Trends in Analytical Chemistry 133 (2020) 116071

Contents lists available at ScienceDirect

Trends in Analytical Chemistry

journal homepage: www.elsevier.com/locate/trac

Microplastics in different environmental compartments in India: Analytical methods, distribution, associated contaminants and research needs

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ARTICLE INFO

Article history:
Available online 22 October 2020

Keywords:
Microplastics
India
Standardized analytical methods
Sources
Transport pathways

ABSTRACT

This study aims at reviewing the scientific literature related to microplastic (MP) pollution in various environmental matrices in India and highlighting the research gaps for future research priorities. Currently used methods for sampling, extraction, identification, characterization and quantification of MPs were assessed, and sources, distribution, transport pathways, fate, impacts, chemical risks and MP-biota interactions in the marine and freshwater ecosystems of India were examined. Studies on the spatial and temporal transport pathways of MPs are very scarce, especially w.r.t. river discharge, anthropogenic activities, beach morphology, bottom topography, biofouling and hydrodynamics. Though some amount of baseline data of MPs at select regions along the Indian coast have been generated, the extent of MP pollution in air, major rivers and nearshore continental shelf is still poorly understood. Moreover, this study highlights an urgent need for the harmonized and standardized sampling and analytical methods for MP research, that can enable us to study the spatial and temporal comparisons around the world meaningful.

1. Introduction

With rapid industrialization, population growth and economic development, plastics are continuing to be introduced into the ocean via several pathways, and may potentially result in associated environmental, economic and health problems [1]. The global plastic production has increased from 1.5 million tons in 1950 to 359 million tons in 2018 [2] and part of these plastics (4.8–12.7 million tons) reaches the ocean through different pathways [3]. Many studies on plastic litter in the ocean were conducted since 1970s [4]. However, in the past few years, the research interest towards microplastic (<5 mm synthetic polymer particle, hereafter referred to as MP) pollution has been increased exponentially [5–7]. A more recent definition of MPs follows the logical differentiation along standard international (SI) unit nomenclature, that is, size of MPs = 5 mm to 1 μm [8]. MPs are a pervasive and persistent environmental contaminant, impinging on freshwater, terrestrial, and marine ecosystems across the globe [9–11]. There are two main classifications of MPs: primary MPs and secondary MPs. Primary MPs directly enter the environment in the microscopic size (<5 mm in diameter). Primary MPs are produced through extrusion or grinding, either as a feed stock for manufacture of products [12] or for direct use [13]. For example, in cleaning products [14], microbeads in cosmetics and as air-blasting media [15]. The secondary MPs are derived from fragmentation of larger plastic debris [14]. The issue of MPs in the marine environment is one among the major contaminants since marine organisms misidentify MPs as prey and can be toxic or even lethal to them when ingested [16]. Moreover, MPs act as vector for transferring

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https://doi.org/10.1016/j.trac.2020.116071

toxic chemicals (especially, persistent organic pollutants and metals) from environment to biota [17].

India has a long coastline of about 7500 km (including the islands) along the Bay of Bengal in the east and the Arabian Sea in the west. The exclusive economic zone (EEZ) of India encompasses nearly 2.5 million km^2 with a vast shelf area (0.13 million km^2). It has 13 coastal states and union territories. Indian coast is enriched with vast diversity of habitats, including mangrove forests, seagrass beds, coral reefs, sand dunes, wetlands, mudflats, and rocky and sandy shores [18]. The coast of India is under increasing threat from fishing, urbanization, industrialization, and the introduction of non-native species [19–22]. According to the Central Pollution Control Board, 62 MT of solid waste was generated in India in 2015; out of which 82% waste was collected and 18% litter; only 28% of the collected waste was treated, and the remaining 72% was openly dumped; open dumping cause surface water pollution due to leachate mismanagement and material uncontrolled flows. A visible impact that is affecting the seas and the oceans globally is the marine litter, caused primarily by the plastic waste [100]. Production, import and export of plastics in India have increased drastically over the past three decades to meet the demands of exponentially growing population of the country (Figs. S1a,b,c). Hence, it is prudent to assume that most of the plastics deposited in the nearshore region might have derived from the land-based sources in the past three decades.

Jambeck et al. [3] estimated that 4.8 to 12.7 million tons of land-based plastic waste has entered into the ocean. Of the top twenty countries releasing plastic waste into the oceans, ten have shores along the Indian Ocean, the third largest ocean. Moreover, it is estimated that between 1.15 and 2.41 million tons of plastic currently flows from the global riverine system into the ocean every year. Further, top 20 polluting rivers are located in Asia and accounted for more than two thirds of the global annual input. The River Ganges is considered in global modelling studies as the second largest contributor of plastic to the ocean [101]. There is a growing interest on the prevalence of MPs in different environmental matrices in India. The recent microplastic review articles and book chapters published in India are mainly dealing with only the ecotoxicological and environmental impacts of MPs [6,20,21,88–99]. Though a few review articles addressed the analytical methods of microplastic pollution in the Pacific, Atlantic, Artic, and Antarctic Oceans, no review has been conducted for the Indian Ocean. In that sense, this is the first review article evaluating the state of the currently applied analytical methods for identification and quantification of MPs in various environmental matrices (sediment, water, biota, atmospheric dust and salt) in India, and providing a harmonized guideline for future research priorities.

To assess the level of MP pollution in India at various environmental matrices, various sampling and analytical techniques have been adopted. However, due to inconsistency in these methods, the spatial and temporal comparisons are rather difficult. In this background, this paper aims at (i) summarizing the current state of knowledge concerning MPs in different environmental matrices in India, (ii) understanding the advantages and limitations in various MP sampling and analytical methods, (iii) discussing the distribution, sources and interaction between MPs-organic/inorganic pollutants and (iv) providing recommendations for the standardization and adaptation of accepted analytical methods from national to the global levels for effective MP pollution monitoring.

2. Data collection

The literature review was conducted through a bibliographical search in several databases such as Scopus, PubMed and ISI Web of Science. Research articles (published till May 30, 2020) were identified by searching records in English for the following terms: “microplastic(s)”, “plastic debris”, “India”, “Arabian Sea”, “Bay of Bengal”, “Indian Ocean”, “Sediment”, “water”, “biota”, “salt” “atmosphere” and “dust”. The retrieved articles were then screened by study area, and only studies pertained to India, including its beaches, estuaries, offshore, and atmosphere, were selected (Fig. S2, Table S1). Book chapters and review articles were excluded. A total of 41 research articles has been considered for this study (Fig. 1). We have attempted to summarize the following information: (i) sampling methods, (ii) MP extraction processes, (iii) identification techniques, (iv) abundance and characterization of MPs, and (v) Interactions between MPs and persistent organic pollutants/metals.

3. Sampling methods

The sampling methods used for MP data collection in sediment, water, biota, salt and atmospheric dust along the east and west coasts of India are summarized in Tables 1 and 2.

3.1. Sediment

The abundance of MPs in sediments from beach, coast, island and lake has been investigated from 24 articles. MPs in sediments from the beaches and coastal areas were generally collected by placing a metal or wooden frame on the sediment surface, pushing it to a depth of 1–5 cm, scooping out the material and taking the sample using a steel spoon or shovel. The different sizes of frames used in India are 25 × 25 cm, 30 × 30 cm, 50 × 50 cm, 100 × 100 cm and 200 × 200 cm; sampling depth varies from 0 to 5 cm; underwater sediment samples are collected using Van veen or Peterson grab sampler. No study has been conducted to collect core sediments for the establishment of vertical distribution of MPs. In some cases, MP pellets were collected using stainless tweezers or hand picking [51,52,64,83,86]. In most of the studies, sampling unit for MPs is reported as items/kg [31,36,40,42,44,46,47,58] or items/g [22,32], and in a few studies as items/m^2 [34,37,38,41,45].

