Microplastics as contaminants in Indian environment: a review

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Received: 27 April 2021 / Accepted: 26 September 2021 / Published online: 14 October 2021
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Abstract

The increased production and consumption scale of plastic items has led to the generation of microplastics (MPs), an emerging class of contaminants, in our environment. MPs are plastic particles less than 5 mm in size and could originate due to primary and secondary sources. The primary ones are generated as such in the MP size range while the secondary MPs are a result of fragmentation of larger plastic particles which eventually enters the aquatic, terrestrial and atmospheric environments. The increasing concern of MP pollution in every compartment of our environment is being globally explored, with relatively fewer studies in India. Among the total studies published on MP prevalence in the Indian environments, marine systems have received significantly higher attention compared to the other compartments like freshwater, atmosphere, terrestrial and human consumables. This review article is an effort to present current understanding of MP pollution in aquatic systems, terrestrial systems, atmosphere and human consumables of India by reviewing available scientific literature. Along with this, the review also focuses on identification of the gap areas in current knowledge and highlights way forward for future research. This would further help in meeting the goals of this emergent pollutant management.

Keywords Microplastics · Emerging contaminant · Aquatic systems · Atmosphere · Terrestrial systems · Human consumables

Introduction

Plastic production has seen a huge growth since the last 70 years across the globe, to such a point that we can say that we are living in a plastic world. These polymers have become indispensable in modern life because of their properties like low manufacturing cost, adaptability, water-resistant nature, high strength-to-weight ratio and high thermal and electrical insulation properties, and are prevalent in almost every area like clothing, storage, transportation, packaging and construction, and in consumer goods (GESAMP 2015). However, in view of identification of the various emerging risks to the environment and human health associated with these synthetic polymers, concern is being raised regarding the massive production and disposal of plastics (Thompson et al. 2009; Sedlak 2017). For instance, in the present COVID-19 pandemic, the inadequate usage of plastic items has generated a massive chaos in the environment. In the review study by de Sousa (2021), it is elaborately discussed how a single-use plastic item like disposable face masks can impose variable levels of problems in our environment. From reports of deaths in organisms like Magellanic penguin (Spheniscus magellanicus) to generation of hazardous emissions in the environment due to incineration of infected plastic items, these synthetic materials are creating a severe threat for virtually every type of living organism thriving in our environment (de Sousa 2021). Bhuyan et al. (2021) have reviewed the global impacts of plastic exposure in different organisms and found reports of impairment in functioning of different body parts in humans, while entanglement issues, injury, accidental ingestion and fatalities in aquatic organisms.

Plastics are highly persistent in nature due to which their degradation occurs at a slower rate and their accumulation at a faster pace (Barnes et al. 2009). In the present scenario, worldwide prevalence of smaller fraction of plastics, i.e. microplastics (MPs) and nanoplastics (NPs), is gaining significant attention of the researchers globally due to their serious environmental consequences (Wright...
et al. 2013). MPs refer to any piece of plastic smaller than 5 mm to 1 µm in size along its longest dimension and comprise polymers such as polyethylene (PE), polystyrene (PS), polypropylene (PP), polyethylene terephthalate (PET) and polyvinyl chloride (PVC) (Crawford and Quinn 2017). Depending on the specific sources of origin, MPs can be categorized into primary and secondary. Primary MPs are the ones that are intentionally manufactured by industrialists and other chemical agencies for use in cosmetics, personal care products, dermal exfoliators, etc. (Crawford and Quinn 2017), while the fragmentation of larger plastic items like fishing gear, food packaging, plastic bottles, synthetic textiles, car tyres, paints and cosmetics gives rise to a secondary fraction of MPs (Barboza and Gimenez 2015).

MPs have been present in the environment for many years; there is no doubt in this fact. They are distributed across the aquatic systems, land surface, inside biological organisms, human consumables and even in the air (Zbyszewski and Corcoran 2011; Klein et al. 2015; Prata 2018; Rezania et al. 2018; Waring et al. 2018; Barletta et al. 2019; Patel et al. 2020). The huge demand of plastic products owes to this widespread prevalence of MPs in the environment. According to the study reported by Law et al. (2020), the USA is the largest producer of plastic waste (generating around 42 million metric tons of plastic waste annually), followed by European Union, India, China, Brazil, Indonesia, Russian Federation, Germany and other countries. The gradual accumulation and subsequent fragmentation of these lead to the generation of MPs. Unfortunately, studies on this aspect is very limited yet, and out of the total 192 countries, only 22.9% have carried out research on MPs (Ajith et al. 2020).

Plastics industry is a fast-growing industry in India, where Western India has been the largest consumer of plastics (47%) with major consumption in the states of Gujarat, Maharashatra, Madhya Pradesh, Daman and Diu, Chhattisgarh, and Dadra and Nagar Haveli (FICCI 2014). Overall, the annual consumption of plastics in India is approximately 11 kg per capita (CSE 2019), and being a major consumer, it generates approximately 26 million metric tons of plastic wastes annually (Law et al. 2020), thereby holding an important position in the plastic waste generation community. Weathering and fragmentation of this plastic waste eventually leads to the generation of MPs, and its presence in various components of Indian environment is being researched by many scientists. As indicated by Ajith et al. (2020), the research on MPs has progressed in India from 2010 onwards (also represented in Fig. 1a based on our literature survey) and requires much more comprehensive studies in this domain due to various toxicities associated with this emergent pollutant.

Depending on the environmental matrix where these MPs are released, a wide array of consequences can occur. In aquatic systems, these can be ingested by the inhabiting organisms by mistaking MPs as their food, or sometimes due to their natural metabolism, organisms are exposed to MPs like in filter feeding organisms (Dowarah et al. 2020). In terrestrial systems, MPs are known to impact the functioning of organisms inhabiting these systems such as the soil dwelling invertebrates, plant pollinators and fungi (de Souza Machado

Fig. 1 Microplastic studies conducted in India. a The number of studies conducted year-wise; b percentage of studies conducted in different compartments; c percentage of studies conducted in different regions
et al. 2018; Madhav et al. 2020). While due to their increased bioavailability, subsequent changes can occur in the physical, chemical and biological properties of soil which might affect the terrestrial vegetation as well (Bi et al. 2020). In addition to this, trophic transfer of MPs or bioaccumulation can also occur (Madhav et al. 2020; Daniel et al. 2020; Selvam et al. 2020b). Ragusa et al. (2021) have found in their study that MPs have permeated the human placenta as well and possible routes of transport are indicated via respiratory and gastrointestinal systems. In addition to this, synergistic impacts of MPs are also being encountered due to the adsorption of harmful substances like persistent organic pollutants (POPs), heavy metals, pesticides, antibiotics, pathogenic microorganisms and destructive algal blooms on their surface (Naik et al. 2019; Sathish et al. 2020a). Naik et al. (2019) have further indicated ballast water as an important router for channelization of such contaminated MPs in global environmental matrices.

The pervasive occurrence of plastic pollution in different environmental matrices needs effective tracing for mitigation and control of the variable sources of this pollutant. As per the present scenario, limited reports are available to discuss the consequences of MPs prevailing in different parts of our environment. Majority of MP research has been conducted in North America, Europe and Australia while India has a very limited database in comparison to the expanse of the problems occurring due to these MP pollutants (Bhattacharya and Khare 2019). The present study is therefore an effort to highlight the immediate need of MP research in India as these pollutants create a multitude of problems in our environment.

**Microplastic pollution in India**

Situated in the southern portion of Asia, India is surrounded by the Arabian Sea in the south west and the Bay of Bengal in the south east and ultimately connects to the Indian Ocean. The country is situated between the latitude 8°4′ and 37°6′ N and the longitude 68°7′ and 97°25′ E and has a coastline of 7517 km (Kumar et al. 2006). For the assessment of status of MP pollution in the Indian environments, a detailed research of the literature was carried out using Google Scholar, Web of Science and SciFinder database till November 2020. A total of 64 studies conducted in different compartments of Indian environment (aquatic, atmospheric, terrestrial and human consumables) were found by searching these databases, which were further utilized to essence the construct of the present review article. A graphical representation (year-wise, compartment-wise and region-wise) of these studies is presented in Fig. 1. The locations where MP studies were carried out in India are represented in Fig. 2. Figure 1a clearly shows that the trend of MP research in Indian environments has caught the attention of the scientific community recently only. Furthermore, it is also revealed through these figures that the majority of the studies were conducted in marine environments (Fig. 1b), making a 63% contribution to the entire dataset. Figure 1c gives an overview of the percentage of studies conducted in different parts of India with maximum studies conducted in Southern India (Tamil Nadu, Kerala, Karnataka, Goa, Pondicherry, Andaman and Nicobar Islands, Lakshadweep and Indian Ocean) followed by Western India (Maharashtra and Gujarat) and Eastern India (Bihar and West Bengal) and lowest in Northern India (Delhi and Uttar Pradesh). The research interventions in freshwater systems, terrestrial systems, atmosphere and human consumables are lacking significantly at present, demanding a greater focus as these resources are equally important to us. Based on the present literature survey, three review articles concerning the presence of MPs in different environmental matrices of India were published by Veerasingam et al. (2020), Sarkar et al. (2020) and Pandey et al. (2021). The present review is an attempt to further add on to the available knowledge.

The hazards of MP pollution and its transport and accumulation in the environment (terrestrial, aquatic and atmosphere) are being researched upon globally, but the share of India in this global database is quite less. In India, this topic is slowly coming into existence. This comprehensive review is intended to summarize the research findings on MP prevalence in different compartments of Indian environment (aquatic, atmospheric, terrestrial and human consumables) along with the associated issues concerning these domains.

