y., Yao, X.L., et al., 2021. A review of the removal of microplastics in global wastewater treatment plants: characteristics and mechanisms. Environ. Int. 146.

Long, Z.X., Pan, Z., Wang, W.L., Ren, J.Y., Yu, X.G., Lin, L.Y., et al., 2019. Microplastic abundance, characteristics, and removal in wastewater treatment plants in a coastal city of China. Water Res. 155, 255–265.

Luo, H.W., Liu, C.Y., He, D.Q., Xu, J., Sun, J.Q., Li, J., et al., 2022. Environmental behaviors of microplastics in aquatic systems: a systematic review on degradation, adsorption, toxicity and biofilm under aging conditions. J. Hazard. Mater. 423.

Lusher, A.L., Tirelli, V., O'Connor, I., Officer, R., 2015. Microplastics in Arctic polar waters: the first reported values of particles in surface and sub-surface samples. Sci. Rep. 5, 9.

Magni, S., Binelli, A., Pittura, L., Avio, C.G., Della Torre, C., Parenti, C.C., et al., 2019. The fate of microplastics in an Italian Wastewater Treatment Plant. Sci. Total Environ. 652, 602–610.

Magnusson, K., Norén, F., 2014. Screening of microplastic particles in and down-stream a wastewater treatment plant. Environ. Sci.

Malli, A., Corella-Puertas, E., Hajjar, C., Boulay, A.M., 2022. Transport mechanisms and fate of microplastics in estuarine compartments: a review. Mar. Pollut. Bull. 177, 113553.

Mamun, A.A., Prasetya, T.A.E., Dewi, I.R., Ahmad, M., 2023. Microplastics in human food chains: food becoming a threat to health safety. Sci. Total Environ. 858.

Mani, T., Hauk, A., Walter, U., Burkhardt-Holm, P., 2015. Microplastics profile along the Rhine river. Sci. Rep. 5, 7.

Mason, S.A., Garneau, D., Sutton, R., Chu, Y., Ehmann, K., Barnes, J., et al., 2016. Microplastic pollution is widely detected in US municipal wastewater treatment plant effluent. Environ. Pollut. 218, 1045–1054.

McEachern, K., Alegria, H., Kalagher, A.L., Hansen, C., Morrison, S., Hastings, D., 2019. Microplastics in Tampa Bay, Florida: abundance and variability in estuarine waters and sediments. Mar. Pollut. Bull. 148, 97–106.

McWilliams, J.C., 2021. Oceanic frontogenesis. Annu. Rev. Mar. Sci. 13, 227–253.

Meijer, L.J.J., van Emmerik, T., van der Ent, R., Schmidt, C., Lebreton, L., 2021. More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. Sci. Adv. 7.

MESTECC, 2018. Malaysia's Roadmap towards Zero Single-Use Plastics, 2018–2030. Ministry of Energy, Science, Technology, Environment & Climate Change.

Miao, L.Z., Gao, Y.X., Adyel, T.M., Huo, Z.L., Liu, Z.L., Wu, J., et al., 2021. Effects of biofilm colonization on the sinking of microplastics in three freshwater environments. J. Hazard. Mater. 413.

Mintenig, S.M., Int-Veen, I., Loder, M.G.J., Primpke, S., Gerdts, G., 2017. Identification of microplastic in effluents of waste water treatment plants using focal plane array-based micro-Fourier-transform infrared imaging. Water Res. 108, 365–372.

Mohapatra, S., Menon, N.G., Mohapatra, G., Pisharody, L., Pattnaik, A., Menon, N.G., Bhukya, P.L., Srivastava, M., Singh, M., Barman, M.K., Gin, K.Y.H., Mukherji, S., 2021. The novel SARS-CoV-2 pandemic: possible environmental transmission, detection, persistence and fate during wastewater and water treatment. Sci. Total Environ. 765, 142746.

