Chapter 15
Microplastic Pollution in Freshwater Systems: A Potential Environmental Threat

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Abstract Plastic particles of size <5 mm are called microplastics. In terms of quality, directly or indirectly, microplastics are among the contaminants of emerging concern that adversely impact freshwater systems. Such fragments of microplastic are so frangible that they could not be facilely abstracted. Most of the studies show the presence of microplastics in the ocean or sea or estuaries, and very few studies have reported the presence of microplastics in freshwater systems or inland waters such as lakes, rivers, ponds, and reservoirs. Due to high assiduousness and toxicity, these microplastic particles make the freshwater systems more vulnerably susceptible to water quality degradation and ultimately lead to microplastic pollution. There are numerous risks associated with microplastic pollution on sundry components of an ecosystem, such as plants, animals, and especially human beings. These minute particles are an earnest threat to the environment and can act as a medium to convey various toxic chemicals, metals, pathogens, antibiotics, inimical algal blooms, and can be carcinogenic to humans. Till now, there is no defined remedial technique for the abstraction of microplastics from freshwater other than filtration, but there are studies reported which can degrade these particles photo-catalytically, that too for some designated microplastics types. Some studies have reported the biotechnological techniques to degrade some designated microplastics from wastewater. This book chapter is an endeavor to define the microplastic pollution in freshwater systems and present a piece of state-of-the-art information about microplastics, risks associated, and possible remediation techniques.

Keywords Micro-plastics · Morphology · FT-IR · Freshwater systems · Water quality degradation · Remediation techniques

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1 Introduction

Plastics are a versatile gift to modern mankind. The term “plastic” was derived from the ancient Greek word “*plastikos”* and the Latin word “*plasticus”* which is attributed to substances that can be easily molded (Crawford and Quinn 2017a). Plastics are synthetic polymers derived from the polymerization of individual monomers. The first polymer developed was natural rubber latex in the year 1839 by Charles Goodyear (Lambert and Wagner 2018). The characteristics of plastics, which makes them essential material in our daily life are plasticity, resistance to chemicals, buoyancy, high durability, lightweight, and cost-effectiveness (Shim et al. 2018). This leads to the global production of plastics in an enormous amount from 1.7×10^6 tons in 1950 to 3.2×10^8 tons in 2015 (Plastic Europe 2016). Although plastics can be persistent in the aquatic environment, it can degrade and results in enormous micro- and nano-sized particles (Koelman et al. 2015).

Studies conducted on surface water and sediments of freshwater systems including estuaries (Zbyszewski and Corcoran 2011), rivers (Mani et al. 2015), lakes (Biginagwa et al. 2016), and reservoirs (Zhang et al. 2015) reported these tiny-sized particles (<5 mm) as “microplastics,” which can be quantified using a microscope. Currently, there is no defined lower size of microplastics (MPs), but according to Lee et al. 2013, microplastic particles <0.001 mm are termed as nano-plastics, whereas particles >5 mm are classified as meso-plastics, and those particles of size >25 mm are macro-plastics. Based on their origin, MPs are broadly classified into primary MPs and secondary MPs. Plastics originally manufactured of size <5 mm are termed as primary MPs, whereas plastics derived from the disintegration of any external force are called secondary MPs (Sruthy and Ramasamy 2017).

Since numerous studies were inclined toward marine ecosystems, freshwater systems were given less attention. However, studies based on the ecotoxicological impact of MPs on the environment were emphasized from the last few years (Ogonowski et al. 2016; Booth et al. 2016). There is some evidence that these MPs can impact aquatic organisms of freshwater systems (Scherer et al. 2017). Ingestion of MPs by some aquatic organisms may lead to implications on environmental health (Wright et al. 2013). These MPs can be a vector to many persistent organic pollutants and can contaminate the food chain (Li et al. 2015). Besides particles toxicity, due to ingestion of MPs, these can cause additional toxic effects on the gastrointestinal tract of various species (Rochman et al. 2013). Basically, there is a knowledge gap between exposure of MPs in the environment and their effects on the ecosystem including humans.

