# Plastic Pollution

## Nature Based Solutions and Effective Governance




Gail Krantzberg, Savitri Jetoo,
Velma I. Grover and Sandhya Babel (*eds.*)

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# PLASTIC POLLUTION

## Nature Based Solutions and Effective Governance


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# Chapter 11

# Microplastic Research in India: Current Status and Future Perspectives

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## INTRODUCTION

Plastics are undoubtedly one of the most important inventions of the twentieth century. Because of their unique properties such as lightweight, high strength, durability, ease of molding into any shape, low cost of production, etc., plastics have found application in almost all aspects of human life, including health care. Consequently, the global production of plastics has increased from 2 million tons in 1950 to 380 million tons in 2015 and is projected to increase in the coming decades (Geyer et al., 2017). However, the proliferation of single-use plastics (SUPs) has put the waste management system under pressure. It is estimated that approximately 6,300 million tons of plastic waste has been generated globally between 1950 and 2015, and 79% of this has been accumulated in landfills and the natural environment (Geyer et al., 2017). It is further estimated that if current production and waste management trends continue in business as usual (BAU) mode, approximately 12,000 million tons of plastic waste will be in the natural environment and landfills by 2050. Another estimate indicated that 4 million to 12 million tons of plastic waste entered the marine environment in 2010 alone (Jambeck et al., 2015). The majority of the plastic debris in the oceans arises from land-based sources. Lebreton et al. (2017) estimated that rivers transport 1 million to 2.5 million tons of plastic to the seas every year.

Microplastics (MPs), which are defined as plastic particles < 5 mm in size, are emerging as a contaminant of global concern. They are ubiquitous and pervasive in the environment, and their presence has been detected in lakes (Sruthy and Ramasamy, 2017), rivers (Mani et al., 2015), oceans (Andrady, 2011), terrestrial ecosystems (Beriot et al., 2021; de Souza Machado et al., 2018), and atmosphere (Chen et al. 2020). MPs

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are even reported from remote areas, such as the Arctic (González-Pleiter et al. 2020; Ramasamy et al. 2021) and Antarctic regions (Waller et al., 2017). MPs originate from both primary and secondary sources. The primary sources include microbeads used in personal care products, fibers used in textiles, and pellets used as raw materials in manufacturing plastic products. The secondary MPs result from the fragmentation of larger plastics in the environment due to photo-oxidation, thermal degradation, mechanical action of waves and wind, and biological actions. The major sources of plastics and MPs in the environment come from unscientific waste disposal, discharge of treated and untreated domestic and industrial wastewater, stormwater runoff, road and tire wear particles, atmospheric deposition, shipping, etc.

Many recent studies reported the ingestion of MPs by aquatic and terrestrial organisms, including humans (Daniel et al., 2020a; Kutralam-Muniasamy et al., 2020; Schwabl et al., 2019). However, the consequences of MP ingestion by aquatic and terrestrial organisms are not well understood. The ingested MPs can significantly impact organisms through food intake and digestive system impairment. The additives in plastics can also leach into the digestive system of organisms. Apart from this, the MPs have been reported to adsorb many chemicals, including persistent organic pollutants and heavy metals from the surrounding environment (Dong et al., 2020). Therefore, MPs can act as vectors of toxic contaminants in organisms. All these factors signify the requirement for stringent control measures and policies to reduce plastic and MP pollution.

With more than 1.2 billion population, India is the second-most populous country globally. It is also one of the major consumers of plastic items. However, due to inadequate infrastructure and poor waste management practices, huge quantities of plastic waste are littered in the environment. It is estimated that in 2018, approximately 3.3 million tons of plastic waste were generated in India (CPCB, 2019). The lack of public awareness and inadequate infrastructure to collect and treat municipal solid waste leads to the littering of plastic waste in every nook and corner of the country. Fragmentation of these plastics leads to the formation of MPs. The discharge of untreated municipal wastewater also contributes significantly to MP pollution in the environment.

Estimating MP contamination in various environmental matrices and examining the sources of such MPs is necessary to develop suitable policies to mitigate plastic waste and evaluate the effectiveness of such policies. In this context, selected studies from India reporting MPs in various environmental matrices, biota, and food items are reviewed in the present study. The concentration of MPs in various ecosystems and biota is highlighted, and the impact on human health is discussed. The present policies on plastic waste management are briefly discussed. The major challenges facing MP research in India are highlighted, and the priority areas for future research are proposed as well.