**Microplastics in aquatic environments**

**Marine systems**

Microplastic pollution is considered as a serious issue in the marine environment (Ma et al. 2016). These micro-sized polymers are widely distributed in world’s oceans and seas, ranging from Atlantic to Pacific Ocean and from Caribbean to Mediterranean Sea (Law et al. 2010). Recently, MPs have also been discovered in Arctic sea ice, the Antarctic, remote mountain ranges and deep ocean trenches (Waller et al. 2017; Peeken et al. 2018; Jamieson et al. 2019; Allen et al. 2019). The distribution of MPs is quite versatile in the global marine systems, and their presence has been seen prominently in the benthic, pelagic and shoreline sections of these environments (Wagner et al. 2014; Barletta et al. 2019). Approximately 80% of the marine plastic debris
originate from inland sources and are majorly transported to the oceans through rivers (Mani et al. 2016). The contamination of marine environments with MPs is dependent on several factors of natural and anthropogenic origin. Natural ones include wind currents, coastline geology, etc., while anthropogenic ones comprise mismanaged plastic debris releases, unregulated industrial discharges, etc. (Barnes et al. 2009). These MPs are capable of escaping even the water treatment plant processes (Fok et al. 2017). Furthermore, MPs can be transported via inland streams to estuaries and the marine environment (Lechner et al. 2014; Rech et al. 2020). In a study by Selvam et al. (2020a), Punnakayal estuary situated in the south-east coast of India was found to be contaminated with up to 19.9 MPs per L, indicating the capability of this estuary for MP channelization from inland sources to the Gulf of Mannar. In another study by Manickavasagam et al. (2020), the transport of plastic debris from densely populated areas to seas via South Juhu creek was estimated. The study revealed that a major proportion of transported plastic debris comprised macroplastic and megaplastics.
which undergoes fragmentation during their course and ultimately converts into MPs, which is an important issue to be addressed. With this ongoing scenario of plastic debris mismanagement, it has been predicted that by the year 2050, there will be a greater number of MPs in our oceans than the total number of fishes (World Economic Forum 2016).

The global contribution of different geographical areas with respect to marine MP debris (majorly primary MPs) was analysed by Ajith et al. (2020), revealing a 15.9% contribution by Southeast Asia, 17.2% by North America and 8.7% by Africa and Middle East. Numerous expeditions have been carried out by researchers for estimating the abundance of MPs in the Pacific Ocean, Atlantic Ocean, Bay of Bengal, Southern Ocean and other marine regions; however, the Indian Ocean has been relatively less focussed and less explored (Ajith et al. 2020). Investigations of marine MPs are gradually pacing up in India, and as per the present survey, the number of studies is higher for sediments in comparison to the water and biota counterpart. Table 1 shows the summary of MP studies conducted in the marine system of India comprising sediments and surface water. In addition to the abundance of MPs found in each of these matrices, studies reporting the presence of some other contaminants (conducted by the same author or different authors) at the same sites have also been mentioned. This has been done because MPs have a great potential to adsorb a variety of contaminants due to their large surface area-to-volume ratio; hence, incorporation of these studies will aid in understanding the plausible risks associated with these MPs and pollutants in the same compartment (Browne et al. 2013; Brennecke et al. 2016). The next three sub-sections critically analyse the literature published for MP pollution in marine environments of India, and it has been broadly categorized into MP occurrence in marine sediments, marine waters and marine organisms.

Marine sediments

The accumulation of MPs in the benthic layers, particularly the sediments, starts occurring when their density exceeds that of seawater (> 1020 kg/m³); otherwise, they float on the surface (Cauwenbergh et al. 2015). Sediments are known to act as the long-term sinks of MPs because floating particles are easier to remove as compared to those present in the sediments (Lima et al. 2014). MPs have been widely reported in the marine sediments of Gujarat, Tamil Nadu, Goa, Pondicherry, Maharashtra, Kerala, Karnataka, Andaman and Nicobar Islands and Lakshadweep. The preliminary study on MP contamination in marine environments of India was initiated by Reddy et al. (2006), in which they analysed the intertidal sediments at a ship-breaking yard in Gujarat. The characterization of MPs using Fourier Transform Infrared (FTIR) spectroscopy revealed that nylon, polyester, polyurethane and polystyrene were the major polymers in the sediments, which are generally used in the construction of ships.

Beaches are an important reservoir of highly fragmented plastic debris and can transport these MPs to coastal waters (Fok et al. 2017). MPs in these beaches arise due to different natural and anthropogenic sources. Anthropogenic sources include fishing, tourism, recreational, religious, port and industrial activities, mismanaged plastic waste and untreated wastewater discharges while natural sources include surface and wind currents, aeolian processes, run-off and riverine transport (Jayasiri et al. 2013b; Balasubramaniam and Phillott 2016; Veerasingam et al. 2016b; Karthik et al. 2018; Vidyasagar et al. 2018, 2020; Tiwari et al. 2019; Maharana et al. 2020; Robin et al. 2020). A significant majority of MPs found in these studies are irregularly shaped fragments. These studies further suggest that the intensity of natural and anthropogenic activities determines the MP abundance in a particular area. For instance, MPs studied across the six beaches in Puducherry showed a significant correlation with the rate of tourism activities (Dowarah and Devipriya 2019). Likewise, in another study by Karthik et al. (2018), 25 beaches of the south coast (Tamil Nadu) were analysed and it was found that beaches adjacent to the rivers had higher MP abundance, suggesting majority of these particles were transported by rivers from land-based sources.

