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Microplastics pollution in inland aquatic ecosystems of India with a global perspective on sources, composition, and spatial distribution

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ABSTRACT

Study region: Indian inland aquatic ecosystems.
Study focus: Microplastics (MPs) have been identified as emerging contaminants, potentially impacting public and ecosystem health. This comprehensive review discusses the current state of knowledge on MP contamination and mechanistic process understanding in Indian inland aquatic ecosystems. It highlights knowledge gaps regarding current MP data and discusses methodological differences in MP sampling and sample processing that can lead to contrasting results.
New hydrological insight for the region: Most studies reviewed here have provided evidence of MP contamination in water, sediment and certain indicator species of inland aquatic ecosystems at specific locations and times. Significant seasonal variations in MP concentrations have been identified for pre-, during and post-monsoon periods.
We found that only a few of the reviewed studies have considered the inherent spatio-temporal variability of MP concentrations, and the intricate interplay with hydrological key parameters has largely been overlooked. However, in order to improve our understanding of how MPs are transported within these aquatic ecosystems (e.g., river networks) and decide on potential pollution mitigation, it is imperative to link data on MP concentration and physico-chemical characteristics with key hydrological information such as flow velocity or discharge. This will provide information on MP loads and help to establish loading functions for these aquatic ecosystems that are needed to better understand the impacts of MP pollution on public and ecosystem health.

1. Introduction

Plastics are used in numerous commercial and industrial sectors, including packaging, consumer goods, transport, textile, medical and construction and are widespread for domestic use (Andrady and Neal, 2009; Ankita Sharma, R.L. 2020; Geyer et al., 2017; Nanda et al., 2022). Due to their persistence, lightweight, durability, low costs and ease to be molded into desired forms and shapes, the global

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demand for plastics has been increasing rapidly. For example, Geyer et al. (2017) and Law et al. (2020) have reported that global plastic production has increased by 26% from 334 to 422 million metric tons (MMT) from 2010 to 2016, and the Organisation for Economic Co-operation and Development (OECD) estimated plastic production of 460 MMT for 2019 (OECD, 2022). While the ongoing Covid-19 pandemic has seemingly led to a slight reduction in plastic use in 2020 (OECD, 2022), it has further increased the demand for single use plastic for instance for personal protective equipment (Shams et al., 2021). For example, since March 2020, about 1.6 million tonnes of plastic garbage have been created every day worldwide, and 3.4 billion disposable face masks have been disposed of per day (Benson et al., 2021; Yousefi et al., 2021). Beyond PPE, industries like packaging, e-commerce, fashion, personal care, etc., contribute to this environmental challenge (Phelan et al., 2022). Plastic packaging stands as the predominant segment in the global plastic market, and it also produces half of the total plastic waste generated worldwide (MacArthur et al., 2016; Phelan et al., 2022). The pervasive use of single-use plastic packaging exacerbates the challenge of waste management, as these items are designed for short-term use but persist in the environment for extended periods. This packaging is a major contributor to the millions of tons of plastic waste which end up in waterways annually (Hartmann et al., 2019; MacArthur et al., 2016). Trailing its economic growth, plastic use in India has increased by more than 20 times over the past 30 years (FICCI, 2014; Kumkar et al., 2021). These plastics constitute a high percentage of packaging materials, mostly of single use (FICCI, 2014; Kumkar et al., 2021). The current state of waste management in India is ineffective, with hardly any source separation, little resource recovery and a large part of garbage ending up in dump sites or often carelessly littering neighbourhoods and the wider environment (Kumar and Agrawal, 2020). According to Sharma and Mallubhotla. (2019), India has generated approximately 9.4 MMT of plastic waste in 2016. Out of these, only 60% of plastic waste was recycled, and the remaining 40% either ended up in landfills or circulating in the environment, polluting precious soil and water resources.

A substantial amount of plastic waste leaking into the environment consists of MP particles, i.e., a heterogeneous mixture of plastic particles between 1 μm and 5 mm in diameter (Thompson et al., 2004). They originate as either primary MPs (designed to be MPs) or are considered secondary MPs resulting from the weathering and fragmentation of larger plastic waste items by UV exposure, temperature and salinity effects, mechanical abrasion, and biological degradation (Chamas et al., 2020; Zettler et al., 2013). MP pollution has been reported for but is not limited to soils, groundwater resources, wastewater, landfill leachate, seawater, freshwater, and the atmosphere (Barnes et al., 2009; Browne et al., 2011; Eriksen et al., 2013; Liu et al., 2019; Moeck et al., 2023; Rillig, 2012; Ying Zhang et al., 2020). MPs accumulating in freshwater systems can pose a severe threat to the environment and public health (Szymańska and Obolewski, 2020) and can act detrimentally on aquatic ecosystems including food webs (Krause et al., 2021; Kukkola et al., 2021). Rivers play an important role in carrying MPs from terrestrial sources to seas and oceans (Lebreton et al., 2017). However, they can also constitute medium to long-term storage zones for MPs themselves (Drummond et al., 2022, 2020). Several studies have revealed substantial spatial variability of MP concentrations in streams (Kye et al., 2023; Margenat et al., 2021; Mintenig et al., 2020). River water management and water abstraction practices can have a profound impact on downstream MP loading while redistributing MPs in river corridors or even across catchments (Kukkola et al., 2023b). Lacustrine ecosystems accumulate a wide range of pollutants and somewhat unsurprisingly high MP concentrations have also been identified in numerous lakes (Dusaucy et al., 2021; Free et al., 2014), where gravitational settling of MPs plays a more prominent role due to the slower flow rates as compared to rivers, especially those with often more turbulent flow conditions near the streambed and considerable hyporheic exchange (Drummond et al., 2020; Free et al., 2014; Iannilli et al., 2020; Zhao et al., 2022).