## MPs in Rivers, Lakes, and Wetlands

The contamination of rivers, lakes, and wetlands by MPs is a serious concern as the local people depend on these ecosystems for water, food, and livelihood. These aquatic ecosystems also reflect the level of contamination in the terrestrial environment. The rivers act as a major transport route for MPs into the marine environment. Napper et al. (2021) estimated that 1–3 billion pieces MPs are discharged into the Bay of Bengal through the Ganges every day. As these aquatic ecosystems play a significant role in groundwater recharge, the presence of MPs in the sediments of these ecosystems also has implications for groundwater contamination. Despite these facts, the contamination of freshwater ecosystems with MPs has received less attention globally than marine ecosystems. Despite having a large number of rivers, lakes, and wetlands in India, very few studies were conducted on MP pollution in these ecosystems.

The first Indian lake to be investigated for MP contamination was Lake Vembanad in Kerala (Sruthy and Ramasamy, 2017). Later, Lake Red Hills (Gopinath et al., 2020) and Lake Veeranam (Bharath et al., 2021) in Tamil Nadu and Lake Renuka (Ajay et al., 2021) in Himachal Pradesh were investigated for MP contamination (Table 1). The surface water and sediment samples were analyzed from these lakes, except for Vembanad, where only the sediment was analyzed. From the reported literature, it is observed that MPs are present in all the lake samples. Hence, it could be inferred that MPs are pervasive pollutants in the lakes of India. The common morphological classifications of MPs reported in these studies are fibers, films, fragments, and pellets. Fourier-transform infrared spectroscopy (FTIR) and Raman Spectroscopy were used to identify the polymers. The polymers such as polyethylene (PE), polypropylene (PP), and polystyrene (PS) are reported in all the studies, thus indicating the wide use of these polymers across the country. In addition to these polymers, polyvinyl chloride (PVC) and nylon were reported from Lake Veeranam (Bharath et al., 2021). Most of the studies targeted MPs in the size range of 0.3 mm to 5 mm. The abundance of MPs in water and sediment samples of Lake Renuka varied from 2–64 particles per liter and 15–632 particles per kg respectively (Ajay et al., 2021). The abundance of MPs in most studies falls within the range reported from Lake Renuka.

MPs of different morphologies, such as fragments, fibers, foams, films, pellets, and microbeads are reported from Indian rivers (Table 1). The different polymers reported are PE, PP, PS, PA, PET, PVC, polyester, nylon, acrylic, etc. Most studies reported MPs in the size range of 0.3 mm to 5 mm. However, there are disparities in selecting the size range of MPs among different studies. Few studies reported MPs as small as 20 μm. The MPs in the river sediments range from 17 to 3,485 particles per kg (Table 1).

The presence of low-density polymers, such as PE and PP, in the lake and river sediments indicates biofouling and adsorption of contaminants over the surface of MPs, which increases their density leading to subsequent sedimentation. Most studies reported land-based sources as a significant contributor to MPs in aquatic ecosystems. It includes garbage dumping, littering, laundry, tourism, plastic manufacturing and recycling industries, sewage treatment plants, agricultural discharge, recreational activities, fishing, road and tire wear particles, atmospheric deposition, etc. (Baensch-Baltruschat et al., 2020; Vanapalli et al., 2021). The flow velocity, residence time of water, population density, and waste management practices in the area are the crucial factors that influence the abundance and distribution of MPs in the sediments of water bodies. It was observed that there is no unified standard protocol for collecting, processing, and extracting MPs from water and sediment samples. Moreover, the size range of MPs reported often varied significantly across studies. Therefore, comparing the MPs across different studies is difficult. The abundance of MPs reported in rivers and lakes might be an underestimation as the methodologies adopted by most of the authors did not account for smaller MPs.

India currently has 75 Ramsar sites (wetlands of international importance) with a surface area of 1,326,677 hectares (PIB, 2022). However, the MP contamination