Mohapatra, S., Mrozik, W., Acharya, K., Menon, N.G., 2022. Suspect and nontarget screening of pharmaceuticals in water and wastewater matrices. In: Legacy and Emerging Contaminants in Water and Wastewater: Monitoring, Risk Assessment and Remediation Techniques. Springer International Publishing, Cham, pp. 77–92.

Mohapatra, S., Bhatia, S., Senaratna, K.Y.K., Jong, M.C., Lim, C.M.B., Gangesh, G.R., Lee, J.X., Giek, G.S., Cheung, C., Yutao, L., Luhua, Y., Yong, N.H., Peng, L.C., Wong, J.C.C., Ching, N.L., Gin, K.Y.H., 2023. Wastewater surveillance of SARS-CoV-2 and chemical markers in campus dormitories in an evolving COVID-19 pandemic. J. Hazard. Mater. 446, 130690.

Murphy, F., Ewins, C., Carbonnier, F., Quinn, B., 2016. Wastewater Treatment Works (WwTW) as a source of microplastics in the aquatic environment. Environ. Sci. Technol. 50, 5800–5808.

Naidoo, T., Glassom, D., Smit, A.J., 2015. Plastic pollution in five urban estuaries of KwaZulu-Natal, South Africa. Mar. Pollut. Bull. 101, 473–480.

Napper, I.E., Thompson, R.C., 2016. Release of synthetic microplastic plastic fibres from domestic washing machines: effects of fabric type and washing conditions. Mar. Pollut. Bull. 112, 39–45.

Nel, H.A., Dalu, T., Wasserman, R.J., 2018. Sinks and sources: Assessing microplastic abundance in river sediment and deposit feeders in an Austral temperate urban river system. Sci. Total Environ. 612, 950–956.

Parashar, N., Hait, S., 2023. Recent advances on microplastics pollution and removal from wastewater systems: a critical review. J. Environ. Manage. 340, 118014.

Parker, L., 2018. A whopping 91% of plastic isn't recycled. Natl. Geogr.

Pazos, R.S., Bauer, D.E., Gomez, N., 2018. Microplastics integrating the coastal planktonic community in the inner zone of the Rio de la Plata estuary (South America). Environ. Pollut. 243, 134–142.

Pazos, R.S., Amalvy, J., Cochero, J., Pecile, A., Gomez, N., 2021. Temporal patterns in the abundance, type and composition of microplastics on the coast of the Rio de la Plata estuary. Mar. Pollut. Bull. 168.

Pinheiro, L.M., Agostini, V.O., Lima, A.R.A., Ward, R.D., Pinho, G.L.L., 2021. The fate of plastic litter within estuarine compartments: an overview of current knowledge for the transboundary issue to guide future assessments. Environ. Pollut., 279.

Qin, M., Chen, C., Song, B., Shen, M., Cao, W., Yang, H., et al., 2021. A review of biodegradable plastics to biodegradable microplastics: another ecological threat to soil environments? J. Clean. Prod. 312.

Radhakrishnan, K., Sivapriya, V., Rajkumar, A., Akramkhan, N., Prakasheswar, P., Krishnakumar, S., et al., 2021. Characterization and distribution of microplastics in estuarine surface sediments, Kayamkulam estuary, southwest coast of India. Mar. Pollut. Bull. 168.

Ragusa, A., Svelato, A., Santacroce, C., Catalano, P., Notarstefano, V., Carnevali, O., et al., 2021. Plasticenta: first evidence of microplastics in human placenta. Environ. Int. 146.

Rashid, C.P., Jyothibabu, R., Arunpandi, N., Abhijith, V.T., Josna, M.P., Vidhya, V., et al., 2021. Microplastics in zooplankton in the eastern Arabian Sea: the threats they pose to fish and corals favoured by coastal currents. Mar. Pollut. Bull. 173.

Rillig, M.C., Lehmann, A., 2020. Microplastic in terrestrial ecosystems. Science 368, 1430–1431.