This chapter outlines the risk associated with MPs exposure in freshwater systems. The first segment provides certain aspects of plastics and MPs. The consecutive section discusses the protocols for monitoring MPs, fate, distribution, and remedial techniques for microplastic pollution.

2 Plastic Production and its Applications

Plastics are processed with a variety of chemical additives to modify their basic characteristics and make the application for our use. In the modern age, plastics are considered as one of the essential materials for human beings. This resulted in a rapid increase in the demand and supply of these materials globally. China (26%), Europe (20%), and North America (19%) were the top three global manufacturers of plastics by the year 2014 (Plastic Europe 2015). In Europe itself, countries such as Germany (24.6%), Italy (14%), and France (9.6%) contribute approximately 60% of the total demand of Europe. Plastics have a variety of applications in almost every sector including packaging, building and construction, automotive, agriculture, household, electrical and electronics, sports and leisure, and medical equipment. Most of the plastics are used for packaging purposes. Plastics are broadly classified as thermosets and thermoplastics (Plastic Europe 2018). Thermosets are a family of plastics that cannot be reshaped and re-formed. Polyurethane (PU), Epoxy resins, Vinyl ester, Silicone, Acrylic resins, and so on are thermosets. Thermoplastics are a family of plastics that can be reshaped and re-formed. Thermoplastics include polyethylene (PE), polypropylene (PP), polycarbonate (PC), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), polystyrene (PS), polyethylene terephthalate (PET), acro-nitrile butadiene styrene (ABS), and so on. PP, PE, PET, and PS are some of the most consumed plastics across the globe (Plastic Europe 2018). It was forecasted that by 2050, plastic production will vary between 850 million tons/year (Shen 2009) to 1124 million tons/year (Neufeld et al. 2016).

3 Microplastic Pollution in Inland Waters

MPs are considered surface water pollutants due to their density. Most of the plastic materials are denser than water, which compels the plastics to float. This resulted in the accumulation of immense plastic garbage in five main gyres: The North Atlantic Gyre, The South Atlantic Gyre, The North Pacific Gyre, The South Pacific Gyre, and The Indian Ocean Gyre (Lebraton et al. 2012). The garbage trapped in the swirling vortex of the North Pacific Gyre is known as The North Pacific Garbage Patch and is a serious environmental challenge (Mitchell 2015). It was estimated that approximately 25,000 pieces of plastics per km^2 are floating in the North Atlantic Gyre and approximately 20,000 pieces of plastics per km^2 are floating in the South Atlantic Gyre (Moore et al. 2001; Law et al. 2010). The Mediterranean Sea is considered one of the most polluted regions of the world and is polluted due to plastic materials (Crise et al. 2015). Thus, plastic pollution is clearly evident in the oceans.

In the case of freshwater systems, plastic pollution may be the outcome of direct littering of plastic debris, leisure or recreational activities, drainage systems, flooding, storms, or transportation of plastics by urban water sources (Crawford and Quinn 2017b). It is a fact that MPs in freshwater systems are less acknowledged than MPs in marine ecosystems (Wagner et al. 2014). Numerous publications reported the presence of MPs in marine ecosystems which includes poles (Obbard et al. 2014), tropics (Costa and Barletta 2015), pelagic open ocean habitat (Kooi et al. 2016), deep-sea benthic habitat (Taylor et al. 2016), deep-sea corals (Woodall et al. 2014), and coastlines of continents (Browne et al. 2011).

In contrast, publications based on MPs in freshwater systems have given attention in the last two decades. The first study of MPs in inland waters was reported on North American rivers by Haze and Cormons in 1974. Then more emphasis was given to freshwater systems, especially lakes. Some of the studies reported on freshwater systems are summarized in Table 15.1.

MPs can immigrate into freshwater systems through different pathways. Land-based activities, as well as water-based activities, contribute to MPs concentration in freshwater systems (Njeru 2006; Pon and Becherucci 2012). Land-based activities include direct littering of plastics, agricultural activities (Xu et al. 2018), wear and tear of tires (Councell et al. 2004), constructional activities, discharge of wastewater (Lambert and Wagner 2018), washing of clothes, and usage of personal care products. Water-based activities include shipping, fishing, and recreation activities (Sruthy and Ramasamy 2017). MPs can be transported from land to water via stormwater (Lambert et al. 2014). The movement of MPs depends on factors such as weather conditions, land cover type, the distance of freshwater system from land, type of plastic waste, and soil characteristics (Lambert and Wagner 2018).