**Table 1.** MPs in Indian Lakes and Rivers.

| Sl No. | Location | Sample Type | Abundance of MPs | Size range of MPs | Shape of MPs | Identified Polymers* | References |
|---|---|---|---|---|---|---|---|
| 1 | Lake Vembanad, Kerala | Sediment | 252.80 ± 25.76 particles per $m^2$ | < 5 mm | Film, foam, fiber, pellet, andfragment | LDPE, PS, PP, and HDPE | (Sruthy and Ramasamy, 2017) |
| 2 | LakeRed Hills, Chennai, Tamil Nadu | Sediment | 27 particles per kg | 0.3 to 5 mm | Fiber, fragment, film, and pellet | HDPE, LDPE, PP, and PS | Gopinath et al., 2020 |
| 3 | Lake Veeranam, Tamil Nadu | Sediment | 309 particles per kg | 0.3 to 5 mm | Fiber, film, pellet,and fragment | Nylon, PE, PS, PP, and PVC | (Bharath et al., 2021) |
| 4 | Lake Renuka, Himachal Pradesh | Sediment | 15–632 particles per kg | < 4.75 mm | Fiber, fragment, foam, and film | PE, PP, and PS | (Ajay et al., 2021) |
| 5 | LakeRed Hills, Chennai, Tamil Nadu | Water | 5.9 particles per liter | 0.3 to 5 mm | Fiber, fragment, film,and pellet | HDPE, LDPE, PP, and PS | Gopinath et al., 2020 |
| 6 | Lake Veeranam, Tamil Nadu | Water | 28 particles per $km^2$ | 0.3 to 5 mm | Fiber, film, pellet, and fragment | Nylon, PE, PS, PP, andPVC | (Bharath et al., 2021) |
| 7 | Lake Renuka, Himachal Pradesh | Water | 02–64 particles per liter | > 0.2 µm | Fiber, fragment, foam, film, and bead/pellet | PE and PP | (Ajay et al., 2021) |
| 8 | Ganga River | Sediment | 107.57–409.86 particles per kg | 63 µmto 10 mm | Fiber, filament, film, foam/ bead,and fragment | PET, PE, PP, and PS | (Sarkar et al., 2019) |
| 9 | Netravathi River | Sediment | 9.44–253.27 pieces per kg | 0.3 to 5 mm | Fragment, fiber, film, foam, and pellet | PE, PET, PP, and PVC | (Amrutha and Warrier, 2020) |
| 10 | Brahmaputra River | Sediment | 20 to 3,485 particles per kg | 20 µm to 5 mm | Fragment, fiber, and bead | PP, PE, PA, PET, PVC, and PTFE | (Tsering et al., 2021) |
| 11 | Indus River | Sediment | 60 to 1,752 particles per kg | 20 µmto 5 mm | Fragment andfiber | PP, PE, PET, PA, PTFE, and PS | (Tsering et al., 2021) |
| 12 | Ganga River | Sediment | 17–36 particles per kg | 0.7 to 7.5 mm | Fragment, foam, film, andfilament | PE, PS, PP, PVC, PE-P, Cellophane, and Polyester | (Singh et al., 2021) |
| 13 | Netravathi River | Water | 56–2328 particles per $m^3$ | 0.3 to 5 mm | Fiber, film, fragment, and foam, pellet | PE, PET, PP, and PVC | (Amrutha and Warrier, 2020) |
| 14 | Ganga River | Water | 0.038 particles per liter | < 300 µm | Fiber and fragment | Rayon, acrylic, PET, PVC, polyester, and nylon | (Napper et al., 2021) |
| 15 | Ganga River | Water | 380–684 particles per 1000 $m^3$ | 0.7 to 7.5 mm | Fragment, foam, film, and filament | PE, PS, PVC, PE-P, Polyester, and Cellophane | (Singh et al., 2021) |

*PE – Polyethylene; PS – Polystyrene; PP – Polypropylene; PVC – Poly Vinyl Chloride; PA – Polyamide; LDPE – Low Density Poly Ethylene; HDPE – High Density Poly Ethylene; PTFE – Polytetrafluoroethylene; PET: Polyethylene terephthalate; PE – P: Polyethylene Propylene in a few Ramsar sites, such as Vembanad and Renuka lakes, has been studied so far. Similarly, very few rivers are studied for their MPs' contamination. Most of the studies are based on one-time sampling, which may not be adequate to understand the temporal variations, sources, and dynamics of MPs in the environment. Moreover, there is a need for unified sampling, extraction, and analysis protocols for MP research in India. The size of the MPs monitored should be unified and smaller particles need to be accounted for considering their greater impact on human health as compared to larger particles. Therefore, nationwide comprehensive monitoring programs using standard protocols are required in the future to understand the spatial and temporal variations in MPs.

## MPs in the Marine Environment and Beaches

The marine environment is considered a major sink of MPs. India has a long coastline of 7,500 km, which makes the country one of the world's major fishing and shipping hubs. The coastal regions are densely populated, and several major cities are located on the coast. The urban runoff, sewage, industrial effluents, and discharge from numerous rivers into the coastal waters make it a hot spot for MP pollution.

The beach sediments, beach sand, and surface water have been examined for MP contamination from various coastal regions in India. The MPs reported from the marine environment are diverse in their morphology and polymer composition. MPs are commonly classified as fibers, films, fragments, and pellets. For identifying the polymer content of MPs, most of the studies used FTIR. However, few studies adopted Raman spectroscopy and SEM EDX methods. The polymers, like PE and PP, are the most abundant polymers reported from the marine environment. However, other polymers, such as PS, PET, PVC, PA, PMMA, etc., were also reported in less abundance (Table 2). The time of sample collection, method of sample collection and extraction of MPs, reagents used for density separation, and techniques used for polymer identification influenced the abundance of MPs. Due to the variations in these parameters among the studies reported, a comparison of spatial and temporal variations in MPs is not feasible (Veerasingam et al., 2020).

