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REVIEW

Environmental perspectives of microplastic pollution in the aquatic environment: a review

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Abstract
Microplastics are a highly concerning pollutant that have gained attention from the scientific community and other regulatory authorities due to their potential risks to organisms and ecosystems. Microplastics are widespread in both terrestrial and aquatic ecosystems and can be found even in Antarctica and deep-sea sediments. The ability to survive for long periods in the environment and their aptitude of inter- and intra-environmental translocation can prompt poor environmental outcomes. The adsorption of heavy metals and other toxic persistent organic pollutants is a further cause for concern. Furthermore, microplastics enable the development of a distinct microbial niche within an ecosystem, which could potentially impair ecosystem function by promoting the growth of selective microbial communities. The acquisition of metal-resistant, antibiotic-resistant genes, and the enrichment of antibiotic-resistant bacteria on microplastic surfaces have recently been reported. Moreover, some studies have also reported the colonization of pathogenic bacterial strains such as *Vibrio* spp. on microplastic surfaces. This review aims to address the sources of microplastic pollution in the freshwater and marine environments and to discuss their potential functions in the environment.

Keywords Microplastic · Heavy metals · Pollutant reservoir · Distinct microbial habitat · Gene exchange

Introduction

Plastic has become an indispensable part of human life. It is a synthetic organic polymer produced through the polymerization of monomers procured from fossil fuels, gas, or coal. Certain attributes such as durability, lightweight, resistance to corrosion, and low price have led to the extensive use of plastic-based materials. While plastic was invented a century ago, mass production did not start until the mid-nineteenth century (Ivleva et al. 2017). The annual global production of plastic in 2015 was 320 million tons (PlasticsEurope 2015), and this is increasing annually. Plastics have served human society in many ways, for example, reduced CO_2 emission, enhanced consumer health, increased product durability, drinking water storage, and transportation (Andrady and Neal 2009). However, since its extensive use worldwide, it has become recognized as a recalcitrant pollutant in both terrestrial and aquatic ecosystems (Erni-Cassola et al. 2019). Plastics exist in the environment in a broad size range, from macro- to micro-size particles.

Microplastics, generally, refer to plastic particles that are less than 10 mm in size (Graham and Thompson 2009); however, this classification varies from study to study (Barnes et al. 2009; Claessens et al. 2011; Derraik 2002; Ryan et al. 2009). The existence of microplastic in the environment is becoming a global environmental and health problem. There are two main categories of microplastics: primary microplastics and secondary microplastics. Primary microplastics are plastic particles initially produced at the microscopic size.

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These are widely used in cosmetics, facial cleansers, and pharmaceutics (drug delivery) (Gregory 1996). Secondary microplastics are plastic particles that are produced from the breakdown of large plastic materials in both terrestrial and aquatic systems (Cole et al. 2011; Ryan et al. 2009). Secondary microplastic is considered the major cause of microplastic pollution in the marine environment (Hidalgo-Ruz et al. 2012).

The distribution and abundance of microplastic in an ecosystem mostly depends on the surrounding anthropogenic activities (Eriksen et al. 2013). In the 1970s, the presence of microplastic was first accentuated in the open ocean (Carpenter and Smith 1972). Since then, a renewed research interest over the last few decades has shown that microplastics are now ubiquitous in the marine environment (Derraik 2002; Moore 2008; Thompson et al. 2004). The distribution, abundance, and ecological consequences of microplastic pollution in the marine environment are hot topics of the current research. Similarly, interest is growing in determining the levels of microplastic pollution in freshwater bodies, including rivers and lakes. Several studies have documented the abundance and distribution of microplastic pollution in freshwater systems, including the water column and sediments (Alam et al. 2019; Eriksen et al. 2013; Nan et al. 2020; Wagner et al. 2014). Riverine and estuaries ecosystems, especially the rivers that flow through populous cities, are considered as dumping sites for microplastic pollution (Eerkes-Medrano et al. 2015). These rivers also serve as the main source of microplastic pollution in the marine environment (Eerkes-Medrano et al. 2015). Domestic waste, littering, and improper waste management are the major routes through which plastic waste enters the riverine systems in populated areas.

Microplastic pollution has been identified as one of the most pervasive and damaging of human stresses in aquatic environments (Wagner et al. 2014). Compared to macroplastic, microplastic pollution can cause serious environmental, ecological, and health issues. The adverse effects and ecological consequences of microplastic pollution have been documented recently in several reports. For example, due to their small size, microplastics can be ingested as food particles by aquatic organisms and hence enter the food chain (Ivleva et al. 2017). Moreover, some studies have reported that microplastics provide a surface for the deposition of persistent organic pollutants such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) (Bakir et al. 2012; Frias et al. 2010). Similarly, heavy metals tend to accumulate on the surface of different microplastic materials (Turner 2016). Furthermore, due to the distinct physiochemical characteristics, microplastics offer a unique habitat for the colonization of microbial communities. These physiognomies could lead to different ecological, microbiological, and evolutionary events. For example, it has been reported that microplastics can act as a reservoir for antibiotic-resistant and metal-resistant genes (Arias-Andres et al. 2018). Similarly, some studies have also found that pathogenic bacteria were able to colonize microplastic surfaces and hence could facilitate the transportation of pathogenic bacteria (Kirstein et al. 2016). This review aims to address the potential sources of microplastic pollution, to review the possible routes by which microplastic enter the environment, and to discuss the environmental consequences of microplastic pollution.

