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Review

Microplastics in Asian freshwater ecosystems: Current knowledge and perspectives

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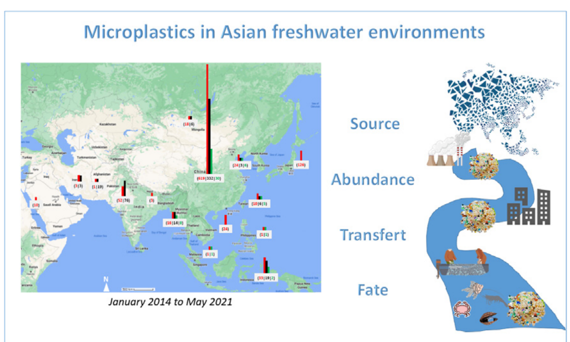
HIGHLIGHTS

- Overview of microplastics (MPs) in Asian freshwater ecosystems
- High variability in MP abundances in water and sediment samples between studies
- Various sources and factors influencing MP contamination and transfers in Asia
- Perspectives for better MP management for sustainable development in Asia

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic pollution in freshwater ecosystems, including microplastics (MPs) smaller than 5 mm, has become an emerging global concern. Asia is considered a "hot spot" for plastic pollution due to rapid economic and demographic growth, together with rapid urbanization. Here, we provide an overview of the current knowledge on MP abundance, sources, fate, and transfer in Asian freshwater ecosystems based on publications from January 2014 to May 2021. MP contamination in freshwater compartments, including water, sediment, and biota, was found to vary strongly. In water, it ranged from 0.004 items m^{-3} in a moderately urbanized region to more than 500,000 items m^{-3} in a dumping river in a highly populated watershed. In the sediment, MP abundance ranged from 1 to more than 30,000 items kg^{-1} dry weight. Polyethylene (PE) and polypropylene (PP) were predominant in both water and sediment compartments. MP was detected in biota samples from all the studied species, but their abundance depended on the locations and species studied. Overall, MP characteristics (form, size, color, and polymer type) depended on sources and natural constraints (mainly hydrodynamics). This study also revealed that MP in Asian freshwater ecosystems mainly originated from domestic wastewater/runoff, followed by industrial emissions, fisheries and aquaculture wastewater.

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Sediment
Biota
Asia

Plastic waste is not efficiently recycled or incinerated in Asia, leading to MP transfer and accumulation in the aquatic environment, and, more importantly, to ingestion by low to high trophic level organisms. This work highlights several knowledge gaps to guides future research to improve MP pollution management for the sustainable development of highly populated regions such as Asia.

Contents

1. Introduction

The rapid economic and demographic growth associated with environmental contamination are recognized as a current challenge, especially in developing countries. As a temporary or final sink for contaminants, surface waters and sediments are the most vulnerable (Devault et al., 2009) and are strongly impacted by anthropogenic activities that undermine environmental quality. Given its potential toxicity, microplastic (MP) contamination in freshwater ecosystems has become a global issue that requires careful attention (Rochman et al., 2013; J. Wang et al., 2017; F. Wang et al., 2018; Lahens et al., 2018; Cera et al., 2020; Li et al., 2020). Continental waters, however, are the subject of fewer studies than marine waters (Li et al., 2020), although most plastic inputs into the global ocean occur through rivers, and that concentrations are locally greater in inland waters than in the marine environment, implying potentially higher toxicity (Lebreton et al., 2017).

Among scientists and citizens, MPs are a growing concern (Cole et al., 2011; W. Wang et al., 2018; Phuong et al., 2021). Since their widespread use in the 1950s, plastics have advantageously substituted many materials owing to their versatility, cost and energy savings, functionality, and amenities on which society and economy have become dependent (GESAMP, 2015). Nowadays, the demand for plastic materials is increasing and plastics are essential to modern societies because of their unique properties, such as durability, resistance, flexibility, and reduced weight (Lahens et al., 2018; Wen et al., 2018). With an annual global production of 368 million tons in 2019 (fibers excluded), plastic is the third most abundant man-made material, after steel and concrete (PlasticsEurope, 2020). A significant proportion of plastic waste that breaks down into smaller debris ends up in the aquatic environment (Thompson et al., 2004). After being exposed to the environment, plastic waste is degraded through abiotic factors such as light, temperature, air, water, and external forces, and by biotic factors such as organisms. Degradation processes cause oxidation and chain-scission of plastic polymers, leading to alterations in both their mechanical and physicochemical properties, including weight loss, modification in appearance and texture, increase in crystallinity, changes in thermal stability and surface area, and deterioration in tensile strength and shear strength. Plastic waste enters ecosystems of all shapes and sizes and can be broken down into macroplastics (>25 mm), mesoplastics (5–25 mm), MPs (<5 mm) and nanoplastics (<0.1 μm) (GESAMP, 2019). Several MP sources are well identified, such as mismanaged plastic litter, wastewater treatment plants (WWTPs), and industrial and domestic drainage systems (Cózar et al., 2014). Human activity (Barnes et al., 2009; Wen et al., 2018; Kataoka et al., 2019; Irfan et al., 2020), and hydrological and meteorological conditions (Lebreton et al., 2017; Xiong et al., 2019) can affect transport, fate, and transformation of MP in ecosystems (Xu et al., 2020).

MP transport in water bodies is potentially more controlled by non-anthropogenic than anthropogenic factors with six key hydrological processes involved in the transport of non-buoyant and buoyant MPs: (i) turbulent transport, (ii) settling, (iii) aggregation, (iv) biofouling, (v) resuspension, and (vi) burial (Kooi et al., 2018). Aggregation and biofouling may increase the density of MPs and boost their settlement (Long et al., 2015). Fibers, which have a relatively large surface-to-volume ratio, tend to biofouling and settlement, while spherical particles with a lower surface-to-volume ratio, such as pellets and microbeads, are more buoyant and are transported by currents. Owing to their unique properties such as light weight, persistence, and remarkable longevity up to thousands of years, plastics are not completely degraded under natural conditions but are broken down into smaller pieces owing to external forces. These weathering processes include physical degradation (i.e., erosion), photodegradation (i.e., UV rays), thermal degradation (i.e., high temperature), chemical degradation (e.g., oxidation and hydrolysis), and biodegradation (i.e., microorganisms) (Andrady, 2011). Biodegradation utilizes the action of enzymes and/or chemical deterioration associated with microorganisms to convert polymers to small molecular weight fragments (Klein et al., 2018). Therefore, many nations have gradually preferred the use of biodegradable plastics that can be degraded by microbiota. However, plastics such as polyethylene (PE) and polystyrene (PS) with higher molecular weights are more resistant to biodegradation. Considerable amounts of MP may enter biota, food webs, and ecosystems via ingestion, inhalation, entanglement and trophic transfer (Setälä et al., 2018; Xiong et al., 2019), resulting in long-term accumulation in both freshwater and marine ecosystems.

Previous ecotoxicological studies have reported that the ingestion of small-sized plastics can damage aquatic animals, for example, through growth inhibition (Besseling et al., 2014), internal injury (Yu et al., 2020), starvation (Rist et al., 2016) or even death (Steer et al., 2017; Cera et al., 2020; Xu et al., 2020). Ingestion by living organisms has been investigated at different trophic levels, including lugworms (Van Cauwenberghe et al., 2015), *Tubifex* worms (Hurley et al., 2017), bivalves (Avio et al., 2015; Su et al., 2018), fish (Rochman et al., 2015; Karami et al., 2016; Karbalaei et al., 2019), and waterfowl (Holland et al., 2016). Sun et al. (2021) showed the effects of MP exposure on growth, mortality, and photosynthesis in a freshwater zooplankton species (*Euglena gracilis*), while the ecological impacts of MP on benthic invertebrates were documented by Huang et al. (2021). Consequently, human exposure levels via seafood consumption have been investigated (Rochman et al., 2015; Hwang et al., 2020). In addition, human exposure to MP via drinking water and inhalation has been reported (Prata, 2018; Revel et al., 2018).