3.2. Water

Seven studies investigated the occurrence and distribution of MPs along the Indian coast. The manta trawl nets of different mesh sizes, 112, 200, 300, 333 and 335 μm, were used in collecting samples from depths varying from 20 cm to 3–5 m. Eriksen et al. [23] used a high-speed AVANI (All-purpose Velocity Accelerated Net Instrument) trawl with rectangular opening 60 cm × 14 cm (4 m long net with 335 μm mesh size) and a manta trawl with rectangular aperture 16 cm × 61 cm (3 m long net with 335 μm mesh size) for MP sampling in the Bay of Bengal. A flow meter was attached in the mouth of manta trawl nets to estimate the volume of water sampled. However, some studies have not reported whether a flow meter was installed on the net, and substantial errors could be introduced by measuring only the distance during sampling if the net is not fully immersed or blocked by excess abundance of suspended and floating materials. If the net is fully immersed in water, it might not sample the surface layer which is likely to have large number of floating MPs. Moreover, sampling from windward direction or back of a boat also influences the quantification [24]. In most of the studies, the net was towed at a speed of 1–4 knot for 10–20 min. No effort has been taken to collect samples from waste water treatment plants to study the sources of MPs from waste water. The occurrence of MPs in water samples were expressed in units such as items/km^2, items/m^3 and

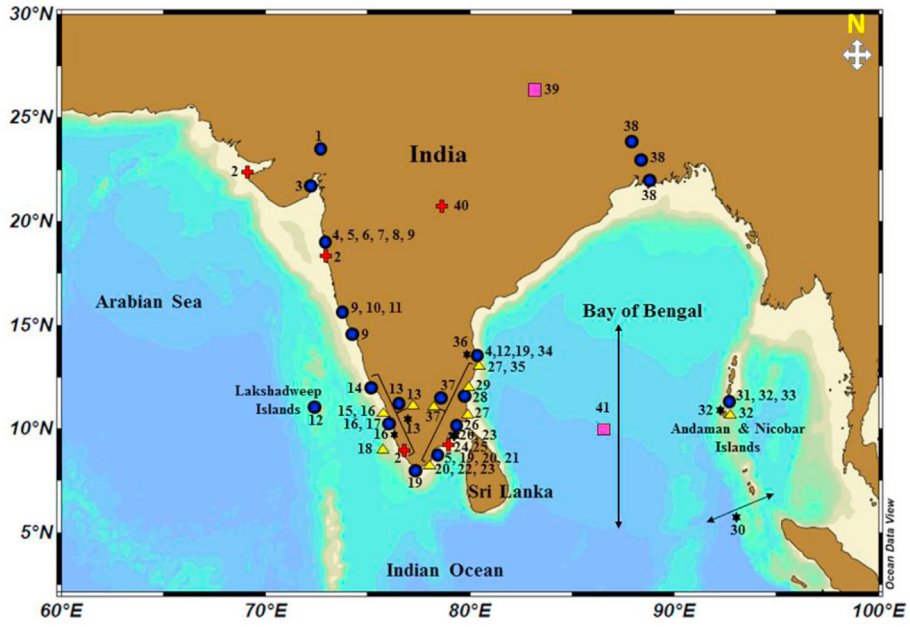

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Fig. 1. Map showing the microplastic concentrations in different environmental matrices reported along the Indian coast. Sediment (●), water (✱), biota (▲), salt (✚) and dust (■). 1. Ram and Kumar [84]; 2. Seth and Shriwastav [27]; 3. Reddy et al. [58]; 4. Ogata et al. [64]; 5. Tiwari et al. [42]; 6. Jayasiri et al. [37]; 7. Jayasiri et al. [85]; 8. Jayasiri et al. [65]; 9. Maharana et al. [38]; 10. Nigam [86]; 11. Veerasingam et al. [51]; 12. Mugilarasan et al. [83]; 13. Robin et al. [34]; 14. Ashwini and Varghese [36]; 15. Daniel et al. [87]; 16. James et al. [35]; 17. Sruthy and Ramasamy [41]; 18. Naidu et al. [56]; 19. Sathish et al. [47]; 20. Patterson et al. [46]; 21. Jeyasanta et al. [45]; 22. Kumar et al. [49]; 23. Sathish et al. [50]; 24. Selvam et al. [25]; 25. Sathish et al. [26]; 26. Vidyasakar et al. [39]; 27. Karuppasamy et al. [60]; 28. Dowarah and Devipriya [32]; 29. Dowarah et al. [54]; 30. Eriksen et al. [23]; 31. Patchaiyappan et al. [40]; 32. Goswami et al. [44]; 33. Krishnakumar et al. [43]; 34. Veerasingam et al. [52]; 35. Naidu [48]; 36. Ganesan et al. [59]; 37. Karthik et al. [33]; 38. Sarkar et al. [31]; 39. Zhang et al. [30]; 40. Kim et al. [28]; 41. Wang et al. [29].

items/L. Vessels of different types, sizes and speeds were used for sampling and data collection.

3.3. Biota

There are 11 studies, which addressed the issue of MPs in different aquatic biota (zooplankton, fish, shrimps, mussel, oyster, bivalves and invertebrates) from the field and laboratory investigations in India. Among these investigations, fish is the most commonly used biota (7 studies) to study the ingestion of MPs. Biota samples were collected using fishing nets, trawl nets, cages or hand collection. Biota samples bought from the market were also used. The collected biota samples were frozen at −20 °C until further analysis.

3.4. Salt

The presence of MPs in various brands of commercial salt available to consumers in Indian supermarkets was quantified in four studies. In Tuticorin, Tamil Nadu, 25 salt samples collected from different salt pans [25] and 14 different salt brands produced from seawater and bore-well water [26] were analyzed. Seth and Shriwastav [27] used 8 commercial brand salts manufactured from the west coast of India. Kim et al. [28] purchased three commercial brands of sea salts in Indian supermarkets.

3.5. Dust

Only two studies on the distribution of MPs in atmospheric dust have been investigated in India [29,30]. In the east Indian Ocean, atmospheric dust samples were collected along the ship track using the KB-120F type intelligent middle flow total suspended atmospheric particulate sampler with a sampling flow rate of 100 ± 0.1 L/min [29]. Zhang et al. [30] collected 33 indoor dust samples from the living rooms of Patna city in 2014 b y directly sweeping the floor with a nylon brush. Multiple dust samples were collected from each house/apartment and pooled as a single sample. After sampling, the dust samples were wrapped in aluminum foil, and stored in sealed containers. Dust samples were sieved through a 150 μm sieve, and samples below 150 μm in size were collected, homogenized and stored at 4°C until analysis. The field blanks were prepared by exposing aluminium foil to air during sampling (from three randomly selected bedrooms).

4. Microplastic extraction methods

After sampling, the segregation of MPs from sediment, water, biota, salt and dust samples was conducted in most of the published studies. The larger size MPs were examined visually and picked up using tweezers, whereas the small size MPs were extracted using density separation and filtration methods.

4.1. Sediment

The dried sediment samples were sieved with different size sieves. For example, 63 μm [31], 300 μm [32–34], 0.1 mm [35], 1 mm [36–38], 2 mm [39], 3 mm [40], and 5 mm [41,42]. In the density separation method, MPs were extracted from sediments using NaCl (9 studies), $ZnCl_2$ (4 studies), NaI (2 studies) and $CaCl_2$ (1 study). Digestion using 30% H_2O_2 was conducted in 11 studies before or after density separation to dissolve organic matter. After density separation and digestion, the supernatant was filtered through variable mesh size filter paper such as 0.4 μm [35], 0.45 μm [34,43], 0.7 μm [31,44], 0.8 μm [45–47], 1.2 μm [39] and 38 μm [42],

Table 1
Microplastic studies in various environmental matrices along the east coast of India.