Due to the easy accessibility and sampling, sandy beaches have been the main focus of researchers for identifying the abundance of MPs in marine environments of India. Based on the literature review for MP sampling in Indian beaches, it is observed that variable sampling procedures were used by different researchers. Sampling was done using forceps, non-plastic spoon, spatula, tweezers or shovel from quadrats of various sizes like 25 × 25 cm², 30 × 30 cm², 50 × 50 cm², 1 × 1 m² and 2 × 2 m² (Jayasiri et al. 2013a; Veerasingam et al. 2016a, b; Dowarah and Devipriya 2019; Sathish et al. 2019, 2020c; Ashwini and Varghese 2019; Jayasanta et al. 2020b; Sundar et al. 2020; Maharana et al. 2020; Robin et al. 2020). Collection of deep sea sediment samples was preferably done using a vessel and specialized equipment including the Van Veen grab sampler, the Peterson grab sampler and a box corer (Sruthy and Ramasamy 2017; Goswami et al. 2020; Jayasanta et al. 2020a; James et al. 2020; Patterson et al. 2020). After sediment collection using the grab sampler, sieving was also done for some sites to separate samples in different size ranges like 0.5 mm, 3 mm, 1 mm and 5 mm (James et al. 2020; Patchaiyappan et al. 2020a). For extraction of MPs, wet peroxide oxidation and density separation were the most preferably used methods. In some studies, prior to density separation, treatment with acids like hydrochloric acid was also given in order to remove the carbonates (Vidyasagar et al. 2020). For density separation, sodium chloride (NaCl) was found to be the most commonly
| Location                                      | Source of the sample | Abundance of MPs | Type of MPs                           | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites | Reference                                      |
|-----------------------------------------------|----------------------|------------------|---------------------------------------|------------------------------|--------------------------------------------------------------------------|-----------------------------------------------|
| Tamil Nadu (Silver Beach) Sediment            |                      | 204 items/kg     | Pellet, fibre, irregular              | PVC, PE, NY                  | Fe (1459.46 µg/g)                                                         | Vidyasagar et al. (2020); Krishnakumar et al. |
|                                               |                      |                  |                                       |                              | Mn (69.85 µg/g)                                                           | (2020b)                                       |
|                                               |                      |                  |                                       |                              | Pb (3.95 µg/g)                                                            |                                               |
|                                               |                      |                  |                                       |                              | Zn (2.52 µg/g)                                                            |                                               |
|                                               |                      |                  |                                       |                              | Cr (36.11 µg/g)                                                           |                                               |
|                                               |                      |                  |                                       |                              | Cu (1.05 µg/g)                                                            |                                               |
|                                               |                      |                  |                                       |                              | Co (2.46 µg/g)                                                            |                                               |
|                                               |                      |                  |                                       |                              | Ni (4.26 µg/g)                                                            |                                               |
| Andaman and Nicobar Islands (Port Blair Bay)  | Sediment             | 45.17 items/kg   | Fibre, fragment, pellet              | Surlyn ionomer, PEI, acrylic, | Fe, Cr, Mn, Ni, Cd, Cu, Zn, Pb, Al, B, Ag, Te, Ti, Sn, Ba, Be, Li, Ti, Ge, Si | Goswami et al. (2020)                          |
| Tamil Nadu (Rameswaram Island) Sediment       |                      | 55–259 items/kg  | Fibre, fragment, film, foam          | PE, PP, PET, PA, CP, PU, PEST, PS, PVA, PVC | Fe, Cr, Mn, Ni, Cd, Cu, Zn, Pb, Al, B, Ag, Te, Ti, Sn, Ba, Be, Li, Ti, Ge, Si | Jeyasanta et al. (2020a)                      |
| Tamil Nadu (Tuticorin) Sediment               |                      | 25–83 items/m²   | Fibre, film, fragment, foam          | PE, PVC, PP, PS, PET, NY     | Cd (0.12 mg/kg)                                                           | Jeyasanta et al. (2020b); Rajaram et al. (2020) |
| Kerala (Kochi) Sediment                       |                      | –                | Film, filament, foam, pellet, fibre, fragment | –                            | Al (3524–57,375 mg/kg)                                                   | James et al. (2020); Joseph et al. (2019)     |
|                                               |                      |                  |                                       |                              | Fe (2975.4–47,629.4 mg/kg)                                                |                                               |
|                                               |                      |                  |                                       |                              | Mn (6.8–187.8 mg/kg)                                                      |                                               |
|                                               |                      |                  |                                       |                              | Cr (5.5–202.0 mg/kg)                                                      |                                               |
|                                               |                      |                  |                                       |                              | Li (3.94–212.70 mg/kg)                                                    |                                               |
|                                               |                      |                  |                                       |                              | Zn (6.73–129.8 mg/kg)                                                     |                                               |
|                                               |                      |                  |                                       |                              | Sr (4.69–92.85 mg/kg)                                                     |                                               |
|                                               |                      |                  |                                       |                              | Ba (0.97–72.38 mg/kg)                                                     |                                               |
|                                               |                      |                  |                                       |                              | Ni (0.06–64.5 mg/kg)                                                      |                                               |
|                                               |                      |                  |                                       |                              | Cu (0.89–40.68 mg/kg)                                                     |                                               |
|                                               |                      |                  |                                       |                              | Pb (0–18.11 mg/kg)                                                        |                                               |
|                                               |                      |                  |                                       |                              | Co (0–11.71 mg/kg)                                                        |                                               |
|                                               |                      |                  |                                       |                              | As (0–4.79 mg/kg)                                                         |                                               |
|                                               |                      |                  |                                       |                              | Ag (0–4.68 mg/kg)                                                         |                                               |
|                                               |                      |                  |                                       |                              | Cd (0–1.34 mg/kg)                                                         |                                               |
|                                               |                      |                  |                                       |                              | Hg (0–0.68 mg/kg)                                                         |                                               |
| Location | Source of the sample | Abundance of MPs | Type of MPs | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites¹ | Reference |
|----------|---------------------|-----------------|-------------|------------------------------|---------------------------------------------------------------------|------------|
| South Andaman Islands | Sediment | 414.35 items/kg | Fragment, fibre, spherule | Poly(dimer acid-co-alkyl polyamine), PP, melamine, PVF, poly(perfluoroethylene oxide), polysulfide, polybutadiene, poly(butadiene-acrylonitrile acrylate acid), PVB, PVC, nylon 6, epoxy epichlorohydrin, ABS | Fe (42.8 mg/kg) Mn (327 mg/kg) Cr (104.1 mg/kg) Cu (33.4 mg/kg) Co (13.98 mg/kg) Ni (45.8 mg/kg) Pb (21.95 mg/kg) Zn (155 mg/kg) As (19.88 mg/kg) | Patchaiyappan et al. (2020a); Sachithanandam et al. (2020)⁴ |
| Tamil Nadu (Tuticorin & Vembar Coral Islands) | Sediment | 50.0–103.8 items/kg | Fibre, fragment, film, foam | PE, PP, PS, PA, PEST, PET, PVC, PVA, PEU, alkyd resin | Pb (14.4–30.1 µg/g) As (0.002–0.003 µg/g) Ni (2.4–15.4 µg/g) Hg (0.02–0.23 µg/g) Cr (3.6–24.7 µg/g) Mn (34.0–32.7 µg/g) Zn (83.1–90.3 µg/g) | Patterson et al. (2020)⁵ |
| Tamil Nadu (Tuticorin) | Sediment | 24.45–235.12 items/kg | Fibre, fragment, film, foam | PE, PP, PA, PEST, PET, PVC, PVA, PEU, blended PE-PP | Cd (0.12 mg/kg) Cu (15.89 mg/kg) Pb (14.64 mg/kg) Zn (41.19 mg/kg) | Sathish et al. (2020c); Raja-ram et al (2020)⁶ |
| Tamil Nadu (Kanyakumari) | Sediment | 6860 items/kg | Fibre, fragment | – | Cd (0.35–0.50 µg/g) Cu (17.27–17.32 µg/g) Fe (201.73–4370.59 µg/g) Pb (5.89–11.23 µg/g) Zn (10.47–18.76 µg/g) | Sundar et al. (2020); Gurumoorthi & Venkatachalapathy (2016)⁷ |
| Andaman & Nicobar Archipelago | Sediment | – | Irregular, filament, film, pellet | PE, PVC, PP, PS, NY, others | Mg (2018.46–6204.00 µg/g) Fe (508–3930 µg/g) Al (333.68–420.80 µg/g) Mn (23.18–524.80 µg/g) Cu (6.64–7.04 µg/g) Cr (5.76–9.56 µg/g) Zn (10.40–27.72 µg/g) Ni (2.16–2.88 µg/g) Co (0.82–0.88 µg/g) Cd (0.69–1.96 µg/g) | Krishnakumar et al. (2020a); Nobi et al. (2010)⁵ |
| Location | Source of the sample | Abundance of MPs | Type of MPs | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites | Reference |
|----------|---------------------|------------------|-------------|-------------------------------|---------------------------------------------------------------------|-----------|
| Maharashtra (Aksa, Juhu, Dadar, Girgaon) | Sediment | 43.6–346.0 items/m² | Fragment, fibre, film, pellet | PE, PP, others | Cu, Cr, Ni, Cd, Mn, Zn, Fe, Co, Pb | Maharana et al. (2020); Jayasiri et al. (2014)³ |
| Karnataka (Devbagh, Karwar, Kasarkod) | Sediment | 21.0–155.3 items/m² | Fragment, fibre, film, pellet | PE, PP, others | – | Maharana et al. (2020) |
| Goa (Vagator, Calangute, Colva) | Sediment | 17.0–95.6 items/m³ | Fragment, fibre, film, pellet | PE, PP, others | – | Maharana et al. (2020) |
| Kerala (Mahe, Koyilandy, Padinjarekkara, Munakkal, Azheekkal, Varkala, Veli, Poovar) | Sediment | 40.7 items/m³ | Fragment, fibre/line, foam | PE, PP, PA, PS, PET, RY, PU, alkyd, CE, ABS, PVC, PPF | Ba, Bi, Br, Cd, Cl, Cr, Cu, Fe, Hg, Ni, Pb, Sb, Sn, Ti, V, Zn | Robin et al. (2020) |
| Tamil Nadu (Marina Beach, Kanyakumari, Thiruchendur, Manapad, Tuticorin) | Sediment | 119–439 items/kg (HTL) 33–179 items/kg (LTL) | Fibre, fragment, foam | PE, PP, NY, PS, PEST | – | Sathish et al. (2019) |
| Maharashtra (Girgaon, Mumbai) | Sediment | 220 items/kg | Granule, fibre, film | PE, PET, PS, PP, PVC, others | Cr (203 mg/g) Mn (957 mg/g) Co (30 mg/g) Ni (31 mg/g) Cu (38 mg/g) Zn (24 mg/g) Hg (2.4 mg/g) | Tiwari et al. (2019); Ingole & Kadam (2003)¹⁰ |
| Tamil Nadu (Tuticorin) | Sediment | 181 items/kg | Granule, fibre, film | PE, PET, PS, PP, PVC, others | Cd (0.12 mg/kg) Cu (15.89 mg/kg) Pb (14.64 mg/kg) Zn (41.19 mg/kg) | Tiwari et al. (2019); Rajaram et al. (2020)¹³ |
| Tamil Nadu (Dhanushkodi) | Sediment | 45 items/kg | Granule, fibre, film | PE, PET, PS, PP, PVC, others | – | Tiwari et al. (2019) |
| Tamil Nadu (Tuticorin) | Sediment | 8.22–17.28 items/kg | Fragment, fibre, film | PE, PP, PEST, PA, paint | Cd (0.12 mg/kg) Cu (15.89 mg/kg) Pb (14.64 mg/kg) Zn (41.19 mg/kg) | Patterson et al. (2019); Rajaram et al. (2020)¹² |
| Pondicherry (Puducherry) | Sediment | 720.30 items/kg | Fragment, fibre/line, pellet, film/sheet, foam | PP, HDPE, LDPE, PS, PVC, EAA copolymer, CA, PVK, polypolyethylene acrylic acid, polymer resin, poly(ester urethane), polyvinyl behenate, acrylonitrile/styrene copolymer | Mn (65.2–544.9 µg/L) Cr (71.4–811.1 µg/L) Cu (18.7–85.1 µg/L) Ni (0.2–43.9 µg/L) Pb (10.4–119.0 µg/L) Zn (18.8–95.4 µg/L) Cd (1.2–4.5 µg/L) | Dowarah & Devipriya (2019); Solai et al. (2013)¹³ |
Table 1 (continued)