Sources of microplastic

Primary microplastics, those originally synthesized at the microscopic level, are widely used in a variety of manufacturing industries, for example, therapeutics (drug delivery, diagnostics reagent, injectable biomaterial), food science, and exfoliants in personal care products and cosmetics (Kawaguchi 2000). Moreover, microplastic "scrubber," an important component of facial scrub and hand cleanser, has replaced the traditional use of natural ingredients, such as ground almond, pumice, and oatmeal (Derraik 2002; Fendall and Sewell 2009). A large increase in the use of microplastic "scrubbers" was seen in cosmetic industries after the process was patented in the 1980s (Fendall and Sewell 2009; Gregory 1996). Furthermore, various products such as toothpaste, shampoo, shower gel, liquid makeup, baby lotion, shaving cream, mascara, eye shadow, lotion, hair colors, nail polish, sunscreen, bubble bath have all been reported to be potential sources of microplastics (Conkle et al. 2018; Hintersteiner et al. 2015). According to an investigation of soaps usage conducted by Cosmetics Europe (Europe Cosmetics Industry Association) and Euromonitor International (Consumer database) in Norway and Switzerland, the total annual usage of microplastic beads was 4130 t, resulting in an average discharge of 17.5 ± 10 mg/day per individual (Gouin et al. 2015). In another study conducted by Chang (2015), the annual contribution of microplastics from Berkeley student housing was calculated to be around 5 kg/year. Similarly, the daily discharge from women's lifestyle products in the UK was around 4594–94,500 microplastic particles (Napper et al. 2015). Furthermore, an investigation on German daily use of care products, including soaps, shower gels, skincare, body cleansers, and sunblock, was around 6.2 g per person per year (Essel et al. 2015). However, the estimated input of microplastic to the environment varies between nations because of different habits and different calculation methods (Galafassi et al. 2019). In addition, a large quantity of microplastics, comprised mostly of melamine, polyester and acrylic, is used in air blasting technology, associated with scrubbers in engine, machines, and boat hulls to remove rust and paint (Browne et al. 2007; Derraik 2002; Gregory 1996).

Secondary plastics are those produced from the breakdown of large plastic material, and the breakdown products enter the environment as a result of environmental weathering of the plastic objects. Over time, the mechanical integrity of the plastic material diminishes due to biological, physical, and chemical action, causing the disintegration of the corresponding material (Browne et al. 2007). Physical factors such as sunlight, including ultraviolet radiation, cause photo-degradation through the oxidation of the polymer matrix (Andrady 2011; Barnes et al. 2009; Moore 2008; Shah et al. 2008). In coastal areas, especially on the beaches, high sunlight and oxygen levels synergize plastic fragmentations (Browne et al. 2007). Furthermore, the continuous effects of turbulence, wave action, and abrasion boost the disintegration of the plastic materials (Barnes et al. 2009). As a result, the plastic material loses its structural integrity and falls apart into small fragments. This process of fragmentation continues until the original macroplastic material turns into microplastic particles. Further disintegration of microplastic particles could result in the formation of nanoplastic particles, with a minimum size of 1.6 µm (Galgani et al. 2010). To overcome the susceptibility to environmental conditions and to enhance the durability of plastic materials, adhesive materials have been added to the polymer matrix; this could result in further environmental and health complications (Talsness et al. 2009).

In terrestrial and freshwater ecosystems, secondary microplastics are mostly in a fibrous form, made of polyester, acrylic, and polyamide, originating from washing clothes and usually introduced to the environment at a density of around 100 particles per liter of effluent (Browne et al. 2011; Habib et al. 1998). According to one investigation, the washing of 5–6 kg of garments released around 137,951–6,000,000 particles to the environment (De Falco et al. 2018; Napper and Thompson 2016). Similarly, Pirc et al. (2016) calculated that with each wash, garments lose around 0.00012% of their mass and estimated that every individual release was around 70 g/year of microplastics annually. Moreover, secondary microplastics are also produced from a wide range of materials, including the tyres, car breaks, paints, asphalt, artificial turf, and artificial playgrounds (Galafassi et al. 2019). Secondary microplastic particles can thus be generated from every plastic material that enters the environment, and every plastic material can serve as a potential source of microplastics (Fig. 1). Secondary microplastics are considering the major source of microplastic pollution in the marine environment (Hidalgo-Ruz et al. 2012).

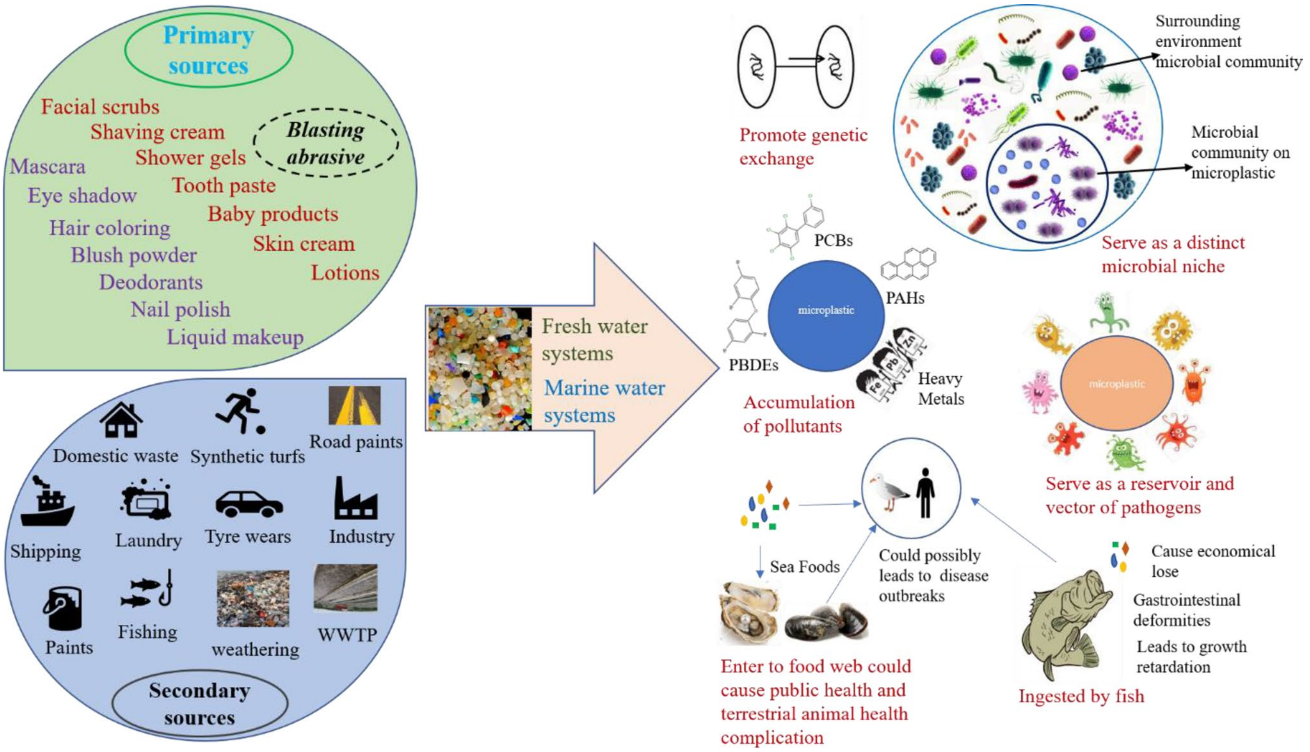

Fig. 1 A conceptual diagram showing the sources of microplastic pollution and their environmental, ecological and health related impacts