The issue of MP pollution in India has recently been receiving increased attention in the scientific community (Shahul Hamid et al., 2018; Vaid et al., 2021; Vanapalli et al., 2021) as well as among the public (L. Deng et al., 2020; Dowarah et al., 2022). Reddy et al. (2006) conducted the first systematic study of MPs in the Indian marine environment, followed by some more recent studies (Kumar et al., 2018; Naidu et al., 2017; Sruthy and Ramasamy, 2017; Badola et al., 2023; Jain et al., 2024; Talukdar et al., 2023; Tsering et al., 2022, 2021) on MP contamination in different environmental compartments. However, not unlike to other parts of the world, the effects of MPs in Indian aquatic ecosystems are mostly speculative due to fragmented and often inconsistent information related to the methodologies employed and the lower size limit considered in assessing MP pollution. As such, this systematic study on the current state of MP pollution in Indian inland aquatic ecosystems aims to provide an overview of the available data and knowledge that can serve as baseline for future studies and the design of more targeted and sustainable monitoring and mitigation strategies where those are needed. Our study is especially timely, as various programmes and initiatives have recently been launched to tackle MP pollution in India. For example, India has joined the United Nations Environment Programme Clean Seas Campaign with the aim to address and reduce marine plastic pollution (Raha et al., 2021; UNEP, 2021). On the occasion of the World Environment Day 2018, India declared its commitment to phase out single use plastic products by 2022 at the fourth session of the UN Environment Assembly (Nøklebye et al., 2023; Sivadas et al., 2022). Later on, two amendments were added to the Plastic Waste Management rules by the Government of India on August 12 and September 22, 2021 notifying bans on 17 problematic single use plastic products from July 1, 2022 (Chitra and Gobindgarh, 2022; Nøklebye et al., 2023). Single use plastic made from composite material is exempt from the bans, but manufacturers must register with the Central Pollution Control Board before selling them (Nøklebye et al., 2023). Recognising the importance of these initiatives, it becomes evident that an enhanced mechanistic understanding of MP pollution and its driving factors in the Indian inland aquatic ecosystem is crucial. This understanding is pivotal as it contributes to the effective implementation and assessment of these measures, ensuring a consistent evaluation of their broader impact on the state of the environment.

Previous review studies on MPs in India have predominantly focused on the occurrence, distribution and environmental effects of MPs in different environmental compartments with a strong emphasis on the marine environment (Mishra et al., 2023; Neelavannan and Sen, 2023; Sarkar et al., 2020; Vaid et al., 2021). They have not discussed the size range of MPs found and their potential effect on freshwater species while comparing their abundance and distribution across different regions and water bodies. Furthermore, the majority of these previous studies have overlooked the informational aspects related to estuarine environments, which are crucial components of inland aquatic ecosystems. In that context, this review article aims to provide (a) a comprehensive and systematic overview of the current state of research on MP pollution in the entire Indian inland aquatic system (rivers, lakes, reservoirs, estuaries, and aquatic organisms), incorporating insights from recently published articles. (b) The review critically examines the observed physical and chemical properties of MPs in India, shedding light on the diverse range of techniques employed for their identification and quantification. (c) The review then emphasizes the connecting knowledge on spatial and temporal MP pollution to hydrological aspects for a more holistic understanding. (d) The discussion intricately integrates a global perspective, forming a comprehensive comparison that explains the growing impact of MPs on aquatic ecosystems worldwide. This comparative examination serves to broaden the contextual understanding, emphasising the urgency of addressing the MPs issue on a global scale. This study therefore contributes to directing future initiatives focusing on tackling the complexity of the MPs pollution problem as well as highlighting the importance of considering hydrological aspects in studying the fate and transport of MPs.

2. Review methodology

A comprehensive literature search on MPs in India's inland aquatic ecosystems was conducted. The literature search was refined using keywords specific to inland waters such as "freshwater", "sediment", "lake", "river", "estuary", "pond", "aquatic animals" or "biota". The first research paper related to the quantification of MPs at Indian beaches was published in 2013 (Jayasiri et al., 2013). After that, an exponential increase in the number of research articles, particularly between January 2017 to February 2024 (end of 2023 shown in Fig. 1) has been observed, following the worldwide trend of scientific research on MPs in aquatic ecosystems (Fig. 1a, b). For the meta-analysis performed on data analysed in our review, we have identified 52 main research articles (refer to Table 1) that contain relevant data on MP pollution in India's inland aquatic ecosystems. These studies have focused on MP pollution in rivers (44.24%), lakes (30.76%), estuaries (19.24%), and reservoirs (5.76%). From these selected papers, data on sampling locations, MP abundances, and their characteristics have been analysed and discussed with respect to potential sources and in the context of global MP occurrences as well as mechanistic process understanding.