A threefold increase in MPs in the coastal environment was observed after a flood event in Chennai, Tamil Nadu (Veerasingam et al., 2016). They also observed that the MP abundance is higher near the river discharge points. A similar observation was also reported in Kerala (Kumar and Varghese, 2021a). Therefore, it can be inferred that floods can transport large quantities of plastic debris, including MPs from land-based sources, into the oceans. The abundance of MPs in the coastal environment also may be influenced by the direction of winds and currents (Veerasingam et al., 2016).

Identifying the sources and routes is a critical primary step in the regulation of MP pollution (Vanapalli et al., 2021). The reported studies trace the source of the MPs in the marine environment to land-based sources. The major land-based sources include improper solid waste management, discharge of treated/untreated sewage, inadequate wastewater treatment, industrial effluents, etc. From these sources, the MPs enter the marine environment through stormwater runoff, rivers, and streams. Shipping, fishing, tourism, and pilgrimage activities also lead to the discharge of MPs into the coastal environments (Kumar and Varghese, 2021b, 2021a; Patchaiyappan et al., 2020; Vanapalli et al., 2021).

**Table 2.** MPs in the Marine Environment and Beaches in India.

| Sl No. | Location | Sample Type | Abundance of MPs | Size Range of MPs | Shape of MPs | Commonly Identified Polymers* | References |
|---|---|---|---|---|---|---|---|
| 1 | Chennai, Tamil Nadu | Beach sediment | 304 (before the flood) to 896 (after the flood) | 2 to 5 mm | Pellets | PE and PP | (Veerasingam et al., 2016) |
| 2 | Tamil Nadu | Beach sediment | 2 to 178 particles per $m^2$ | 0.3 to 4.75 mm | Fragment, fiber, and foam | PE, PP, and PS | (Karthik et al., 2018) |
| 3 | Tuticorin, Tamil Nadu | Sediment | 8.22 ± 0.92 to 17.28 ± 2.53 particles per kg | 0.005 mm to 5 mm | Fiber, fragment, and film | PE, PP, PA, polyester,and paint | (Patterson et al., 2019) |
| 4 | Port Blair Bay, Andaman Islands | Sediment | 45.17 ± 25.23 particles per kg | 46.72 to 5024 μm | Fiber, fragment, and pellet | Nylon, PU, PVC, and Acrylic | (Goswami et al., 2020) |
| 5 | South Andaman | Beach sediment | 414.35 ± 87.4 particles per kg | < 5 mm | Fragment, fiber, and spherule | PP, PVC, nylon, polyvinyl formal, and polybutadiene | (Patchaiyappan et al., 2020) |
| 6 | Maharashtra, Karnataka, Goa | Beach sand | 162 to 820 particles per $m^2$ | 1–5 mm | Fragment, fiber, film, and pellet | PE and PP | (Maharana et al., 2020) |
| 7 | Mandovi-Zuari Estuary, Goa | Sediment | 800 to 17,300 particles per kg.(Average 4873 to 7,314 particles per kg) | 20 μm to 5 mm | Fragment, film, fiber, and bead | PA, PVP, PVC, PAM, polyacetylene, polyimide (PI) | (Gupta et al., 2021) |
| 8 | Calicut Beach, Kerala | Beach sediment | 80.56 to 467.13 particles per kg | 1–5 mm | Film, fiber, and lump, | PE, PP, PET, PE + PP, PS, PVC, and PCU | (Kumar and Varghese, 2021a) |
| 9 | Tuticorin coast, Gulf of Mannar | Water | 12.14 ± 3.11 to 31.05 ± 2.12 particlesper liter | 0.005 to 5 mm | Fiber, fragment, and film | PE and PP | (Patterson et al., 2019) |
| 10 | Port Blair Bay, Andaman Islands | Surface seawater | 0.93 ± 0.59 particles per $m^3$ | 35.29 to 5,010 μm | Fiber, fragment, and pellet | Nylon, PU, PVC, and acrylic | (Goswami et al., 2020) |
| 11 | Mandovi-Zuari Estuary, Goa | Water | 0.057 to 0.141 particles per $m^3$ | 20 μm to 5 mm | Fragment, film, fiber, andbeads | PA, PVP, PVC, PAM, polyacetylene, and polyimide (PI) | (Gupta et al., 2021) |
| 12 | Northern coast of Kerala | Surface seawater | 0.96–7.12 particles per $m^3$ | 0.08 to 2 mm | Fiber, fragment, and flake | PP, PEVA, PA, PE, and polybutadiene | (Pavithran, 2021) |

*PE – Polyethylene; PP – Polypropylene; PS – Polystyrene; PA – Polyamide; PVC – Polyvinyl chloride; PAM – Polyacrylamide; PET – Polyethylene terephthalate; PAN – Polyacrylonitrile; PMMA – Polymethyl methacrylate; PEVA – Polyvinyl acetate ethylene; PVAL – Polyvinyl alcohol; PVP – Polyvinyl pyrrolidone; PCU –Polycarbonate urethane.