S. No	Location	Sample type	Size	Shape	Polymer type	Abundance	Extraction method	Detection method	Reference
1	Ganga river	Sediment	<5 mm	Fibers, films, and foams	PET, PE, PP, PS	107.57 to 409.86 items/kg	Sieving; treated with H_2O_2; Density separation using $ZnCl_2$; filtration through 0.7 μm	Microscope and ATR-FTIR	[31]
2	Chennai	Sediment	2–5 mm	Pellets	PE and PP	304 (before flood), 896 (after flood)	Hand picking	Stereoscopic microscope and ATR-FTIR	[52]
3	Chennai and Sundarbans	Sediment	NA	Pellets	PE and PP	NA	Stainless steel tweezers	NIR	[64]
4	Tamil Nadu coast	Sediment	300 μm to 5 mm	Fragments, fibers, and foams	PE, PP, PS	1323 ± 1228 mg/m^2 (High tide); 178 ± 261 mg/m^2 (Low tide)	Sieving; Density separation using Sodium chloride; filtration	Stereomicroscope and ATR-FTIR	[33]
5	Chennai, Tuticorin, Tiruchenthur, Manapad, and Kanyakumari	Sediment	0.5–3 mm	Fibers, Fragments, and foams	Polyethylene (PE), Polypropylene (PP), Nylon (NY), polystyrene (PS) and polyester (PES)	439 ± 172 to 119 ± 72 items/kg in high tide; 179 ± 68 to 33 ± 30 items/kg in low tide	Sieving; Treated with H_2O_2; Density separation using Zinc Chloride; Filtration through 0.8 μm cellulose nitrate filter	Dissecting microscope, FTIR and SEM-EDS	[47]
6	Chennai	Sediment	2–5 mm	Pellets	NA	201 numbers	Hand picking	Stereoscopic microscope	[83]
7	Puducherry	Sediment	300 μm to 5 mm	Fragments, fibers, films, foams and pellets	PP, HDPE, LDPE, PS, polyurethane (PU)	72.03 ± 19.16 items/100 g	Sieving; Density separation using Sodium chloride; filtration	Microscope and Raman Spectroscopy	[32]
8	Rameswaram, Gulf of Mannar	Sediment	1.01–4.75 mm	Irregular shapes, Fibers, and Pellets	PP, PE, PS, NY, PVC	403 items	Sieving; Density separation using Zinc chloride; Treated with H_2O_2 and HCl; Filtration through 1.2 μm nitrocellulose filter paper	Stereo zoom binocular microscope and ATR-FTIR	[39]
9	Dhanushkodi and Tuticorin	Sediment	36 μm to 3 mm	Fibers, Granules and films	PE, PET (Polyethylene terephthalate), PS, PP, PVC (polyvinylchloride)	45 ± 12 to 181 ± 60 items/kg	Sieving; Density separation using Calcium chloride; Filtration through 38 μm mesh sieve; Treated with H_2O_2	Fluorescence microscopy, FTIR and SEM-EDS	[42]
10	Tuticorin, Gulf of Mannar	Sediment	0.5–3 mm	Fibers, fragment, and films	PE, PP, PES, polyamide (PA) and paint	8.22 ± 0.92 to 17.28 ± 2.53 items/kg	Treated with H_2O_2; density separation using NaI solution; filtration through 0.8 μm filter paper	Stereomicroscope, ATR-FTIR and SEM-EDS	[46]
11	Tuticorin	Sediment	0.05–5 mm	Fibre, film, fragment, and foam	NY, PE, PP, PS, PET, PVC	25 ± 1.58 to 83 ± 49 items/m^2	Sieving; treated with H_2O_2; Density separation using NaI; filtration through 0.8 μm	Microscope and ATR-FTIR spectroscopy	[45]
12	Andaman	Sediment	100 μm–1000 μm	Fragments, fibres, and spherules	PP, PVC	414.35 ± 87.4 items/kg	Sieving; treated with H_2O_2; Density separation using NaCl	Nile Red staining, microscope, and Raman spectroscopy	[40]
13	Port Blair Bay, Andaman Island	Sediment	<5 mm	Fibre, fragment, pellet	NY, PU, PVC	45.17 ± 25.23 items/kg	Sieving; treated with H_2O_2; Density separation using NaCl; filtration through 0.7 μm	Microscope and FTIR spectroscopy	[44]
14	Andaman and Nicobar Archipelago	Sediment	<5 mm	Irregular, Filament, film, pellet	PE, PP	73 to 151 items	Sieving; treated with H_2O_2 and HCl; Density separation using $ZnCl_2$; filtration through 0.45 μm	Microscope and FTIR spectroscopy	[43]
15	Chennai	Water	<5 mm	Fragment, fibre	PET, PA	2 to 11 items/L	Filtration through 0.45 μm cellulose nitrate filter paper	Microscope and FTIR spectroscopy	[59]
16	Port Blair Bay, Andaman Island	Water	<5 mm	Fibre, fragment, pellet	NY, PU, PVC	0.93 ± 0.59 items/m^3	Sieving; Density separation using NaCl; filtration through 0.7 μm	Microscope and FTIR spectroscopy	[44]
17	Bay of Bengal	Water	0.355–4.75 mm	Fragments, fibers, foams, films, pellets	NA	16107 ± 47077.63 items/km^2	Preserve with isopropyl alcohol; sieving	Microscope	[23]
18	Tuticorin, Gulf of Mannar	Water	0.5–1 mm	Fibers, fragments and films	PE and PP	12.14 ± 3.11 to 31.05 ± 2.12 items/L	Sieving, Treated with H_2O_2; density separation using NaI solution; filtration through 0.8 μm filter paper	Stereomicroscope, ATR-FTIR and SEM-EDS	[46]