3.1 Morphological Characterization of Microplastics

MPs are derived from plastic materials. There are numerous types of plastics with specific characteristics. This implies that MPs, which are originally originating from plastics, will also have different characteristics. These different characteristics of MPs were differentiated into morphological characterization and chemical characterization. Morphological characterization of MPs includes shape, size, and color.

3.1.1 MPs Shape

MPs are classified as fragments, fibers, films, foams, microbeads, and pellets in terms of shape (Sruthy and Ramasamy 2017). However, there is no well-defined protocol for the identification of the shape of MPs in freshwater systems. The shape of these MPs can be used for source determination and trace their pathways. For example, a study conducted by Peng et al. (2018) in sediments of the freshwater river of Shanghai, China, reported that sphere-type MPs were maximum (88.98%) followed by fibers (7.55%), and fragments (3.47%). These MPs were generated from land-based sources such as cloth washing, upstream runoff, shipping, or waste dumping. Source identification of MPs in Vembanad lake, Kerala, was carried out by Sruthy and Ramasamy (2017) in which she reported that the probable source of

Table 15.1 A summary of MPs pollution in various freshwater systems across the globe

Freshwater system	Location	Abundance	References
Lakes			
Lake Geneva	Switzerland	4.81×10^{4} p/km^{2}	Alencastro (2012)
Wuhan Lakes	China	8.93×10^{3} p/m^{3}	Wang et al. (2017)
Taihu lake	China	6.8×10^{6} p/km^{2}	Su et al. (2016)
Taihu lake	China	2.58×10^{4} p/m^{3}	Su et al. (2016)
Lake Hovsgol	Mongolia	4.44×10^{4} p/km^{2}	Free et al. (2014)
Lake Winnipeg	Canada	7.48×10^{5} p/km^{2}	Anderson et al. (2017)
29 great lakes tributaries	USA	32 p/m^{3}	Baldwin et al. (2016)
Laurentian great lakes	USA	4.66×10^{5} p/km^{2}	Eriksen et al. (2013)
Lake Huron	Canada	3209/85 m^{2}	Zbyszewski and Corcoran (2011)
Vembanad lake	India	252.8 ± 25.76 p/m^{2}	Sruthy and Ramasamy (2017)
Lake Garda	Italy	1108 ± 983 p/m^{2}	Imhof et al. (2013)
Remote lakes in Tibet	China	8–563 p/m^{2}	Zhang et al. (2016)
Dongting and Hong lakes	China	900–4650 p/m^{3}	Wang et al. (2017)
Lake Superior	USA	0–110 p/1000 m^{2}	Hendrickson et al. (2018)
Lake Michigan	USA	0–100 p/1000 m^{2}	Mason et al. (2016)
Rivers			
Danube river	Austria	141.7 p/m^{3}	Lechner et al. (2014)
Rhine river	Europe	3.9×10^{6} p/km^{2}	Mani et al. (2015)
Dutch river delta and Amsterdam canal	Netherlands	1.87×10^{5} p/m^{3}	Leslie et al. (2017)
Los Angeles river, San Gabriel river, coyote creek	USA	1.29×10^{4} p/m^{3}	Moore et al. (2011)
Raritan river	USA	–	Estahbanati and Fahrenfeld (2016)
Saigon river	Vietnam	172–519 p/L	Lahens et al. (2018)
Seine river	France	182–200 p/m^{3}	Dris et al. (2015)
Raritan river	USA	1.3–3.5 p/m^{3}	Estahbanati and Fahrenfeld (2016)
Estuaries			
Yangtze estuary	China	1.02×10^{4} p/m^{3}	Zhao et al. (2014)
Goiana estuary	Brazil	0.19 p/m^{3}	Lima et al. (2014)
Changjiang estuary	China	23.1 ± 18.2 n/100 L	Xu et al. (2018)
Tamar estuary	UK	–	Sadri and Thompson (2014)
Pearl river estuary	Hong Kong	5595 ± 27.417p/m^{2}	Fok and Cheung (2015)
5 urban estuaries of KwaZulu-Natal	South Aftrica	745.4 ± 129.7 p/500 mL	Naidoo et al. (2015)
4 estuarine rivers	USA	< 1.0 to >560 g/km^{2}	Yonkos et al. (2014)
Gulf of Mexico estuary	USA	5–117 p/m^{2}	Wessel et al. (2016)

