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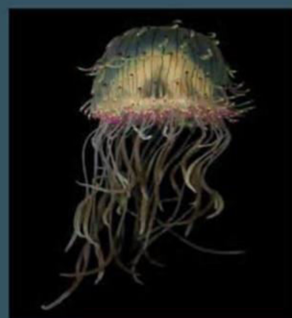

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Microplastic Pollution in India's Marine and Inland Environmental Matrices: A Comprehensive Review

Rebecca Cathrine Jayakumari D.[1], Deborah Anne Rose N.[1], Sheeba Anitha Nesakumari C.[2], Mahesh T.C.[3], Saravanan R.[1] and Thirunavukkarasu N.[1]*

[1]Department of Zoology, Dr. Ambedkar Government Arts College (Autonomous), Vyasarpadi, Chennai, Tamil Nadu, India
[2]Department of Zoology, Madras Christian College (Autonomous), Tambaram, Chennai, Tamil Nadu, India
[3]Department of Zoology, Vivekananda College, Agasteeswaram, Tamil Nadu, India

**Corresponding Author*

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Abstract: Microplastics (<5mm) are plastic particles that either originated directly or formed because of larger plastic particle degradation. These microplastics (MPs) eventually enter the terrestrial, aquatic, and atmospheric environments, leading to microplastic pollution. MP pollution is an emerging global environmental issue, with India being no exception. This review paper discusses the occurrence of the infiltration of microplastics into Indian sediments and water bodies, the ingestion of microplastics by fish and other aquatic organisms, and the resulting ecotoxicological implications. The main prospect is to determine the abundance and distribution of microplastics in various locations in India and the methodologies used in sampling, quantifying, and identifying this microplastic debris. The primary objective of this review was to offer more valuable insights into the already existing literature, identify key findings and identify research gaps. This will be helpful for future research in the field of microplastic pollution in India.

Keywords: Microplastics, Environmental matrices, Sediment pollution, Water contamination, Fish bioaccumulation

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Introduction

In 1907, Bakelite discovered truly synthetic plastic resins that revolutionized material making global trade. Since then, there has been no cessation in the manufacturing and utilization of plastics and its byproducts. Plastic pollution is a result of poorly managed plastic items and because of their long-lasting characteristics they have a detrimental impact on Earth's environment. In the late 1960s, researchers conducting plankton studies were the first to document the occurrence of plastic pollution in the ocean. The very first ever identification of plastic particles such as polystyrene spherules in the digestive tracts of fishes' dates backs to early 1970s (Carpenter *et al.*, 1972). Later, researchers called this emerging plastic pollution issue as a worldwide oceanic problem (Coleman and Wehle, 1984). In 2018 UNEP (United Nations Environment Programme) recognized the world's ocean plastic pollution as an international environmental issue.

Microplastics are basically plastic particles between 5 mm and 1 µm in size (GESAMP, 2015). They can be categorized into primary and secondary based on their origin, with secondary microplastics formed when larger plastics break down, and primary microplastics released directly from the sources like personal care products, textile fiber shedding etc. (Arthur *et al*., 2008). Microplastics were first discovered as aquatic pollutants in marine environments in 1972 and have since become a global concern due to their potential negative impacts on ecosystems and human health. In this review, a bibliographical search was used to collect pertinent research across several databases, including ScienceDirect, Google Scholar and ResearchGate.

Plastic pollution in India:

India's yearly production of plastic currently stands at an astonishing of 9.46 million metric tons, thereby resulting in an impressive 25,490 per capita. Notably, the production of plastic waste in India has undergone a fourfold increase within the past five years. The pandemic has played a significant role in the substantial surge of plastic manufacturing, particularly in the domains of Fast-Moving Consumer Goods (FMCG), the e-commerce industry and food delivery services (Recykal, 2022). Due to India's swift industrialization, population expansion and economic progress, it has become the second-largest consumer of plastic on a global scale.

India exports a yearly aggregate of 59,260 tons of plastic waste, amounting to 0.8% of its overall waste, while simultaneously importing 98,860 tons of plastic waste, accounting for 1.33% of its total waste (Hossain *et al.*, 2022; Feiyi Li *et al*., 2023). The Central Pollution Control Board (CPCB) reports that only 60% of plastic waste goes through the recycling process. The remaining waste frequently finds its way into landfills, rivers, and oceans, thereby imparting irrevocable harm upon the environment and marine organisms. This extensive plastic pollution carries dire repercussions, impacting both human well-being and the ecological system.

Microplastic status in India:

It was expected that in 2023 India will be responsible for releasing an average of 3,30,764 tons of microplastic into waterways. In addition, additives are used in the manufacture and processing of plastic, which can have detrimental effects. It was anticipated that in 2023, plastic waste mismanagement in India will result in the release of 44,535 tons of pollution from chemical additives into the waterways (Feiyi Li *et al*., 2023). The complete measurement of microplastic contamination and its resulting effects in India have not yet been entirely determined. The primary objective of this investigation was to tackle this issue by evaluating the prevalence, dispersion, and attributes of microplastics in various environmental matrices.