Transportation of microplastic

Specific features of microplastics, such as being lightweight, having different morphologies, and an extremely long shelf life, are making a significant contribution to the inter-/intra-environmental transportation of microplastics. These properties also make microplastics one of the most ubiquitous pollutants on earth. Almost all the plastic and derived plastic materials are produced on land, from where it enters different environments via a variety of routes. In most scenarios, the land act as the first dumping site for microplastics; these then enter the environment through direct littering, improper waste management, accidentally loss during the disposal process, and industrial spillages (Horton and Dixon 2018). The use of sewage sludge as fertilizer in agriculture also introduces a significant amount of plastic (Nizzetto et al. 2016). Compared to urban lands, agricultural and forestry land is more prone to retain the microplastics due to their higher soil permeability and a lower rate of surface water flow (Nizzetto et al. 2016). Moreover, downward drainage and bioturbation can facilitate the transport of microplastic within the soil system, which ultimately causes the deposition of microplastics in deeper layers of soil (Lwanga et al. 2017; Zubris and Richards 2005). Furthermore, soil arthropods (e.g., *Folsomia candida* and *Priosoma minuta*) facilitate the transportation of microplastic particles in the soil system (Maaß et al. 2017).

Agricultural runoff, wastewater treatment plants, floods, etc., are the main sources of microplastic input to freshwater systems. Once it enters into an environment, microplastic particles undergo transportation by different mechanisms, which depends on the type of particle. In riverine systems, microplastic transport depends on water current, i.e., rivers with a greater flow have a high capacity to transport large numbers of particles (Horton and Dixon 2018). Alternatively, in slow-moving sections of a river, microplastics are more likely to settle, along with sinking sediment particles, and be buried. However, in lakes and ponds, the rate of sedimentation of microplastic is very high compared to the riverine systems. The physical and chemical properties (shape, buoyancy, chemical composition) of microplastic particles also have a substantial effect on their transport and retention in aquatic systems. For example, microplastics with a density lower than water usually float on the surface, while denser particles sediment out. However, the density of microplastics and other particulate objects does not remain constant because the colonization of microalgae and other microbial communities can increase their density, which then leads to enhanced sinking (Lagarde et al. 2016). At a local scale, sediment deposition and transportation can lead to the translocation of buried microplastic in freshwater systems. Floods (natural disasters) and the progressive change in river channel morphology (long time-scale), however, can also cause erosion of the river banks, which ultimately leads to the re-suspension and mobilization of buried particles (Horton and Dixon 2018).

Riverine systems serve as the biggest source of microplastic input in the oceanic environment. Once they enter the ocean, the microplastic particles can travel great distances and be spread rapidly by water current, winds, turbulence (van Sebille et al. 2012). Microplastics also undergo vertical transportation in the water column. Phenomena such as marine snow, biofouling, and egestion in fecal pellets are considered the major routes involved in the vertical transport of microplastic particles (Cole et al. 2016; Kowalski et al. 2016; Rummel et al. 2017). The size and composition of microplastic particles also affect vertical transport in the water column. Tekman et al. (2020) observed a positive correlation between microplastic size and the abundance of particulate organic matter, which controls the biological processes and leads to the particle settlement. Turbidity currents also play a significant role in the deposition and translocation of microplastic in the seafloor (Pohl et al. 2020).

Microplastic in the fresh and marine environment

Several factors that affect the number and distribution of microplastic particles in an environment have been identified. For example, in addition to physical parameters (pressure, winds, turbulence, wave action, sunlight intensity, etc.), human population, density, anthropogenic activities, distance from the water body, size of water reservoirs, urban waste management practices and the quantity of sewage effluent are important factors (Eerkes-Medrano et al. 2015; Eriksen et al. 2013; Moore et al. 2011). Information on microplastic pollution, accumulation, and their ecological impacts in freshwater systems and terrestrial environments are not well documented compared to the marine environment (House of Commons Science and Technology Committee 2013; Eerkes-Medrano et al. 2015; Thompson et al. 2004). Freshwater ecosystems include rivers, streams, ditches, lakes, and ponds; all have distinct features (Horton and Dixon 2018). Freshwater systems also serve as the dumping site for plastics, act as a source of microplastic pollution to the marine environment, and provide a medium for microplastic production (secondary microplastic). Investigations of microplastic particles in the water column and sediments of freshwater systems across the globe have been conducted by Castañeda et al. (2014), Faure et al. (2012), Imhof et al. (2012), Lechner et al. (2014), Sadri and Thompson 2014, and Wagner et al. (2014), as in Table 1. Microplastic

Table 1 Distribution and abundance of microplastic in the water column and sediments in freshwater ecosystems