## MPs in Salt

The widespread occurrence of MPs in the marine ecosystem, including water, sediment, and biota, is a major concern for human health. The high abundance of MPs reported in coastal water indicates the possible transfer of these particles to the human food chain via salts. India has a long coastal area and is one of the major salt-producing countries in the world. The leading salt-producing states in India are Gujarat and Tamil Nadu (Vidyasakar et al., 2021). Evaporation of coastal water in salt pans is the primary method of salt production in India. Hence, contaminated coastal water may be a significant source of MPs in salts. The review of reported literature on MPs in salts from India revealed that all the samples irrespective of their origin are contaminated with MPs (Table 3). The abundance of MPs in salts ranges from 2 particles per kg (Sathish et al., 2020a) to 575 particles per kg (Vidyasakar et al., 2021). The size range selected for studying MPs varies considerably from 3.8 µm to 5.2 mm between studies and might influence the abundance of MPs reported. The common shapes of MPs found in salts include fibers and fragments; few studies also reported the presence of films and pellets. FTIR was the most commonly used technique for identifying polymers from salt samples. The different polymers reported are PE, PS, PA, PET, PVC, Nylon, Polyester, etc. (Table 3). The studies suggest that contaminated seawater is the primary source of MPs in salts. However, the possibility of contamination during the processing and packaging of salts cannot be ruled out.

A comparative study of salts produced from Gujarat and Tamil Nadu suggests that MP abundance is high in salts produced from Gujarat than from Tamil Nadu (Vidyasakar et al., 2021). The average concentration of MPs (34 particles per kg salt) from commercially available six brands of sea salts in the state of Kerala has been reported by Ramasamy et al. (2019). By comparing salts produced from different sources, sea salts are more contaminated with MPs than bore-well salts (Sathish et al., 2020a). They estimated that people using sea salts consume 216 particles of MPs per year, while people consuming bore well salts consume 48 particles per year. It was also suggested that a simple sand filtration of seawater before evaporation could significantly reduce the MP content in salt (Seth and Shriwastav, 2018).

## MPs in Dust

The MP contamination in the terrestrial environments in India has received little attention compared to the aquatic ecosystems. The MPs in street dust from Chennai, Tamil Nadu, have been reported to contain 227.94 ± 91.37 MPs per 100 g, and the particles are mostly fragments and fibers (Patchaiyappan et al., 2021). The nine polymers identified in the street dust are PVC, HDPE, poly(ethylene-co-vinyl-acetate), poly (tetrafluoroethylene), cellulose microcrystalline, lyocell, superflex-200, wax-1032, and AC-395 (Patchaiyappan et al., 2021). On the other hand, indoor dust from Patna, India, has been reported to contain MPs, such as PET (55–6,800 µg/g) and PC (0.11–530 µg/g) (Zhang et al., 2020). The above mentioned studies signify the importance of dust as a route of exposure to MPs through inhalation. The sources of MPs in the indoor dust may be attributed to textile fibers, furniture, packaging items, toys, carpets, paints, etc. The MPs in street dust may be attributed to improper waste management, littering, tire and road wear particles, road paints, building materials, and atmospheric transport.