19	Tuticorin	Water	150 μm to 5 mm	Fibre, fragment, film, foam	PE, PES, PS, PA, PP	3.1 ± 2.3 to 23.7 ± 4.2 items/L	Sieving; treated with H_2O_2; Density separation using NaI; filtration through 0.8 μm	Microscope and FTIR spectroscopy	[50]
20	Port Blair Bay, Andaman Island	Zooplankton	<5 mm	Fibre, fragment, pellet	NY, PU, PVC	MP occurrence found in 27 out of 30 zooplankton samples (i.e. 90%)	Digested with HNO_3; filtration through 0.7 μm	Microscope and FTIR spectroscopy	[44]
21	Port Blair Bay, Andaman Island	Fishes	<5 mm	Fibre, fragment, pellet	NY, PU, PVC	MP occurrence found in 33 out of 72 fish samples (i.e. 45.83%)	Digestive tracts were dissected and treated with KOH digestion	Microscope and FTIR spectroscopy	[44]
22	Southeast coast of the Bay of Bengal	Fishes	<5 mm	Fibre, film, pellet	PE, PET, PA	20 items found in 17 fishes	Gastrointestinal tracts were dissected and treated with KOH digestion	Microscope and FTIR spectroscopy	[60]
23	Fishing harbour, Chennai	Green Mussel	5–103 μm	Fibers and particles	PS	0.9 ± 0.3 items/10 g to 3.2 ± 3.2 items/10 g	Mussel tissues treated with HNO3; filtration through 5 μm filter paper	Microscope and Raman Spectroscopy	[48]
24	Pondicherry	Bivalves	<100 μm	NA	PU, PVC, PES, and PET	0.18 ± 0.04 to 1.84 ± 0.61 items/g; 0.50 ± 0.11 to 4.8 ± 1.39 items/individual	Soft tissues treated with KOH digestion	Nile Red staining, microscope, and Raman spectroscopy	[54]
25	Tuticorin, Gulf of Mannar	Oyster	0.25–5 mm	Fibers, fragments and films	PE and PP	5.21 ± 4.85 to 9.74 ± 8.92 items/ individual	Tissues treated with KOH digestion; KOI added; filtration through 0.8 μm nitrate cellulose filter paper	Stereomicroscope, ATR-FTIR and SEM-EDS	[46]
26	Tuticorin, Gulf of Mannar	Fish	0.5–1 mm	Fibers and fragments	PE and PP	Ingestion found in 12 fishes out of 40 fish samples	Digestion of intestinal content of fish with KOH; filtration	Stereoscopic microscope and FTIR	[49]
27	Tuticorin	Fishes	85 μm to 5 mm	Fibre, fragment, film, foam	PE, PS, PA	0.0002 ± 0.0001 to 0.2 ± 0.03 items/g; 0.11 ± 0.06 to 3.64 ± 1.7 items/individual	Digestive tracts were dissected and treated with KOH digestion	Microscope and FTIR spectroscopy	[50]
28	Tuticorin, Gulf of Mannar	Sea Salt	<2 mm	Fragments, Fibers, sheets	PP, PE, NY, Cellulose	NA	Treated with H_2O_2; incubation of 60 °C + 85 rpm for 24h; treated with NaI; Centrifuged	Stereo zoom microscope, μ-FTIR and AFM	[25]
29	Tuticorin	Sea Salt	<5 mm	Fragments, fibre	PE, PP, PS, PA	35 ± 15 to 72 ± 40 items/kg	Treated with H_2O_2; incubation of 65 °C for 24h; Centrifuged at 1900 rpm for 1h; filtered through 0.8 μm pore size cellulose nitrate filter	Microscope and FTIR spectroscopy	[26]
30	Tuticorin	Bore-well Salt	<5 mm	Fragments, fibre	PE, PP, PS, PA	2 ± 1 to 29 ± 11 items/kg	Treated with H_2O_2; incubation of 65 °C for 24h; Centrifuged at 1900 rpm for 1h; filtered through 0.8 μm pore size cellulose nitrate filter	Microscope and ATR-FTIR spectroscopy	[26]
31	Patna	Indoor dust	<5 mm	NA	PET, PC	55–6800 μg (PET); <0.11–530 μg (PC)	Treated with KOH and 1-Pentanol	HPLC-MS/MS	[30]
32	East Indian Ocean	Atmospheric dust	58.591–988.37	Fibers, fragment	PET, PP, PAN-AA, PR	0.4 ± 0.6 items/100 m^3	NA	Microscope and μFTIR spectroscopy	[29]

Table 2
Microplastic studies in various environmental matrices along the west coast of India.

S. No	Location	Sample type	Size	Shape	Polymer type	Abundance	Extraction method	Detection method	Reference
1	Sabarmati river, Ahmedabad	Sediment	75 μm to 5 mm	Fibers	NA	47.1 mg (MP size from 75 μm to 212 μm) and 4 mg (212 μm to 4 mm)	Sieving and density separation with NaCl	Microscope	[84]
2	Alang-Sosiya, Gujarat	Sediment	NA	Fragments, foams and fibers	PU, NY, PS, PES	81 mg items per kg sediment	Sieving, density separation using NaCl and filtration	FTIR	[58]
3	Narmada estuary	Sediment	0.1 μm to 5 mm	Fragments	PC, PA, PVC	5.8 ± 0.4 to 11 ± 1.0 m^2/g	Sieving; treated with H_2O_2	FTIR spectroscopy	[22]
4	Mumbai	Sediment	NA	Pellets	PE and PP	NA	Stainless steel tweezers	NIR	[64]
5	Mumbai	Sediment	36 μm to 3 mm	Fibers, Granules, and films	PE, PET (Polyethylene terephthalate), PS, PP, PVC (polyvinylchloride)	220 ± 50 items/kg	Sieving; Density separation using Calcium chloride; Filtration through 38 μm mesh sieve; Treated with H_2O_2	Fluorescence microscopy, FTIR and SEM-EDS	[42]
6	Mumbai	Sediment	≤5 mm	Fragments, fibers, foams, films and pellets	NA	194.33 ± 46.32items/m^2	Sieving	NA	[37]
7	Mumbai	Sediment	1–5 mm	Fragments, fibers, foams, films and pellets	NA	NA	Sieving	NA	[85]
8	Mumbai	Sediment	<5 mm	Pellets	NA	NA	NA	NA	[65]
9	Maharashtra, Goa, Karnataka	Sediment	1–5 mm	Fragments, fibres, films and pellets	PE, PP	43.6 ± 1.1 to 346 ± 2 items/m^2	NA	Microscope and FTIR spectroscopy	[38]
10	Goa	Sediment	3–5 mm	Pellets	NA	50 to 300/m^2	Hand picking	NA	[86]
11	Goa	Sediment	1–5 mm	Pellets	PE and PP	1655 (SW monsoon), 1345 (NE monsoon)	Hand picking	Stereoscopic microscope and ATR-FTIR	[51]
12	Tinnakkara Island, Lakshadweep	Sediment	2–5 mm	Pellets	NA	603	Hand picking	Stereoscopic microscope	[83]
13	Kerala coast	Sediment	0.3–4.75 mm	Fragments, fibers, foams, films, and pellets	PE, PP, PA, PS, PET, PUR, Rayan (RY), cellulose	40.7 ± 33.2 items/m^2	Sieving; Density separation using NaCl; filtration through 0.45 μm	Microscope and ATR-FTIR	[34]
14	Nattika beach, Kerala	Sediment	<5 mm	Fragments, fibres and films	PE, PP, PS	70.15 and 120.85 items/kg	Sieving and washing with ethanol	Microscope and ATR-FTIR spectroscopy	[36]
15	Kochi, Kerala	Sediment	1–5 mm	Fragments, fibers, pellets, foams, filaments and films	NA	10–70%	Sieving; treated with H_2O_2; Density separation using NaCl; filtration through 0.4 μm	Microscope	[35]
16	Vembanad lake, Kerala	Sediment	<5 mm	Fragments, fibers, foams and films	PE, PP, PS	252.80 ± 25.76 items/m^2	Sieving; treated with H_2O_2; Density separation using NaCl; filtration through 25 mm	Microscope and μ-Raman spectroscopy	[41]
17	Kerala coast	Water	0.3–4.75 mm	Fragments, fibers, foams and films	PE, PP, PS, RY, CE, PUR	1.25 ± 0.88 items/m^3	Sieving; Density separation using NaCl; filtration through 300 μm	Microscope and ATR-FTIR	[34]
18	Kochi, Kerala	Water	1–5 mm	Fragments, fibers, pellets, foams, filaments and films	NA	10–80%	Preserve with 4% formalin and sieving	Microscope	[35]
19	Kerala coast	Fishes	0.2–0.5 mm	Fibers, fragments and foams	PE, CE, RY, PP	Ingestion found in 15 fishes out of 70 fish samples	Isolation of digestive tracts; incubation in KOH solution	Microscope and ATR-FTIR	[34]
20	Kochi, Kerala	Fishes	0.27 mm–3.2 mm	Fragments, filaments, and pellets	PE, PP	Among the 653 samples, ingestion found in 4.6% of fishes	Digestive tracts were dissected and treated with KOH digestion	Microscope, μRaman spectroscopy and FTIR spectroscopy	[35]
21	Cochin, Kerala	Shrimps	0.25–5 mm	Fibres, fragments and sheets	PE, PS, PP, PA	0.39 ± 0.6 items/individual	Gastrointestinal tracts were dissected and treated with KOH digestion	Microscope and FTIR spectroscopy	[87]
22	Kochi, Kerala	Benthic invertebrates	<20 μm	Fragments and fibers	PS	NA	Dissecting the samples and clean with Milli-Q water	Microscope and μ-Raman spectroscopy	[56]
23	Kerala, Maharashtra, and Gujarat	Salt	500–2000 μm	Fibers and fragments	PE, PET, PS, PES, PA	56 ± 49 to 103 ± 39 items/kg	Treated with H_2O_2; incubation of 65 °C + 80 rpm for 24h; Centrifuged; filtered through 0.45 μm pore size cellulose nitrate filter	Microscope and μ-FTIR	[27]

and dried naturally or in oven for further examination under microscopic and spectroscopic techniques.