Detection methods of Microplastic in Indian Environment:

In India, the first study of the origin of plastic pellets in the marine environment was reported in 1982 (Nigam, 1982). Several studies investigated the presence of microplastics in various water bodies (Sruthy and Ramasamy, 2017), sediment (Sarkar *et al*., 2019) and biota (Naidu *et al*., 2018; Daniel *et al*., 2020) throughout India in the past decade. Microplastic samples were collected and prepared using various methods depending on the environmental matrix. MPs in the environment are mainly characterized using physical and chemical methods. Physical characterization classifies MPs based on morphology, size and color (Utsav *et al.*, 2018), while chemical characterization distinguishes MPs from other natural materials in the sample. These methods are combined to create a wide range of MP spectra in one sample.

For identifying MPs, spectroscopic techniques are commonly used in India. These techniques include Raman spectroscopy (Dowarah and Devipriya, 2019), Fourier transform infrared micro spectroscopy (Sarkar *et al*., 2019), scanning electron microscopy with energy dispersive x-ray spectroscopy (Tiwari *et al*., 2019) followed by pyrolysis gas chromatography coupled to mass spectrometry (Sivasankar *et al*., 2023). Globally there are many other methods for analyzing microplastics in complex environmental matrices including CHN analyzers, optical microscopy, densitometry, differential scanning calorimetry, hyperspectral imaging (Verla *et al*., 2019, Vitor *et al*., 2020). Since they are environmental samples, these MPs undergo degradation processes due to continuous exposure to various stresses, altering their spectral signature. This can be resolved by matching the spectral signatures in an open-source spectral library with a higher degree of competency and completeness (Zhang *et al*., 2017).

Microplastic in Sediments:

The investigation of the presence of MPs in sediments from various geographical locations such as beaches, coasts, islands and lakes has been extensively explored in more than 25 articles conducted throughout India (Tables 1, 2). The variation of microplastics presence in coastal sediment is contingent upon the extent of urban development (the influx of waste from residential materials, sewage treatment facilities, and rivers into the ocean), the process of incineration, the operation of landfills, tourism and industrial waste disposal (Sathish *et al*., 2019). Also, the level of abundance and the spatial arrangement of these MPs are heavily influenced by numerous factors, mainly the direction of winds and ocean currents, seasonal variations, beach characteristics and the local geomorphological features along the coast (Gopinath *et al*., 2020). Furthermore, the combined effects of wave action, longshore drift, mixing and layering of saline and freshwater, as well as the morpho dynamic state of beaches, are also crucial factors that can significantly impact both the spatial and temporal distribution patterns of MPs (Veerasingam *et al*., 2016; Tiwari *et al*., 2019).

Sediment Sampling:

The detection of microplastics in sediment samples can be achieved using different approaches. For example, sediment samples can be directly gathered with forceps or collected using sieving methods. Generally in India, MPs from the sediments are collected by positioning a metallic or wooden framework atop the sediment surface, typically spanning from 25 x 25 cm to 100 x 100 cm (Dowarah and Devipriya, 2019; Sathish *et al*., 2019, 2020c; Ashwini and Varghese, 2019; Jeyasanta *et al*., 2020b; Maharana *et al*., 2020; Robin *et al*., 2020). These frameworks are then inserted to a depth of 1 - 5 cm and a steel spoon or shovel is used to facilitate the extraction process. Certain researchers have even utilized specialized equipment like the grab sampler, box corer, Van Veen grab (Srinivasalu *et al*., 2021), or Peterson grab sampler to collect the sample.

Extraction Methods:

Dissimilarities in density can be utilized in the process of segregating plastics; thus, for the dried sediment samples sieves of different sizes ranging from 1 mm up to 5 mm were used (Ashwini and Varghese, 2019, Patchaiyappan *et al*., 2020).

Sodium chloride (NaCl) is the most used salt for density separation, accounting for 65% of studies. Its low cost and environmental friendliness make it a popular choice (Miller *et al*., 2017). However, some polymers, like polyester, PVC, and PET, have higher density than NaCl, making this method unsuitable. To increase recovery rates, some authors have explored higher density salts such as calcium chloride, zinc bromide ($ZnBr_2$), zinc chloride ($ZnCl_2$), sodium iodide (NaI), sodium bromide (NaBr) (Tiwari *et al*., 2019, Sathish *et al*., 2019; Patterson *et al*., 2019, 2020). The remaining organic matter was dissolved using H_2O_2 in some studies (Sruthy and