| Location | Source of the sample | Abundance of MPs | Type of MPs | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites | Reference |
|----------|----------------------|------------------|-------------|------------------------------|-----------------------------------------------------------------------|-----------|
| Kerala (Nattika Beach) | Sediment | 70.15 items/kg (2017) 120.85 items/kg (2018) | Fragment, fibre, film, bead, pellet | PE, PP, PS, blended PE-PP, PCU | – | Ashwini & Varghese (2019) |
| Tamil Nadu (Gulf of Mannar, Nallathani Island) | Sediment | – | – | PE, PVC, PS, NY, others | – | Krishnakumar et al. (2018) |
| Tamil Nadu (Kanyakumari, Idinthakarai, Uvari, Manapad, Thiruchendur, Tuticorin, Kilakarai, Rameswaram, Thondi, Mananelkudi, Mallakkottai, Velankanni, Karaikal, Poompuhar, Pazhayar, Parangipettai, Cuddalore, Puducherry, Marakkanam, Mahabalipuram, Muttukadu, Cooum, Adyar, Ennore) | Sediment | 9–178 items/m² (HTL) 2–64 items/m² (LTL) | Fragment, film, pellet, foam, fibre/line | PE, PP, PS, NY, others | – | Karthik et al. (2018) |
| Tamil Nadu (Rameswaram Island) | Sediment | 403 items | Irregular, fibre, pellet | PVC, NY, PE, PP, PS | Fe (43,210.82 ppm) Mn (287.73 ppm) Cu (41.15 ppm) Cr (54.82 ppm) Co (15.82 ppm) Ni (37.12 ppm) Pb (13.72 ppm) Zn (27.68 ppm) | Vidyasakar et al. (2018); Pradhap et al. (2017) |
| Lakshadweep (Tinnakara) | Sediment | 603 items | Pellet | – | Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Zn | Mugilarsan et al. (2017); Thangaradjou et al. (2014) |
| Location (continued) | Source of the sample | Abundance of MPs | Type of MPs | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites1 | Reference |
|----------------------|----------------------|------------------|-------------|-----------------------------|-----------------------------------------------------------------|-----------|
| Tamil Nadu (Chennai) | Sediment             | 201 items        | Pellet      | –                           | Mg (1918 mg/kg) Al (25,436 mg/kg) K (9852 mg/kg) Ca (9859 mg/kg) Ti (2109 mg/kg) Fe (9209 mg/kg) V (41.58 mg/kg) Cr (34.14 mg/kg) Mn (160.80 mg/kg) Co (2.85 mg/kg) Ni (18.79 mg/kg) Zn (29.12 mg/kg) | Mugilanasan et al. (2017); Tholkappian et al. (2018)15 |
| Goa (Palolem Beach)  | Sediment             | 520 items/kg     | Fibre       | –                           | –                                                               | Balasubramaniam & Phillips (2016) |
| Tamil Nadu (Chennai) | Sediment             | 304 items (March) 896 items (November) | Pellet | PE, PP | As (0.46–3.19 µg/g) Cr (0.62–1.11 µg/g) Cu (0.23–2.92 µg/g) Pb (0.14–1.85 µg/g) | Veerasingam et al. (2016a); Suman et al. (2020) |
| Goa (Keri, Vagator, Calangute, Colva, Mobor and Galgibaga beaches) | Sediment | 1345 items (January) 1655 items (June) | Pellet | PE, PP | – | Veerasingam et al. (2016b) |
| Maharashtra (Aksa, Versova, Juhu, Dadar) | Sediment | – | Pellet, fragment | – | Fe (31,150 mg/kg) Cu (32.24 mg/kg) Cr (151.98 mg/kg) Ni (67.52 mg/kg) Cd (18.75 mg/kg) Mn (535.04 mg/kg) Zn (54.65 mg/kg) Co (92.76 mg/kg) Pb (59.57 mg/kg) | Jayasiri et al. (2013a, 2014) |
| Maharashtra (Aksa, Versova, Juhu, Dadar) | Sediment | – | Pellet, fragment | – | Fe (31,150 mg/kg) Cu (32.24 mg/kg) Cr (151.98 mg/kg) Ni (67.52 mg/kg) Cd (18.75 mg/kg) Mn (535.04 mg/kg) Zn (54.65 mg/kg) Co (92.76 mg/kg) Pb (59.57 mg/kg) | Jayasiri et al. (2013b, 2014) |
| Location | Source of the sample | Abundance of MPs | Type of MPs | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites¹ | Reference |
|----------|---------------------|-----------------|-------------|-----------------------------|---------------------------------------------------------------------|-----------|
| Maharashtra (Mumbai), Tamil Nadu (Chennai) & West Bengal (Sundarbans) | Sediment | – | Pellet | PE, PP, others | PCBs (20–141 ng/g) DDTs (9.58–29.80 ng/g) HCHs (1.77–3.24 ng/g) | Ogata et al. (2009) |
| Gujarat (Alang-Sosiya ship-breaking yard) | Sediment | 81.43 mg/kg | Fragment | PU, NY, PEST, PS | Cd (32.70 ppm) Co (52.55 ppm) Cu (214.41 ppm) Cr (290.18 ppm) Fe (137.990 ppm) Mn (4643.1 ppm) Ni (172.53 ppm) Pb (169.98 ppm) Zn (1222.18 ppm) | Reddy et al. (2006, 2004) |
| Goa (Caranzalem Beach) | Sediment | 50–300 items/m² | Pellet | – | – | Nigam (1982) |
| Tamil Nadu (Tuticorin) | Water | 3.1–23.7 items/L | Fibre, fragment, film, foam | PE, PEST, PA, PS, P, PVA, poly(ethylene propylene diene) copolymer | Cd (0.84 mg/L) Cu (3.73 mg/L) Pb (20.98 mg/L) Zn (3.75 mg/L) | Sathish et al. (2020b); Rajaram et al. (2020) |
| Andaman and Nicobar Islands (Port Blair Bay) | Water | 0.93 × 10⁻³ items/L | Fibre, fragment, pellet | Surlyn ionomer, PEI, acrylic, PPS, ethylene vinyl alcohol, acrylonitrile, NY, EVA, PIP, PU, PVC | – | Goswami et al. (2020) |
| Tamil Nadu (Tuticorin) | Water | 8.76–30.98 items/L | Fibre, film, fragment, foam | PE, PP, PA, PEST, RY, PET, PVC, PVA, PS, blended PE-PP | Cd (0.84 mg/L) Cu (3.73 mg/L) Pb (20.98 mg/L) Zn (3.75 mg/L) | Sathish et al. (2020c); Rajaram et al. (2020) |
| Tamil Nadu (Rameswaram Island) | Water | 24–96 items/L | Fibre, fragment, film, foam | PE, PP, PET, PA, CP, PU, PEST, PS, PVC | Cd (0.84 mg/L) Cu (3.73 mg/L) Pb (20.98 mg/L) Zn (3.75 mg/L) | Jeyasanta et al. (2020a) |
| Tamil Nadu (Tuticorin & Vembar Coral Islands) | Water | 60.0–126.6 items/L | Fibre, fragment, film, foam | PE, PP, PS, PA, PEST, PET, PVC, PVA, PU, alkyd resin | Cd (0.84 mg/L) Cu (3.73 mg/L) Pb (20.98 mg/L) Zn (3.75 mg/L) | Patterson et al. (2020); Rajaram et al. (2020)¹⁶ |
| Tamil Nadu (Punnakayal estuary) | Water | 2.8 items/L | Line, film, foam, fragment | PP, PA, PE, PVC, CE | Ni (0.10–0.33 ppm) Cr (BDL–0.88 ppm) Cd (BDL–0.06 ppm) Pb (0.10–0.98 ppm) Mn (BDL–0.42 ppm) Fe (BDL–0.88 ppm) | Selvam et al. (2020a); Ravindran & Rajesh (2013)¹⁷ |

¹ Abundance of other contaminants reported in the same sampling sites.
Table 1 (continued)

| Location                  | Source of the sample | Abundance of MPs | Type of MPs                  | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites¹ | Reference                          |
|---------------------------|----------------------|------------------|------------------------------|-------------------------------|---------------------------------------------------------------------------|------------------------------------|
| Kerala (Kochi)            | Water                | –                | Film, filament, foam, pellet, fibre, fragment | –                             | –                                                                         | James et al. (2020)                |
| Maharashtra (Juhu creek, Mumbai) | Water            | 1–2 g/kg         | –                            | –                             | –                                                                         | Manickavasagam et al. (2020)       |
| Kerala                    | Water                | 1.25 × 10⁻³ items/L | Fragment, fibre/line, foam | PE, PP, alkyd, RY, PS, CE, others | –                                                                         | Robin et al. (2020)                |
| Tamil Nadu (Tuticorin)    | Water                | 12.14–31.05 items/L | Fragment, fibre, film        | PE, PP                         | Cd (0.84 mg/L), Cu (3.73 mg/L), Pb (20.98 mg/L), Zn (3.75 mg/L)           | Patterson et al. (2019); Rajaram et al. (2020)¹⁸ |
| Tamil Nadu (Chennai)      | Water                | 11 items/L       | Fibre, fragment               | PA                            | Na, Mg, Al, Si, Cl, K, Ca                                                | Ganesan et al. (2019)              |

HTL high tide line, LTL low tide line, BDL below detection limit, PE polyethylene, NY nylon, PEI polyetherimide, PPS polyphenylene sulphide, EVA ethylene vinyl acetate, PU polyurethane, PVC polyvinyl chloride, PP polypropylene, PET polyethylene terephthalate, PA polyamide, CP cellophane, PEST polyester, PS polystyrene, PVA polyvinyl acetate, PVF polyvinyl formal, PVB polyvinyl benzoxa, ABS acrylonitrile butadiene styrene, PEU polyurethene, CE cellulose, RF rayon, CA cellulose acetate, PKV poly(N-vinyl carbazole), EAA ethylene acrylic acid, PIP polyisoprene; PCU polycarbonate urethane.
¹Abundance of other chemical constituents reported for the respective studies.
²Total eight sites were analysed for the MP study while heavy metals were analysed for fifteen sites.
³Three sampling stations were selected for the MP study while heavy metal assessment was carried out at 6 stations.
⁴Total forty-eight samples were collected for MP studies while twenty-three sediment samples were collected for the heavy metal study.
⁵MP and heavy metal analysis were conducted in the same study.
⁶Total eleven sites were chosen for the MP study while heavy metals were sampled from fifteen locations.
⁷Total twenty-four samples were collected for the MP study while fifteen surface sediment samples were collected for heavy metal studies.
⁸MPs were analysed in the Andaman and Nicobar group of islands while heavy metal studies were carried out in the Andaman Islands only.
⁹MPs were analysed in four beaches while heavy metal concentrations were found in three out of four beaches.
¹⁰Total ten samples were collected for the MP study while heavy metals were analysed only once.
¹¹Total ten samples were collected for the MP study while heavy metals were analysed for fifteen sites.
¹²Three sites were analysed for MPs while fifteen sites were analysed for heavy metals.
¹³Total thirty-four samples were collected for the MP study while heavy metals were analysed for twenty-five sites only.
¹⁴Total eight samples were collected for the MP study while heavy metals were analysed for two sites only.
¹⁵Total six samples were collected from the beach for the MP study while heavy metal studies were conducted at twenty-two sampling points from the same coastline.
¹⁶The MP study was carried out on thirty sites for Tuticorin and Vembar Coral Islands while heavy metal studies were carried out in the ten sites of Tuticorin Islands only.
¹⁷Total twenty water samples were collected for the MP study while six stations were selected for heavy metal studies.
¹⁸MP samples were collected from three sites, while for heavy metal analysis, ten sampling sites were chosen.
used salt whereas zinc bromide (ZnBr₂), zinc chloride (ZnCl₂), sodium iodide (NaI), calcium chloride (CaCl₂) and sodium bromide (NaBr) were preferred for the separation of heavier polymers (Tiwari et al. 2019; Sathish et al. 2019; Patterson et al. 2019, 2020). After treatment, supernatant solution was subjected to filtration and sorting and isolation of MPs was carried out under a microscope. Identification of MPs was preferably done using Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) spectroscopy while other techniques like fluorescence microscopy using Nile red dye (Patchaiyappan et al. 2020a) and Raman spectroscopy (Dowarah and Devipriya 2019) were also used. Present variations in the sampling and analytical procedures for MPs could lead to a significant bias in the overall output as indicated by Müller et al. (2020). In this study, it was found that MP analysis using different procedures can lead to large variances in the overall results for the same dataset. This biasness would cause difficulties in comparison of MP abundance and distribution data in global environmental matrices, as the present scenario of MP research in Indian environments is already restricted to certain regions; hence, adoption of such variable analytical protocols would lead to limitations in the data comparability and applicability. This issue demands that the concerned stakeholders take necessary steps to standardize the MP sampling and analytical procedures at the national as well as global level, so that the creation of MP database for these environmental matrices is harmonized.