4.2. Water

The collected water samples were filtered or sieved for size selection in all seven studies. Density separation was conducted to extract the MPs from water samples using NaCl [34,44] and NaI [26,46], whereas 30% H_2O_2 digestion was used to remove the organic matter. The digestion was allowed to proceed for 12–72 h at room temperature to 75 °C. After density separation and digestion, the supernatant was filtered through filter papers of different mesh sizes, such as 0.7 μm and 0.8 μm. Then the filter papers were dried at room temperature to 55 °C and stored in petri dishes.

4.3. Biota

The frozen biota samples were thawed at room temperature, prior to examination. The length and weight of the biota were recorded. Full gastrointestinal tract of fish and shrimp samples, and soft tissues from the shell of mussel and bivalves were examined. Samples were digested with 10% KOH and 30% H_2O_2, followed by filtration with different mesh size filter papers (0.7 μm, 0.8 μm, 5 μm, and 11 μm) [44,46,48]. Then the filter papers were transferred to petri dishes and dried.

4.4. Salt

200–250 g of salt was mixed with H_2O_2 to digest the organic matter and the mixture was kept in the incubator at 65°C for 24h, and then at room temperature for 48h [25–28]. After organic matter digestion, 1 L distilled water was added to the sample to dissolve the salt. The solution was centrifuged, and the supernatant solutions of salt were filtered with various sizes (0.2 μm, 0.45 μm, 0.8 μm, and 2.7 μm) of filter paper. Then the filter papers were transferred to petri dishes and dried.

4.5. Dust

Dust samples collected from the city of Patna were weighed and mixed with KOH and 1-pentanol and this mixture was digested by heating (135°C for 30 min) [30]. Then the mixture was allowed to cool down at room temperature, and the pentanol solution was transferred into a 50 ml PP tube. The depolymerized products of PET and PC-based MPs were extracted from pentanol by shaking the PP tube at 180 strokes per minute for 5 min in an orbital shaker, followed by centrifugation at 1620g for 5 min. The upper organic phase of pentanol was transferred to another tube to which 20 ml of HPLC grade water was added, and the extraction was repeated. The aqueous layer that contained TPA and BPA was combined to a total volume of 50 ml with HPLC grade water. The processed final centrifuged solution was then transferred into an amber glass vial for HPLC-MS/MS analysis. However, Wang et al. [29] have not followed any digestion process for the dust samples collected from the east Indian Ocean.

5. Identification, chemical characterization and quantification of MPs

5.1. Visual inspection

In all the reviewed studies, visual inspection by naked eye or using a stereoscope/microscope is the most common quantification technique for MPs in various environmental matrices in India. Larger MPs can be sorted out directly, whereas small size MPs need further observation under microscope. The MPs were visually determined based on the homogeneous colour, brightness, and absence of cellular structures [27]. Some researchers have used visual identification coupled with confirmation of plastic presence (opposed to organic or inorganic material) by hot-needle test [26,45,47,49,50]. During visual identification and enumeration of MPs, Goswami et al. [44] used the following visual identification criteria: (i) no cellular or organic structure was observed, (ii) fibers were not segmented and did not appear as twisted flat ribbons, (iii) coloured particles were homogenously coloured, and (iv) particles that melted when heated by touching with a hot needle were considered plastics. Visual inspection is used to classify the MPs by size, colour, shape and allowing to infer their origin [51–53]. Though visual sorting is a time-saving method for enumeration of MPs, it can lead to either extreme over or underestimations of plastic content, based on the size ranges of plastics, as well as the risk of counting non-plastic particles as plastic.

5.2. Nile Red staining – fluorescence microscope

The Nile Red (NR) is found to be a promising staining protocol for identification of MPs. The dye adsorbs onto plastic surfaces and renders them fluorescent when irradiated with blue light. Fluorescence emission is detected using simple photography through an orange filter. Image-analysis allows fluorescent particles to be identified and counted. In India, NR staining fluorescence microscope technique was used to detect and quantify the MPs in sediments and bivalves [40,42,54]. Staining of MPs was carried out using NR dye with concentration of 10 μg/ml (in acetone). The NR solution was spread on the filter paper 30 min prior to observation. The filter papers were observed under a fluorescence microscope fitted with research-grade camera. The MPs were observed using blue excitation range 420–495 nm. The NR is a solvatochromic dye and its fluorescence emission is dependent on the polarity of the solvent, possibly allowing classification of MPs in large chemical groups based on fluorescent shift.

5.3. Fourier Transform Infrared spectroscopy

Fourier Transform Infrared (FTIR) spectroscopy is the most widely used method for identification and quantification of MPs [55]. FTIR spectroscopic technique has a long tradition in the analysis and characterization of MPs, offering the possibility of accurate identification of polymer types of MPs based on the characteristic fingerprint spectra of molecular vibrations. Among the 41 reviewed articles, FTIR technique was used in 80% of the studies to identify the polymer types of MPs in different environmental matrices (Tables 1 and 2). The mid-infrared region (400-4000 cm^{-1}) was the most used FTIR spectral region in MP research. Attenuated Total Reflectance (ATR) and transmission are the most popular modes of FTIR spectroscopy. ATR-FTIR technique was used to characterize the large size MPs (>500 μm) in sediments and water [26,33,34,36,45,47,50–52]. FTIR equipped with a confocal microscope (known as μ-FTIR imaging or chemical imaging) was used to identify the polymer types of small size MPs (<500 μm) in salt, dust and biota [25,27]. In addition to identification and characterization of MPs, FTIR technique was also applied to study the weathering pattern or aging of MPs using the carbonyl index values [51,52]. However, among the reviewed articles, FTIR spectral preprocessing and chemometric techniques have been mostly neglected in MPs analysis. Though FTIR is a promising technique to identify the polymer types of MPs, it has the following limitations: (i) FTIR spectra for MPs acquired from different modes are not the same, (ii) it is critical to investigate the effects of chemical

degradation on FTIR spectral bands of plastics before MP identification, (iii) a substrate is required to hold the particles in place during spectrum collection and the spectral interference of introducing a substrate filter has not been well addressed, (iv) MPs below 10 μm cannot be analyzed by FTIR technique, (v) irregular-shaped small size MPs would produce non-interpretable FTIR spectra due to refractive error, and (vi) FTIR is strongly active for water content, which produces broad peaks over 3000 cm^{-1}. Thus, the sample preparation is required prior to measurement [7].