Table 1: Microplastics in sediments along the Eastern region of India

S. No.	Location	Sediment type	Size	Color and Shape	Abundance	Polymer Type	Detection method	Author and Year
1.	Odisha coastal beaches	Beach sediment	500 to 1000 µm	Colors: white, transparent, red/orange, blue Shapes: Fragments, Fibers and Spherules	258.7 ± 90.0 particles/kg	High Density Polyethylene, PS, PVC, and acrylonitrile copolymer	Fluorescent microscope, Raman spectral analysis	Patchaiyappan, *et al.* (2021)
2.	Brahmaputra river	River sediment	150 µm to 5 mm	↑Dark, transparent, multicolor, white, red ↑Fragments, Fibers and beads	20-24 MP/kg dw	PE, PP, PA, PTFE, PVC, PS	Microscope FTIR and SEM	Tsering *et al.* (2021)
3.	Indus river	River sediment	150 µm to 5 mm	↑White, transparent, dark, multicolor, red ↑Fragment, fiber	60–340 MP/kg dw	PE, PP, PA, PS	Microscope, µFTIR and SEM	Tsering *et al.* (2021)
4.	Golden Beach of Puri, Odissa	Dry beach sediment	-	white, red, black, blue, green and transparent ↑Fragments, foams, fibers, films, microbeads and pellets	731±719 particles/kg	HDPE, LDPE, Polyurethane, PP, PS, Nylon, Ethylene-Vinyl Acetate	Stereomicroscope, ATR-FTIR	Singh *et al.* (2022)
5.	Ganga river	Both dry and wet sediment taken	<5 mm	Fibers, foams, and films	107.57 to 409.86 items/kg	PET, PE, PP and PS	FT-IR analysis	Sarkar *et al.* (2019)
6.	Chilika Lake	Lake sediment	<1 mm	Fragments and foams	25.2 ± 9.8 items/kg to 7 ± 2.2 items/kg	polypropylene and polystyrene	SEM and spectroscope	Singh *et al.* (2023)
7.	Beaches of Chennai	Beach Sediment	-	Fibers were dominant	302.7 items/kg)	PE and PP	SEM, FTIR and EDS	Ranjani *et al.* (2022)
8.	Tamil Nadu (Kanyaku-mari)	Sediment	< 5 mm	Fibre, fragment	6860 items/kg	-	-	Sundar *et al.* (2021)
9.	Rameswaram, Gulf of Mannar	Surface sediment	1.01 – 4.75 mm	White colored irregular shapes, fibres and pellets	Apprx.403 items	PE, PP, PVC, and PS	FTIR and SEM	Vidyasakar *et al.* (2018)
10.	Puducherry	Beach	300 µm-1 mm	Fragments are dominant	72.03±19.16	PP, LDPE, HDPE,	Raman	Dowarah

		Sediment		White colored MPs were abundant	microplastic particles/100 g	PS, PVC	spectroscopy	and Devipriya (2019)
11.	Kodai-kanal Lake	Surface sediment core sediment	3-5 mm	Fibres, Foams and Fragments	PE, PP, PS, PET	28.31 ± 5.29 items/ kg 25.91 ± 7.11 items/ kg	Microscope ATR-FTIR, and SEM with EDAX	Laju *et al.* (2022)
12.	Cove beach, Quarry beach and Wandoor beach	Beach sediment	-	Fragments, pellets, foams and fibres Transparent MPs were abundant	Highest in Wandoor beach 249.82 ± 105.78 particles kg^{-1}	HDPE, PS, PP, PET	FTIR	Mohan *et al.* (2022)
13.	Silver beach, Cuddalore	Beach sediment	> 2 mm	White-colored (44%) and irregularly-shaped (82%) plastics were prevalent	-	PVC, PE, and nylon	FT-IR spectroscopy	Vidyasakar *et al.* (2020)
14.	Andaman and Nicobar Archipelago	Surface sediment	<5mm	Fiber, fragment, and pellet	45.17 ± 25.23 particles per kilogram	Nylon, PU, PVC	Microscope and FTIR spectroscopy	Goswami *et al.* (2020)
15.	Central East coast of India	Shelf sediment	<1 mm	Mostly blue coloured. Fragments were dominant	209 ± 99 particles. kg−1 of dry weight	Polyolefin (polyethylene and polypropylene) Were dominant	Stereomicroscopy, Raman spectroscopy, and micro Fourier Transform Infra-red Spectroscopy	Sambandm *et al.* (2022)
16.	Thoothukudi	sediment	0.5 – 5mm	Blue was dominant followed by green, white and red Fragments, fibre, irregular foam, and film	32 ± 26 to 232 ± 229 items/kg	PE, PP, PS, PET, PA	ATR-FTIR	Keerthika *et al.* (2022)
17.	River Noyyal, Tamil Nadu	River sediment		foams, films, fragments, and fibre	-	PS, Polycarbonate, Nylon, PVC	SEM	Crispin and Parthasarathy (2023)

Table 2: Microplastics in sediments along the Western region of India

S. No.	Location	Sediment type	Size	Color and Shape	Abundance	Polymer Type	Detection method	Author and Year
1.	Mumbai	mixture of beach sand and dry sediment	36 mm to 3 mm	Granules, fibres and films	220 ± 50 items/kg	PE, PS, PP, PVC (polyvinyl Chloride) and PET	Fluorescence microscopy, FTIR and SEM-EDS	Tiwari *et al.* (2019)
2.	Lonar lake, Maharashtra	Lake sediment	0-5mm	↑Transparent, green, black, yellow, red, and white ↑Fragment, Film, Filament, Bead and Foam	14.44 particles/kg	↑PP, PE, HDPE, PVC, SRG	FTIR-ATR	Gosavi and Phuge (2023)
3.	Maharashtra, Karnataka, and Goa	Sandy beaches sediment	~1–100 mm	↑White, pale-yellow, transparent and red. ↑Fragments and pellets.	19±1–346 ± 2 items/m²	PP and PP	FT-IR analysis	Maharana *et al.* (2020)
4.	Veraval Chowpatty, western coast of Gujarat	Beach Sediment	2 - 4 mm	Transparent, white, green, brown ↑Foam, Fiber, Fragments, pellet, and film.	3.83 to 11.83 pieces per 100 g of dry sediment	-	stereo-zoom digital microscope	Kumar *et al.* (2023)
5.	River Sharavathi, Karnataka	Riverine sediment	↑0.3–1 mm, 1–5 mm	↑ Transparent, white, green, brown Fragments, films, foams, and fibres	2.5 to 57.5pieces/kg pre monsoon 0 to 15 pieces/kg Post monsoon	PE, PET, PP	stereo zoom microscope FTIR-ATR	Amrutha *et al.* (2023)
6.	Kerala	Beach sediment	0.3–0.6 mm	Fragments, fibre/line, and foam	40.7 ± 33.2 particles/m²	PE, PP, PA	FTIR-ATR	Robin *et al.* (2019)
7.	Kerala (Nattika Beach)	Beach sediment	-	↑White, colorless, black. Fragment, fibre, film, bead, and pellet	70.15 items/kg (2017) 120.85 items/kg (2018)	PE, PP, PS	FTIR	Ashwini and Varghese (2019)
8.	Alang- Sosiya, Gujarat	Intertidal sediment	-	Fragments, fibres and foams	81 mg items per kg sediment	PU, Nylon, PS, PES	FTIR	Reddy *et al.*, 2006
9.	Sabarmati River, Gujarat	River sediment	75–212µm 212–4 mm	-	134.53 mg/kg 581.706 mg/kg	-	Gravimetric analysis and SEM	Patel *et al.* (2006)
10.	Mangalavanam mangrove ecosystem, Kerala	Air-dried sediment	1 µm - 5000 µm	↑Black, Transparent, Red, Green, yellow and blue ↑Fragments, Foam, Fibre, Sphere	1275 ± 532 particles/kg d.w.	PE, PP, PVC.HDPE, PE,1-octene copolymer, Polypropylene isotactic	Raman spectroscopic analysis	Kannankai *et al.* (2022)