**Marine waters**

Low-density MPs are reported to be the predominant versions of plastic particles in the surface layers of the marine waters (Derraik 2002), and the attachment of fouling organisms to these MPs may lead to their sinking in the benthic layers (Browne et al. 2010). In contrast, high-density MPs including PVC, PEST and PA are found in the benthic layers (Barnes et al. 2009); however, due to the variations in hydrodynamic conditions (flow rate, tidal fronts, etc.), these particles can sometimes remain in the suspension as well (Browne et al. 2010).

MP samples in Indian marine waters were collected using different techniques comprising manual collection in glass bottles (Sathish et al. 2020c; Ganesan et al. 2019) or using a boat equipped with various types of nets such as manta trawl net, neuston net and plankton net of different mesh sizes (Patterson et al. 2019, 2020; Goswami et al. 2020; Sathish et al. 2020b; Jeyasanta et al. 2020a; James et al. 2020; Robin et al. 2020) or using a Teflon pump and subsequent filtration through stainless steel sieves (Selvam et al. 2020a). After collection, samples were either refrigerated or additional preservation was done by adding 4–5% formalin (James et al. 2020; Selvam et al. 2020a) or 5% formaldehyde solution (Sathish et al. 2020b; Patterson et al. 2019). Further processing of the collected samples for the separation of MPs was carried out using wet peroxide oxidation followed by density separation or density separation alone. As mentioned in the previous section, the variations adopted in MP sampling and analytical procedures in the present dataset can also lead to inconsistencies. Thus, it is important to prioritize standardized MP sampling and analysis protocols in order to avoid any discrepancies and have more significant and uniform database for marine waters also.

The choice of selected locations by the researchers and limited explorations of Indian marine environments are insufficient to identify the role of this country in global marine MP pollution. Due to the ease of sampling, beaches have been the main focus of researchers whereas water column has gained comparatively lesser attention. A portion of southern coastline has been extensively studied while the rest of the regions have remained untouched. Hence, the current scenario depicts that the research explorations in India are non-uniform and require a much greater number of studies to fill in the gap areas for better understanding of the MP pollution in marine domain in India.

**Marine organisms**

A huge amount of population in India is dependent on the coastal and marine ecosystems and their resources (Kumar et al. 2018). Despite this fact, the marine ecosystem is under constant threat due to various anthropogenic activities. Among the different threats that marine organisms are facing, MPs are emerging as a new and relatively less studied threat. The present understanding of MP prevalence in the marine biota suggests that a significant proportion of organisms are at risk of ingesting these synthetic polymers which can lead to variable levels of health complications. Studies have found that due to the increasing exposure to MPs, marine biota can experience oxidative stress, reduction in filtration capacity, inflammation in tissues, impaired digestive tract, pseudo-satiation and reduced immunity (Dowarah et al. 2020; Maharana et al. 2020; Daniel et al. 2020; Sathish et al. 2020b). In India, studies on ingestion of MPs by fishes have been a major attraction for the researchers. In fishes, MPs have been found in the range 0.05 to 10.65 items per individual while the range of MPs found in marine waters is 0.93 to 126.6 × 10³ items/m³. In recent investigations on impact of MPs in a marine fish (Carassius carassius), it was found that ingestion of MPs in the range of 15 to 76 items per individual for the exposure duration of 6 weeks could lead to a decrease in weight, disruptions in the buccal cavity, inflammations and microgranulomas in the liver (Jabeen et al. 2018; Wang et al. 2020a), while based on abundance in their habitat, a concentration of 100 items/L for the exposure
| Organism | Sampling location | Body part used for MP analysis | Size range of MPs detected (µm) | Abundance of MPs (items/individual) | Predominant type of MP ingested | Type of MP polymers detected | Reference |
|----------|-------------------|-------------------------------|---------------------------------|-----------------------------------|---------------------------------|--------------------------------|-----------|
| Shellfish species: shrimp & crab (Metapenaeus dobsoni, Fenneropenaeus indicus, Portunus pelagicus, Urotethis (Photololigo) dancscke) | Kerala (Cochin & Kalakukku fishing harbours) | Tissue | 100 to 300 | 0.07 | Fragment | PP, PE, PS | Daniel et al. (2021) |
| Bivalve species (Perna viridis, Meretrix meretrix) | Pondicherry (Puducherry) | Tissue | Less than 100 to 1500 | 0-10.8 | Fragment | Polyester urethane, plasticized PVC, PES, PVCA copolymer, ABS, SBR copolymer, PVK, PET, PVC, PEVA | Dowath et al. (2020) |
| Fish species (Gymnocephalus malarbus, Alepes diehado, Saurida timbal, Cynoscion leucas, Gymnosomus nemipterus peroni, Upenius vitatus, Portunus pelagicus, Peneaus indicus) | Andaman and Nicobar Islands (Port Blair Bay) | Gut (fish) | 111.58 to 5094.00 (fish) | 10.65 (fish) | Fibre (fish) | Surlyn ionomer, PET, acrylic, PPS, ethylene vinyl alcohol, NY, EVA, PIP, PU, PVC | Groswami et al. (2020) |
| Zooplankton groups (copepod, Chaetognath, jellyfish, shrimp, fish larvae) | Kerala (Kochi) | Tissue (zooplankton) | 21.57 to 22.25.00 (zooplankton group) | 0.12 (zooplankton) | Fragment (zooplankton) | | |
| Fish species (Sardinella longiceps, Sardinella gibbosa, Stolephorus indicus, Rastrelliger kanagurta, Cynoscion macrostomus) | Kerala (Vembanad Lake) | Gut | 800 to 4850 | 0.56 | Fibre | PE, nylon 6, PP, PBT, PET | Devi et al. (2020) |
| Fish species (Harpadon nehereus, Chirocentrus dorab, Sardinella albida, Rastrelliger kanagurta, Katsuwonus pelamis, Istiophorus platypterus) | Tamil Nadu (Tuticorin) | Gut | 85 to 5000 | 0.11–3.64 | Fibre | PE, PEST, PA, PS, PP, acrylic | Sathish et al. (2020b) |
| Clam species (Donax cuneatus) | Tamil Nadu (Tuticorin) | Tissue | 100 to 5000 | 0.29–2.70 | Fibre | PE, PP, PA + PP, PEST, PET, PS, RA | Sathish et al. (2020c) |
| Shrimp species (Fenneropenaeus indicus) | Kerala (Kochi) | Tissue (including gut) | 157 to 2785 | 0.39 | Fibre | PEST, PA, PE, PP | Daniel et al. (2020) |
| Fish species (Decapterus macarellus, Decapterus ruscelli, Dasomia via elopoides, Eleutherorhina tetradactylus, Nemipterus japonicus, Pentapiron longimanus, Rastrelliger jauberti, Sardinella longiceps, Scomberomorus guttatus, Scoloplos indicus, Tespon putha, Escualus thoracatus, Callidus sumieri) | Tamil Nadu (Kasimedu & Nagapatnam fish landing centre) | Gut | 1300 to 4800 | 0.10 | Film | PE, PA, PEST | Karuppusamy et al. (2020) |
duration of 96 h could lead to reductions in predatory performance and overall efficiency in *Pomatoschistus microps* (Carlos de Sá et al. 2015; Wang et al. 2020a). Also, from the literature, it can be concluded that these types of studies were more prevalent in the states of Tamil Nadu and Kerala in India. Table 2 shows the summary of MP occurrence in Indian marine biota.

According to the current research studies, the sampling protocols for assessment of MPs in marine organisms generally involve either direct capture using fishing nets or purchase of samples from the market and immediate storage in ice boxes until further analysis in the laboratory. Analysis was primarily carried out by dissecting the organism followed by direct visual observations under a microscope, or the dissected contents were further digested using aqueous or alcoholic potassium hydroxide (KOH), nitric acid (HNO₃) or hydrogen peroxide (H₂O₂). MPs were then finally isolated from these samples and subjected to microscopic observations and characterization for confirmation of the plastic nature and polymer. In India, majority of studies have been conducted to find the prevalence of MPs in marine organisms. We could find only one study in the literature by Goswami et al. (2020) who have done extended research on trophic transfer and bioaccumulation of MPs. Since MPs pose a serious threat to animals and human health due to ingestion of these compounds by marine biota followed by bioaccumulation and biomagnification through food chain, more extensive research is required in this domain for better understanding of the risks associated with MP ingestion by marine biota.