5.4. Raman Spectroscopy

Raman technique (spectroscopy and microscope) is widely employed for the identification of polymer types of MPs, and it was used in 7 studies to identify MPs in sediment and biota along the east coast of India [32,40,54], wherein the spectra were obtained within the range of 200–3500 cm^{-1}. The μ-Raman (Raman imaging) technique was applied for scanning (with excitation wavelength of 532 nm) the MPs extracted from biota and sediment to characterize their polymer types along the west coast [35,41,56] and east coast [48] of India. Raman spectroscopy can detect MPs with a size of 1 μm and enables a simultaneous determination of particle number, size distribution, and morphological parameters [57]. Compared to FTIR spectroscopy, Raman technique has better lateral resolution (1 μm vs. 20 μm), and provides larger spectral coverage with highly specific fingerprint spectrum and lower interference from water. The drawback of Raman Spectroscopy is the weak intensity of Raman scattering, requiring relatively long acquisition times to achieve a decent signal to noise ratio. Though Raman microscopy is used to characterize the MPs (<20 μm), it is limited by weak signals, but can be overcome by increasing measurement duration and fluorescence interference, depending on material characteristics such as colour, biofouling and degradation. Considering that the Raman spectra of weathered MPs are prone to change and that there is no specific Raman database of weathered MPs, it is essential to build a spectral database of weathered plastics and use it when identifying unknown MPs in environmental samples [57].

5.5. Scanning electron microscope/energy dispersive X-ray spectrometer

Scanning electron microscope combined with energy dispersive X-ray spectrometer (SEM/EDS) is used to study the morphology, ageing and origin of the examined MPs as it provides the high-resolution data of surface state and the qualitative information about the chemical composition. In India, SEM/EDS technique was applied to characterize the MPs extracted from sediments [22,42,46,47,58], water [46,59], biota [46,50,60] and salt [26]. Though SEM/EDS is used extensively to characterize the morphology and elemental composition, it is a time-consuming and expensive method. Moreover, chemical characterization may be subject to a selection bias, since the isolation of the MP depends on the researcher's skill [61].

5.6. Atomic force microscope

Atomic force microscopy (AFM) provides images at nanometre resolutions, and AFM probes can be operated in both contact and non-contact modes with objects [62]. Selvam et al. [25] applied AFM technique to study the abrasion and weathering pattern (pits, fractures, flakes and adhering particles) of MPs extracted from commercial sea salts. Sharma et al. [22] studied the surface morphology of MPs (prepared from e-waste and sediments of the Narmada estuary, west coast of India) using AFM. They have also determined the adsorption capacity of the MPs and nature of binding affinity between polycyclic aromatic hydrocarbons and MPs. However, AFM has the following limitations: (i) it usually scans samples at relatively slow rates to acquire high-quality images, and (ii) the tip-sample interactions or the image-processing processes may introduce artifacts.

5.7. Thermogravimetry

Thermogravimetry (TGA) is a thermo-analytical method in which mass of the sample is monitored for its dependence on time or temperature while the temperature is programmed (isothermal or ramp) under a specific atmosphere (inert or air) [63]. In India, Sharma et al. [22] used TGA method to determine the thermal profiles of MPs extracted from the Narmada estuary. The thermogram of MPs extracted from the estuarine sediments was reported differently as it was indicating existence of different polymer compositions such as polyamides, polyvinylchloride and other polymers. TGA technique provides a quantitative analysis by monitoring the mass-loss of the MP during heating program. However, this technique requires labour-intensive cleaning and pre-concentration procedures before the analyses due to complexity of the matrix.

5.8. Chromatography

Gas Chromatography-Mass Spectrometry (GC-MS) is widely used to measure the dissolved or extracted polymer components of MPs, the adsorbed persistent organic pollutants (POPs) as well as organic plastic additives (OPAs) that may release from MPs [62]. Under international pellet watch (IPW) program, Ogata et al. [64] collected MPs in metropolitan Indian beaches (Chennai, Mumbai and Sundarbans) and quantified the concentration of polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) using GC-MS and Gas Chromatography – Electron capture detector (GC–ECD), respectively. Jayasiri et al. [65] estimated the bimonthly variability of persistent organochlorines in MPs from 4 beaches in Mumbai coast using GC–ECD. Zhang et al. [30] used a high-performance liquid chromatography (HPLC) interfaced with Electrospray triple quadrupole mass spectrometer (ESI-MS/MS) for accurate quantification of PET- and PC-based MPs in indoor dust samples at Patna city, and the results were compared with 11 other countries.

5.9. X-ray fluorescence spectrometer

X-ray fluorescence (XRF) spectrometer is used to determine the concentration of heavy metals in the MPs. Field portable XRF is a rapid and non-destructive spectroscopic technique to characterize the elemental composition of MPs. Heavy metal concentrations in 4 different polymer categories (PE, PP, PS and PA) from the beach sediments along the west coast of India (Kerala coast) were measured using field portable XRF by Robin et al. [34].

6. Current knowledge of MPs in different environmental matrices

6.1. Abundance and distribution

The MP concentration in sediment, water, biota, salt, and dust samples in India varies considerably. As summarized in Tables 1 and 2, the number of MP studies related to the east coast of India (ECI) were higher than those on the west coast. However, most of the studies were conducted only in the southeast part (especially in Tamil Nadu coast) of ECI, whereas along the west coast of India

(WCI), occurrence of MPs was reported mostly in the entire coastal stretch. It may be noted that the abundance of MPs in the surface sediments in the remote island (Andaman Nicobar: 973.3 ± 76.59 items/kg) [40] of Bay of Bengal was higher those found in the metropolitan city (Chennai: 439 ± 172 items/kg) [47] and major river (Ganga: 409.86 items/kg) [31]. In the west coast of India (Arabian Sea), the highest MPs abundance (220 ± 50 items/kg) was found in Mumbai [42]. Investigation of distribution of MPs in water along the east (4 studies) and west (2 studies) coasts of India showed that quantitative results of MPs are presented in different units (viz., items/L, items/km^2, items/m^3 and %) based on the approaches adopted in sampling. Therefore, it is difficult to compare those data. Along the east coast of India (ECI), the presence of MPs in the surface water along Chennai coast (2–11 items/L) [59] is lesser than those found in Tuticorin (12.14 ± 3.11 to 31.05 ± 2.12 items/L) [46] (3.1 ± 2.3 to 23.7 ± 4.2 items/L) [50]. In the offshore of Bay of Bengal, MP survey revealed that the concentration of MPs in the surface water is 16107 ± 47077.63 items/km^2), [23]. For biota, 'items/individual' and 'items/g' are the reporting units for MP abundance; fishes were abundantly used to investigate the ingestion of MPs in both east and west coasts of India (Tables 1 and 2). Along ECI, 30% of MP ingestion rate was found in the nearshore fish species at Tuticorin [49], whereas in the Island region (Port Blair) the MP ingestion rate was 45.83% [44]. Along WCI, 21% MP ingestion rate was found in fish species (Kerala coast) [35]. The concentration of MPs in sea salts was higher (56 ± 49 to 103 ± 39 items/kg) in the WCI [27] than in the ECI (35 ± 15 to 72 ± 40 items/kg) [26]. MPs of polyethylene terephthalate (55–6800 μg) and polycarbonate (<0.11–530 μg) in indoor dust samples was quantitatively determined in Patna [30]. The results of MP concentration in different environmental matrices from India were compared with studies from other countries using similar particle size ranges and methodology (Fig. S3 and Table S2). The results described herein show lower MP abundance, compared to those reported from the countries situated in the North Pacific Ocean. Unfortunately, a more comprehensive comparison between different studies was not possible due to the broad range of methodologies employed in the literature. MPs found in the Indian Ocean are originated from both land and sea-based sources. The number of major rivers discharging into the Bay of Bengal along the ECI is higher than those discharging into the Arabian Sea along the WCI. Two of the mega cities (Kolkatta and Chennai) are also situated along the ECI. Therefore, it is prudent to assume that the quantity of land-based MPs along the ECI is higher than that on the WCI. However, the marine traffic and shipping lanes are higher in the Arabian Sea than the Bay of Bengal. Therefore, it is expected that the higher level of sea-based MPs concentrations could be found in the Arabian Sea. The potential fishing activities are also one of the major sources of sea-based MPs in the Indian Ocean. The MP research studies conducted in India (Tables 1 and 2) confirmed that MP accumulated on the beaches, nearshore and offshore region, especially close to the river mouths, may be a matter of concern, due to its ability to enter into the marine food web, and highlighted the necessity of having long-term monitoring programs.