(↑* indicates higher availability/more prevalence of that specific type of microplastic)

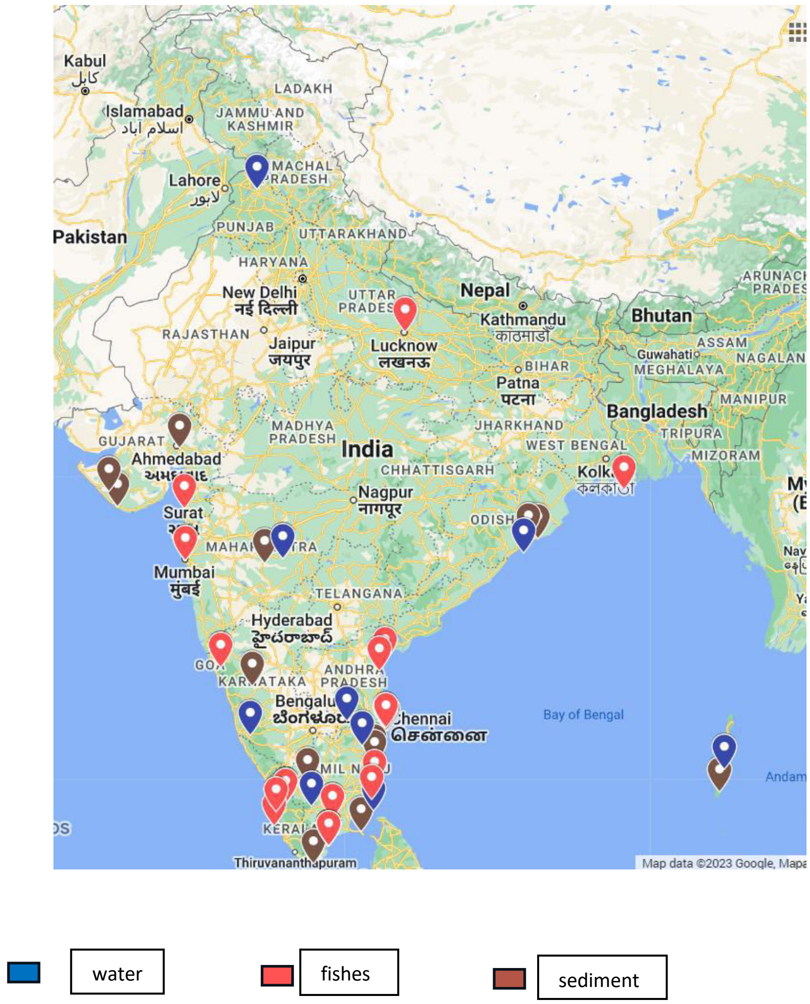

Fig. 1: Microplastic works carried out in the Eastern and Western parts of India.

Ramasamy, 2017). After treatment, the supernatant was subjected to filtration through filter paper with mesh size ranging from 0.4 mm to 38 mm (Sathish *et al*., 2019; James *et al*., 2020; Goswami *et al*., 2020) and the suspected MPs were isolated under microscope which then stored for further spectroscopic studies. Microplastics research carried out in both Eastern and Western parts of India has been given in Figure 1.

Microplastic in Water bodies:

Several studies have documented the presence and distribution of microplastics along the Indian coast, including beaches, rivers, lakes, and surface waters (Tables 3, 4). The accumulation of MPs is affected by a multitude of anthropogenic, environmental, and geological elements. These elements comprise wind orientation, oceanic streams, fluctuations across seasons, proximity to coastlines, distinctive beach attributes and regional geo-morphological configurations. In the surface layers of marine waters, low-density MPs are reported to be the most prevalent type of plastic particles and the attachment of fouling organisms to these MPs can cause them to sink into the benthic layers. On the other hand, high-density MPs such as PA and PVC are typically found in the benthic layers, but they can also remain suspended in the water column under certain hydrodynamic conditions, such as flow rate and tidal fronts (Barnes *et al*., 2009; Browne *et al*., 2010).