A significant concern arises from the effects of the combination of MP with both inorganic and organic pollutants. Various toxic chemicals, including persistent organic pollutants (POPs), additives (Endo et al., 2005; Teuten et al., 2009; Rochman et al., 2013; Hermabessiere et al., 2017; Paluselli et al., 2019; Fauvelle et al., 2021), oligomer-derived substances (Tetu et al., 2019; Capolupo et al., 2020; Gewert et al., 2018), and trace metals (Holmes et al., 2012; J. Wang et al., 2017) can reach humans and organisms through their association with MP and subsequent release. The small-sized particles have a large specific surface area where hazardous pollutants sorb more easily (Devriese et al., 2017; J. Wang et al., 2017; Yin et al., 2019). MP can thus be considered a source of these chemicals (GESAMP, 2015) to the food web (Setälä et al., 2018), posing a threat to the safety of freshwater ecosystems (F. Wang et al., 2018).

Studies on emerging pollutants, including MPs, are urgently needed to define the conditions necessary for sustainable development in Asia. Despite available reports on MP abundance in surface waters in Asia, most studies have focused on China (Su et al., 2018; W. Wang et al., 2018; Wu et al., 2018; Tien et al., 2020; Y. Liu et al., 2020). The occurrence and distribution of MPs in freshwater have so far been poorly investigated compared to those in marine areas, especially in Asia (Li et al., 2020). No standardized synthesis of observation data currently exists on MP contamination levels and their potential risks to the ecosystem and human health in Asia. The aims of this paper are (i) to provide an overview of the current research on the abundance and characterization of MP in Asian freshwater environments (water, sediment, and organisms); (ii) to discuss the sources, transport methods, and fate of MP in Asian freshwater ecosystems; and (iii) to identify current knowledge gaps and provide recommendations to improve our understanding of MP dynamics in the environment and therefore MP pollution management in Asia.

2. Methodology

Asia is a hot spot of MP contamination, but the presence of MPs in freshwater ecosystems (including water, sediment, and organisms) is still unevenly and insufficiently investigated. Hence, these are the topics of this review research. The selection of scientific articles presented for this review was performed on the Web of Science using three keywords: "Microplastic," "Freshwater" and "Asia" The original studies were carefully examined before selection. Seventy-seven research papers (from January 2014 to May 2021, 85% published in the 2018–2021 period) were selected from 21 different journals. Most of the articles (61%) were published in three journals: Environmental Pollution, Science of the Total Environment, and Marine Pollution Bulletin. Once a paper was selected, information on sampling sites (location), MP abundances, and MP characteristics was analyzed. We also focused on the sources, transfer, and fate of MP, if presented in the discussion section of the paper. The results obtained were synthesized, allowing us to achieve the aims of this study.

3. Studies on MP in freshwater ecosystems in Asia

MP has been reported in all compartments of freshwater ecosystems, including water, sediment, and other organisms (bivalves, gastropods, and fish). These studies were conducted in 15 Asian countries (Fig. 1). Most of them were from eastern and southern Asia. Water was investigated in 62 studies, while sediment and biota were analyzed in 41 and 15 studies, respectively. Numerous locations and aquatic species were studied (960 locations for water, 478 for sediment, and 55 for biota). While China is the most studied country, representing 70% of both overall locations and living species studied, no data is available for nearly 70% (34/49) of the Asian countries, mainly in the north-central and western regions. Rivers are the most studied systems, with 60% of biota samples and 70% of water samples, compared to lakes, reservoirs, dams, and lagoons. The Yangtze River and the Poyang Lake were the most studied due to their watershed surface area, economic activities, and high population density. Most of the previous research papers only focused on MP pollution in freshwater ecosystems within a specific country, except for the research conducted on the Ganges River in both India and Bangladesh (Napper et al., 2021).

3.1. MP occurrence in freshwater ecosystems in Asia

MP was found in all environmental freshwater compartments investigated in Asia. Specific aspects, such as quantitative results, MP characteristics, and factors influencing MP pollution, are presented and discussed below.

3.1.1. MP in freshwater

On review of the quantitative results, a high variation of MP abundance was reported in freshwater studies (Fig. 2). The lowest value (0.004 items m^{-3}) was observed in the Cherating River (Malaysia; Pariatamby et al., 2020). Conversely, the highest value was found in the Saigon River (Vietnam), reaching more than 500,000 items m^{-3} (Lahens et al., 2018). The Saigon River crosses the dense megacity of Ho Chi Minh City and is affected by wastewater discharge from industrial areas composed of large textile and garment industries. The use of different methods throughout the MP assessment procedure, such as the mesh size of the sampling net (80, 150, or 300 μm) or the solution used for the density separation steps, can affect the comparison of the results. Fifty percent of the studies reported MP abundances ranging from 100 to 5000 items m^{-3} (Fig. 2). Another unit used to express MP concentrations in water is the number of MP items by surface area sampled. In that regard, MP abundance in freshwater in Asia ranges from 28 to more than 15 million items per km^2. The lowest and highest values were detected in Veeranam Lake (South India) and the Three Gorges Reservoir (China), respectively (Bharath et al., 2021; Zhang et al., 2017). While the two units of measurement are convertible, the equivalent value is not always provided to the reader. Hence, we recommend that future studies include both units to facilitate the comparison of the results.

The predominant MP characteristics (form, size, color and polymer type) encountered in freshwater environments in Asia are shown in Fig. 3. Among different MP forms, fibers and fragments were predominant, accounting for 79% of the particles. Other forms detected include films, foams, and spheres. While fragments are mainly formed through the fragmentation of plastic litter, MP fibers mainly result from textile release (Napper and Thompson, 2016; Cesa et al., 2017; Horton and Dixon, 2018). Particles less than 1 mm account for 68% of the items. Blue, white, and transparent MPs constitute 68% of the MPs. Polyethylene (PE) and polypropylene (PP) were the most common polymers, with relative abundances of 31% and 37%, respectively. These polymers are the two main plastic types produced, with production volumes representing nearly half of the total plastic production (PlasticsEurope, 2020). Both are less dense than water, suggesting that they are found in water rather than in sediment samples.

3.1.2. MP in sediment

The MP abundance in freshwater sediments in Asia is presented in Fig. 4. The concentration by sediment mass was reported in 35 out of 41 studies, with 60% of the data in the range of 100–1000 items kg^{-1} dry weight (dw). The lowest and highest concentrations were reported in the Haraz River, Iran (Naeeji et al., 2020) and the Wen-Rui Tang River, China (W. Wang et al., 2018), respectively (Fig. 4). The highest concentration was up to 30,000 times higher than the lowest concentration reported (32,947 kg^{-1} dw (W. Wang et al., 2018) compared to 1.25 kg^{-1} dw (Naeeji et al., 2020) items). The discrepancy may be due to the targeted MP size, protocols, and identification techniques used. Several studies