Rochman, C.M., Hentschel, B.T., Teh, S.J., 2014. Long-term sorption of metals is similar among plastic types: implications for plastic debris in aquatic environments. PLoS One 9.

Rochman, C.M., Kross, S.M., Armstrong, J.B., Bogan, M.T., Darling, E.S., Green, S.J., et al., 2015. Scientific evidence supports a ban on microbeads. Environ. Sci. Technol. 49, 10759–10761.

Samir, A., Ashour, F.H., Hakim, A.A.A., Bassyouni, M., 2022. Recent advances in biodegradable polymers for sustainable applications. Npj Mater. Degrad. 6.

Sarijan, S., Azman, S., Said, M.I.M., Jamal, M.H., 2021. Microplastics in freshwater ecosystems: a recent review of occurrence, analysis, potential impacts, and research needs. Environ. Sci. Pollut. Res. 28, 1341–1356.

Schmidt, C., Kumar, R., Yang, S., Buttner, O., 2020. Microplastic particle emission from wastewater treatment plant effluents into river networks in Germany: loads, spatial patterns of concentrations and potential toxicity. Sci. Total Environ. 737.

Schymanski, D., Goldbeck, C., Humpf, H.U., Furst, P., 2018. Analysis of microplastics in water by micro-Raman spectroscopy: release of plastic particles from different packaging into mineral water. Water Res. 129, 154–162.

Simon-Sanchez, L., Grelaud, M., Garcia-Orellana, J., Ziveri, P., 2019. River Deltas as hotspots of microplastic accumulation: the case study of the Ebro River (NW Mediterranean). Sci. Total Environ. 687, 1186–1196.

Song, Y.K., Hong, S.H., Jang, M., Han, G.M., Jung, S.W., Shim, W.J., 2017. Combined effects of UV exposure duration and mechanical abrasion on microplastic fragmentation by polymer type. Environ. Sci. Technol. 51, 4368–4376.

Song, Z.F., Yang, X.Y., Chen, F.M., Zhao, F.Y., Zhao, Y., Ruan, L.L., et al., 2019. Fate and transport of nanoplastics in complex natural aquifer media: effect of particle size and surface functionalization. Sci. Total Environ. 669, 120–128.

Sruthy, S., Ramasamy, E.V., 2017. Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. Environ. Pollut. 222, 315–322.

Su, L., Xue, Y.G., Li, L.Y., Yang, D.Q., Kolandhasamy, P., Li, D.J., et al., 2016. Microplastics in Taihu Lake, China. Environ. Pollut. 216, 711–719.

Suhring, R., Baak, J.E., Letcher, R.J., Braune, B.M., de Silva, A., Dey, C., et al., 2022. Co-contaminants of microplastics in two seabird species from the Canadian Arctic. Environ. Sci. Ecotechnol. 12.

Sun, J., Peng, Z.T., Zhu, Z.R., Fu, W., Dai, X.H., Ni, B.J., 2022. The atmospheric microplastics deposition contributes to microplastic pollution in urban waters. Water Res. 225.

Ta, A.T., Babel, S., 2019. Microplastic pollution in surface water of the Chao Phraya River in Ang Thong Area. Environ. Asia 12, 48–53.

Takdastan, A., Niari, M.H., Babaei, A., Dobaradaran, S., Jorfi, S., Ahmadi, M., 2021. Occurrence and distribution of microplastic particles and the concentration of Di 2-ethyl hexyl phthalate (DEHP) in microplastics and wastewater in the wastewater treatment plant. J. Environ. Manage. 280.

Talbot, R., Chang, H.J., 2022. Microplastics in freshwater: a global review of factors affecting spatial and temporal variations. Environ. Pollut. 292.

Talvitie, J., Mikola, A., Koistinen, A., Setala, O., 2017a. Solutions to microplastic pollution—removal of microplastics from wastewater effluent with advanced wastewater treatment technologies. Water Res. 123, 401–407.