Water Sampling:

Microplastic samples were collected using variety of techniques. These techniques include manual

Table 3: Occurrence of microplastic in various water bodies along the Eastern region of India

S. No.	Location	Sample collection	Size	Color and Shape	Polymer type	Abundance	Detection method	Author and Year
1.	Gulf of Mannar and Palk bay	Surface water	1 to 5 mm	Fragments, filaments, pellets, fibers, films, and foams	-	-	Stereomicroscope	James *et al.* (2021)
2.	Tuticorin	Surface water	< 5mm	Fragment, fibre, film	PE, PP	12.14–31.05 items/L	SEM-EDAX analysis FTIR-ATR analysis	Patterson *et al.* (2019)
3.	Red Hills Lake	Lake water	Between 0.3 mm, 1 mm, and 2 mm	Fibers (37.9%), fragments (27%), films (24%), and pellets (11.1%)	high-density polyethylene, low-density PE, PP, and PS	5.9 particles/L	FTIR and (SEM) coupled with energy dispersive X-ray spectra (EDX)	Gopinath *et al.* (2020)
4.	Kodaikanal Lake	Surface water	0.25–5 mm	Black, Red, and White Fibers, fragments, foams, and films	PE, PP, PS, PET	24.42 ±3.22 items/L	Microscope, ATR-FTIR, and SEM with EDAX	Laju *et al.* (2022)
5.	Veeranam Lake	Surface water	-1 mm to 0.3 mm	↑white, red, black, green, blue Fibres, Fragments, Foam, pellets	PVC, PE, PP, PS, NY	13 to 54 items/km2	Microscope andATR-FTIR	Bharath *et al.* (2021)
6.	Adyar River and Kosasthalaiyar river	Surface water	335 µm – 5mm	Fibers, films, fragments, and pellets	PE, PP, PS	330 items/m^3 670 items/m^3	Microscope and ATR-FTIR	Lechthaler *et al.* (2021)
7.	Chilika lake	Lake water	2–5 mm	White-color foams, Fragments	polypropylene and polystyrene	110.7 ± 35.6 items/100L to 26 ± 8.1 items/100L	FTIR and SEM	Singh *et al.* (2023)
8.	Port Blair Bay, Andaman and Nicobar Islands	water	0.3–5.0 mm	Fibre, fragment, pellet	nylon, acrylic, and ionomer surlyn	0.93 × 10^{-3} items/L	ATR-FTIR	Goswami *et al.* (2020)

Table 4: Occurrence of microplastic in various water bodies along the Western region of India

S. No.	Location	Sample source	Size	Color	Shape	Polymer type	Abundance	Detection method	Author and Year
1.	Lonar lake, Maharashtra	Surface water	0 to 5mm	White, Blue, Red, yellow, transparent, green, black.	↑Film, fragment, bead	HDPE, PP, LDPE, PS, PE, PVC, PES	2.66 particles/L	FTIR-ATR	Gosavi and Phuge (2023)
2.	Harike wetland	surface water	4mm to 60µm	-	Fragments and fibres	Nylon6 and HDPE	-	Hot needle test, FTIR, RAMAN and GC-MS	Manzoor *et al. (*2021)
3.	Manipal Lake, Udupi	Surface water	0.3 – 5mm	Various colored MPs were seen throughout monsoon and post-monsoon season	↑Fibers, films, pellets, and fragments	PET, CL	Monsoon season :0.423 particles/L Post monsoon season: 0.117 particles/L	Microscope, ATR-FTIR and SEM with EDS	Warrier *et al. (*2022)
4.	Kerala	Coastal waters	0.3–0.6 mm	Green, red, yellow, blue, and violet, comprised the majority (70%).	Fragments 42%, fiber/line 38%, foam 14%, and film 6%.	23.89% PE, 15.93% PP, 8.85% PS, 7.08% CE, and 21.24% other types of polymers	0.22 and 3.58 particles/m^3	FTIR-ATR	Robin *et al. (*2019)
5.	Cochin estuary	Surface water	0.25mm to 5mm	White, Black, brown, blue, red, green, black	↑Fiber, Film, fragment, and foam	Cellophane, PE, PP and PS	751.7 ± 452.21 particles/m^3	SEM and Fourier Transform Infrared Spectroscopy analysis	Suresh *et al. (*2020)
6.	Goa	Water column	100 µm to 1 mm	Black, blue, green, red, white, and transparent	Fibers, fragments, films and beads	Polyacrylam-ide (PAM), polyacetylene, polyimide, and ethylene vinyl alcohol (EVOH)	48 ± 19 MP particles/L	m-FTIR spectroscopic analysis	Saha *et al. (*2021)
7.	Netravathi River	Water column	0.3 – 5mm	↑Transparent, white, brown, black and others	Fibers, films,foams and pellets	PE, PET, PP, PVC	56 to 2328 pieces/m^3, 288 pieces/m^3	Microscope, ATR FTIR, and SEM with EDS	Amrutha and Warrier (2020)

(↑* indicates higher availability/more prevalence of that specific type of microplastic)

collection using glass bottles (Ganesan *et al.*, 2019), as well as the use of a boat equipped with different types of nets such as neuston net, a high-speed AVANI trawl (All-purpose Velocity Accelerated Net Instrument) (Eriksen *et al.*, 2018) and a plankton net with various mesh sizes (Patterson *et al.*, 2019; James *et al.*, 2020; Robin *et al.*, 2020) and manta trawl net with mesh sizes ranging from 112 µm to 335 µm. Usually flow meter was affixed at the opening of the manta trawl nets to assess the magnitude of water that was sampled. The occurrence of MPs in water samples were expressed in units such as items/km^2, items/m^3 and items/L.