(continued)

Table 15.1 (continued)

Freshwater system Lakes	Location	Abundance	References
Reservoirs			
Three gorges dam	China	1.36×10^7 p/km^2	Zhang et al. (2015)
Three gorges dam	China	1.26×10^4 p/km^3	Di and Wang (2018)
Teltow Canal	Germany	0.01–95.8 p/L	Schmidt et al. (2018)

films was the breakdown of plastic carry bags, fibers from fishing nets, foams from packaging materials, and microbeads from personal care products. In the Three Gorges Reservoir, fragments and films were the most dominant type of MPs (Zhang et al. 2015), whereas fibers, granules, films, and pellets were predominant in the freshwater of Wuhan (Wang et al. 2017).

3.1.2 MPs Size

As the size of MPs decreases, detection of these MPs also gets more difficult. A study conducted on lake Hovsgol by Free et al. (2014) reveals that 40% of MPs fall into the size class of 0.355 mm–0.999 mm and 40% of MPs fall into the size class of 1.00 mm–4.749 mm. Size distribution of MPs observed by Peng et al. (2018) was 31.19% of total MPs were < 100 μm, 3.56% of total MPs were between 500 μm and 1000 μm, 2.8% of total MPs were between 1000 μm and 5000 μm, and most of the MPs (62.15%) lies between 100 μm and 500 μm. In Yangtze Estuary, Zhao et al. (2014) classified MPs into four size categories, that is, 0.5 mm–1 mm (67%), 1 mm–2.5 mm (28.4), 2.5 mm–5 mm (4.4) and > 5 mm (0.2%). The size pattern of MPs can be related to the degree of weathering and origin of MPs.

3.1.3 MPs Color

Color of MPs was inherent from their parent plastics, but MPs can get discolored due to continuous weathering. The color of MPs can be used to indicate the potential to be ingested by various aquatic organisms (Lambert and Wagner 2016). In Taihu lake, the color of detected MPs was blue, black, green, yellow, white, and transparent among which blue color was the dominant one (Su et al. 2016). Similar study was done by Peng et al. (2018) in which he observed that most of the MPs were white (90%). Other colors of MPs observed includes blue (3%), transparent (3%), white (2%), red (2%), and transparent. Further investigation on the impact of MPs color on ecology and environment needs more attention.

3.2 Chemical Characterization of MPs

Chemical characterization of MPs is done in terms of the type of polymer. A variety of polymers were used for the manufacturing of plastic products. Different polymers possess different unique properties which include strength, elasticity, persistence, and buoyancy. In case of freshwater systems, generally FT-IR technique (Peng et al. 2018) and Raman spectroscopy (Sruthy and Ramasamy 2017) were adopted for the identification of polymer type. μ-FT-IR technique was used for identification of polymer type by Peng et al. (2018) in which he identifies that polypropylene contributes 51.1%, polyester constitutes 17.1%, rayon constitutes 11.4%, cotton constitutes 5.7%, phenoxy resin constitutes 2.9%, and poly(vinyl stearate) constitutes 2.9%. Raman spectroscopic technique was adopted by Sruthy and Ramasamy (2017) reveals that low-density polyethylene was most abundant, followed by polystyrene and polypropylene. Low-density polymers such as polyethylene, polypropylene, and polystyrene were identified in Three Gorges Reservoirs (Zhang et al. 2015). Transparent cellophane was detected in Tahiu lake (Su et al. 2016).