6.2. Physical characterization of MPs

In India, the observed MPs in various environmental matrices are fibers, fragments, pellets, films and foams. Fibers and fragments were the predominant shapes found among studies in both east and west coasts of India. The physical characterization of MPs indicates that most of the MPs found in India were secondary MPs (fragments, fibers, films and foams) than the primary MPs (pellets), which could be formed from the fragmentation of larger plastic items. In general, shapes of MPs are used to identify their origin [53]. The MP fibers are derived from the use of sea based deteriorated fishing gears (ropes, lines and nets) and land-based washing of synthetic fabrics, whereas films are originated from plastic bags and agricultural films. The foams are derived from both land (packaging containers) and sea based (thermocol buoys) sources. Along both ECI and WCI, the presence of primary MPs (pellets) was found to be higher in the beach sediments than in the water and biota. Fibers and fragments are the dominant shapes of MPs found in both water and sediment samples. In biota, fibers are the major types of MPs.

6.3. Polymer types of MPs and their weathering pattern

The polymer types of MPs in various environmental matrices were confirmed using spectroscopic methods in most of the reviewed studies. The abundant polymer types were polyethylene (PE), polypropylene (PP) and polyethylene terephthalate (PET), which is expected as these materials accounted for 74% of global plastic production (in 2015) and were commonly used in short life-cycle products [66]. Other polymers such as polystyrene (PS), polyvinyl chloride (PVC), nylon (NY), polyamide (PA), and polyurethane (PU) were also reported in some studies. Since the density of the dominant polymers (PE and PP) is lower than the seawater (1.02 g cm^{-3}), these polymers are distributed abundantly in the water and water associated biota. However, when the density of these polymers is increased due to biofouling activities, they sink in the sediment. The transportation and distribution of MPs in the water and sediment are subject to the prevailing hydrodynamic (wind, waves and currents) conditions [51,52]. The rate of weathering of MPs is influenced by the hydrodynamic condition, biofouling and UV light from sun. The surface morphology and physical characteristics of MPs have been assessed through visual examination and scanning electron microscope (SEM). SEM visualizes the surface cracks of an object with high resolution, and provides information to determine the weathering stages of MPs [42,46,47]. FTIR spectroscopy was used to assess the aging/weathering pattern of MPs based on their carbonyl index (CI) values. For example, based on the intensity ratio at 1715 cm^{-1} and 720 cm^{-1} in FTIR spectra of MPs from the east (Chennai) and west (Goa) coast of India, Veerasingam et al. [51,52] calculated the CI values to measure the light induced photo-oxidation in the environment. Sathish et al. [47] calculated CI values, based on the area ratio at carbonyl group (1715 cm^{-1}) and methylene group (2870 cm^{-1}), in MPs collected from five coastal areas in Tamil Nadu. Though many sophisticated analytical methods (including FTIR and Raman spectroscopy) are available to identify the polymer types of MPs, most of the studies conducted in India and other countries have used the visual identification method. However, there always exists a potential for bias during visual identification of MPs. The quality of visual identification depends on factors such as the experience of the analyst, sample matrix, shape and size of MPs. Therefore, in addition to visual examination, utilization of some spectroscopic instruments or other analytical methods to confirm the polymer types of MPs (especially for small items) is recommended.

6.4. Interactions between MPs and persistent organic pollutants/metals

Research studies have demonstrated that MPs absorb hydrophobic organic pollutants, concentrate them several orders of magnitude than the levels found in their surrounding environment, and therefore they could be potential vectors of these contaminants to biota [64]. Under the International Pellet Watch (IPW) program, the level of adsorbed organic pollutants (PCBs, DDTs and HCHs) in the beached plastic resin pellets in Mumbai, Chennai and

Sunderbans was assessed by Ogata et al. [64]. They found that the PCB concentrations in the MP pellets from India (especially in Chennai) were higher than those in the other tropical Asian countries. Jayasiri et al. [65] also confirmed that MP pellets from Mumbai beach adsorbed various cyclodiene compounds in addition to PCB, HCH and DDT. Recycling of electronic waste and poor management of ship-breaking activities were suggested as potential sources of PCBs in India [67]. Adsorption of charged metal ions to plastics that are inherently neutral may seem counterintuitive, but while suspended in the marine environment plastics acquire charge and a greater surface area through biofilm formation and precipitation and attrition of inorganic minerals [12]. Robin et al. [34] estimated the concentration of 16 trace elements in four different polymer types (PE, PP, PS and PA) of MPs along the Kerala coast. Among these MPs, the highest mean elemental concentrations of Br, Cd, Cl, Cr, Hg, Pb and V were recorded in the PE materials.

7. Plastic waste management and regulation in India

In India, the plastic waste management is governed by the Ministry of Environment and Forests and Climate Change (MoEF-CC), the Ministry of Urban Development (MoUD), the National Environmental Engineering Research Institute (NEERI), Central Pollution Control Board (CPCB), and State Pollution Control Boards (SPCBs) and ground level implementation responsibility lies with the urban local bodies [69]. Plastic waste management in India is a challenging task due to the generation of huge amount of plastic waste (mostly PE and PET); illegal dumping, infective legislation, shortage of infrastructure and reluctance in administration enactment add to these; its implications created mammoth challenges [70]. In India, people consume 50% of single-use plastics. In every household, plastic wastes account for more than 10% of the total wastes that produced every day [71]. Significant amount of waste is disposed off with an open dumping method in India, accounting for over 60% of the total municipal solid waste (MSW). In India, the following conventional waste disposal techniques are used: chaotic landfilling, indiscriminate dumping of wastes, and mass burning [72]. To strengthen the already existing regulations for handling plastics, 'Plastic waste management rules, 2016' was enforced in India, which ensure that plastics below 50 μm cannot be produced (Ministry of Environment and Forest, India, 2016). However, through further amendments in 2018, manufacturers are allowed to claim that their product does not violate the stipulated policy. There is still a lack of clarity on the enforcement of the rules laid out in 2018 b y the central government [71]. In Tamil Nadu (southern state of India), the single use of plastics is banned with effect from January 1, 2019 (Tamil Nadu Pollution Control Board, 2020). Similar proposal has come up in the state of Maharashtra [73]. At present, nearly 60% of recyclable plastic is recycled in India, most of it being down cycled. There is a lack of cohesion in the development and implementation of policies for the handling of single use plastics, although enforcement of a nationwide ban has been considered [74]. The recent development of regional action plan on marine litter for India [68] has highlighted the following strategies to manage the marine plastics: (i) identifying the sources of land and sea based plastic wastes and controlling at the origin itself, (ii) enhancing the public awareness of MP pollution through environmental education that informs behavioral change, (iii) creating the incentives and disincentives, and (iv) strengthening research and development.

The most direct and efficient method for mitigating the MP pollution is source control. In many developed countries (The USA, Canada, The Netherlands and New Zealand), the usage of microbeads (Primary MPs) in personal care products has been banned through relevant laws and regulations [75]. However, in many developing countries including India, it is yet to be implemented. The recycling of plastic waste will prevent the plastic waste entering the environment. In India, the disposable plastic products are inexpensive and easy to obtain, making them easy to discard into the environment. Therefore, the cost of disposable plastics should be increased. Moreover, the biodegradable eco-friendly polymers need to be developed for the replacement of traditional plastic materials. Above all, raising public awareness of the problems caused by MPs is an important task, as this will govern people's behaviour towards plastic consumption.