**Freshwater systems**

Microplastic pollution has been identified as a pervasive and damaging environmental stressor in the world’s ocean, but still only a small body of research has been conducted on freshwater MPs, despite the fact that freshwater is a source for drinking water. Though research in this domain is gradually progressing all over the world, unfortunately, this domain has not gained enough attention in India according to the literature reviewed (Sruthy and Ramasamy 2017; Sarkar et al. 2019; Ganesan et al. 2019; Gopinath et al. 2020; Manikanda Bharath et al. 2020). Other responsible factors could be leakage of primary MPs from personal care products or industries, riverine transport of MPs, run-off activities due to rainfall and dry deposition. MP investigations in Indian lakes were conducted in sediments and surface water sections. For surface waters, sample collection was generally conducted using glass bottles (grab sampling), nylon plankton nets (20 µm mesh size) or plankton nets (120 µm mesh size) (Ganesan et al. 2019; Gopinath et al. 2020; Manikanda Bharath et al. 2020), while for sediment samples, the Van Veen grab was preferred (Sruthy and Ramasamy 2017; Gopinath et al. 2020; Manikanda Bharath et al. 2020). For MP extraction, standard protocols of National Oceanic and Atmospheric Administration (NOAA) were generally preferred; however, Ganesan et al. (2019) analysed the samples by direct filtration without any pre-treatment followed by visual observations under the microscope for MP identification.

**Rivers**

Approximately 80% of the total plastic debris in the marine environments are coming from terrestrial sources which are known to be transported by rivers (Wagner et al. 2014). In a recent study by Napper et al. (2021), approximately 1–3 billion of MPs are estimated to be daily discharged into the Bay of Bengal by the Ganges, Brahmaputra and Meghna rivers. However, MPs found in the rivers do not reach oceans as a whole but some pieces get accumulated in their sediments, which can act as an important sink of MPs (Sruthy and Ramasamy 2017; He et al. 2020). River water pollution is a global problem,
Table 2 (continued)

| Organism (Samples) | Sampling location | Body part used for MP analysis | Size range of MPs detected (µm) | Abundance of MPs (items/individual) | Predominant type of MP ingested | Type of MP polymers detected | Reference |
|--------------------|-------------------|-------------------------------|---------------------------------|-------------------------------------|---------------------------------|-------------------------------|-----------|
| Fish species (Johnius amblycephalus, Rhytchothamphus georgii, Penrhiaha anom, Nemipterus japonicus, Lutjanus lutjanus, Apis d extraordinary, Carangoides melalacra, Hypothamnus dussumieri, Pseudakus maculatus, Carans heberi, Lutjanus vitia, Lutjanus russelli, Arsis anora, Pinnigliza macrodepa, Gieress filamentosus, Mugil cephalus, Silbago sihama, Sardinella longiceps, Rastrellger kanagurta, Bilhisa megalopera, Nematastra nausus, Anodontostoma chacunda) | Kerala (Koyilandy, Thakadappuzam, Thalikalam, Kozhikode, Palithottam, Manjeswar, Munakkal, Thottappally, Kodi, Payyanbham, Chovakkad) | Gut | 300 to 4750 | 0.31 | Fibre | PE, PP, RY, CE, PL | Robin et al. (2020) |
| Fish species (Perna viridis) | Tamil Nadu (Chennai) | Tissue | 5 to 25 (fibre) 30 to 103 (particle) | – | Fibre, particle | PS | Naidu (2019) |
| Oyster species (Magallana bilineata) | Tamil Nadu (Tuticorin) | Tissue | 5 to 5000 | 6.9 | Fibre | PE, PP | Patterson et al. (2019) |
| Fish species (Rastrellger kanagurta, Epinephelus membr) | Tamil Nadu (Tuticorin) | Gut | – | – | Fibre | PE, PP | Kumar et al. (2018) |
| Fish species (Siganus javus, Mugil cephalus, Leiognathus equious, Arsis anora, Rastrellger kanagurta) | Tamil Nadu (Kanyakumari, Munnad, Tuticorin, Kilakani, Rameswaram, Mallipatnam, Vallankanni, Panagipet, Cuddalore, Puducherry, Marakkanam, Mahabalipuram, Coosum, Adyar, Enoor) | Gut | Less than 500 | 0.10 | Fragment | PE, PP | Karthik et al. (2018) |
| Benthic invertebrates (Sternaspis scintilla, Magelona cinta, Tellina sp.) | Kerala (Kochi) | Direct observation (S. scintilla, M. cinta) Tissue (Tellina sp.) | – | – | Particle, fibre | PS | Naidu et al. (2018) |

PVCA polyvinyl chloride acetate, PES poly(p-phenylene ether sulfone), SBR styrene-butadiene rubber, PEVA poly(ethylene-co-vinyl acetate), PBT polybutylene terephthalate.
and being home to around 20 river basins (Central Water Commission 2019), a majority of basins in India are victim to different types of pollution like heavy metals, pesticides, POPs and other harmful biological and chemical compounds. Inefficient waste management practices are further leading to the discharge of plastic wastes in these rivers particularly MPs. Sources of MPs in Indian rivers primarily comprise fragmentation of macroplastic debris items like plastic packaging materials, ropes, fishing nets, wrappers, pipes and synthetic textiles. Furthermore, variations in the hydrodynamic and climatic factors like wave height, flow velocity and wind speed facilitate channelization of these synthetic polymers to different sections of the water column (Sarkar et al. 2019; NPC 2020; Amrutha and Warrier 2020; Ram and Kumar 2020). Studies conducted on contamination of Indian rivers with MPs have analysed the surface water and sediment layers. Sample collection from surface waters was preferred using stainless steel bucket and sieves or neuston nets (300 μm mesh size), while for sediments, stainless steel spoon or scoop was preferred. Extraction of MPs from the collected samples was then done using wet peroxide oxidation method or density separation or both. Depending on the load of organic matter in the collected sample, preference to wet peroxide oxidation is given because its primary aim is to digest the labile organic matter for easy separation and identification of MPs (Amrutha and Warrier 2020).

Groundwater

Globally, water resources are facing a high risk of contamination with MP pollutants. However, for occurrence of MPs in groundwater of India, only two studies could be found in the present literature survey (Ganesan et al. 2019; Selvam et al. 2020a). Tourism-dominated activities, industrial and domestic effluent discharges, fragmentation of mismanaged plastic debris and riverine leaching are some of the major reasons of MP contamination in the groundwater across India as per the present analysis. Groundwater samples tested for MP contamination followed different methodologies of collection and processing. In the study conducted by Ganesan et al. (2019), samples were directly collected in the glass bottles and MP isolation was performed by filtration of the samples in the laboratory. Observation of MPs collected on the filter was then done using an optical microscope. While in another study by Selvam et al. (2020a), sample collection was preferred using a Teflon pump followed by on-site filtration through stainless steel sieves (50 μm mesh size). Further processing and extraction of MPs was conducted using wet peroxide oxidation method and subsequent filtration of this oxidized solution. Filters were then analysed under a stereomicroscope for MP presence and identification. In the same study, adsorption capacities of PP, PVC, PA, CE and PE were tested against the heavy metals Mn, As, Cd, Zn, Cr, Cu and Pb. It was found that MPs comprising of PP and PE polymers could adsorb significant quantities of metals even in trace concentrations, depicting a situation of severe risk if these MPs are ingested by any of the aquatic or terrestrial biota (Selvam et al. 2020a).

Microplastics in atmosphere

Air is one of the most important requirements of living beings to survive and exist. Out of the many pollutants present in the atmosphere, airborne MPs have recently emerged as contaminants of concern. MPs in the air are able to enter directly in the human body and pose significant risk to human health (Gasperi et al. 2018; Prata 2018). Early studies concerning airborne MPs were reported by Dris et al. (2016) in Paris and it was found that MP fibres can become airborne, after their disintegration from its source. The major source of MPs in air remains synthetic textiles (Dris et al. 2016) while gradual releases from landfills, streets and incomplete incineration of garbage is also important to be considered (Liu et al. 2019). Several experiments were conducted to check airborne MP–associated risks to human health. For instance, Vianello et al. (2019) used a breathing thermal manikin (BTM) to study the effect of indoor air exposure (24-h duration) on humans and found that an average human can inhale up to 272 MP particles from indoor air within 24 h. Inhalation of airborne fibres is much more prevalent in comparison to other shapes (Wang et al. 2020b; Naradma et al. 2020). Prata (2018) in her study has made a very good review on health implications to humans due to airborne MPs. The author has reported that the workers associated with textile industries (which are a major source of fibrous MPs) are known to suffer from various ailments including dyspnea, interstitial inflammations in their airway and respiratory failure in extreme cases due to this exposure (Prata 2018).