Location	Sampling	Abundance	Size range	Type	References
Yangtze River estuary	Water samples collected from 1.00 m depth	4137.30 ± 2461.50 particles/m^3	0.50–5.00 mm (more than 90.00% abundance)	Not mentioned	Zhao et al. (2014)
Pearl River delta	Surface samples collected at a depth of 50.00 cm	379.00–7924.00 particles/m^3	0.02–1.00 mm (44.80%) and 1.00–2.00 mm (36.50%)	Polyethylene, polypropylene, polyethylene terephthalate, and other derivatives	Lin et al. (2018)
Wei River	Surface water (around 30.00 L were used for MPs collection)	3.67–10.70 particles/L	< 0.50 mm (40.80–68.80%) 0.50–1.00 mm (15.10–27.10%)	Polyvinyl chloride, polyethylene, and polypropylene	Ding et al. (2019a, b)
Ciwalengke River	Surface water at a depth of 45.00 cm	5.85 ± 3.28 particles/L	50.00–2000.00 µm (50.00–100.00 µm highly abundant)	Polyester, polyamide, and cotton fibers	Alam et al. (2019)
Small streams	phytoplankton net (diameter = 83.00 mm, 63.00 mm mesh) deployed for 30 min in the surface water and around 0.19–4.52 m^3 were filtered	17.00–303.00 particles/m^3	63.00–500.00 µm	Ethylene/ethyl acrylate copolymer, polyethylene, polypropylene, and their derivatives	Dikareva and Simon (2019)
Storm water	722.00–1139.00 L storm water samples were filtered for MPs extraction	490.00–22,894.00 particles/m^3	532.00–1030.00 µm	Polyvinylchloride, polypropylene, polyester, polyethylene, and polystyrene	Liu et al. (2019)
Al-Hassan irrigation network	Water samples collected at a depth of between 0.00 and 1.00 m	0.70–9.00 particles/L	250.00–5000.00 µm	Not mentioned	Pico et al. (2020)
Carpathian basin	Surface water samples collected at a depth of 10.00–20.00 cm	3.52–32.05 particles/m^3	Not mentioned	Polyethylene, polypropylene, polystyrene, polyacrylate, polyester, and polytetrafluoroethylene	Bordos et al. (2019)
Han River and its tributaries	Around 3.00–5.00 m^3 surface (0.00–30.00 cm) and at 2.00-m depth were filtered for MPs collections	0.00–42.90 particles/m^3 (surface water) 20.00–180.00 particles/m^3 in the water column at 2-m depth	0.10–5.00 mm < 1.00 mm accounted for 90.00% MPs	Polyethylene, silicon, polystyrene, and polytetrafluoroethylene	Park et al. (2020)
Streams and wetlands	Surface water (0.00–15.00 cm)	0.40 ± 0.27 particles/L	3.60–466.80 µm	Rayon, polyester, polypropylene, polyethylene, polyamide, and acrylic	Nan et al. (2020)
Laurentian Great Lakes	Surface water, MPs were collected by trawling	$450.00–4.50 \times 10^5$ particles/km^2	0.35–4.75 mm 0.35–0.99 mm accounted for 81.00% of all MPs	Polyethylene and polypropylene microbeads	Eriksen et al. (2013)
Wei River	Surface sediment, 5.00 kg samples were processed for extraction of MPs	360.00–1320.00 particles/kg	< 0.50 mm (40.80–68.80%) 0.50–1.00 mm (8.30–24.80%)	Polyvinyl chloride, polyethylene, and polypropylene	Ding et al. (2019a, b)
Brisbane River	Surface sediment samples at a depth 0.00–3.00 cm were collected	0.18–129.20 mg/kg, or 10.00–520.00 particles/kg	1.00–5.00 mm > 3.00 mm accounted for the highest concentration	Polyethylene, polyamide, polypropylene	He et al. (2020)

Table 1 (continued)

Location	Sampling	Abundance	Size range	Type	References
Ciwalengke River	Sediment samples collected from Ekman grab sampler	3.03 ± 1.59 particles/100 g	50.00–2000.00 µm (1000.00–2000.00 µm highly abundant)	Polyester, polyamide and cotton fibers	Alam et al. (2019)
Small streams	Microplastic extracted from 1.00 kg surface sediment sample	9.00–80.00 particles/kg	63.00–500.00 µm	Ethylene/ethyl acrylate copolymer, polyethylene, polypropylene, and their derivatives	Dikareva and Simon (2019)
Atoyac River basin	Surface sediment samples (MPs extracted from 30.00 g dry sediments)	1633.34 ± 202.56, 1133.33 ± 72.76, 833.33 ± 80.79 and 900.00 ± 346.12 particles/kg in different water reservoir	Size did not mention. films (25.90%), fragments (22.20%), fibers (14.80%) and pellets (11.10%)	Not mentioned	Shruti et al. (2019)
Three Gorgeous Reservoirs	Surface sediment samples (0.00–20.00 cm) collected through stainless steel towel	55.00 ± 0.12–1458.00 ± 56.70 particles/m^3	0.10–5.00 mm	Polyethylene, polypropylene, and polystyrene	Zhang et al. (2019a, b)
Yellow River estuary	Surface sediments samples, MPs were extracted from 1.00 kg sample	136.00–2060.00 particles/kg	13.00–5000.00 µm	Not mentioned	Duan et al. (2019)
Tibet plateau lakes	20.00 × 20.00 cm surface sediment (2.00 cm) samples collected in triplicate from each site	8.00 ± 14.00–563.00 ± 1219.00 particles/m^2	0.50–5.00 mm 1.00–5.00 mm the most abundant particles	Polyethylene, polypropylene, polystyrene, polyethylene terephthalate and polyvinylchloride	Zhang et al. (2016)

particles have been found in all major rivers and freshwater reservoirs: in China, in the Pearl River and Pearl River estuary (Yan et al. 2019), in the Yellow River (Duan et al. 2019) in the Three Gorges Reservoirs (Zhang et al. 2019a, b), in the Yangtze River (Xiong et al. 2019), America: in the Los Angeles Basin (Moore et al. 2011), in the Lawrence River (Castañeda et al. 2014) and the Great Lakes (Eriksen et al. 2013), in the rivers and lakes of Europe; Geneva Lake (Faure et al. 2012), Italian lake Gerda (Imhof et al. 2012), Austrian Danube River (Lechner et al. 2014), the German, Elbe, Necker, Mosel, and Rhine rivers (Wagner et al. 2014). Furthermore, Table 1 summarizes the distribution and abundance of microplastic in these freshwater systems.

The uncontrolled disposal of waste produced from the onshore activities ultimately enters the ocean. Plastic materials are ubiquitous in marine habitats, i.e., they can be found in beaches, polar regions, and even in the deep-sea sediments (Browne et al. 2011; Goldberg 1997; Law et al. 2010). It has been reported that around 80% of microplastic items in the marine environment originates from terrestrial sources (Andrady 2011). Approximately half of the global population lives near coastal regions, and the microplastic debris resulting from anthropogenic activities most likely enters the ocean via rivers and domestic and industrial drainage systems (Derraik 2002; Moore 2008; Thompson et al. 2005). Microplastics are varyingly distributed across the different habitats of the oceanic environment (Table 2). For example, in two independent studies, van Sebille et al. (2015) reported 90–235 thousand tons, and Eriksen et al. (2013) reported 66 thousand tons of plastic debris floating on surface seawater. Similarly, at the shoreline the highest concentration of microplastics, 50,000 particles/kg, was detected on East Frisian Island (Liebezeit and Dubaish 2012) and 285.673 particles/m^3 on a coastline in South Korea (Kim et al. 2015). Browne et al. (2011) observed a correlation between microplastic abundance and anthropogenic activities by identifying the sources and sinks of microplastic pollution along shorelines worldwide. Table 2 shows the distribution and abundance of microplastic in marine ecosystems at different locations.