8. Challenges and recommendations

Over the past one decade, increased scientific interest has produced an expanding knowledge base for MPs, nevertheless, fundamental questions and issues remain unresolved. The inconsistencies in the sampling design and processing of MPs hinder our ability to examine the spatial and temporal patterns of this contaminants. Thus, it is important to develop an integrated and harmonized sampling and processing method for future investigation. To assess the level of MP (items/m^3) in freshwater and marine water, net sampling is an ideal method, which is a time saving method with the advantages of covering large sampling areas and reducing the water volume of samples. The usage of different net aperture size, trawling speed and duration has hampered inter-study comparison. The net aperture size plays a major role in the calculation of abundance of MPs - higher abundance was observed in the use of a smaller mesh size. Therefore, trawling with a 333 μm mesh size at a speed of 3–4 knots for 30 min is recommended for surface water sampling [76]. The abundance of MPs in sediments did not vary with the type of sampling equipment used. Therefore, shovel, grab sampler and box corer can be used to collect sediments from beaches, coastal and marine environments for the assessment of MP abundance (items/kg) in sediments [77]. Vertical distribution of MPs in sediment cores have not yet studied in India. For the assessment of MPs in biota (items/individual), most organisms were either captured in the field by bottom trawling or directly bought from markets/aquaculture farms. MPs in the atmospheric dust could be collected using active and passive sampling methods. However, passive sampling (total or bulk deposition samplers) is ease of use, methodology standardization and no requirement for power to the study site [30]. Airborne fibers can cause considerable overestimation of MPs in all environmental matrices (water, sediment, biota, salt and dust). Therefore, it is important to check the background MP contamination during sampling and laboratory handling processes. Density separation is an important method to extract the MPs from sediments prior to chemical digestion. NaCl solution is commonly used in density separation method due to its eco-friendliness and inexpensiveness, but it underestimates MP particles with densities higher than 1.2 g cm^{-3}. Therefore, NaI solution is advised for density separation process instead of NaCl and $ZnBr_2$ [78]. Based on this review, we have suggested a standardization in MP sampling and laboratory procedures (Fig. 2). In addition to standardization of microplastic sampling methods, researchers must adopt strict contamination control measures during sample processing and analyses in the laboratory. In order to obtain reliable MP data, the following control measures need to be considered during MP analyses: (i) wearing cotton lab coat, (ii) using cleaned laminar flow hood, (iii) using materials made of glass or metal and avoiding plastic, (iv) all working solutions must be filtered and kept in closed glass bottles, (v) using high quality filters (glass fibre filters), (vi) all solutions and materials need to be covered with aluminum foil or glass lids, (vii) using field blanks, procedural blanks and open filters to control deposition of MPs from air [79].

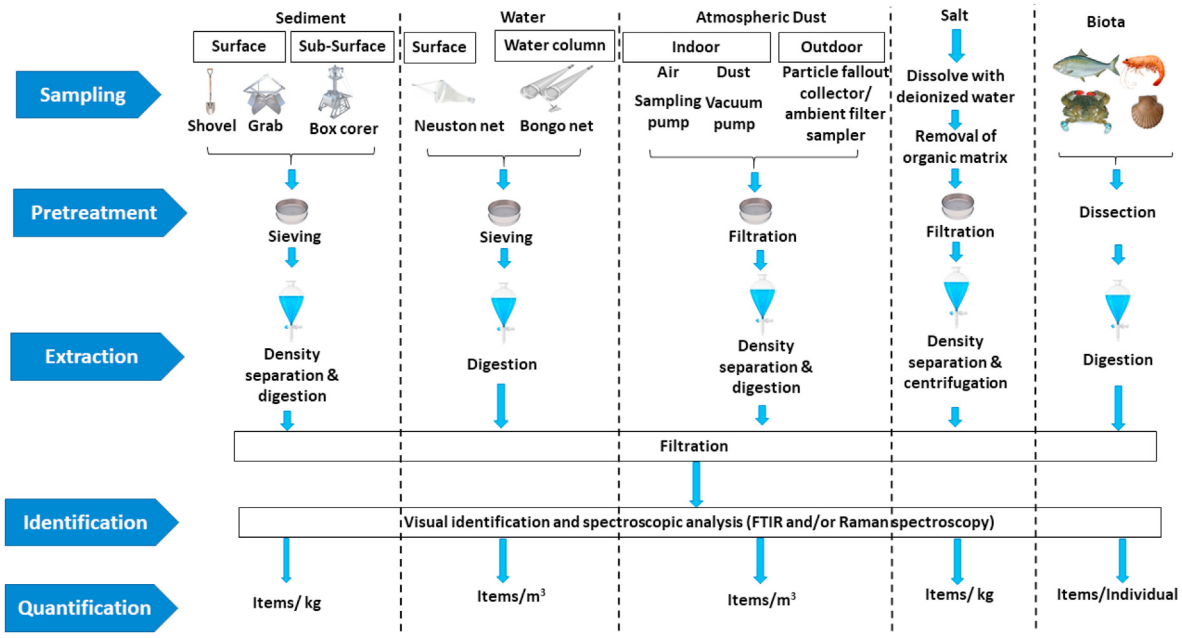

Fig. 2. Recommended sampling and analytical methods for MP in various environmental matrices.

9. Conclusions

The current knowledge of MPs in various environmental matrices along the east and west coasts of India is predominantly based on the studies conducted in the last one decade. The adaptation of different methodologies for sample collection, preprocessing and analytical methods makes direct comparison of concentration of MP values in various environmental matrices quite futile. Moreover, in none of the 41 articles on MP studies in India, the quality control and quality assurance in MP analysis are given. Therefore, in this review, we have suggested standardized definition for size of MPs [8] and standardized protocols for monitoring MPs in sediment [80], water [81] and biota [82] to overcome some of the challenges identified in MP research globally, and in India in particular. Research gaps in understanding the sources, fate, transport pathways, toxicity of MPs and their associated persistent organic pollutants and metals in the aquatic environment still exist. Though the land derived plastic waste through rivers is affecting the marine environment significantly, even the distribution of baseline level of MPs in the major rivers along the east and west coasts of India is yet to be studied. In addition, contribution of waste water treatment plants (WWTPs) to regional MP pollution needs to be studied. The vertical distribution of MPs in core sediments needs to be studied to establish the level of historical MP pollution trends in coastal, estuarine and marine environment. We have also proposed the use of mussels as target species to monitor MPs and call for a uniform, efficient and economical approach, which is suitable for a large-scale monitoring program in the freshwater and marine water systems of India. To understand the fate and transport pathways of MPs in coastal and marine environments, a new 3D numerical modelling framework is proposed. Since the major Indian metropolitan cities are affected by air pollution severely, it is also important to assess the level of MPs in the atmospheric dust for risk estimation. Though globally considerable progress has been made in the past few years in toxicological effects of MPs, our understanding of these compounds and their associated contaminants in Indian water bodies, especially in freshwater, is relatively incomplete and that provides opportunities for future research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This work is part of the joint Indo-Russian research project, entitled “Identification and modelling of microplastics transport in the coastal areas under the influence of dominant wind patterns”. It has been funded by Department of Science and Technology through the Grant INT/RUS/RFBR/P-339, India, and Russian Foundation for Basic Research (RFBR), Russia through Grant RFBR.No.18-55-45024. Qatar University authors were supported by the project funded by the Qatar Petroleum (QUEX-ESC-QP-TM-18/19). Open Access funding provided by the Qatar National Library.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trac.2020.116071.

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