Extraction Method:

Following collection, samples were either placed in the refrigerator or further preserved by being added to a formalin (James *et al.*, 2020) or formaldehyde solution (Patterson *et al.*, 2019). In India density separation technique is widely used to extract microplastics from water samples by using NaCl (Goswami *et al.*, 2020) and NaI (Sathish *et al.*, 2020a) followed by filtration or sieving. Wet peroxide oxidation, which is typically carried out for up to 72 h at room temperature, was also used in some studies to break down organic matter. After completing the density separation and digestion procedure, the supernatant was passed through filter papers with varying mesh sizes such as 0.7 mm, 0.8 mm and 0.9 mm. Then the filter papers were dried at room temperature and safely stored in petri dishes for further spectroscopic studies.

Microplastic in Fishes:

India has a large population that is reliant on the resources of the coastal and marine ecosystems (Kumar *et al.*, 2018). Because of the constant human activities that take place adjacent to or on these ecosystems, MPs are becoming one of the new threats that these aquatic organisms must contend with. Fishes often mistake microplastics (MPs) for prey due to their size and color. This is particularly concerning because most aquatic organisms are visual predators and the color of MPs may play a significant role in fish's decision to consume them (Okamoto *et al.*, 2022). This issue of microplastics in fish has gained attention from researchers in India in recent years (Tables 5, 6). The studies have shown that fish species in marine, freshwater and estuarine ecosystems had a huge variety of polymers such as PE, PP, PVC, PS, PET, Nylon6 etc in them (Devi *et al.*, 2020; Gurjar *et al.*, 2021; Keerthika *et al.*, 2023; Harikrishnan *et al.*, 2023). According to the present understanding of MP prevalence in the aquatic biota, many organisms are potentially at risk of ingesting these synthetic polymers, which can result in various health complications. Research shows that the presence of MPs negatively impacts the physiological functions of fish (Mahamud *et al.*, 2022). As exposure to these pollutants rises, marine organisms experience various negative effects such as oxidative stress, decreased filtration ability, inflamed tissues, impaired digestion tract, false satiation, and weakened immunity (Dowarah *et al.*, 2020; Maharana *et al.*, 2020; Daniel *et al.*, 2020; Sathish *et al.*, 2020b).

In India, the most used method for detecting the amount of microplastics (MP) consumed by fish is fish gut analysis. However, some studies have also examined the entire visceral organs. A few researchers have even compared the MP levels in different fish organs, such as the gut and gills, to get more accurate results (Nithin *et al.*, 2023). Several efforts have been undertaken to examine the impact of MPs in the diet of cultivated fish and to understand the process of translocation takes place within the fish's anatomy (Vijayaraghavan *et al.*, 2022). Microplastics can transport chemical additives into organisms (Bakir *et al.*, 2014). There is little information available about how microplastics (MPs) attached to POP (persistent organic pollutant) react inside organisms (Tang *et al.*, 2020).

Extraction:

Fish are typically collected from their natural habitats and placed in compact containers before they are dissected. Various methods have been developed to extract microplastics (MPs) from

Table 5: Microplastics in fishes from natural aquatic environments along the Eastern region of India

S. No.	Location	Fish Species / Habitat	Targeted Organs	Abundance	Size	Color	Shape	Polymer type	Detection Method	Author and Year
1.	Mangrove ecosystem of Sundarbans	13 estuarine fishes	Gastro-intestinal tract	Microplastics were found in all the 13 species	100µm to <5mm	-	Irregular fragments, Films and fiber	Visual confirmation of polymers	Fluorescence microscope, stereo-microscope	Bhattacharjee *et al.* (2023)
2.	Gulf of Mannar and Palk bay	Pelagic and demersal fishes belonging to 12 families	Gut	MPs found in 6 species out of 14	<5mm	-	Fragment, fiber, film, pellet	Visual confirmation of polymers	Stereo-microscope	James *et al.* (2021)
3.	Adyar and Ennore	12 mid water and demersal fishes 4 Pelagic fishes	Gills Gut	3.2-7.6 MPs per fish	<0.5mm to 7mm	↑Transparent, pale white, blue, black, yellow, red, and green	Fibers, Fragments, Films, foams, and granules	PE, PP, PA, and PS	SEM, ATR-FTIR analysis	Harikrishnan *et al.* (2023)
4.	Bay of Bengal – Chennai: Kasimedu and Nagapattinam	10 Pelagic fishes 2 Demersal fishes 1 Reef fish	Gastro intestinal tracts	20 particles were found in 17 fishes	< 5mm	Yellow, Black, Transparent, and blue	Fibre, films, and pellets	PE, PA, and PET	FTIR, SEM analysis and Stereo microscope	Karuppasamy *et al.* (2020)
5.	Parangipettai	Cynoglossus arel *Rastrelliger kanagurta* *Mugil cephalus*	Gills and Gut	↑1.7 ± 0.01 particles/ind in gills and ↑2.3 ± 0.26 particles/ind in guts	100 to 1000 µm	-	fibers (97%) and pellets (3%)	LDPE, PP and PS	stereo zoom microscope and µFTIR	Nithin *et al.* (2023)
6.	Pulicat lake	*Nemipterus japonicus, Mugil cephalus, Scomberomorus guttatus, Terapon*	Gastro intestinal tracts	-	3.5 mm to 9 mm	Transparent, Blue, yellow, black	Fibre, sheet like, fragment	Polylactic acid, Polythene,	Bruker Alpha FTIR ATR spectrophotom	Surya *et al.* (2022)