Many previous studies have documented that freshwater systems, including rivers, are the major source of microplastic input into the marine environment. According to Moore et al. (2011), in which they quantified the microplastic particles in the water sample of two Los Angeles rivers, extrapolating the data showed that these rivers alone could introduce around 2 billion microplastic particles into the ocean within 3 days. Similarly, it has been estimated that on an annual basis, around 13.6 thousand tons of plastic debris entered the South China Sea via the Pearl River (Lebreton et al. 2017). Natural disasters and extremes weather, including floods or hurricanes, enhance the transportation of terrestrial waste into the ocean (Browne et al. 2011; Thompson et al. 2005). Moore et al. (2002) found that following a storm the transfer of neustonic plastic particles (<4.55 mm in diameter) into Californian waters near the entrance of the Los Angeles stormwater conveyance system increased from 10 plastic particles/m^3 to 60 particles/m^3. Coastal tourism, shipping (commercial and recreational), oil rigs, and aquaculture practices are all causes of microplastic pollution in the marine environment. While secondary microplastic is the major source of microplastic pollution in the marine environment, physical parameters such as winds, sunlight, ultraviolet radiation, wave action, and turbulence are all essential factors contributing to the creation of these particles and their transportation to other ecosystems.

Microplastics as vectors

Microplastic as a reservoir of heavy metals

Due to their unique physicochemical characteristics, microplastics offer a distinct surface for chemical acquisition, pollutant accumulation, and microbial communities. Because of their low degradation rates, microplastics can persist in the environment for decades or even centuries. The long-lasting presence of microplastics in the aquatic environment is considered a threat to many aquatic animals. In addition to aesthetic concerns, plastic debris poses several threats to marine organisms, such as entrapment, choking, entanglement, and suffocation (Boren et al. 2006; Browne et al. 2008). Plastic materials can also act as a cause of organic pollution to biotic organisms because organic pollutants, such as polycyclic aromatic hydrocarbons and polychlorinated hydrocarbons, tend to accumulate on the microplastic surfaces. Plastic surfaces have usually been considered to be inert for the acquisitions of heavy metals; however, metals accumulated during storage in a plastic container and during the experimental processes are generally stated problems (Cobelo-Garcia et al. 2007; Fischer et al. 2007; Weijuan et al. 2000). Table 3 summarizes some important environmental functions of microplastic particles.

Recently, many studies reported that heavy metals accumulate on microplastic surfaces in the marine environment. Brennecke et al. (2016) studied the adsorption of Cu and Zn metals on the surfaces of aged polyvinyl chloride (PVC) and virgin polystyrene (PS) microplastics in marine waters. They concluded that heavy metals leached from antifouling paint tended to absorb on the surface of the studied microplastics; moreover, PVC absorbed a relatively high concentration of metals compared to PS. Similarly, Turner (2016) detected the presence of heavy metals, metalloids, and other toxic elements on the surface of marine plastic debris. Microbeads that are extensively used in cosmetic products could adsorb lead (Pb) onto their surface from the surrounding

Table 2 Distribution and abundance of microplastic in the water column and sediments of marine environments

Location	Sampling	Abundance	Size range	Type	References
Persian Gulf	Surface water	1500.00–46,000.00 particles/km^2	100.00–5000.00 µm	Polyethylene, polypropylene, and polystyrene	Kor and Mehdinia (2020)
South China Sea	Water samples	1400.00–8100.00 particles/m^2	0.10–5.00 mm < 0.50 mm = 80.00% abundance	Polypropylene, polyamide, polystyrene, and polyvinyl chloride etc.	Huang et al. (2019)
Nordic Seas	Surface water (10.00–50.00 cm)	1.90 ± 0.28 particles/L (East Greenland current) 2.43 ± 0.84 particles/L (Greenland Sea gyre)	0.10–50.00 mm	Polyester, polyethylene, polypropylene, polystyrene, polyvinyl acetate and polyamide	Jiang et al. (2020)
South China Sea	Water samples (10.00–40.00 m depth) from outer reef slopes	0.20–12.20 particles/L	7.00–4856.00 µm	Rayon, polyethylene, polyethylene terephthalate, polyamide, polyvinyl chloride, polyvinylidene chloride and chlorinated polyethylene	Ding et al. (2019a, b)
Baltic Sea	Surface water	0.40 ± 0.58 particles/L	0.50–5.00 mm	Not mentioned	Bagaev et al. (2018)
Kingston Harbour	Surface water (depth not mentioned)	0.00–5.73 particles/m^3	1.00–2.50 mm	Polyethylene, polypropylene and polystyrene	Rose and Webber (2019)
Southern Ocean	Water samples	188.00 ± 589.00 particles/km^2	0.68–21.50 mm < 5.00 mm = 93.00% abundance	Nylon, polystyrene, polyethylene, and Polypropylene	Suaria et al. (2020)
Ligurian and Tyrrhenian Seas	Surface water	1009.00–122,817.00 particles/km^2	2.50–5.00 mm	Polyethylene, polypropylene, polystyrene, and polyamide etc.	Caldwell et al. (2019)
Coastal Metropolis	Surface water (0.00–5.00 cm)	0.06–2.50 particles/L	1.26 ± 0.93 mm (mean size)	Polyester, polypropylene, polyamide, polystyrene, polyethylene, polyvinyl chloride, rayon and acrylic etc.	Su et al. (2020)
Coastal shelf of KwaZulu-Natal	Surface water (0.00–15.00 cm)	4.01 ± 3.28 particles/100 m^2	1.00–5.00 mm	Not mentioned	Naidoo and Glassom (2019)
Persian Gulf	Surface sediment (5.00 cm depth)	1258.00 ± 291.00 (Bostanu), 122.00 ± 23.00 (Gorsozan), 26.00 ± 6.00 (Khor-e-Yekshabeh), 14.00 ± 4.00 (Suru)	0.14–5.69 mm	Polyethylene, nylon and polyethylene terephthalate	Naji et al. (2017)
Mediterranean Sea	Surface sediment (2.00–3.00 cm)	141.20 ± 25.98–461.25 ± 29.00 particles/kg	0.10–5.00 mm	Polyethylene, polypropylene and polystyrene	Abidli et al. (2018)
Scapa Flow, Orkney	Surface sediment (3.00 cm)	730.00–2300.00 particles/kg	Not mentioned	Poly(tetrafluoro)ethylene polyethylene, polyamide, polyester, and polyacrylonitrile	Blumenroder et al. (2017)

Table 2 (continued)