**Table 3.** MPs in Salt.

| Sl No. | Location | Sample Type | Abundance of MPs | Size range of MPs | Shape of MPs | Identified Polymers* | References |
|---|---|---|---|---|---|---|---|
| 1 | Kerala, Maharashtra, Gujarat | Commercial salt | 56 ± 49 to 103 ± 39 particles per kg | < 5 mm | Fiber and fragment | PE, PS, PET, PA, and polyesters | (Seth and Shriwastav, 2018) |
| 2. | Kerala | Commercial salt | 34 particles per kg | < 5 mm | Fiber, fragment, bead, and sheet | PS, PA, PET, PP, PE, and PVC | Ramasamy et al. (2019) |
| 3 | Tamil Nadu | Salt pans | Na | na | Fragment, fiber, and film | PP, PE, nylon, and cellulose | (Selvam et al., 2020) |
| 4 | Tamil Nadu | Sea salt | 35 ± 15 to 72 ± 40 particles per kg | 55 µm to 2 mm | Fiber and fragment | PE, PP, Polyester, and PA | (Sathish et al., 2020a) |
| 5 | Tamil Nadu | Tube welll salt | 2 ± 1 to 29 ± 11 particles per kg | 55 µm to 2 mm | Fiber and fragment | PE, PP, Polyester, and PA | (Sathish et al., 2020a) |
| 6 | Tamil Nadu | Salt | 23 to 101 particles per 200 g | 100 µm to 5mm | Fiber, film, pellet, and irregular | PE, Polyester, and PVC | (Vidyasakar et al., 2021) |
| 7 | Gujarat | Salt | 46 to 115 particles per 200 g | 100 µm to 5mm | Fiber, film, pellet, and irregular | PE, Polyester, and PVC | (Vidyasakar et al., 2021) |
| 8 | Tamil Nadu | Salt from salt pans | 3.67 ± 1.54 to 21.33 ± 1.53 particles per 10g | na | Fiber | Nylon, PP, LDPE, and PET | (Nithin et al., 2021) |
| 9 | Tamil Nadu | Commercial salt | 4.67 ± 1.15 to 16.33 ± 1.53 particles per 10g | na | Fiber | Nylon, PP, LDPE, and PET | (Nithin et al., 2021) |
| 10 | India | Commercial salt | 700 particles per kg | 3.8 µm to 5.2 mm | Fragment, fiber, and pellet | Cellophane, PS, PA, and polyarylether (PAR) | (Sivagami et al. 2021) |

*PE – Polyethylene; PS – Polystyrene; PP – Polypropylene; PVC – Poly Vinyl Chloride; LDPE – Low Density Poly Ethylene; PA – polyamide; PVC – Polyvinyl chloride.

## MPs in Biota

The infiltration of MPs in the human food chain is drawing more attention globally. In this context, the presence of MPs in different aquatic organisms, such as zooplanktons, shrimps, mussels, oysters, and fishes, has been reported from various parts of India (Table 4). Most of the studies came from south Indian states, like Kerala and Tamil Nadu. In the extraction procedure of MPs, the majority of the studies used 10% KOH for the digestion of organic matter. However, very few studies used $H_2O_2$ for the removal of organic matter. Fibers, fragments, films, and pellets are commonly reported in biota. Few studies also reported beads and foam. FTIR was most commonly used to identify the polymers. Very few studies used Raman spectroscopy for polymer identification. A number of investigators used SEM EDAX to evaluate the surface morphology and estimate the adsorbed chemicals, including heavy metals, on the surface of MPs. Polymers, such as PE, PP, PS, PVC, nylon, and acrylic, are most commonly reported to be ingested by aquatic species. The abundance of MPs varies considerably depending on the species, feeding behavior, size, and age of the organism investigated. MPs were observed to be more in pelagic fishes than demersal fishes (James et al., 2021). We observed that most of the studies reported a high abundance of low-density polymers, such as PE and PP in the surface waters. Hence, it could be inferred that the pelagic fishes are exposed to higher levels of low-density MPs that float in the seawater. However, more studies are required to reach a consensus on this matter.

Few studies investigated the toxic effects of MPs on biota. It is reported that MPs cause abrasion in the ciliated structure and induced toxic physiological and structural alterations in the mussel *Pernaviridis* (Vasanthi et al., 2021). They also reported significantly high levels of oxidative stress markers in response to MP exposure in *P. viridis*. An increase in lipid peroxidation and enzymatic antioxidants in the shrimp *Litopenaeus vannamei* due to short-term exposure to PE microbeads was also reported (Maharana et al., 2020). These studies highlight the need to investigate the ecological implications of MP pollution.

Most of the studies investigated MPs in the digestive tracts of fishes. However, except for small fishes, the digestive tract is normally removed before cooking. However, dietary exposure to MPs via fish could be possible if these particles were able to translocate across the gastrointestinal tract (GIT) or gills via paracellular diffusion or transcellular uptake (Wright and Kelly, 2017). On the other hand, plastics contain several additives, such as phthalates, bisphenols, colorants, etc., which are known as endocrine disruptors. Moreover, owing to their large surface-to-volume ratio, MPs can accumulate significantly high amounts of pollutants from the surrounding environment and can act as vectors of these pollutants to the organisms. The release of such additives and adsorbed pollutants in the digestive system of fishes may adversely affect the organism concerned. Additionally, the accumulation of these pollutants in the tissues of such organisms assumes a greater risk to human health and therefore needs more attention in the future.