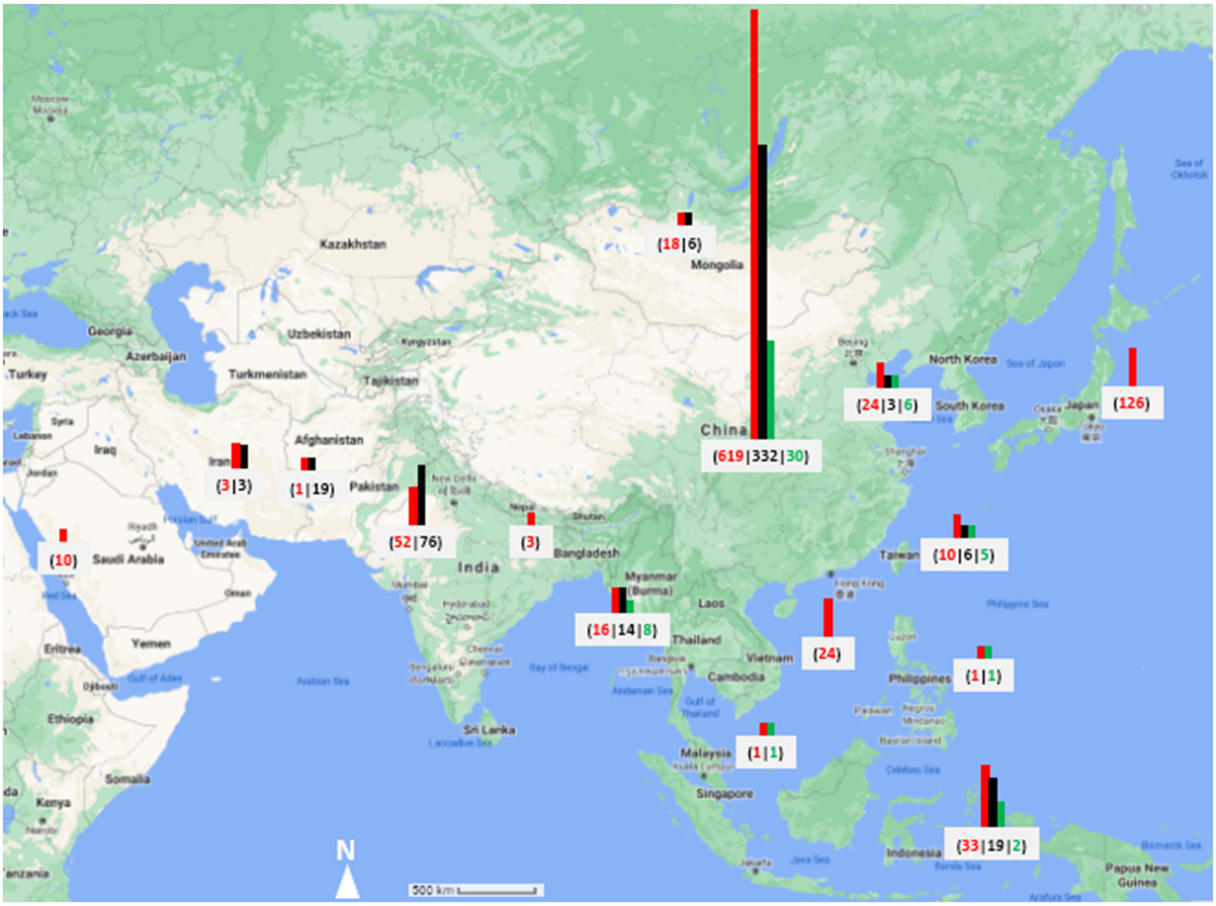

Fig. 1. Number of studies on MP in freshwater ecosystems in Asia between January 2014 and May 2021. Bars represent the different compartments (red, black and green correspond to water, sediment and living organisms, respectively; the number of studies is indicated below the bars).

have reported MP concentrations by surface area, but without knowing the sampling height and the specific sediment density, it is difficult to convert these results to mass concentrations. With more than 5000 items m^{-2}, the Three Gorges Reservoir (China) was the most contaminated, followed by the Ravi River (Pakistan) with 3700 items m^{-2} (Zhang et al., 2019; Irfan et al., 2020). Note that 67% of reported concentrations were in the range of 100–350 items m^{-2}.

The MP characteristics of freshwater sediments in Asia are presented in Fig. 5. The two predominant forms of MP in the water samples were fibers and fragments, which represented up to 80%. MPs less than 1 mm constituted up to 85% of the total particles, compared to 68% in the water samples. This may be the result of the differences in sampling and extraction used (net for water samples and sieve for sediment samples) or might have implications for the vertical distribution of MP in freshwater systems. White MP was predominant in sediment samples (41%), whereas the abundance of blue MP decreased strongly (22% in water and 9.4% in sediment). The loss of MP color could be the result of the ageing of the plastic by discoloration under environmental conditions or the ingestion selectivity of organisms (de Sá et al., 2015). The nature of the plastic polymers was found to be very similar between the water and sediment samples. The sum of PE and polypropylene (PP) constituted almost 67% of the plastic particles present in both compartments, mainly because of their low density, which facilitates their dispersion by winds, waves, and currents (He et al., 2021; Yuan et al., 2019).

3.1.3. MP in biota

The MP studies in Asian continental hydrosystem organisms are summarized in Table 1. Fishes were the most investigated species, comprising nearly 90% of all species, probably because of their importance for human consumption. In bivalves, the Asian clams (*Corbicula fluminea*) were contaminated in the range of 0.2–12.5 items g^{-1} wet weight (ww) in the Taihu Lake, China (Su et al., 2016) and 0.3–4.9 items g^{-1} ww in the Yangtze River (Su et al., 2018). By comparing MP characteristics found in the Asian clams to those in the surrounding environment, the authors suggested clams as a bio-indicator for MP contamination in freshwater ecosystems. Two gastropoda (*Nerita articulate* and *Nerita polita*) sampled in the Klang River (Malaysia) exhibited 0.5 to 1.75 items g^{-1} ww (0.25 to 0.88 items per individual) (Zaki et al., 2021). Among the four tadpole species sampled in the Yangtze River Delta (China), the highest MP value (168 items g^{-1} ww) was found in *Rana limnochari* (Hu et al., 2018). Among freshwater species, fish are of great interest for research on MP accumulation because of their high harvest and cultured production for human consumption. For fish species, a range of 0–94 items per individual was reported (Table 1). Most results were obtained from the intestine/gut of fishes, whereas MP extraction from fish tissues has only been performed in a few studies (Fareza and Sembiring, 2020; Sembiring et al., 2020). MP concentrations in omnivorous *Kuhlia rupestris* were not correlated with fish weight (Cabansag et al., 2021). Moreover, the authors demonstrated that MP ingestion by freshwater fish from the Lawaan River (Philippines) is lower than that of marine fish. This was also observed in a study of six fish species sampled in Taihu Lake (Jabeen et al., 2017). These results confirmed that the marine environment is an endpoint for MP pollution. According to a literature review, MP occurrence in fishes was not related to body weight, as observed in the omnivorous *Kuhlia rupestris* (Cabansag et al., 2021), and was rather related to body length (Tien et al., 2020). However, the surrounding environment itself plays an

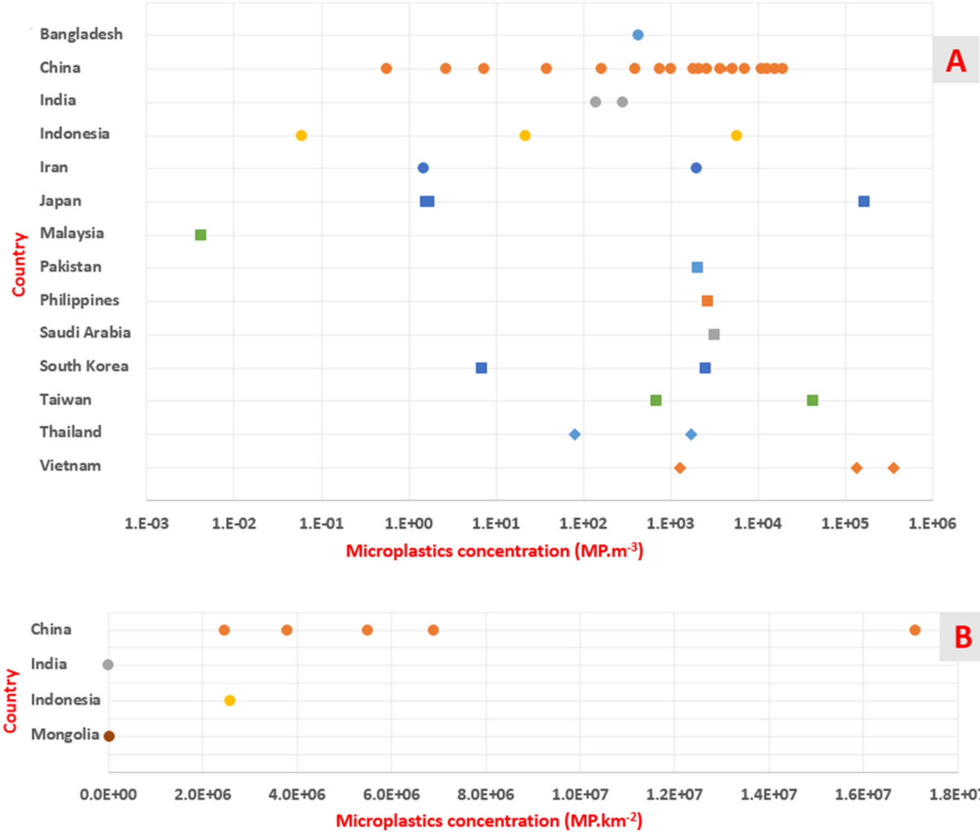

Fig. 2. MP abundances (items m^{-3}) detected in freshwater in Asia (n = 64) reported by volume (A) and surface area (B). Points represent the mean concentrations.

important role in the variability of MP occurrence within a specific species. For example, MP concentrations in *Carassius auratus* were measured at 1.9 items individual^{-1} in Taihu Lake (Jabeen et al., 2017), and at 55 items individual^{-1} in the Fengshan River (Tien et al., 2020). Similarly, no MP was detected in *Cyprinus carpio* sampled in the Xiangxi River (Zhang et al., 2017), while 2.5 ± 1.3 items individual^{-1} were measured in Taihu Lake (Jabeen et al., 2017) and 30 items individual^{-1} in the Han River, South Korea (Park et al., 2020). In the Han River, the ingestion of MP by six fish species depends on their habitat rather than on their feeding mode (Park et al., 2020).