India being one of the most polluted cities with respect to air pollution is also at high risk of airborne MP contamination. In a recent report by IQAir (2020), 22 of the 30 most polluted cities in the world were present in India, particularly in terms of PM$_{2.5}$ (particulate matter less than 25 μm in size). MPs in conjunction with other pollutants present in the Indian atmosphere can lead to various health complications, but due to the significant lack of research in this domain, the severity of situation is unclear. During the present literature survey, two studies reporting the presence of MPs in Indian atmosphere (Naradma et al. 2020; Wang et al. 2020b) were located.
### Table 3 Presence of microplastics in freshwater systems

| Location | Source of the sample | Abundance of MPs | Type of MPs | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites | Reference |
|----------|----------------------|------------------|-------------|-----------------------------|-----------------------------------------------------------------------|-----------|
| Lakes    |                      |                  |             |                             |                                                                       |           |
| Tamil Nadu, Chennai (Red Hills Lake) | Surface water | 5.9 items/L | Fibre, fragment, film, pellet | HDPE, LDPE, PP, PS | Na, Mg, Al, Si, Cl, K, Ca, Ti, Fe | Gopinath et al. (2020) |
|          | Sediment            | 27 items/kg      |             |                             |                                                                       |           |
| Kerala (Veeranam Lake) | Surface water | 28 items/kg | Fragment, foam, film, pellet, fibre | PE, PP, PVC, PS, NY | – | Manikanda Bharath et al. (2020) |
|          | Sediment            | 309 items/kg     |             |                             |                                                                       |           |
| Tamil Nadu, Chennai (Chembarambakkam Lake) | Surface water | 9 items/L | Fibre, fragment | PET | O, Na, Al, Si, Cl, K, Ca | Ganesan et al. (2019) |
| Kerala (Vembanad Lake) | Sediment | 252.8 items/m² | Film, foam, fibre, fragment, pellet | HDPE, LDPE, PS, PP | Hg (3.11 mg/kg), Cd (6.35 mg/kg), Pb (17.92 mg/kg), Zn (6.2954 mg/kg), Cu (27.00 mg/kg) | Manikanda Bharath et al. (2020); Suresh et al. (2012) |
| Rivers   |                      |                  |             |                             |                                                                       |           |
| Uttar Pradesh, Agra (Yamuna River) | Surface water | $4.00 \times 10^{-2}$–$4.62 \times 10^{-3}$ items/L | Bead, film, fibre, fragment | Polyacrylene, IPP, EVOH, PA, styrene/isoprene, PVC, butadiene, PVAL, PC, PP, polycrylamide, polyamide, polybutene, poly(α-methyl styrene), PMMA, LDPE | Fe (420.0–608.5 µg/L), Pb (12.7–34.0 µg/L), Cd (0.8–5.0 µg/L), Zn (1632–2482 µg/L), Cu (40–71 µg/L), Cr (0.130 mg/L), Cd (0.027 mg/L), Ni (0.094 mg/L), Fe (0.536 mg/L), Pb (0.248 mg/L), Mn (0.035 mg/L) | NPC (2020); NPC (2020); Pal et al. (2017); Suresh & Ramasamy (2017); Shyleshchan-dran et al. (2018); Naushad et al. (2014) |
| Uttar Pradesh, Prayagraj (Yamuna River) | Surface water | $2.43 \times 10^{-3}$ items/L | | EVOH, polycrylonitrile, PIP, PVC, PVAL, PA, PP, styrene/isoprene, PVB, Irgazol MD 1024, polysulfone, polycarbonate, polyacrylamide | – | NPC (2020) |
| Uttar Pradesh, Prayagraj (Ganga River) | Surface water | $1.47 \times 10^{-3}$–$5.69 \times 10^{-3}$ items/L | | Polyacrylamide, EVOH, IPP, PVC, ABS, styrene/isoprene, copolymer, PVAL, polycrylonitrile, polyacrylamide, PP, polystyrene, PE, PES, lanoline, acrylonitrile film, polyvinyl pyrrolidone, polyvinyl acetate, PEST | – | NPC (2020) |
| Uttar Pradesh, Prayagraj, Sangam (Ganga & Yamuna River) | Surface water | $1.23 \times 10^{-3}$ items/L | | EVOH, polycrylonitrile, IPP, polycrylamide, PVAL, PP, styrene/isoprene, polyvinyl pyrrolidone, lanoline, PVC, polycrylamide, polyacetal, CE | Cr (0.130 mg/L), Cd (0.027 mg/L), Ni (0.094 mg/L), Fe (0.536 mg/L), Pb (0.248 mg/L), Mn (0.035 mg/L) | NPC (2020); Naushad et al. (2014) |
**Table 3** (continued)

| Location                  | Source of the sample | Abundance of MPs | Type of MPs                  | Type of MP polymers detected | Abundance of other chemical contaminants reported in these sampling sites | Reference                                      |
|---------------------------|----------------------|------------------|------------------------------|------------------------------|--------------------------------------------------------------------------|------------------------------------------------|
| Karnataka (Netravathi River) | Surface water        | $2.88 \times 10^{-1}$ items/L | Fragment, fibre, film, foam, pellet | PE, PET, PP, PVC             | –                                                                       | Amrutha & Warrier (2020)                        |
|                           | Sediment             | 96 items/kg      |                              |                              | Al (47.827.2 mg/kg)                                                     | Amrutha & Warrier (2020); Gayathri et al. (2021)* |
|                           |                      |                  |                              |                              | Pb (322.6 mg/kg)                                                        |                                                 |
|                           |                      |                  |                              |                              | Mn (213.6 mg/kg)                                                        |                                                 |
|                           |                      |                  |                              |                              | Ni (140 mg/kg)                                                          |                                                 |
|                           |                      |                  |                              |                              | Zn (14.6 mg/kg)                                                         |                                                 |
|                           |                      |                  |                              |                              | Cr (90.8 mg/kg)                                                         |                                                 |
|                           |                      |                  |                              |                              | Cu (70.8 mg/kg)                                                         |                                                 |
|                           |                      |                  |                              |                              | Co (12.8 mg/kg)                                                         |                                                 |
| Gujarat, Ahmedabad (Sabarmati River) | Sediment          | –                | –                            | –                            | –                                                                       | Ram & Kumar (2020)                             |
| Bihar & West Bengal (Ganga River) | Sediment           | 107.57–409.86 items/kg | Fibre, film, foam              | PE, PP, PS, PET, other       | Cr, Cd, Cu, Ni, Pb, Zn, Mn, Fe                                        | Sarkar et al. (2019); Siddiqui & Pandey (2019)* |
| Ground water              |                      |                  |                              |                              |                                                                         |                                                 |
| Tamil Nadu (Tuticorin)     | Well and bore well  | 4.2 items/L      | Line, film, foam, fragment     | NY, PEST, PP                | –                                                                       | Selvam et al. (2020a)                          |
| Tamil Nadu (Chennai)       | Ground water        | 4–7 items/L      | Fibre, fragment                 | PA                           |                                                                         | Ganesan et al. (2019)                          |
|                           |                      |                  |                              |                              | O, Na, Mg, Al, Si, Cl, K, Ca, Rn, Cs, TI, Ba, Mo                        |                                                 |

EVOH ethylene vinyl alcohol, PVAL polyvinyl alcohol, PMMA poly(methyl methacrylate), PC polycarbonate, PIP polyisoprene, PVB polyvinyl butyral.

1MP sampling was done in ten sites of Vembanad Lake whereas heavy metals were collected from twelve sites.

2MP samples were collected only once from two sampling sites while heavy metal samples were collected twice from five sampling sites in Agra.

3In both studies, MP and heavy metal samples were taken from four locations including Sangam as common location.

4MP sampling was done in fourteen sites of the Netravathi River whereas heavy metals were collected from ten sites.

5MP sampling was done in seven sites of the Ganga River whereas heavy metals were collected from nine sites.
in the databases. A summary of these studies is presented in Table 4. These studies have reported synthetic textiles to be the major source of MP fibres in the sampling locations while the presence of fragments, films and spheres has been linked with releases from fragmentation and disintegration of macroplastic debris. The transport of MPs due to the aeolian processes can play an important role in the contamination of terrestrial and aquatic environments. Understanding the importance of a healthy atmosphere in our lives, it becomes very important to do regressive research about MP prevalence, transport and fate in this domain. The number of studies conducted in India is very limited to justify the problem of atmospheric MP and thus require scientist’s and researcher’s interventions.

### Microplastics in terrestrial systems

With increased consumption of plastic items in our daily lives, their ageing and subsequent fragmentation leads to leaching of MPs in our terrestrial systems. The sources of these MPs can include mismanaged plastic waste, tyre wear and tear, fragmentation of construction and building materials, or aeolian transport of MPs from widespread sources (Patchaiyappan et al. 2020b). A summary of MPs detected in Indian terrestrial systems is shown in Table 5. The dust samples in these studies were collected from outdoor (Patchaiyappan et al. 2020b) and indoor (Zhang et al. 2020) systems, and significant abundance of MPs was found, indicating the ubiquitous reach of these particles. According to the study conducted by Zhang et al. (2020), the estimated ingestion of MPs originating from the dust samples in different age groups (adults, teenagers, toddlers and infants) is 770–10,000 ng/kg bw/day (PET-based MPs) and 0.88–11.00 ng/kg bw/day (PC-based MPs). Furthermore, it has also been indicated that human exposure to MP particles via this route is much more extensive in comparison to the consumable items. For instance, mussel consumption can cause an annual plastic consumption of 123 particles per capita and sea salt consumption can lead to ingestion of 0–36,135 MP particles per capita, but exposure to dust in homes can lead to a huge exposure of 13,731–68,415 particles per capita as suggested in some recent studies (Zhang et al. 2020; Peixoto et al. 2019; Catarino et al. 2018). Apart from this, in another study by Maity et al. (2020), the impacts of MP exposure were evaluated in a common terrestrial plant, i.e. *Allium cepa* (onion). This study has revealed cytogenotoxic impacts in *A. cepa* due to polystyrene MPs, indicating that the presence of MPs in our terrestrial environments has the potential to harm plant species as well as aquatic species, as discussed earlier.