4 Fate and Impact of MPs

Once the MPs are exposed to freshwater systems, it poses a risk to the environment in various ways. MPs having different morphological and chemical characteristics encompass several risks to biota (Eerkes-Medrano and Thompson 2018). Studies reported that MPs reaching freshwater systems may undergo photochemical degradation, thermal degradation, or biological degradation (Lambert et al. 2013). The MPs can degrade by a single mechanism or incorporation with other mechanisms (Lambert and Wagner 2016). Degradation mechanisms gravitate to investigate the tensile strength, weight loss, depolymerization of molecular structure, and microbial strain of specific type of MPs (Gigault et al. 2016). The breaking down of MPs further leads to lower size fractions and even nano-size fractions.

As soon as these MPs disintegrate from parent material, these particles are exposed to the biota of the freshwater system. These MPs can be ingested by a variety of organisms and enters into the food chain. Now, MPs can directly impact the organism, or it can be transferred to higher trophic levels. For instance, if MPs are ingested by fish in large amounts, fish will die due to starvation, whereas, while MPs are ingested in small amounts by fish, it may be consumed by humans and can impact indirectly (Bem 1990).

4.1 Impact on the Environment

MPs possess a ubiquitous environmental threat to flora and fauna (Prata et al. 2019). The environmental impacts of MPs are categorized as biological, chemical, and physical. The biological impacts include the transfer of microorganisms that colonize on the surface of MPs (Oberbeckmann 2015). As the size of MPs decreases, the surface area to volume ratio increases, which allows enormous microbes to adhere to the surface of these tiny particles (Crawford and Quinn 2017c). MPs have the potential to support the growth of microbial colonies on their surface. Limited literature are available on the introduction of pathogens attached with MPs. A study conducted by McCormick et al. (2014) on an urban river in Chicago, Illinois, reveals that some microbes and pathogens were attached to the surface of MPs which degrades the plastic materials. This study also suggested that these attached microbes and pathogens can get transported from freshwater systems to higher trophic levels. A study conducted on Yangtze Estuary, China, confirms that potential pathogens were attached to these suspected MPs (Jiang et al. 2018). Morphological characteristics get tampered which includes increment of the density of MPs and reduction of hydrophobic nature of MPs, due to biofilms attached on the surface of MPs (Carr et al. 2016).

Ingestion and entanglement of MPs by the organisms of freshwater systems are the main physical impact of MPs on the environment (Li et al. 2018). More than 200 species get affected due to entanglement and ingestion of plastic debris (Laist 1997). These MPs look like food to the aquatic species. Once ingested, they may die due to starvation or suffocation (Derraik 2002). Exposure to MPs results in reduced body size and reproduction efficiency in *Daphnia magna* (Besseling et al. 2014). Exposure to polystyrene-type MPs resulted in chronic effects to larvae of the brine shrimp *Artemia franciscana* (Bergami et al. 2016). Della Torre et al. (2014) reported that developmental defects were observed in the genes of urchin embryos(*Paracentrotuslividus*) after fertilization. Cole et al. (2015) reported that the reproductive capability of pelagic copepod, *Calanus helgolandicus,* gets affected after MPs ingestion. Once ingested, MPs can get transferred from digestive systems to adjacent tissues (Harmon 2018). MPs can translocate from the gut of the mussels (*M. edulis)* to the circulatory system (Browne et al. 2011) or MPs from gills of *M. edulis* reaches stomach, transferred to digestive glands, and ultimately gets accumulated in lysosomal systems, resulting in inflammation (von Moos et al. 2012). MPs can get transferred from the stomach to the liver of fish (Avio et al. 2015). Ingestion of MPs by lower trophic levels such as fish (Rochman et al. 2013) gets transferred to higher trophic levels such as birds (Romeo et al. 2015), turtles (Bugoni et al. 2001), dolphins (Denuncio et al. 2011), or humans (Mattsson et al. 2015). Bioaccumulation of MPs to higher tropic levels is a serious concern since humans are ultimate consumers.