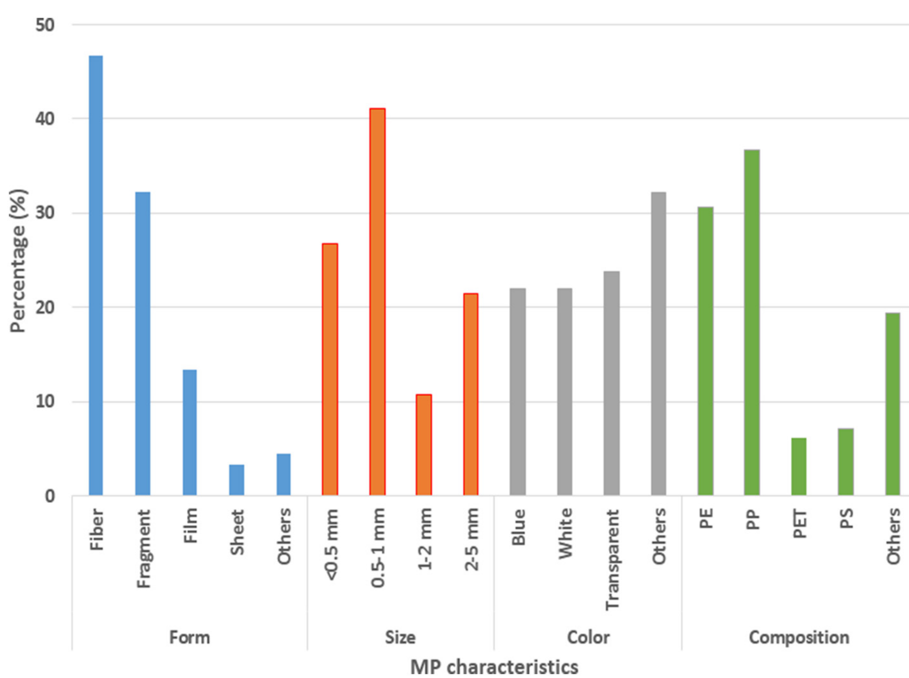

Fig. 3. Characteristics of MP found in freshwater in Asia. PE: Polyethylene; PP: Polypropylene; PET: Polyethylene terephthalate and PS: Polystyrene.

Fig. 4. MP concentrations detected in freshwater sediment in Asia (n = 41) reported by dry mass (A) and surface area (B), points are representing average values from each study. Several results in wet weight were converted to dry weight using an average wet sediment/dry sediment ratio of 1.25.

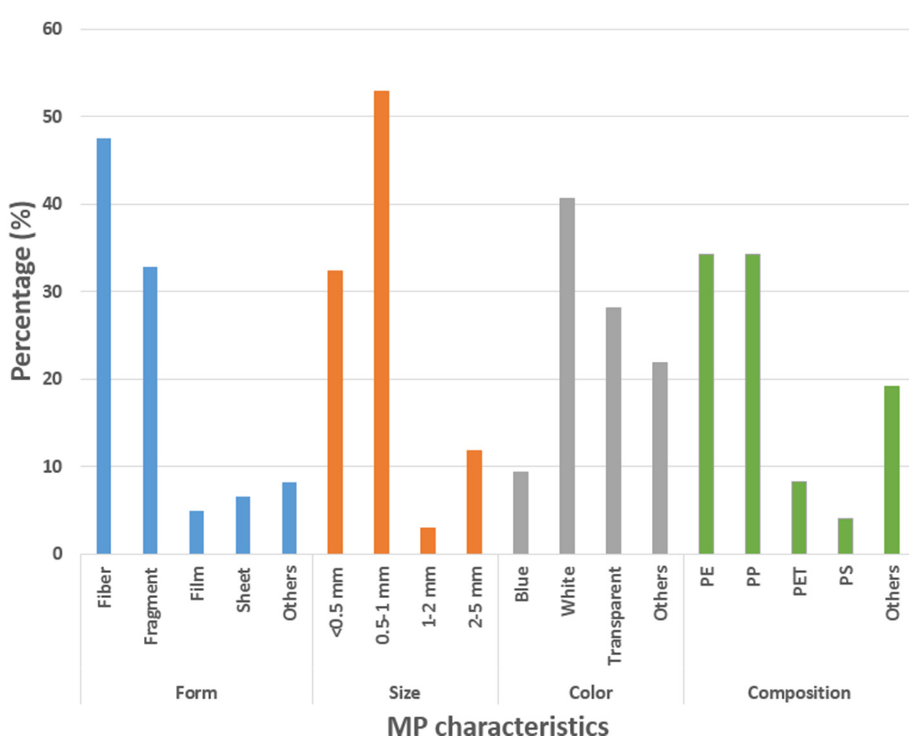

Fig. 5. Characteristics of MP found in freshwater sediments in Asia. PE: Polyethylene; PP: Polypropylene; PET: Polyethylene terephthalate and PS: Polystyrene.

Table 1
Microplastics studies in freshwater ecosystem in Asia.

Country	Organisms	Species	Microplastic		References
			Quantity[a]	Predominant form, color, size, composition[b]	
China	Bivalve	*Corbicula fluminea*	0.2–12.5 items g^{-1} ww	Fiber, blue, 0.1–1 mm, Cellophane	Su et al. (2016)
China			0.3–4.9 items g^{-1} ww (0.4–5.0 items ind.[1])	Fiber, blue, 0.25–1 mm, Polyester	Su et al. (2018)
Malaysia	Gastropoda	*Nerita articulate* *Nerita polita*	0.5–1.75 items g^{-1} ww (0.25–0.88 items ind.$^{-1}$)	Fiber, black, 0.3–1 mm, PE-PDM	Zaki et al. (2021)
China	Amphibian	*Bufo gargarizans*	2.44–56.88 items g^{-1} (0.17–1.89 items ind.$^{-1}$)	Fiber, <0.5 mm, polyester	Hu et al. (2018)
		Microhyla ornate	0.53–2.6 items g^{-1} (35.2–157.9 items ind.$^{-1}$)		
		Rana limnochari	2.73 items g^{-1} (168 items ind.$^{-1}$)		
		Pelophylax nigromaculatus	1.27–1.8 items g^{-1} (3.01–4.46 items ind.$^{-1}$)		
China	Eel	*Monopterus albus*	3.3 items ind.$^{-1}$	Fiber, white, <1 mm, PP	Lv et al. (2019)
	Loach	*Misgurnus anguillicaudatus*	1.8 items ind.$^{-1}$		
	Fish	*Procambarus clarkii*	2.5 items ind.$^{-1}$		
Philippines		*Kuhlia rupestris*	41% fish had MP	Fragment	Cabansag et al. (2021)
Indonesia		*Chanos chanos*	2.2 items fish^{-1} (gut and gill), 1.1 items fish^{-1} (tissue)	Fragment, black, >0.5 mm	Fareza and Sembiring (2020)
		Chanos chanos	1.3 items fish^{-1} (gut and gill), 1.1 items fish^{-1} (tissue)	Fragment, black, 0.5–1 mm, PE	Sembiring et al. (2020)
Thailand		*Mystus bocourti*	73.3% fish had MP	Fiber, blue, >0.5 mm	Kasamesiri and Thaimuangphol (2020)
		Puntioplites proctozysron	86.7% fish had MP		
		Henicorhynchus siamensis	71.4% fish had MP		
		Laides longibarbis	83.3% fish had MP		
		Labiobarbus siamensis	50% fish had MP		
		Cyclocheilichthys repasson	70.4% fish had MP		
		Hemibagrus spilopterus	70% fish had MP		
		Labeo chrysophekadion	75% fish had MP		
South Korea		*Cyrinus carpio* *Carassius cuvieri* *Lepomis marcochirus* *Micropterus salmoides* *Silurus asotus* *Channa argus*	4–48 items fish^{-1} (intestine), 1–16 items fish^{-1} (gill)	Fragment, 0.3–0.6 mm, PE	Park et al. (2020)
Taiwan		*Oreochromis niloticus*	14–94 items ind.$^{-1}$	Fiber, red, <1 mm, PP	Tien et al. (2020)
		Pterygoplichthys pardalis	26–76 items ind.$^{-1}$		
		Carassius auratus	55 items ind.$^{-1}$		
		Leiognathus equulus	62 items ind.$^{-1}$		
		Pomadasys argenteus	16–67 items ind.$^{-1}$		
China	Fish (continued)	*Gymnocypris przewalskii*	2–15 items ind.$^{-1}$	Fiber, PE	Xiong et al. (2018)
		Carassius auratus	0–18 items ind.$^{-1}$	Fiber, >0.5 mm, PE	Yuan et al. (2019)
		Cyprinus carpio	0.5 items g^{-1} (2.5 items ind.$^{-1}$)	Fiber, transparent, 2–5 mm, Cellophane	Jabeen et al. (2017)
		Carassius auratus	1.7 items g^{-1} (1.7 items ind.$^{-1}$)		
		Hypophthalmichthys molitrix	2.1 items g^{-1} (3.8 items ind.$^{-1}$)		
		Pseudorasbora parva	5.6 items g^{-1} (2.5 items ind.$^{-1}$)		
		Megalobrama amblycephala	0.2 items g^{-1} (1.8 items ind.$^{-1}$)		
		Hemiculter bleekeri	1.5 items ind.$^{-1}$		
		Culter alburnus	0.55 items ind.$^{-1}$	Line, blue, 0.3–0.5 mm, PE	Zhang et al. (2017)
		Culter dabryi	ND	Sheet, transparent, 1 mm, PE	
		Culter mongolicus	ND		
		Culter oxycephaloides	ND		
		Cyprinus carpio	ND		
		Pelteobagrus nitidus	0.33 items ind.$^{-1}$		
		Pelteobagrus fulvidraco	1 items ind.$^{-1}$	Line, blue, 0.3–0.5 mm, PE	
		Pelteobaggrus vachelli	1 items ind.$^{-1}$	Sheet, white, 0.5–0.6 mm, PE	
		Pseudobagrus ussuriensis	1.5 items ind.$^{-1}$	Fragment, white, 1.8 mm, Nylon	
		Siluriformes	ND		
		Siniperca chuatsi	ND		
		Sinibrama wui	ND		
		Squalidus argentatus	ND		