## MPs′ sources, routes of exposure, and human health impacts

MPs are ubiquitous pollutants in the environment and have been reported from a number of ecosystems and food items destined for human consumption. MPs are also reported to be ingested by fishes and other aquatic organisms. Therefore, human exposure to MPs is unavoidable. The sources, routes of exposure, and possible health

**Table 4.** MPs in the Aquatic Biota.

| Sl. No. | Type of Biota | Location | Abundanceof MPs | Size Range of MPs | Shape of MPs | Polymer Type* | References |
|---|---|---|---|---|---|---|---|
| 1 | Zooplankton | Port Blair Bay, Andaman Islands | 0–0.41 particles per individual | 21.57 to 2,225 µm | Fiber, fragment, pellet | Nylon, PU, PVC, and Acrylic, | (Goswami et al., 2020) |
| 2 | Shrimps | Kochi, Kerala | 0.39 ± 0.6 particles per shrimp | 157 to 2,785 µm | Fiber, fragment, sheet | PE, PP, PA, and Polyester | (Daniel et al., 2020b) |
| 3 | Mussels | Kasimedu, Chennai | - | 0.8 mm to 4.7 mm | Fiber, sphere, flake, sheet, fragment | PP, PE, polyester, cellophane, rayon | (Vasanthi et al., 2021) |
| 4 | Oyster | Tuticorin coast, Gulf of Mannar | 6.9 ± 3.84 particles per individual | 0.005–5 mm | Fiber, film, fragment | PE, and PP | (Patterson et al., 2019) |
| 5 | Fishes and shellfishes | Port Blair Bay, Andaman Islands | 10.65 ±7.83 particles per specimen | 111.58 to 5094 µm | Fiber, fragment, and pellet | Nylon, PU, PVC, and acrylic | (Goswami et al., 2020) |
| 6 | Fishes | Chennai and Nagapattinam of Tamil Nadu | 20 particles in 17 fishes | < 5 mm | Fiber, film, pellet | PE, PA, and polyester | (Karuppasamy et al., 2020) |
| 7 | Fishes | Vembanad Lake, Kerala | 15 ± 13 particles per fish | 0.04–4.73 mm | Fiber, fragment, film, microbead | PE, PP, PS, and PVC | (Nikki et al., 2021) |
| 8 | Fishes | Tuticorin, Tamil Nadu | 0.11 ± 0.06 to 3.64 ± 1.7 particles per individual | 85 µm to 5 mm | Fiber, fragment, film, foam | PE, PA, and polyester | (Sathish et al., 2020b) |
| 9 | Fishes | Kerala | 22 particles from 15 fishes | < 5 mm | Fiber, fragment, foam | PE, cellulose, rayon, polyester, and PP | (Robin et al., 2020) |
| 10 | Fishes | Kochi, Kerala | 30 particles from 653 samples | 0.27 mm to 3.2 mm | Fragment, filament, pellet | PE and PP | (James et al., 2020) |

*PE – Polyethylene; PS – Polystyrene; PP – Polypropylene; PVC – Poly Vinyl Chloride; PA – Polyamide; PU – Polyurethane.

impacts of MPs on humans are summarized in Fig. 1. Cox et al. (2019) estimated that annual MPs consumption by humans through food and beverages ranged from 39,000 to 52,000 particles, depending on age and sex. These numbers may increase significantly when exposure through drinking water and inhalation is considered. MPs less than 130 μm in diameter have the potential to translocate into human tissues and initiate a localized immune response (Wright and Kelly, 2017). Inside the tissues, they may also release constituent monomers, additives, and adsorbed contaminants, such as persistent organic pollutants and heavy metals (Cox et al., 2019; Wright and Kelly, 2017). The recent findings of MPs in the feces of humans (Schwabl et al., 2019; Zhang et al., 2021) and the human placenta (Ragusa et al., 2021) highlighted the consumption of MPs by humans and its possible health consequences. However, further studies are required to shed more light on the human health impacts of MPs.

## Policies in India

In order to provide a regulatory framework for the systematic management of plastic waste in the country, the government of India has issued several rules and amendments from time to time. These include the Plastic Waste (Management and Handling) Rules (2011), Plastic Waste Management Rules (2016), Plastic Waste Management (Amendment) Rules (2018), and more recently the Plastic Waste Management (Amendment) Rules (2021). India has also made significant interventions in the international forums for mitigating plastic pollution. In 2019, the United Nations Environment Assembly adopted a resolution piloted by India to address pollution from single-use plastic (SUP) products.