Talvitie, J., Mikola, A., Setala, O., Heinonen, M., Koistinen, A., 2017b. How well is microlitter purified from wastewater? A detailed study on the stepwise removal of microlitter in a tertiary level wastewater treatment plant. Water Res. 109, 164–172.

Taylor, J.R., 2018. Accumulation and subduction of buoyant material at submesoscale fronts. J. Phys. Oceanogr. 48, 1233–1241.

Tee, Y.H., Ibrahim, Y.S., Wan Mohd Khalik, W.M.A., 2020. Microplastic abundance, distribution, and composition in Sungai Dungun, Terengganu, Malaysia. Sains Malaysiana 49, 1479–1490.

Ter Halle, A., Ladirat, L., Gendre, X., Goudouneche, D., Pusineri, C., Routaboul, C., et al., 2016. Understanding the fragmentation pattern of marine plastic debris. Environ. Sci. Technol. 50, 5668–5675.

Thompson, R.C., Olsen, Y., Mitchell, R.P., Davis, A., Rowland, S.J., John, A.W.G., et al., 2004. Lost at sea: where is all the plastic? Science 304, 838.

Uekert, T., Singh, A., DesVeaux, J.S., Ghosh, T., Bhatt, A., Yadav, G., et al., 2023. Technical, economic, and environmental comparison of closed-loop recycling technologies for common plastics. ACS Sustain. Chem. Eng. 11, 965–978.

UNEP, 2021. Addressing Single-Use Plastic Products Pollution using a Life Cycle Approach. United Nations Environment Programme.

UNEP, 2022. Historic Day in the Campaign to Beat Plastic Pollution: Nations Commit to Develop a Legally Binding Agreement. United Nations Environment Programme, United Nations Environment Programme.

UNEP, 2023. Everything You Need to Know About Plastic Pollution. United Nations Environment Programme.

Uurasjarvi, E., Hartikainen, S., Setala, O., Lehtiniemi, M., Koistinen, A., 2020. Microplastic concentrations, size distribution, and polymer types in the surface waters of a northern European lake. Water Environ. Res. 92, 149–156.

van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., Alsina, J.M., Bagaev, A., et al., 2020. The physical oceanography of the transport of floating marine debris. Environ. Res. Lett. 15.

Vermaire, J.C., Pomeroy, C., Herczegh, S.M., Haggart, O., Murphy, M., 2017. Microplastic abundance and distribution in the open water and sediment of the Ottawa River, Canada, and its tributaries. Facets 2, 301–314.

Vivekanand, A.C., Mohapatra, S., Tyagi, V.K., 2021. Microplastics in aquatic environment: challenges and perspectives. Chemosphere 282, 131151.

Waldschlager, K., Lechthaler, S., Stauch, G., Schuttrumpf, H., 2020. The way of microplastic through the environment—application of the source-pathway-receptor model (review). Sci. Total Environ. 713.

Walker, T.R., McGuinty, E., Charlebois, S., Music, J., 2021. Single-use plastic packaging in the Canadian food industry: consumer behavior and perceptions. Hum. Soc. Sci. Commun. 8.

Waller, C.L., Griffiths, H.J., Waluda, C.M., Thorpe, S.E., Loaiza, I., Moreno, B., et al., 2017. Microplastics in the Antarctic marine system: an emerging area of research. Sci. Total Environ. 598, 220–227.

Wang, X., Zhou, Y., 2023. Combat plastics in the Qinghai-Tibetan. Plateau 381, 1419.

Wang, F., Wang, B., Duan, L., Zhang, Y.Z., Zhou, Y.T., Sui, Q., et al., 2020. Occurrence and distribution of microplastics in domestic, industrial, agricultural and aquacultural wastewater sources: a case study in Changzhou, China. Water Res. 182.

Wang, X.J., Bolan, N., Tsang, D.C.W., Sarkar, B., Bradney, L., Li, Y., 2021. A review of microplastics aggregation in aquatic environment: influence factors, analytical methods, and environmental implications. J. Hazard. Mater. 402.