[a] ND: not detected.
[b] PE-PDM: polyethylene-propylene-diene; PP: polypropylene; PE: polyethylene.

4. Source, transfer and fate of MP in freshwater ecosystems in Asia

4.1. Sources of MP

Asia has the highest population with about 4.64 billion inhabitants accounting for 60% of the world population and includes the world's most populous countries: China and India (Statista, 2021). This record population generates an exorbitant amount of waste, making Asia the largest waste-producing continent on Earth. Furthermore, Asia is the largest plastic producer, accounting for 51% of worldwide production (PlasticsEurope, 2019). Lebreton and Andrady (2019) estimated that the Asian continent is the largest contributor to global plastic waste (82 million tons) in comparison to Europe (31 million tons) and North America (29 million tons). Asia is a "hot spot" for MP pollution, and five countries (China,

Table 2
Predominant sources of MP found in freshwater ecosystems in Asia.

Location	Country	Samples	Sources	References
Ciwalengke River	Indonesia	Water, sediment	Washing processes in textile industries, laundry and domestic activities	Alam et al. (2019)
Netravathi River	India	Water, sediment	Pilgrims and tourists	Amrutha and Warrier (2020)
Tuul River	Mongolia	sediment	Wastewater treatment plant and domestic wastes	Battulga et al. (2020)
Veeranam Lake	India	Water, sediment	Fishery activities	Bharath et al. (2021)
Lawaan River	Philippines	Water, fish	Personal care products	Cabansag et al. (2021)
Shaoxing city	China	Water, sediment	Textile industry wastewater and domestic sewage in the industrial textile area	Deng et al. (2020)
Pasig River	Philippines	Water	Domestic and industrial wastes	Deocaris et al. (2019)
Three Gorges Reservoir	China	Water, sediment	Wastewater from nearby plant, river transport tourism, domestic waste, fishing activities	Di and Wang (2018)
Danjiangkou Reservoir	China	Water, sediment	Agriculture and daily use	Di et al. (2019)
Wei River	China	Water, sediment	Agricultural activities, sewage, industrial manufacturing and domestic sewage	Ding et al. (2019)
Nakdong River	South Korea	Water, sediment	Laundry from washing machines, deposition from the atmosphere	Eo et al. (2019)
Hovsgol Lake	Mongolia	Water	Towns, tourist camps, roads and rivers, plastic household debris, wrappers and fishing gear	Free et al. (2014)
Yangtze River Delta	China	Water, sediment	Discharge of sewage from personal care products, laundry wastewater or textile processing plants nearby human activities	Hu et al. (2018)
Dongting Lake	China	Water, sediment	Factories, plants, fishery activities and domestic waste	Hu et al. (2020)
Ravi River	Pakistan	Water, sediment	Domestic activities	Irfan et al. (2020)
Dongting Lake	China	Water, sediment	Riverine input, domestic sewage, industrial wastewater, tourism, fishing tools, agriculture	Jiang et al. (2018)
Six rivers in Tibet Plateau	China	Water, sediment	Daily activities of residents and tourists	Jiang et al. (2019)
Four rivers	Japan	Surface water	Domestic, industrial, commercial agricultural, urban	Kabir et al. (2021)
Chi River	Thailand	Fish	Fishery activity, fibers from clothing	Kasamesiri and Thaimuangphol (2020)
29 rivers	Japan	Water	Homes that are not connected to sewage systems, sewage overflow, rainwater from separate sewage systems	Kataoka et al. (2019)
Saigon River	Vietnam	Water	Domestic wastewater, industrial wastewaters (textile and apparel industry), atmospheric fallout	Lahens et al. (2018)
Saigon River	Vietnam	Water	Domestic wastewater, industrial wastewaters (textile and apparel industry), atmospheric fallout	Strady et al. (2020)
Surabaya River	Indonesia	Water, sediment	Domestic activities, industrial activities	Lestari et al. (2020)
Yangtze River Basin	China	Water, sediment	Wastewater discharge, wastewater treatment plant effluent, human activities and fishing tools or domestic sewage containing fibers from cloth washing	Li et al. (2019)
Pearl River	China	Water and sediment	Municipal sewage	Lin et al. (2018)
Danjiangkou Reservoir	China	sediment, water	Tributaries, the hydro-fluctuation belt (HFB), vegetable greenhouses, agriculture	Lin et al. (2021)
Haihe River	China	Water	Effluents from wastewater treatment plants, textiles, fishing activities, industrial resins and leak out during transportation and production, discarded plastic bags, films, packaging materials, food packaging, laboratory ware and dinnerware rubber, plastic coatings	Y. Liu et al. (2020)
Rice-fish co-culture system	China	Water	Agriculture fertilizers, fish food and atmospheric deposition	Lv et al. (2019)
Haraz River	Iran	Sediment, water	Agriculture, regional activity	Naeeji et al. (2020)
Wastewater (Bandar Abbas city)	Iran	Water, sludge	Sewage discharges	Naji et al. (2021)
Ganges River	India	Water	Fishing gear	Napper et al. (2021)
Cherating River	Malaysia	Water	Fishing and tourism activities	Pariatamby et al. (2020)
Han River	South Korea	Water	Clothes and other textiles, sewage treatment plants	Park et al. (2020)
Five lakes	Saudi Arabia	Water, sediment	Wastewater from nearby plant, wastewater from farms, factories and domestic sewage	Picó et al. (2020)
Jatiluhur Reservoir	Indonesia	Water	Human activities and fisheries industries	Fareza and Sembiring (2020)
Ganga River	India	Sediment	Municipal sewage, fishing gears	Sarkar et al. (2019)
Five rivers, five lakes and two reservoirs	Vietnam	Surface water	Urban, agriculture, industrial, households, aquaculture, high population density	Strady et al. (2021)
Taihu Lake	China	Water, sediment	Industrialization, hydrological conditions, urban, agriculture, river traffic, tourism	Su et al. (2016)
Yangtze River Basin	China	Water, sediment and Asian clam	Industrialization, hydrological conditions, urban, agriculture, river traffic, tourism	Su et al. (2018)
Chao Phraya River	Thailand	Water, sediment	Residential and industrial activities, tourism, fishing	Ta and Babel (2020)
Beijiang River	China	Water	Local sources, metallurgical, mining and thermal power industries	Tan et al. (2019)
Fengshan River	Taiwan	Water, sediment	Industrial, urban and agricultural areas, domestic discharges, shipping and fishery activities	Tien et al. (2020)
Brahmaputra River and Idus River	India	Sediment	Industrial, landfills, construction, littering, harbors, fishing, domestic use of plastic	Tsering et al. (2021)
Manas River Basin	China	Water	Industrial activities, agriculture, trade development	G. Wang et al. (2021)
Yangtze River and Hanjiang River	China	Water	Household waste, effluents from nearby wastewater treatment plants, fishing activities	W. Wang et al. (2017b)
Dongting Lake and Hong Lake	China	Water	Fishing tools, transportation, domestic and sewage plant effluents, surface runoff, agriculture, atmospheric deposition, industrial, aquaculture	W. Wang et al. (2018)
Urban lakes in Changsha city	China	Sediment	Agriculture, domestic wastewater, wastewater treatment plants	Wen et al. (2018)
Tamsui River	Taiwan	Water	Rainwater, atmospheric fallout	Wong et al. (2020)
Qinghai Lake	China	Water, sediment	Tourism	Xiong et al. (2018)