Location	Sampling	Abundance	Size range	Type	References
Yellow Sea	Surface sediment (5.00 cm)	499.76 ± 370.07 particles/kg	34.97–4983.73 μm	Rayon, polyethylene, polypropylene, polyamide, polyethylene terephthalate, polystyrene and polyurethane	Zhang et al. (2019a, b)
Sand beaches of South Korea	Surface sands (25.00 mm)	1400.00–62,800.00 particles/m^2	0.02–1.00 mm	Polystyrene, polyethylene terephthalate, polyethylene urethane, styrene acrylate, alkyd, nylon, etc.	Eo et al. (2018)
Belgian Coast	Surface sediment (2.00–7.00 cm)	390.00 particles/kg	38.00–1000.00 μm	Polystyrene, polyethylene polypropylene, nylon, and polyvinyl alcohol	Claessens et al. (2011)
French Atlantic coastal	Surface sediment (0.00–10.00 cm)	67.00 ± 76.00 particles/kg	10.00–1000.00 μm	Polyvinyl chloride, polystyrene, polyester, nylon, polyacrylonitrile, polyamide, etc.	Phuong et al. (2018)
Po River Delta	Surface sediment (5.00 cm)	2.92–23.30 particles/kg	1.00–5.00 mm	Polyethylene, polypropylene, and polystyrene	Piehl et al. (2019)
Hadal trenches	Deep-sea sediment (4900.00–10,890.00 m)	71.10 particles/kg	73.00–12,376.00 μm	Rayon, polypropylene, and polystyrene	Peng et al. (2020)
Coastal Metropolis	Surface sediments (2.00 cm)	0.90–298.10 particles/kg	1.24 ± 0.84 mm (mean size)	Polyester, polypropylene, polyamide, polystyrene, polyethylene, polyvinyl chloride, rayon and acrylic etc.	Su et al. (2020)

Table 3 Summary of some potential environmental functions of microplastic pollution

S. no.	Functions	Overview
1	Accumulation of heavy metals	Recently many studies reported the adsorption of different heavy metals such as Pb, Cd, Zn, Cu, and metalloids, etc., on microplastic particles in the natural environment and laboratory-scale experiments. Various factors, for example, pH, salinity, surface charges, and the chemical constituency of the surrounding environment, affect the sorption of heavy metals on the microplastic surface
2	Adsorption of persistent organic pollutants	Persistent organic pollutants, such as PCBs, PAHs, and OCPs, etc., are leans toward the microplastic surface. Several studies have been reported the accumulations of these pollutants on microplastic debris in different environments. The hydrophobicity is one of the critical factors which facilitate the adsorption of these pollutants on plastic particles. This phenomenon might facilitate the transportation of these toxic pollutants in the environment
3	Carrier of microorganisms	Once entering the environment, microorganisms (algae, fungi, bacteria etc.) colonize the microplastic surfaces. The microbial community inhabiting microplastic are generally known as plastosphere. Microplastics possibly facilitate the diffusion of microorganisms in the environment
4	Antibiotic-resistant and metal-resistant genes	Several studies reported that microplastic particles could act as a reservoir for antibiotic and metals resistant genes. In addition, microplastic also provides a ground for the enrichment of multi antibiotic-resistant bacteria. This phenomenon might increase the gene exchange among the biofilm microbial communities
5	Colonization of pathogens	Some studies also reported the colonization of pathogenic bacterial strains on microplastic surface in natural environment and laboratory-scale experiment

sediments (Boucher et al. 2016). In another study, a higher concentration of different heavy metals was detected on the surface of microplastic compared to the surrounding seawater, which further demonstrates the sorption of heavy metals onto microplastic surfaces (Marsic-Lucic et al. 2018). The previous investigation also showed that aged microplastic particles have a higher capacity of metals sorption compared to virgin particles. Wang et al. (2020) detected a higher concentration of Zn^{2+} and Cu^{2+} sorption onto the surface of aged polyethylene terephthalate (PET) particles compared to their virgin counterpart in aqueous solution. Guo et al. (2020) also identified several factors such as the types of microplastic, pH, ionic strength, and humic acid that effected the adsorption of Cd^{2+} onto the microplastic surfaces. Similarly, Tang et al. (2020) extensively investigated the Pb(II) uptake mechanism onto nylon particle surfaces in a batch culture experiment. They observed that Pb(II) adsorption was significantly dependent on solution initial pH, NaCl concentration, and fulvic acid concentration. Moreover, they also detected that hydroxyl ions on the surface of aged nylon particles play a fundamental role in controlling Pb(II) adsorption. Sodium dodecylbenzene sulfonate (SDBS), an anionic surfactant, has a broad range of applications, such as personal care products, shampoo, hand-washer, household, and laundry detergents. Zhang et al. (2020a, b) reported that SDBS significantly increases the adsorption capacity of polyethylene microplastic. However, the exact mechanism by which metal ions interact and are adsorbed onto microplastic items in the natural environment is not well understood. Along with the intrinsic properties of the participants (microplastics and heavy metals), the chemical nature of the surrounding environment can also affect this interaction. In addition, the attachment of metals containing small particles with microplastic surfaces possibly facilitates microplastic/metals interaction (Holmes et al. 2012). The accumulation of heavy metals on microplastic surfaces could cause additional complications if ingested by an aquatic organism and could enter the food chain. More research is required to explain the mechanism of how heavy metals accumulate on microplastic surfaces and to address the subsequent ecological, environmental, and health implications.

Microplastic as a carrier of organic pollutants

The accumulation of persistent and toxic organic pollutants on microplastic particles is a highly concerning issue. The sorption of persistent organic pollutants could trigger many environmental problems as it can promote the translocation of these pollutants, can increase their recalcitrancy, and can enter the food cycle via ingestion by animals. Several studies have been reported that show the adsorption of environmentally concerned toxic contaminants, such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbon (PAHs), and organochlorine pesticides (OCPs), onto microplastics. Carpenter and Smith (1972) reported for the first time the presence of PCBs at a concentration of 5000 ng/g on the surfaces of plastic debris in seawater. Similarly, Gregory (1978) detected the presence of PCBs in high concentrations on the surface of virgin polyethylene granules recovered from coastal sediments of New Zealand beaches. In the last two decades, several studies had been conducted around the globe and reported the presence of PCBs on microplastic surfaces at a variety of concentrations (Endo et al. 2005; Frias et al. 2010; Heskett et al. 2012; Rios et al. 2007). Similarly, PAHs, an important class of persistent organic pollutants, had been discovered on the surface of microplastic particles in several studies. For example, Rios et al. (2007) detected PAHs at a concentration of 39–1200 ng/g on plastic debris collected from the North Pacific Gyre, Hawaii, Guadalupe Island, and Mexico beaches. Teuten et al. (2007) observed a 10^6 higher phenanthrene (PAH) concentration on microplastics compared to the surrounding water concentration. Moreover, a survey carried out by International Pellet Watch (IPW), by collecting microplastic samples from 75 locations in 26 countries, found higher PAHs concentrations on Sao Torpes Beach, Portugal (24,400 ng/g), and the Forth Estuary in the UK (162,900 ng/g) (Yeo et al. 2017). Similarly, OCPs are an important group of synthetic chlorinated hydrocarbons mostly used in agriculture and chemical industries. Dichlorodiphenyltrichloroethane (DDTs) and related compounds were widely used chemicals in the agriculture sectors in the past (currently banned in many countries). In four coastal sites of Japan, DDTs were detected on microplastic at varied concentrations, ranging from 0.61 to 3.1 ng/g (Mato et al. 2001). In another study conducted on OCPs, DDT was found at concentrations ranging from 64.4 to 87.7 ng/g on microplastic particles ingested by seabirds (Colabuono et al. 2010).