Wang, T., Zhao, S., Zhu, L., McWilliams, J.C., Galgani, L., Amin, R.M., et al., 2022. Accumulation, transformation and transport of microplastics in estuarine fronts. Nat. Rev. Earth Environ. 3, 795–805.

Wang, T., Tong, C., Wu, F., Jiang, S., Zhang, S., 2023. Distribution characteristics of microplastics and corresponding feeding habits of the dominant shrimps in the rivers of Chongming Island. Sci. Total Environ. 888, 164041.

Wen, Z.G., Xie, Y.L., Chen, M.H., Dinga, C.D., 2021. China's plastic import ban increases prospects of environmental impact mitigation of plastic waste trade flow worldwide. Nat. Commun. 12.

WEPA, 2021. Outlook on Water Environmental Management in Asia 2021. Institute for Global Environmental Strategies (IGES), Japan.

Wessel, C.C., Lockridge, G.R., Battiste, D., Cebrian, J., 2016. Abundance and characteristics of microplastics in beach sediments: insights into microplastic accumulation in northern Gulf of Mexico estuaries. Mar. Pollut. Bull. 109, 178–183.

Woodward, J., Li, J.W., Rothwell, J., Hurley, R., 2021. Acute riverine microplastic contamination due to avoidable releases of untreated wastewater. Nat. Sustain. 4, 793.

Wright, S.L., Kelly, F.J., 2017. Plastic and human health: a micro issue? Environ. Sci. Technol. 51, 6634–6647.

Wu, X., Pan, J., Li, M., Li, Y., Bartlam, M., Wang, Y., 2019. Selective enrichment of bacterial pathogens by microplastic biofilm. Water Res. 165, 114979.

Wu, F.R., Pennings, S.C., Tong, C.F., Xu, Y.T., 2020a. Variation in microplastics composition at small spatial and temporal scales in a tidal flat of the Yangtze Estuary, China. Sci. Total Environ. 699.

Wu, N., Zhang, Y., Li, W., Wang, J., Zhang, X., He, J., et al., 2020b. Co-effects of biofouling and inorganic matters increased the density of environmental microplastics in the sediments of Bohai Bay coast. Sci. Total Environ. 717, 134431.

WWF, 2022. Chemical Recycling Implementation Principles. WWF.

Yan, M., Nie, H., Xu, K., He, Y., Hu, Y., Huang, Y., et al., 2019. Microplastic abundance, distribution and composition in the Pearl River along Guangzhou city and Pearl River estuary, China. Chemosphere 217, 879–886.

Yan, X.Y., Yang, X.Y., Tang, Z., Fu, J.J., Chen, F.M., Zhao, Y., et al., 2020. Downward transport of naturally-aged light microplastics in natural loamy sand and the implication to the dissemination of antibiotic resistance genes. Environ. Pollut. 262.

Yan, M.Q., Wang, L., Dai, Y.Y., Sun, H.W., Liu, C.G., 2021. Behavior of microplastics in inland waters: aggregation, settlement, and transport. Bull. Environ. Contam. Toxicol. 107, 700–709.