Table 2 (*continued*)

Location	Country	Samples	Sources	References
		and fish		
Yangtze River	China	Water, sediment	Human activities	Xiong et al. (2019)
Pearl River	China	Water	Wastewater effluents from urban cities	Yan et al. (2019)
Urban lakes in Changsha	China	Water	Wastewater treatment plants, tourism, domestic wastes	Yin et al. (2019)
Poyang Lake	China	Water, sediment and fish	Domestic sewage, industry, wastewater treatment plants, agriculture and fishing activities	Yuan et al. (2019)
Klang River	Malaysia	Gastropod	Industrial activities, wastewater discharge	Zaki et al. (2021)
Three Gorges Dam	China	Water	Local shipping and fishery activities, human activities	Zhang et al. (2015)
Remote lakes in Tibet plateau	China	Sediment	Riverine input	Zhang et al. (2016)
Three Gorges Reservoir	China	Water, sediment and fish	Transportation	Zhang et al. (2017)
Three Gorges Reservoir	China	Sediment	Dumping site, agriculture	Zhang et al. (2019)
Tuojiang River	China	Water	Industrial wastewater	Zhou et al. (2020)
Fuhe River	China	Sediment	Municipal wastewater treatment plants	Zhou et al. (2021)

Indonesia, Philippines, Thailand, and Vietnam) are responsible for more than 60% of the plastic waste potentially entering the world's oceans (Jambeck et al., 2015). An important part of marine plastic pollution originates from land and is transported to the ocean via rivers and coastlines (Lebreton et al., 2017; Van Emmerik and Schwarz, 2020). A global model of plastic inputs from rivers into oceans based on waste management, population density, and hydrological information estimated the global amount of plastic transported by rivers to the ocean to be between 1.15 and 2.41 million tons per year, of which the heavily polluted Asian rivers accounted for 67% (Lebreton et al., 2017). In addition, high concentrations of MP in surface water and sediments have been reported in several major rivers in China, followed by India, Taiwan, South Korea, and Indonesia (Kumar et al., 2021). Based on their origin, MPs are divided into two types: primary and secondary MPs, and their sources and routes are diverse and numerous (Table 2). The predominant sources of MP reported in the literature include domestic wastewater, industrial activities (textile industry effluent), fisheries, aquaculture, agriculture, WWTPs, and tourist activities.

According to the available data, MPs in freshwater ecosystems mainly originate from domestic wastewater/runoff. A high level of MP contamination is positively correlated with highly populated/urbanized areas with poor waste management systems or surface runoff (Kataoka et al., 2019; Oerlikon, 2009). Among domestic sources, laundry washing machine discharge was reported to have the highest MP abundance, and fibers were the dominant shape detected in most studies (Su et al., 2016; Alam et al., 2019; Eo et al., 2019; Yuan et al., 2019; Amrutha and Warrier, 2020; Mao et al., 2020; Strady et al., 2021). MP can be removed during wastewater treatment processes; however, in developing countries, especially in Asia, domestic wastewater is often discharged directly into nearby channels or rivers without any treatment (Lahens et al., 2018; Lechthaler et al., 2021). Thus, synthetic fibers released from textiles through daily use and washing processes occur in many types of aquatic habitats and are one of the main sources of MP pollution in many hydrosytems such as the Haihe River, China (Y. Liu et al., 2020; Z. Liu et al., 2020), the Ciwalengke River, Indonesia (Alam et al., 2019) and the Nakdong River, South Korea (Eo et al., 2019). While fibers originate mainly from washing machine discharges, washing clothes on the river bank, which is still a common way of doing laundry in rural areas of many Asian countries, is also a potential source of microfibers. For example, the microfibers detected in the Netravathi River of Karnataka, India, were the result of bathing and washing clothes for pilgrims and tourists (Amrutha and Warrier, 2020).

Industrial activities have also been highlighted as sources of MP release into aquatic environments. For example, in China, analysis of post-treatment wastewater from WWTPs in a textile industrial zone with 30,000 tons of daily treatment capacity showed that approximately 4.89×10^8 microfibers were released into the receiving water, comprising both MP and non-MP fibers (Xu et al., 2018). The maximum MP concentration found in the "China Textile City" – the largest textile manufacturing and trading center in the Zhejiang Province, China, was six times higher than the reference agricultural area and three times higher than other aquatic environments in this province (Deng et al., 2020). Zhou et al. (2020) measured MP concentrations (537.5 items L^{-1} on average) in the effluent of a Chinese textile industrial park (Shaoxing, Zhejiang), which were 1 to 4 orders of magnitude higher than in most municipal wastewater in China. Alam et al. (2019) observed the highest MP concentrations near the Ciwalengke River, Indonesia, which is dominated by industrial activities. Industrial wastewater discharge and domestic sewage have been suggested as major contributors to microfiber abundance in both water bodies and sediments of an industrial textile area in Shaoxing City, China (Deng et al., 2020). In the Saigon River, Vietnam, 92% of the anthropogenic waste is MP in the form of synthetic fibers, which demonstrates the impact of textile and apparel production on the industrial wastewater discharge upstream of the sampling site (Lahens et al., 2018; Strady et al., 2020).

Fishery and aquaculture are also considered important MP sources in freshwater environments. Several previous studies highlight that significant MP contamination arises from the breakdown of fishing tools, such as fishing nets, lines, and ropes (Y. Liu et al., 2020; Tien et al., 2020; Yuan et al., 2019; Napper et al., 2021). Fishing, a popular activity at the Three Gorges Reservoir, China, involving colorless plastic fishing lines and nylon nets, contributes a high proportion of transparent MPs (Di and Wang, 2018). Pariatamby et al. (2020) show that the midstream area of the Cherating River, Malaysia, has the highest MP abundance with 0.007 ± 0.0033 items m^{-3} and the highest concentration of line-shaped MP. Consequently, intense fishing is a potential culprit, as this activity is widespread from mid-to downstream. Similarly, Ramadan and Sembiring (2020) demonstrated that the line-shaped MPs in their samples were fragments from the decay of fishing tools, due to the intense fisheries industry in the studied reservoir. Likewise, Dongting Lake (China), with its prosperous aquatic ecosystems, attracts numerous fishermen and hence holds a distinguishable amount of tiny fibrous debris broken down from dumped fishing tools (Hu et al., 2020). W. Wang et al. (2018) stated that the dominance of transparent fibers in Hong Lake could be attributed to the degradation of fishing gear from a large number of aquaculture farms because aquaculture is the main anthropogenic activity in this lake.

Agriculture is another potential source of MP for surface waters in Asia via the application of chemical fertilizers, pesticides, fish food, and decomposition of agricultural equipment (Di et al., 2019; Yuan et al., 2019; Battulga et al., 2020; Lestari et al., 2020; Tien et al., 2020). In previous studies on MP abundance in the Wei River Basin, the authors investigated the correlation between agricultural activities and MP film distribution. The sampling site with the highest MP film abundance was situated in the lower reaches of the Jinghe River, next to extensive farming areas. Farming and agriculture contributed greatly to the appearance of films in both the water and sediment samples. Foams were also generated during agricultural work and were present in vast agricultural planting areas. Chemical fertilizer and fish food may deliver MP into aquatic environments during the rice-planting process (Lv et al., 2019).