The adsorption mechanism of toxic organic pollutants on microplastic surfaces is complex, varied for different chemicals and relatively unexplored process (Verla et al. 2019). Contaminants can adsorb onto microplastic surfaces via three possible mechanisms: (1) adsorption as hydrophobic adsorbents, (2) biofilm-mediated adherence, and (3) additive materials in plastic resins (Verla et al. 2019). Due to their hydrophobicity, organic pollutants are reluctant to attach to floating particles (microplastics). On the other hand, hydrophobic microplastics have a large surface area-to-volume ratio, which makes them an ideal surface for chemical adsorption. Also, environmental weathering of plastic material enhances the capacity of the sorption of different organic pollutants. It has been reported that aged microplastic items exhibit a higher capacity for pollutant accumulation than virgin particles (Fotopoulou and Karapanagioti 2012). This might be due to the fact that environmental weathering removes their surface topology, i.e., makes the surface porous, rough, and irregular, which ultimately increases the surface area. In addition to the physical disruption, environmental weathering also alters the chemical properties of the particle surface. For example, Fotopoulou and Karapanagioti (2012) reported that environmental erosion of polyethylene particles produced a negative charge on the particle surface in seawater. This phenomenon could facilitate the adsorption of specific organic pollutants and other positively charged contaminants. In addition, because microplastics are produced from different plastic materials, they will have a distinct chemical composition, which could also affect the adsorption of organic pollutants. For example, Rochman et al. (2013) found that low-density polyethylene, high-density polyethylene, and propylene-derived microplastics adsorbed higher concentrations of PAHs and PCBs than polyvinyl chloride and polyethylene terephthalate-derived particles (Fig. 1). This attribution of plastic particles has been used to quantify the amount of persistent organic pollutants (POPs) in the aquatic environment (Huckins et al. 1993; Lohmann 2012). Particle size also affects the pattern of pollutant adsorption. For example, Ma et al. (2019) found that small polyvinyl chloride particles had a stronger adsorption capacity and greater distribution coefficient k_d of triclosan than large particles.

Microplastic provide a distinct microbial niche

Understanding the interactions between microbial communities and microplastic particles of different origins is gaining attention. Naturally, in the environments (terrestrial, aquatic, marine), microorganisms tend to attach and colonize surfaces, including both natural and synthetic. The attachment and colonization of microorganisms, including bacteria, fungi, viruses, archaea, algae, and protozoans, on surfaces, is generally known as "biofilm formation."

From the point of production to final sinking, microplastics undergo inter-/intra-environmental transportation. During this process and in final settlement, microorganisms are able to colonize the surface of microplastic particles (Schluter et al. 2015). Biofilm formation is a complex process, and understanding the mechanism on different microplastic surfaces is challenging (Rummel et al. 2017), particularly in the aquatic environment (fresh and marine) where the chemical and biological heterogeneity changes with time and place. Once microplastics are released into the environment, they attract the attachments of organic and inorganic substances. It has been reported that within seconds of primary exposure to the ambient environment, a thin coating layer of organic and inorganic substances forms on virgin microplastic surfaces. This thin coating of organic and inorganic substances is generally known as the "conditioning film" (Loeb and Neihof 1975) and is considered a major factor in the establishment of a biofilm. The chemical constituency of these conditioning films can direct the type of colonizing microbial communities (Jones et al. 2007; Taylor et al. 1997). The distinct physiochemical characteristics of different microplastic particles can also influence the composition of the conditioning film, which in turn could direct the assembly of microbial communities. Different chemicals trigger different stimuli, i.e., they might be chemoattracting, which would attract microbial communities, or it might be a chemorepellent, which would repel microbial communities. However, different microbial communities may respond differently to different chemical substances.

The attachment of various chemicals, including nutrients on microplastic surfaces, provides an additional advantage to the colonizing microbial communities. For example, it can provide physical support, can provide a relatively stable nutrient supply, and provide a stable habitat that could help microorganisms to resist environmental stresses (Oberbeckmann et al. 2015; Shen et al. 2019). These properties of microplastics might facilitate the attachment of biofilm-forming microbial communities, which could cause ecosystem compartmentalization. The distinct composition of microbial communities between microplastic particles surfaces and the surrounding environment (water, sediment, soil) has been documented in many reports (Fig. 1). For example, Ogonowski et al. (2018) demonstrated the impact of plastic and non-plastic microparticles on the composition of microbial communities. They also observed that substrate hydrophobicity was the major factor of variation in community structure on different surfaces.

Microplastic microbial communities have a lower diversity and richness compared to natural surfaces (Miao et al. 2019). Microplastics not only affect microbial community differentiation but also influence the functionality of microbial communities (Miao et al. 2019). Early reports also suggested that different microbial communities occurred on different plastic debris, including low-density polyethylene, polyethylene terephthalate (PET), and polypropylene (Oberbeckmann et al. 2015). Similarly, the work of Frere et al. (2018) showed that variation in microbial communities depended on the type of microplastic particle rather than the size. Therefore, it has been suggested that microplastics develop a distinct microbial niche known as the “plastosphere”. This acquisition of distinct microbial phylotypes on different types of plastic materials could have environmental and ecological implications. For example, microplastics could promote the growth and succession of some microbial phylotypes while hindering the development of others, which might affect the ecological functions of the microbial communities. As discussed earlier, microplastics provide a substrate for organic pollutant deposition, which might favor the colonization of organic pollutants degrading microbial phylotype (Curren and Leong 2019).