Yang, J., Yang, Y., Wu, W.M., Zhao, J., Jiang, L., 2014. Evidence of polyethylene biodegradation by bacterial strains from the guts of plastic-eating waxworms. Environ. Sci. Technol. 48, 13776–13784.
Yang, L.B., Li, K.X., Cui, S., Kang, Y., An, L.H., Lei, K., 2019a. Removal of microplastics in municipal sewage from China's largest water reclamation plant. Water Res. 155, 175–181.
Yang, Y., Liu, G., Song, W., Ye, C., Lin, H., Li, Z., et al., 2019b. Plastics in the marine environment are reservoirs for antibiotic and metal resistance genes. Environ. Int. 123, 79–86.
Yin, L.Y., Chen, B.J., Xia, B., Shi, X.T., Qu, K.M., 2018. Polystyrene microplastics alter the behavior, energy reserve and nutritional composition of marine jacopever (*Sebastes schlegelii*). J. Hazard. Mater. 360, 97–105.
Yonkos, L.T., Friedel, E.A., Perez-Reyes, A.C., Ghosal, S., Arthur, C.D., 2014. Microplastics in four estuarine rivers in the Chesapeake Bay, USA. Environ. Sci. Technol. 48, 14195–14202.
Yu, J.K., Ma, X.Y., 2022. Exploring the management policy of marine microplastic litter in China: overview, challenges and prospects. Sustain. Prod. Consump. 32, 607–618.
Yuan, W.K., Christie-Oleza, J.A., Xu, E.G., Li, J.W., Zhang, H.B., Wang, W.F., et al., 2022. Environmental fate of microplastics in the world's third-largest river: basin-wide investigation and microplastic community analysis. Water Res. 210.
Zainuddin, A.H., Aris, A.Z., Zaki, M.R.M., Yusoff, F.M., Wee, S.Y., 2022. Occurrence, potential sources and ecological risk estimation of microplastic towards coastal and estuarine zones in Malaysia. Mar. Pollut. Bull. 174.
Zha, F.G., Shang, M.X., Ouyang, Z.Z., Guo, X.T., 2022. The aging behaviors and release of microplastics: a review. Gondwana Res. 108, 60–71.
Zhang, Y., Pedersen, J.N., Eser, B.E., Guo, Z., 2022a. Biodegradation of polyethylene and polystyrene: from microbial deterioration to enzyme discovery. Biotechnol. Adv. 60, 107991.
Zhang, Z., Gao, S.-H., Luo, G., Kang, Y., Zhang, L., Pan, Y., et al., 2022b. The contamination of microplastics in China's aquatic environment: occurrence, detection and implications for ecological risk. Environ. Pollut. 296, 118737.
Zhang, Z.Q., Gao, S.H., Luo, G.Y., Kang, Y.Y., Zhang, L.Y., Pan, Y.S., et al., 2022c. The contamination of microplastics in China's aquatic environment: occurrence, detection and implications for ecological risk. Environ. Pollut. 296.
Zhao, S., Zhu, L., Wang, T., Li, D., 2014. Suspended microplastics in the surface water of the Yangtze Estuary System, China: first observations on occurrence, distribution. Mar. Pollut. Bull. 86, 562–568.
Zhao, S.Y., Zhu, L.X., Li, D.J., 2015. Microplastic in three urban estuaries. China. Environ. Pollut. 206, 597–604.
Zhao, S.Y., Ward, J.E., Danley, M., Mincer, T.J., 2018. Field-based evidence for microplastic in marine aggregates and mussels: implications for trophic transfer. Environ. Sci. Technol. 52, 11038–11048.
Zhao, S.Y., Wang, T., Zhu, L.X., Xu, P., Wang, X.H., Gao, L., et al., 2019. Analysis of suspended microplastics in the Changjiang Estuary: implications for riverine plastic load to the ocean. Water Res. 161, 560–569.
Zhao, W.L., Huang, W., Yin, M.C., Huang, P., Ding, Y.C., Ni, X., et al., 2020. Tributary inflows enhance the microplastic load in the estuary: a case from the Qiantang River. Mar. Pollut. Bull. 156.
Zhou, Y., Li, Y., Yan, Z., Wang, H., Chen, H., Zhao, S., et al., 2023. Microplastics discharged from urban drainage system: prominent contribution of sewer overflow pollution. Water Res. 236, 119976.
Zhu, L., Wang, H., Chen, B.J., Sun, X.M., Qu, K.M., Xia, B., 2019. Microplastic ingestion in deep-sea fish from the South China Sea. Sci. Total Environ. 677, 493–501.
Ziajahromi, S., Neale, P.A., Rintoul, L., Leusch, F.D.L., 2017. Wastewater treatment plants as a pathway for microplastics: development of a new approach to sample wastewater-based microplastics. Water Res. 112, 93–99.