Chemical impact includes toxicity to living organisms through various pathways and mechanisms (Li et al. 2018). Various chemicals such as additives, heavy metals, colorants, plasticizers, and stabilizers are used for the production of plastic polymers (Murphy 2001). Sussarellu et al. (2016) conducted a study on oysters by exposing MPs for 2 months and reported that oocyte number, diameter, and sperm velocity get decreased. Additionally, heavy metals present in MPs get desorbed into freshwater systems and can enter the food chain (Li et al. 2018). Chemicals like polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecanes (HBCDs) used in the production of plastic polymers can be desorbed from MPs into freshwater systems during the degradation process (Sun et al. 2016). The chemicals get sorbed into MPs and get desorbed into the stomach of fish and can translocate through blood circulation (Carpenter et al. 1972; Chen et al. 2006). MPs can also act as a vector for hydrophobic pollutants such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), hexachlorocyclohexanes (HCHs), halogenated hydrocarbons, dichlorodiphenyltrichloroethane (DDT), and organochlorine pesticides which are highly toxic and persistent in nature (Velzeboer et al. 2014; Rios et al. 2010). Metal toxicity due to copper and zinc released from antifouling paint and gets adsorbed by microbeads was reported by Brennecke et al. (2016).

4.2 Impact on Humans

There is a lack of sufficient evidence of MPs ingestion by humans. However, a study reported the transition of MPs through the gastrointestinal tract in significant volume (Tomlin and Read 1988). A similar study was conducted on human volunteers in the late 1990s, in which the transition of MPs through the gastrointestinal system was observed. Incidentally, no confirmed effect on humans is reported by the author, but certainly, the reduction of nutrients decreases, and nutritional deficit can occur eventually (Erdman et al. 2012). At the same time, MPs contain various additives and toxic chemicals that can impact humans in various ways (Crawford and Quinn 2017c).

Studies confirmed that MPs can act as a vector to waterborne contaminants in humans. The most common pollutant that can contaminate MPs is polycyclic aromatic hydrocarbons (PAHs) (Frias et al. 2010). The contaminated MPs reach human body through fish (Dhananjayan and Muralidharan 2012). Several studies reported the presence of PAHs in fish such as *Eleutheronematetradactylum, Sardinella longiceps, Otolithesruber, Mystusseenghala, and Coiliadussumieri*(Dhananjayan and Muralidharan 2012). Other pollutants detected in fish are polybromide diphenyl ethers (PBDEs) (Liu et al. 2011) and polycyclic biphenyls (PCBs) (Van Cauwenberghe et al. 2015). Potential exposure of these carcinogenic pollutants along with MPs to humans can be dangerous. Continuous monitoring of the exposure level and impact on humans is required.

5 Remediation Techniques

Remediation of microplastic pollution can be categorized into three categories, that is, legislation, technological tools, and biotechnological tools (Pico et al. 2019). To control the MPs pollution, countries such as the USA enacted a law, namely, "*Microbead-Free Water Act*", in December 2015. A regulation has been proposed by EU packaging and use of lightweight carry bags. In developing countries such as India, government bans the single-use plastics in 2019. In addition, engineering tools such as water treatment plants (WTPs) should be given more emphasis to remove MPs from drinking water. A study conducted for the removal of MPs from wastewater reported the removal efficiency of up to 95% from effluents (Talvitie et al. 2017). Nanotechnological advancement such as visible light photocatalytic degradation was adopted to degrade LDPE residues with zinc oxide nanorods (Tofa et al. 2019).

The most obvious mitigation technique is the identification of the source and sink of MPs. The expected source of MPs can be production, commerce, consumer, and mismanagement of waste (Lambert and Wagner 2018). A circular economy of plastic waste with the support of stakeholders should be initiated, which includes green chemistry, production and use of biodegradable polymers, the responsibility of producers, and awareness in terms of reusing, reducing, and reducing use of plastics.

6 Conclusion

MPs pollution in freshwater systems is an emerging concern. In this chapter, a brief introduction of MPs pollution in freshwater systems has been provided. MPs have been detected in almost all freshwater systems globally. Continuous monitoring needs more attention. The morphological characterization reported in various studies has been done in terms of shape, size, color, and polymer type can be used to determine the origin of these MPs. The ecological and biological risk associated with MPs exposure to the environment has been discussed in this chapter. Various toxic chemicals associated with MPs can be a potential threat to the environment. However, more precise analysis needs to be done to understand the potential risk. MPs are detected in aquatic organisms and humans in a significant amount, but the impact is still not defined clearly. Remediation and control measures should be given more emphasis. Literature-based remediation techniques of MPs from freshwater systems are lacking and need more attention.

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