Microplastic as a vector of antibiotic-resistant and bacterial pathogens

Owing to the low weight and high buoyancy of microplastics, they undergo both inter- and intra-environmental transportation from the point of production to the ultimate settling sites. This transportation of microplastic particles prompts some ecological, environmental, and public health implications. It has been reported that plastic material might act as a reservoir for antibiotic and metal resistance genes in the marine environment (Yang et al. 2019). Zhang et al. (2020a, b) demonstrated that microplastics not only act as a reservoir for antibiotic-resistant genes, but also provide a substrate for the enrichment of multi-antibiotic resistance bacteria (MRAB) in mariculture systems. A range of antibiotic-resistant genes, including tetracycline, penicillin, sulfafurazole, and erythromycin-resistant, was detected in the genome of bacterial strains recovered from some microplastic particles (Zhang et al. 2020a, b). Moreover, microplastics facilitate the exchange of genetic materials via horizontal gene transfer among the microbial communities (Arias-Andres et al. 2018). This phenomenon could aid the spread of antibiotic-resistant, metal-resistant, and virulence genes among microbial communities. In addition to the antibiotic-resistant bacteria, microplastic is also starting to harbor various human, aquatic animals, and plant pathogenic bacterial strains (Virsek et al. 2017; Wingender and Flemming 2011; Wu et al. 2019; Zhou et al. 2019). Wu et al. (2019) observed that *Pseudomonas monteilii* and *Pseudomonas mendocina*, which are opportunistic human pathogens, were selectively enriched on microplastic surfaces rather than on natural surfaces. Similarly, the plant pathogen, *Pseudomonas syringae*, also tends to accumulate and enrich on the microplastic surfaces. Moreover, *Vibrio*, which is a ubiquitous, ecologically and metabolically active marine animal and plankton-associated bacterial group, has been detected on a variety of microplastic surfaces (Foulon et al. 2016; Schmidt et al. 2014; Zettler et al. 2013). *Vibrio*, being a diverse bacterial group, encompasses several human and animal pathogens, including *Vibrio cholerae*, *Vibrio coralliilyticus*, *Vibrio harveyi*, *Vibrio splendidus*, *Vibrio parahaemolyticus*, *Vibrio alginolyticus*, and *Vibrio fluvialis*. Most of these pathogenic *Vibrio* species have been detected on microplastic particles, indicating that microplastics can provide a habitat for the colonization and enrichment of *Vibrio* species (Foulon et al. 2016; Kirstein et al. 2016; Zettler et al. 2013). In addition, fish pathogens, such as *Aeromonas salmonicida*, were found on microplastics collected from north Adriatic seawater (Virsek et al. 2017).

Microplastics possess many of the properties (enriching antibiotic resistance, colonizing pathogens, and enabling their transportation) that might cause severe public health, ecological, and commercial problems. For example, the ingestion of pathogen-loaded microplastic particles could lead to infections in fresh and marine water organisms. By consuming raw, ready to eat, and uncooked food, it could also cause infections in the human population. *Vibrio* species, which preferentially colonize microplastics, were the causative agents of several seafood-borne outbreaks (Elmahdi et al. 2016; Tran et al. 2013). Microplastic particles could also be a vector of infection spread in aquaculture, such as shrimp aquaculture, which could cause severe economic losses.

Microplastic particles are a proven hot spot for the acquisition of antibiotics, enriching antibiotic-resistant bacterial strains, and for the colonization of pathogens. These properties of microplastics can accelerate infection in aquaculture and mariculture farms by promoting the diffusion of pathogens. Due to their buoyancy and mobility, microplastics might promote the translocation of pathogens from one environment to another. For example, Goldstein et al. (2014) observed several coral pathogens on plastic debris recovered from the eastern and western Pacific. Furthermore, a folliculinid ciliate (*Halofolliculina* spp.), which is a coral pathogen causing skeletal eroding band (SED) (Rodríguez et al. 2008), was originally discovered and thought to be limited to Indian and South Pacific Ocean, but was later found in Caribbean (Cróquer et al. 2006) and Hawaiian corals (Palmer and Gates 2010). The actual mechanism of spread of SED is unknown; however, from the frequent recovery of the pathogens on the plastic debris, it has been speculated that plastic materials could facilitate the spread (Dameron et al. 2007; Pham et al. 2012). Hence, microplastics can facilitate the invasion of a new habitat by a pathogen, where they can proliferate and can harm local community structure, impair water quality, and also threaten human health (Kirkpatrick et al. 2004; Kirstein et al. 2016; Shen et al. 2019; Zettler et al. 2013).

Conclusion and future perspectives

Interest has been growing in understanding and assessing the environmental, ecological, and health (human and other animals) consequences of microplastic pollution. Microplastic comes from diverse sources and enters the environment, including terrestrial, freshwater, and marine water, via different routes. Due to their extremely long environmental persistence, microplastic can survive in the environment for decades, even for centuries. The ease of transportation and the attachment of environmental and public health concerning pollutants, including PAHs and PCBs, could have serious implications. Moreover, the enrichment of antibiotic-resistant bacteria and wildlife pathogenic bacteria is the most critical aspect of microplastic pollution. Keeping in view the adverse impacts, more research and understanding is required to comprehensively address all the possible hazardous threats prompted by microplastic pollution. The following studies should be conducted in the future:

1. Currently, different names, such as microplastic, mesoplastic, nanoplastic, and microparticles, have been used for plastic particles. It is important to devise a standard classification system for the nomenclature of microplastic particles.
2. The effect of the chemical composition of the conditioning film on the attachment of subsequent microbial communities and their functions are also important aspects to be investigated.
3. More research is needed to explore the phenomenon of gene exchange at the genomic and transcriptomic levels to identify the key microbial phylotypes involved in this exchange.
4. Research is needed to explore the mechanisms of enhanced antibiotic-resistance development on microplastics. It will be important to include the intrinsic properties of the microplastic particles, or to determine whether the accumulation is due to the various substances and other organic and inorganic contaminants on the microplastics. This is because many reports have documented that heavy metals, PAHs, and PCBs play a significant role in antibiotic-resistance development.
5. The colonization and transport of pathogens (humans, other animals, and plants) by microplastic should be further explored. More research is also needed to determine the potential role of microplastic in pathogen transportation and disease outbreaks.

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Compliance with ethical standards

Conflict of interest All the authors contributed equally and declared no conflict of interest.

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