		puta, Sardinella longiceps, Caranx ignobilis, Stolephorus indicus, Rastrelliger kanagurta, Eleuthronema tetradactylum, Alectis indica, Leiognathus sp., Trichiurus lepturus, Trachurus lathamni, Selaroides leptolepis and Terapon jarbua						Polyamide and Polyester	eter	
7.	Tuticorin	*Harpodon nehereus Chirocentrus dorab Sardinella albella Rastrelliger kanagurta Katsuwonus pelamis Istiophorus platypterus*	Gastro intestinal tracts	0.0002 ± 0.0001 to 0.2 ± 0.03 items/g; 0.11 ± 0.06 to 3.64 ± 1.7 items/individual	85 µm to 5 mm	Most are blur color	Fibre, film, fragment, and foam	PE, PS and PA	Stereomicroscope and characterized by FTIR and SEM-EDAX analysis	Sathish *et al. (*2020)
8.	Tuticorin-Gulf of mannar coast	*Sufflamen fraenatus, Heniochus acuminatus, Pseudo triacanthus Leiognathus brevirostris*	Muscle Intestine	282 particles 308 particles	100–250 µm	↑white color, transparent, blue, and green	Fragment, film, and fiber.	↑PE, PP, polyamide ↑Polyamide, PE, PP	µ-FT-IR, AFM	Selvam *et al. (*2021)
9.	Thoothukodi coast	3 Pelagic fishes 9 Benthic fishes	Gut analysis	0.53±0.11 particles/individual 0.66±0.13 particles/ individual	0.5–1 mm	↑Blue, Green, Transparent, yellow, red, white	↑Fiber, fragment, irregular, foam, and film	↑PE, PP, PS	ATR-FTIR	Keerthika *et al. (*2023)
10.	Southeast Indian coastal zone (Bay of Bengal)	Demersal Sharks	Gill and gut (digestive tract)	4.67 items per individual shark	0.5 to 2 mm	Blue, pale white, black, Transparent	Fibre fragments	PP, PA, PE	FT-IR	Janardhanam *et al. (*2022)

Table 6: Microplastics in fishes from natural aquatic environments along Western region of India

S. No.	Location	Fish Species	Targeted Organs	Abundance	Average Size range	Color	Shape	Polymer type	Detection Method	Author and Year
1.	Arabian Sea – Mumbai Coastal waters	Golden anchovy (*Coilia dussumieri*)	Gastro intestinal tract	28.84 ± 10.13 MPs/g	100–250 µm	Mostly blue, Translucent, red, black, and brown	Fiber, film, fragment, pellet	Polyethylene, polypropylene, polyamide, polyester, and polystyrene	Stereo zoom microscope and Laser Raman Spectroscopy.	Gurjar *et al. (*2021)
2.	Lucknow – West central India	*Channa punctatus, Labeo bata, Labeo rohita, Puntius amphibius* and *Sal mostoma bacaila*	Gut, gills and muscle	7.86 ± 2.0 items/ind. 4.17 ± 0.6 items/ind. 3.03 ± 0.4 items/ind 0.83 ± 0.13 and 0.77 ± 0.2 items/ind.	<5mm	Blue, black, transparent.	↑Fibers, Fragment, pellets	high-density and low-density polyethylene-type polymers	Raman spectroscopy and stereo microscope	Pandey, *et al.* (2023)
3.	Fishing Harbors of Gujarat and Maharashtra	*Harpadon nehere us*	Gastro intestinal tract	6.98 ± 6.73 MPs/g	1–2 mm	Black and blue	↑Thread, Fragment, Flim, Foam	PE, PS, PU	Stereomicroscope FT-IR	Prusty *et al. (*2023)
4.	Goa	*Mugil cephalus, Arius jella, Gerres Filamentosus, Etroplus suratensis*	Gastro intestinal tract	7.8 ± 4, 4.6 ± 2.6, 5.3 ± 4.9, 1.4 ± 0.3 MP/g bw	10-582 mm, with smaller-sized particles (<50 mm) being more abundant.	↑Blue, red, black, transparent, and green.	↑Fibers, fragments, and films	polyacrylamide (PAM), polyacetylene, ethylene vinyl alcohol (EVOH), polyvinyl chloride (PVC), and polyamide (nylon)	m-FTIR (micro–Fourier Transform Infrared Spectrophotometer) analysis	Saha *et al. (*2021)
5.	Kerala	*Mugil cephalus, Liza macrolepis, Sillago sihama and Gerres filamentosus*	Gut content analysis	-	-	White, blue, green and transparent	Fibre/line, foam, film, and fragment	PE and PP	FTIR-ATR	Robin *et al. (*2019)