WWTPs are the primary recipients of MP prior to their release into the environment. Many studies have shown that WWTPs remove MP from effluent, removal efficiencies varying from 65% to 99.9% (Bui et al., 2020; Galvão et al., 2020). Indeed, WWTPs play a key role in removing MPs from domestic sewage (Lin et al., 2018). Tibet, China has a low population density but struggles with the same MP pollution issues as well-developed areas due to the absence of waste disposal and recycling facilities. With modern facilities, applicable legislation, and regulations, several developed nations manage and recycle their waste effectively, minimizing the plastic portion discharged into the ecosystem (Zhang et al., 2016). In contrast, the paucity of wastewater treatment can lead to severe plastic contamination, and effluent discharge from nearby WWTPs is the main source of MP (Y. Liu et al., 2020; W. Wang et al., 2017; Yin et al., 2019). Hence, WWTPs reduce MP pollution from domestic wastewater but release fibers into the Pearl River (Lin et al., 2018). This contradiction can be explained by the fact that (i) some WWTPs cannot remove all MPs effectively due to the lack of a biological treatment stage, and (ii) the influent rate surpasses the treating capacity in extreme weather, such as storms. Furthermore, the application of sewage sludge as fertilizer on farmland may be a significant source of MP (Meng et al., 2020).

Tourist activities generate a significant amount of plastic waste and MP in aquatic environments (Free et al., 2014; Di and Wang, 2018; Xiong et al., 2018; Yin et al., 2019; Jiang et al., 2019; Pariatamby et al., 2020). Most MPs present in aquatic environments result from the breakdown of larger plastic items. Many plastic wastes, such as plastic wraps and bags, bottles, and food packaging, are discarded near or directly into aquatic environments by tourists. For example, even though Qinghai Lake is located in a zone without industry, far away from urban areas in China and is strictly preserved through fishing and shipping bans, in 2015, more than 270 tons of garbage was collected there over one week in the highest tourist season. This renowned place could not escape MP pollution as it attracts numerous tourists each year, over 10-fold the number of total inhabitants in the entire basin. Fibers detected on the lakeshore originate from tourist clothes or prayer flags often placed around the lake (Xiong et al., 2018). Similarly, a recent study revealed higher MP concentrations in Yuejin Lake, a popular tourist destination in the city center, compared to other urban lakes in Changsha, China, (Yin et al., 2019).

Atmospheric transport is an important source of MPs in freshwater in Asia. Atmospheric fallout deposition comprises up to 114 items m^{-2} d^{-1} in Guangzhou city (China; Huang et al., 2021) and up to 917 items m^{-2} d^{-1} in Ho Chi Minh City (Vietnam; Truong et al., 2021). In this urban and tropical environment, population density and space occupation influence the deposition fluxes of MPs, while the tropical monsoon climate (rain and wind regime) has no influence. Interestingly, MPs can be transported by wind from the marine environment and then deposited in continental areas. This hypothesis was confirmed by Allen et al. (2020), who found different MP concentrations in the air between onshore and offshore areas.

4.2. Transfer and fate of MPs

Human activities on land and freshwater ecosystems are recognized as the main source and transport routes of MPs to the oceans. Previous studies have reported that MPs derived from the production and consumption of plastic waste enter aquatic environments through various pathways from point and non-point sources, such as stormwater runoff, WWTP effluent, industrial discharge, direct littering, atmospheric fallout, and agricultural runoff (Eerkes-Medrano et al., 2015; Horton and Dixon, 2018; Kumar et al., 2021; Vanapalli et al., 2021).

The distribution of MPs in the environment depends on many factors leading to different concentrations reported between studies. Rivers have been identified as major pathways of MP transport from freshwater systems to the marine environment and as a sink for suspended matter, plastic debris, and other pollutants (Yang et al., 2021). Previous studies mentioned that the transport and settling of MPs in rivers are mainly driven by hydrodynamic conditions such as water velocity, river geometry, and flood events (Sagawa et al., 2018; Song et al., 2020; Kumar et al., 2021). However, in the tidal Saigon River (Vietnam), there is no correlation between MP concentrations in surface water and abiotic factors such as temperature, pH, dissolved oxygen, conductivity, and concentration of total suspended solids. Therefore, further research needs to be conducted to examine the correlations between MP and hydrodynamic conditions in different freshwater bodies.

The concentration of MPs in surface waters was negatively correlated with the channel width in the study by Mao et al. (2020) since the wider the channels, the more easily MPs are dispersed, resulting in a decline in MP abundance (F. Wang et al., 2018). Moreover, with wider channels, the water velocity decreases and, as a consequence, slows down the turbulence and resuspension processes, so that MPs can easily settle to the bottom through fouling processes and adsorption of natural substances onto the particles' surface (Rodrigues et al., 2018). Under turbulent conditions, resuspension of MP deposited in the sediment contributes MP to the water column (Eo et al., 2019). The concentrations of MP in rivers with low flow velocities and high depths were found to vary with river depth: low-density MP gradually decreased from the water surface to the sediment, while those with high densities presented an opposite gradient, except in very turbulent waters (Ma et al., 2020). Strong hydrodynamics and rapid water flow re-suspended and transported MP that had previously sunk to the river bottom. Xia et al. (2020) recorded a notable increase in MP concentration in Donghu Lake, China, during all five rainfall events included in their research. Rain events and storms are major mobilizing processes for increasing MP concentrations in freshwater systems. The increase in MP abundance in the surface water of Donghu Lake was caused by runoff after precipitation events on land, where most of the plastic is produced, used and discharged (Andrady, 2011). While rivers are characterized by high flow velocities and short residence times, lakes favor sedimentation processes through their extremely slow flow and much longer residence times. Hurley et al. (2018) reported that fluvial sediments can reduce MP concentrations in the water column. However, other studies indicate a more complex situation with low flow, where the bed surface becomes more stable and limits the movement of MP, acting as a sink for MP. In contrast, when the river flow increases (e.g., flood events), the bed surface becomes unstable and boosts the vertical exchange of MP (Horton and Dixon, 2018; Ockelford et al., 2020). Dam construction accelerates the sedimentation process by increasing the water residence time while decreasing the flow velocity. Hence, being blocked upstream by dams, MPs cannot be degraded or ingested by biota, but accumulate behind dams over long timescales (Zhang et al., 2015; J.S. Huang et al., 2020; W. Huang et al., 2020). Wu et al. (2020) showed that riparian vegetation can reduce flow velocity and thus increase MP settlement down the water column. Many studies have provided evidence of MP transport within hydrosystems via wind (Dehghani et al., 2017; Hitchcock, 2020).

The transport of MP particles in aquatic ecosystems is highly dependent on several physical factors, such as their composition, size, shape, and density. Floating MPs [such as PE and polypropylene (PP) particles] with low densities can be easily dispersed by winds, waves, and surface currents (He et al., 2021; Yuan et al., 2019; Besseling et al., 2014). Different types of MPs are distributed at different positions across the water column depending on the MP density. Low-density MPs such as fibers are dominant in the surface layers, whereas MPs with higher densities, such as polyamide (PA) and polyethylene terephthalate (PET), are prone to be retained in the sediment, especially in areas adjacent to source points or in places where there is a low flow velocity (Lestari et al., 2020; He et al., 2021). Fragments tend to be concentrated within the base of turbidity currents, while fibers are distributed more homogeneously throughout the water column due to their large surface-to-volume ratio, which results in slower settlement (Pohl et al., 2020).