These above mentioned rules mandated the generators of plastic waste take necessary measures that minimize the quantity and littering of plastic waste and store segregated plastic waste at the source. These rules stipulated the responsibilities of waste generators, local bodies, gram panchayats, street vendors, and retailers to effectively manage plastic waste. The rules mandated Extended Producer Responsibility (EPR) by the producers, importers, and brand owners and worked out modalities for collecting plastic waste. State-level monitoring committees have been constituted under these rules to effectively monitor and implement the provisions of these rules. Through the Plastic Waste Management (Amendment) Rules, 2021, the government of India aims to prohibit the production and use of identified single-use plastic items having low utility and high littering potential by 2022. Accordingly, the minimum thickness of plastic carry bags was mandated to increase from 50 microns to 75 microns on September 30, 2021. It has been further mandated to increase to 120 microns by December 31, 2022. Moreover, the government prohibited the manufacturing, importing, stocking, distributing, selling,and using of single-use plastic products, such as plastic plates, cups, glasses, cutleries, wrapping or packing films around sweet boxes, invitation cards, cigarette packets, plastic or PVC banners less than 100 microns in thickness,plastics sticks for earbuds, candy, and ice cream, balloons, and plastic flags with effect from July 1, 2022. The waste management rules, along with the budget allocation of Rs. 1,41,678 crore over 5 years from 2021–2026 under the Urban Swachh Bharat Mission 2.0, is expected to improve the environment and health through complete fecal sludge management and wastewater treatment, source segregation of garbage, reduction in single-use plastic, reduction in air pollution by effectively managing waste from construction-and-demolition activities, and bio-remediation of all legacy dump sites.

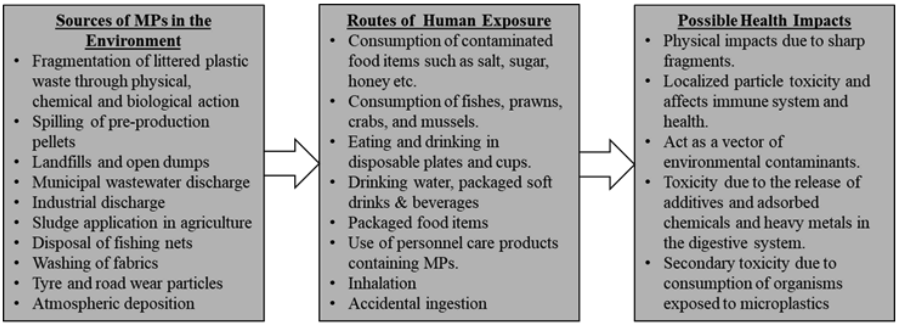


**Fig. 1.** Sources, Routes of Exposure, and Human Health Impacts of MPs.

The above mentioned rules and policies are certainly an impetus for reducing plastic waste; however, considering the gravity of the problem, more stringent measures are required. We believe that public action is the deciding factor for reducing plastic and MP pollution. Therefore, along with the stringent implementation of the rules, we propose the following measures for better reduction of plastic waste and MP pollution.

- Systematic and progressive ban on single-use plastic products and promote environment-friendly alternate materials.
- Ban the use of MPs in paints, personal care products, cleaning products, etc.
- Improve infrastructure for plastic waste recycling.
- Promote circular economy and ensure strict compliance to extended producer responsibility.
- Sensitize the issues of plastics and MPs through regular public awareness campaigns for civilians through mass media and students' curriculum.
- Create awareness among fishermen and give incentives for measures taken to reduce plastic pollution.
- Regular cleanup drives with public participation to remove littered plastics from various environments, especially beaches.
- Impose taxes on plastics and provide fiscal incentives to reduce plastic.
- Popularize the concept of plastic-free markets, campuses, offices, etc.
- Recognize and adopt best practices for plastic waste management.
- Improve waste management and ensure zero dumping of waste in the open.
- Improve wastewater and sludge management.

## Future Research Perspectives

Since most of the studies on MPs are conducted in South India, there is a paucity of data on the occurrence and abundance of MPs from other regions of the country. There is also a need to standardize sample collection and analysis protocol, which will help to compare results and evaluate the spatial and temporal variations in MP pollution. Since MPs are present in large numbers in sediments, the chances of further fragmentation of these particles cannot be ruled out. The long residence time of MPs in sediments may lead to their vertical migration in the sediment column. This has further implications for the contamination of groundwater aquifers. Therefore, we suggest that future research should also focus on the vertical distribution of MPs in sediments through core samples. Most MPs reported in the studies belong to secondary MPs. The sources of them are the fragmentation of larger plastics in the environment. Therefore, future studies need to be focused on tracing the sources of MPs for better control of MP pollution.

MPs in the terrestrial ecosystems, atmosphere, and indoor environments received little attention in India. Therefore, more research needs to be focused on these environments and the exposure of terrestrial organisms and humans to MPs. Research should also focus on developing and improving the waste and wastewater treatment processes to reduce MPs. Apart from this, the impact of policies on the abundance and distribution of MPs needs to be monitored systematically.

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