6.	Kerala	*Sardinella longiceps, Rastrelliger kanagurta, Thryssa dussumier, Anodontostoma chacunda, Sardinella gibbose, Stolephorus indicus, Dussumieria acuta, Sphyraena obtusata, Megalaspis cordyla*	Edible – Muscle and Skin Inedible – Gill and viscera	0.005 ± 0.02 items/g 0.054 ± 0.098 items/g	100 µm ± 400 µm 100 µm ± 5000 µm	Transparent, blue, and white Transparent, Green, and white	↑Fragments and fibers ↑Fragment and sheets	↑PE, PP and Polyurethane ↑PP, PE and Alkyd resin	FTIR analysis with Nicolet iS10 FTIR Spectrometer	Daniel *et al. (*2020)
7.	Vembanad lake, Kerala	*Piaractus brachypomus*	Gut analysis	32 out of the 123 fishes (26%)	0.89 to 4.85 mm	Red, pink, blue, light green, straw-colored and orange	Fibers, Foam, ↑Fragments	PP, Nylon 6, PET and PBT	ATR-FTIR and Raman spectroscopy	Devi *et al. (*2020)
8.	Cochin coastal zone	*Leiognathus sp., Ambassis ambassis, Stelophorus sp., Clarias batrachus, Cyanoglossus* sp.	Gut analysis	-	-	-	Fiber, film was dominant	nylon, cellophane, polyethylene, polypropylene, polystyrene	SEM and Fourier Transform Infrared Spectroscopy analysis	Suresh *et al. (*2020)

(↑* indicates higher availability/more prevalence of that specific type of microplastic)

fish. One technique involves using 10% KOH to digest the intestinal contents for a period of five days at a temperature of 60°C, followed by filtration through a Millipore filtration unit (Karuppasamy *et al*., 2020). MP particles that are suspected based on visual observation are confirmed via a hot needle test (Manzoor and Singh, 2022) and then analyzed using FTIR analysis (Kumar *et al*., 2018). MPs usually can be separated using saline washes, density flotation/separation and visual examination.

Microplastic in other aquatic organisms:

Microplastic ingestion by aquatic organisms possesses a major ecotoxicological effect that affects both the organisms and the people who depend on them for food (Anbumani and Kakkar, 2018). There are several studies that reported MP bioaccumulation in invertebrates such as in bivalves - green mussel (Naidu, 2019), edible oysters (Patterson *et al*., 2019), great clam (Dowarah *et al*., 2020) and crustaceans like white shrimps (Daniel *et al*., 2020), mud crabs (Hossain *et al*., 2023), squids (Daniel *et al*., 2021) and even in zooplankton (Rashid *et al*., 2021). A study even reported microplastic distribution in the coral reef ecosystem (Patterson *et al*., 2020). In long-term exposure to microplastic these organisms can experience oxidative stress, reduced immunity, decreased filtering capacity and even inflammation in tissues (Dowarah *et al*., 2020; Maharana *et al*., 2020; Daniel *et al*., 2020). Most of these organisms were collected using hand, picking fishing nets and trawl nets. In the case of shrimps, the full gastrointestinal tract was taken and for crabs, gills, hepatopancreas, and sometimes muscle tissue were taken. The entire soft tissues from the bivalves are removed from the shells for digestion. Mostly all these researchers followed the same extraction protocol as fish to extract microplastics with few changes in the level of concentration of KOH and H_2O_2 (Patterson *et al*., 2019; Naidu, 2019; Goswami *et al*., 2020). It is suggested that mussels and oysters due to their sessile nature, can act as excellent MPs monitor in the ecosystem (Patterson *et al*., 2019; Vasanthi *et al*., 2021). All these studies indicate that a substantial portion of aquatic organisms are at risk of ingesting MPs, resulting in various health complications, and more extensive research is needed to understand the risks associated with MP ingestion.

More research is necessary to fully understand the extent of microplastic contamination in the intricate ecosystems of mangroves and estuaries, which are constantly impacted by human activity. There was a significant research gap in the northern and central states of India, where microplastic research remains limited in comparison to the coastal regions. This disparity underscores the need for further exploration to comprehensively address the microplastic pollution problem in India.

Accumulation of microplastics in aquatic organisms, notably fish, can result in the potential hazard for human consumers. These microplastics can affect the nutritional quality of fish by reducing absorption of essential nutrients (Mattsson *et al*., 2017). Additionally, microplastics can act as vectors for other pollutants, such as persistent organic pollutants, which can accumulate in marine organisms' tissues (Koelmans *et al*., 2015). This can lead to exposure to harmful levels of these pollutants when consumed by humans. The impact of microplastics on human health is an emerging area of research in India, and more studies are needed to fully understand the potential risks associated with consuming contaminated fish and seafood.

As nanoplastics are anticipated to become the primary emerging pollutant in the next decade, it is crucial to act in this underexplored area in India. Hence, it is extremely important to conduct more research in the field of nanoplastics. This initiative would be aided by suggesting a simple and feasible method for detecting nanoplastics in complex environmental samples.

Conclusion

This review provides insights into the current status of microplastic contamination in India, shedding light on the detection methodologies applied across various environmental matrices, focusing on sediments, water bodies and aquatic organisms. Moreover, the study reveals a geographical disparity in research focus, with a notable concentration of studies in states like Tamil Nadu and Kerala, primarily along coastal regions. In contrast, the northern and central states of India remain relatively underrepresented in microplastic research. This discrepancy calls for immediate attention, emphasizing the need for intensified research endeavors and robust policy implementations to address the multifaceted challenges posed by microplastics, safeguarding both the environment and public health. Achieving a sustainable future in India necessitates close collaboration among scientists, policymakers and the public.

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