### Table 4 Presence of microplastics in atmosphere

| Location                | Sampling technique                                                                 | Concentration of MPs | Type of MPs           | Reference                  |
|-------------------------|-------------------------------------------------------------------------------------|----------------------|-----------------------|----------------------------|
| Maharashtra (Nagpur)    | Collection by high-volume samplers using polytetrafluoroethylene (PTFE) filter paper | 50–120 items/day     | Fibre, fragment, film, sphere | Narmadha et al. (2020)     |
| East Indian Ocean       | Collection using a total suspended atmospheric particulate sampler                   | 0.4 item/100 m³      | Fibre, fragment       | Wang et al. (2020b)        |

### Table 5 Presence of microplastics in dust samples

| Location               | Location specification        | Sampling technique                                                                 | Concentration of MPs | Type of MPs          | Reference                      |
|------------------------|------------------------------|----------------------------------------------------------------------------------|----------------------|----------------------|--------------------------------|
| Tamil Nadu (Chennai)   | Outdoor street dust          | Collection by the quadrat method using paint brush, sterile paper & metal pan     | 2279.4 items/kg      | Fragment, fibre      | Patchaiyappan et al. (2020b)   |
| Bihar (Patna)          | Indoor house dust            | Collection using vacuum cleaner or direct sweeping using nylon brush              | 12 µg/g (free terephthalic acid–based MPs) | Fibre          | Zhang et al. (2020)            |

|                            |                              | 2000 µg/g (PET-based MPs)                                                        |                      |                      |                                |
|                            |                              | 0.71 µg/g (free bisphenol A–based MPs)                                           |                      |                      |                                |
|                            |                              | 20 µg/g (polycarbonate-based MPs)                                                |                      |                      |                                |
Presently, MPs are invading virtually every part of our environment but the extent of research conducted in India to evaluate the situation in terrestrial environments is very limited. It is important to scale up the research investigations in this area so that the current scenario can be better understood and necessary actions to manage this problem could be adopted at the earliest possible.

Microplastics in human consumables

Contamination of hydrosphere, atmosphere and lithosphere with MPs is now a well-established fact, but the extent of research interventions in these segments with reference to India is still a long way to go. The organisms inhabiting these systems are capable of consuming MPs, and their further interaction with humans imposes a significant risk of MP exposure to humans through ingestion or inhalation. The presence of MPs has recently been reported in various human consumables, viz. seafood, salt, drinking water and tap water in India, and this has attracted researcher’s attention towards MP pollution. However, the types of samples collected for MP analysis varied from study to study like, for salt sample, direct collection from the salt pans was done in one study (Selvam et al. 2020b) while majority of other researchers preferred purchasing commercial salt samples from the market or salt manufacturing unit (Sathish et al. 2020a; Sivagami et al. 2020; Seth and Shrivastav 2020). Sea food sampling involved a collection of organisms directly from their natural habitats (Daniel et al. 2021, 2020; Dowarah et al. 2020). On the other hand, for drinking water analysis, packaged bottles were procured from the markets.

Due to the extensive usage of plastics in food packaging industry, the expanse of MPs is gradually dominating in human consumable items. The contamination of sources from where these consumable items are being extracted is also emerging as a cause of concern as it may affect the MP abundance in these items. For instance, in a recent study by Nithin et al. (2021), it has been suggested that manufacturing of consumable items like table salts from groundwater instead of seawater could lead to lesser MP contamination.

In the present review, 11 studies have been found discussing the contamination and risk of exposure to humans by consumption of the items contaminated with MPs (Table 6). The risk of exposure was calculated by using the average dietary intake of that particular item and the amount of MPs present in the item. In a study by Sivagami et al. (2020), the harming potential of the MP particles to human embryonic kidney cells has been analysed and extreme conditions like cell

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Table 6: Presence of microplastics in human consumables

| Location                        | Consumable item                  | Concentration of MPs | MP size (µm) | Type of MPs                      | Estimated risk of exposure | Reference                  |
|---------------------------------|-----------------------------------|----------------------|--------------|----------------------------------|----------------------------|----------------------------|
| Kerala                          | Seafood (shellfish)               | 0.07 item/individual | 100 to 300   | Fragment, sheet, fibre           | 13 items/year              | Daniel et al. (2021)       |
| Pondicherry                     | Seafood (bivalve)                 | 0–10.8 items/individual | Less than 100 to 1500 | Fragment                       | 3917.79 items/year         | Dowarah et al. (2020)      |
| Kerala                          | Seafood (shrimps)                 | 0.39 item/individual | 157 to 2785  | Fibre, fragment, sheet           | –                          | Daniel et al. (2020)       |
| Tamil Nadu                      | Sea & bore-well salt              | 35–72 items/kg (sea salt) | 55 to 2000   | Fibre, fragment                  | 216 items/year (sea salt)  | Sathish et al. (2020a)     |
| Tamil Nadu                      | Sea & bore-well salt              | 2–29 items/kg (bore-well salt) |            |                                  |                            |                            |
| Tamil Nadu                      | Commercial salt                   | –                    | Less than 2000 | Fragment, fibre, sheet           | –                          | Selvam et al. (2020b)      |
| Supermarkets of India           | Commercial salt                   | < 700 items/kg       | 3.8 to 5200  | Fragment, fibre, pellet          | 1000 items/year            | Sivagami et al. (2020)     |
| Tamil Nadu                      | Bottled water                     | 2–6 items/L          | –            | Fibre, fragment                  | –                          | Ganesan et al. (2019)      |
| Kerala, Maharashtra & Gujarat    | Commercial sea salt               | 56–103 items/L       | 0 to 5000    | Fibre, fragment                  | 117 µg/year                | Seth & Shrivastav (2018)   |
| Supermarkets of India           | Sea, rock & lake salt             | 506 items/kg         | 100 to 5000  | Fragment, fibre, sheet           | 2000 items/year            | Kim et al. (2018)          |
| Maharashtra, Tamil Nadu & New Delhi | Bottled water                   | 3.72–826.00 items/L | 6.5 to greater than 100 | Fragment, fibre, film, foam, pellet | –                          | Mason et al. (2018)        |
| New Delhi                       | Tap water                         | 4.34 items/L         | 100 to 5000  | Fibre, fragment                  | 3000–4000 items/year       | Kosuth et al. (2017)       |
death of the exposed cells have been observed. This particular behaviour of cell detachment and apoptosis was observed after exposure of 24 h. In another study by Sharma et al. (2020), the toxic effects of MP behaviour were evaluated in terms of cancer risk to human beings. The researchers have reported that the potential of MPs to adsorb a variety of pollutants can aid in aggravated health issues, if such MPs are ingested. For this particular study, when MPs were interacted with carcinogenic polycyclic aromatic hydrocarbons (PAHs), maximum adsorption of PAHs was achieved within 45 min of interaction and the cancer risk estimated was found to be significantly higher for PAH-adsorbed MPs. The number of studies discussing the impact of MP ingestion or inhalation in humans in India is very limited; therefore, in order to better understand the health complications associated with these synthetic polymers, it becomes very important to scale up the MP research in this domain.

Conclusions and recommendations

India being one of the major producers of plastic waste is gradually pacing up its research in microplastics. At present, the role of India in global MP pollution is not well understood. This study is an effort to identify the gaps and knowledge about MP pollution in different compartments of Indian environment. The database is found to have 64 studies, which is a very small number in comparison to the widespread reach of MP particles. A major portion of MP studies in this dataset has focussed on the marine environments, majorly the south-east coast with the highest number of studies done in the state of Tamil Nadu. Also, sediment portion has been more researched upon for MP contamination within the marine systems. In case of freshwater systems, the river section comprises the highest number of studies in comparison to the lakes and groundwater counterpart. However, the complete understanding of sources, pathways and fate of MPs in these aquatic systems needs to be addressed by the research community. On the other hand, atmosphere and terrestrial systems comprised merely two studies each, which is an insufficient number to understand the extent of MP pollution in these domains for the entire country.

Contamination of different environmental compartments with MPs has widened their expanse to human consumable items as their origin is linked to these matrices. Salt, drinking water, tap water and seafood are the only items that have been looked upon for MP contamination in India while worldwide MPs are being detected in a wide range of food and beverage items. The toxicity associated with these MPs has not been extensively focussed, and at present, the situation of MP prevalence in Indian food and beverage items is not very clear. The exploration of mechanisms involved in MP-associated toxicity to humans as well as other organisms...
is a very important aspect to be looked upon, considering the role of plastic items in our day-to-day lives. In addition to this, it is also very important to explore the capability of MPs to interact with other pollutants present in the Indian environments and the enhanced health impacts they might impose to the interacting biota after ingestion or inhalation.

With the increasing demand and production of plastics, MP contamination will continue to rise and may therefore cause serious damage to our environment. It is very important in the present times to scale up the research investigations at both the laboratory and field scales, with equal focus on each and every component of different environmental matrices comprising marine systems, freshwater systems, terrestrial systems, atmosphere, human consumables and associated toxicities. Furthermore, innovations should also be directed to develop suitable techniques for the removal of these MPs from these matrices. The present review has focussed on the important aspects of MP contamination in different segments of Indian environments, and each section has been discussed with the significant knowledge inputs and lag areas. Future scope and recommendations have also been suggested to cover the gaps in knowledge which will provide directions for future studies and improve the scope of MP research in India (Fig. 3).

**Author contribution** All the authors’ have contributed in the conceptualization and designing of the marine articles. Literature search and data analysis were performed by Ms. Mansi Vaid and Ms. Komal Mehra. The first draft of the manuscript was prepared by Ms. Mansi Vaid and Ms. Komal Mehra. Critical analysis and revision of the work were done by Dr. Anshu Gupta.

**Funding** This study was funded by Guru Gobind Singh Indraprastha University (GGSIPU) under Faculty Research Grant Scheme (FRGS) and University Grants Commission under Junior Research Fellowship (JRF).

**Data availability** The datasets analysed during the current study are cited in the reference list with their respective digital object identifier (DOI) wherever possible.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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