The fate of MP particles in water bodies is highly dependent on currents and their sinking properties in the water column. The occurrence of turbulence or currents on the water surface encourages lightweight particles to remain suspended in the water column and prevents them from settling, while less movement in water layers allows them to sink freely to the bottom. Khatmullina and Isachenko (2017) demonstrated that the MP shape has a significant impact on the settling velocity. The larger the fiber diameter, the faster the sinking rate, and sphere-shaped MPs sink faster than irregular particles of the same size (Waldschläger and Schüttrumpf, 2019). Additionally, Xiong et al. (2019) clarified that estuaries are MP accumulation zones since rivers deliver MP particles from upstream while tides transfer MP from coastal areas. However, as MPs are not completely degraded and persist as tiny shapes in natural environments, the possibility of MP exposure to aquatic species and potential ecological risk is increasing. In the context of Asia, if these discarded plastics are not efficiently recycled or incinerated, they will be transferred and accumulated in aquatic environments, reaching remote regions such as Tibet and China. Aquatic biota can mistake MPs as a food source and ingest them accidentally (Jabeen et al., 2017). Moreover, MP might accumulate or decay inside the digestive systems of biota through gastrointestinal motility, intestinal liquids, and microbes, and consequently, not eliminated (Yang et al., 2015). MP ingestion potentially alters gut function, causing health problems such as blockage, tissue damage, reduction in swimming velocity or energy reserves, and a false sense of satiation that limits nutritional intake, which in turn causes starvation, restrains growth, and reduces the ability to evade predators (Hu et al., 2018). The presence of MP in low-trophic level organisms has been widely documented, yet empirical evidence for high-trophic level organisms such as mammals is still scarce. First, their digestive and respiration systems are much more complex than those of low-trophic level species. Second, the ethical restrictions of subjecting mammals to laboratory work hinder further studies in the field. High-trophic level species, including humans, normally consume the whole prey, suggesting that MP from contaminated prey accumulates in their bodies. Lv et al. (2019) investigated MP ingestion in eels and crayfish and observed that most MPs accumulate in the digestive organs of eels (foregut and hindgut) and crayfish (stomach and gut). Thus, it is advisable to remove the digestive organs when consuming these species to reduce the risk of MP ingestion, although this may not be possible for bivalves, which are eaten whole. The fate of MP presented in this study is also valid for other regions, such as Europe, America, and Africa.

In addition, MPs were investigated as vectors of major pollutants and their hazards to aquatic systems in Asia, including metal adsorption (Dong et al., 2020; Y. Wang et al., 2021; Wang et al., 2020), organic substances such as chlorophenols (Z. Liu et al., 2020), dissolved organic matter (Abdurahman et al., 2020), and antibiotics (Li et al., 2018a; Li et al., 2018b). The synergic effect of MPs with metals was confirmed for the yellow seahorse, *Hippocampus kuda* (Šunta et al., 2020) and the cladoceran *Moina monogolica* (Wang et al., 2020). Therefore, evidence from field sampling in the Asian aquatic system has identified MP as a pollutant vector. Purwiyanto et al. (2020) investigated the adsorption of Pb and Cu on MP in the Musi River (Indonesia) and the environmental effects. Samples collected at 10 sites along the river upstream of the estuary showed that the MP polymer was dominated by PP, followed by PE, polyethersulfone (PES), PVC, and nylon, with average concentrations of Pb and Cu in MP of 0.470 mg kg^{-1} and 0.091 mg kg^{-1}, respectively (Purwiyanto et al., 2020). When investigating metals in a sea cucumber farm in China, it was reported that the average concentrations of Cd, Pb, and Zn were higher in the MP than in the corresponding sediment, although there was no significant correlation between heavy metals in sediment, sea cucumber, and MP (Mohsen et al., 2019).

5. Future directions

5.1. Further studies on MP assessment in the aquatic ecosystem in Asia

Our study found that 85% of papers on MP pollution in aquatic ecosystems in Asia were recent, having been published within the last four years (January 2018 to May 2021). However, some information remains unknown and further studies are needed. Comparison of MP concentrations across studies is difficult due to a lack of standardized methodologies (Gago et al., 2020; Li et al., 2020; Xu et al., 2020). Thus, standardized methods for MP sampling, sample treatment, and laboratory analysis are urgently needed to assess MP pollution levels in freshwater ecosystems in Asia. In Vietnam, more than ten research groups of various cities adopted a common protocol for sampling, analyzing and observing MP in waters and sediments allowing to compare 21 results at the national level (Strady et al., 2021). The temporal and spatial variability of MP concentrations and fluxes in Asia, especially in large rivers, which are responsible for an important part of marine MP pollution (Lebreton et al., 2017; Wu et al., 2018), should be rigorously investigated. A complete database of MP pollution and its potential risks to human health and ecosystems should be established to enable full assessment and understanding of MP in the Asian environment. In addition, MP sources, pathways, distribution, and fates are still uncertain (Gago et al., 2020). In addition, toxic chemicals in plastics (intentionally used or adsorbed from the environment) should be fully considered when assessing the potential risks to human health and the ecosystem. The sources of MP and distribution in freshwater ecosystems should be intensively investigated in regions strongly affected by human activities and natural conditions, as is the case for Asia.

5.2. Study's recommendation on controlling and managing MP pollution

Asia is considered a “hot spot” for plastic pollution (Jambeck et al., 2015; Lebreton et al., 2017), thus further studies focusing on the use, disposal, treatment, and management of plastic waste are needed to better assess MP pollution, particularly in highly populated areas. Single-use plastics are expected to be increasingly produced and used in Asia, notably as packaging materials or consumables (shopping bags/containers and packaging, disposable tableware) (Chen et al., 2021). After being used, most single-use plastics are landfilled or incinerated, which causes the loss of valuable natural resources as well as the contamination of rivers, soils and oceans, resulting in serious impacts on wildlife, as well as emerging harmful effects on human health (Chen et al., 2021; Rouch, 2021). Plastic leaching from landfills has a straightforward impact on the surrounding environment, including river systems, incineration, and especially open burning, which may cause direct contamination of the atmosphere by burning plastic byproducts (Wu et al., 2016; McDuffie et al., 2021) that could eventually and indirectly reach continental water systems. Research can provide a scientific basis for establishing policies and regulatory tools at regional, national, and international scales to strictly reduce the use of single-use plastics or to replace them through multiple-use plastic products or non-plastic materials.

Numerical simulations are usually used to assess the impacts of human activities and climate change on environmental quality to decrease the risks for humans and attain better environmental management (Miller et al., 2013). The development and application of models that can predict the impact of various scenarios (human activities and natural constraints) on MP contamination, accumulation, and transfer in freshwater ecosystems, especially for large rivers and coastal areas in Asia, might guide environmental decision-making at both local and regional scales. In addition, this modeling tool is urgently needed to define the conditions for plastic pollution management and sustainable development in Asia.

Moreover, research on more sustainable plastics and MP waste treatment methods should be promoted to mitigate plastic pollution problems and decrease the pressure on the environment in Asia. In conclusion, further studies and the application of new methods to effectively process plastic and MP wastes are required in this region.

6. Conclusion

The presence of MP in different compartments (water, sediment, and some organisms) of freshwater ecosystems from 15 countries in Asia was reviewed to assess their abundance, sources, transfer, and fate based on available publications from January 2014 to May 2021. The results revealed that MP abundance and characteristics (form, size, color, and polymer type) varied greatly for samples in different compartments, depending on the specific sampling sites, pollution sources, and methodologies used. Multiple sources, notably domestic wastewater/runoff, industrial discharge, fisheries, and aquaculture wastewater were responsible for MP pollution in this region. In addition, plastic waste, which is not efficiently recycled or treated, is another important source contributing to serious MP contamination in different compartments of the aquatic environment, especially accumulation in low to high trophic level organisms.

Although Asia is considered a "hot spot" for plastic pollution and many large Asian rivers discharge into the ocean, information about MP abundance, transfer, fate, and sources of these rivers is still incomplete. Our study highlights the need for a complete database of MP pollution and the potential risks to human health and ecosystems in the Asian aquatic environment. Standardized methodologies for sample collection, treatment, and laboratory analysis should be applied. In addition, MP pollution sources should be carefully and effectively controlled by applying policies, regulatory tools, and new treatment technologies at regional, national, and international scales to minimize MP pollution in Asia, a highly populated region with rapid economic development.

CRediT authorship contribution statement

Ngoc Nam Phuong: Conceptualization, Methodology, Validation, Writing - original draft. **Thi Thuy Duong:** Conceptualization, Methodology, Validation, Supervision, Writing - original draft. **Thi Phuong Quynh Le:** Conceptualization, Methodology, Validation, Supervision, Writing - original draft. **Trung Kien Hoang:** Writing - review & editing. **Ha My Ngo:** Writing - review & editing. **Ngoc Anh Phuong:** Writing - review & editing. **Quoc Tuan Pham:** Writing - review & editing. **Thi Oanh Doan:** Writing - review & editing. **Tu Cuong Ho:** Writing - review & editing. **Nhu Da Le:** Writing - review & editing. **Thi Anh Huong Nguyen:** Writing - review & editing. **Emilie Strady:** Investigation, Writing - review & editing. **Vincent Fauvelle:** Investigation, Writing - review & editing. **Mélanie Ourgaud:** Investigation, Writing - review & editing. **Natascha Schmidt:** Investigation, Writing - review & editing. **Richard Sempere:** Investigation, Writing - review & editing.

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.

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