3. MP concentrations in Indian inland ecosystems and suspected sources

MP concentrations in Indian inland ecosystems have been linked to population density (Amrutha and Warrier, 2020; Lechthaler et al., 2021; Singh and Yadav, 2022; Tsering et al., 2021), land cover (Neelavannan et al., 2022; Sarkar et al., 2019) and flow characteristics (Tsering et al., 2021). For India, the vast diversity in climatic conditions, including annual monsoon conditions, land use practices and cultures present additional factors that pinpoint the different and potentially overlapping sources of MPs as a specific challenge. In this paper, the concentration (MPs per m^3 water or kg sediment) and spatial distribution of MPs have been comprehensively reviewed and summarised based on the studies listed in Table 1. As shown in Fig. 2, most of these studies have been conducted in the northwest of India, its southern peninsular and the north-eastern regions of the country, covering some of the major Indian rivers including sections of the most iconic river, Ganga. Large parts of central India remain inadequately explored with respect to MP occurrence and distribution in space and time, including important landscapes of Madhya Pradesh, Maharashtra, Odisha, Telangana, Andhra Pradesh, Rajasthan and Jharkhand etc.

3.1. Surface waters and sediments

MPs have been detected in most of the Indian rivers, lakes and estuaries studied so far. A direct comparison of concentrations from different studies is often challenging due to different sampling, sample processing and analysis techniques used and size fractions

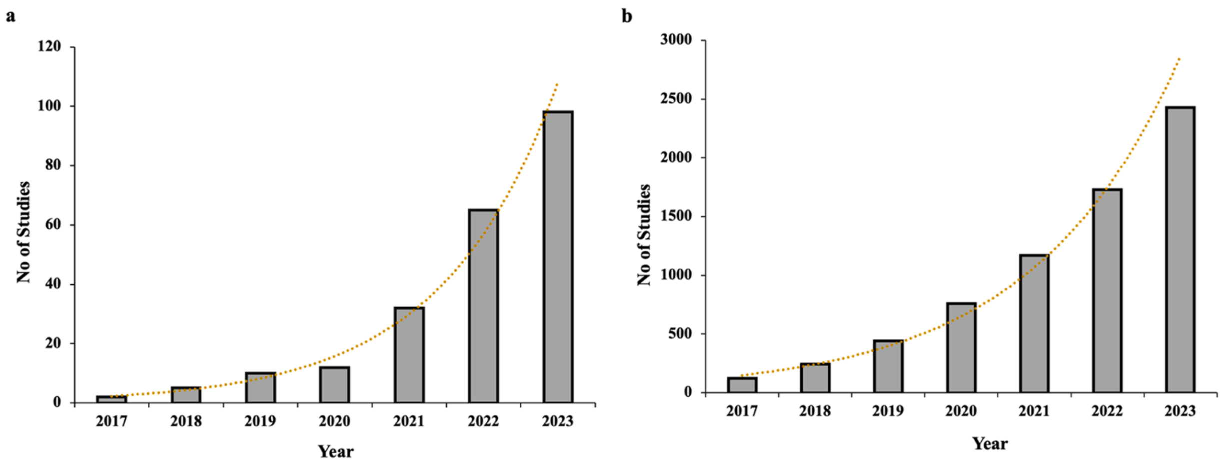

Fig. 1. Yearly numbers of publications on MPs in aquatic ecosystems in (a) India and (b) globally from 2017 to 2023.

Table 1
A summary of sampling and analysis techniques of MPs in India's Inland aquatic ecosystems.

S/N	Waterbody/Location	Sample type	Sampling tool	Pre-treatment		Characterization	Reference
				Digestion	Separation Technique		
1	Lower and estuarine stretches of Ganga River (Buxar,Patna, Bhagalpur, Nabadwip, Barrackpor, Godakhali, Fraserganj)	Sediment	Steel spoon	H_2O_2	Density separation using $ZnCl_2$	ATR-FTIR	(Sarkar et al., 2019)
2	a. Yamuna River, Agra, b. Yamuna River, Prayagraj, c. Ganga River, Prayagraj, d. Confluence point of Ganga and Yamuna Prayagraj,	Surface water	Neuston net with 300 µm mesh size	Biological digestion, formalin	NA	Micro-FTIR	(NPC 2020) (Vaid et al., 2021)
3	Central and lower stretch of Ganga River (Ballia, Patna, Bhagalpur, Farakka, and Diamond Harbour)	Surface water Sediment	300 µm mesh plankton net Stainless-steel scoop	Fenton	Density separation using NaCl	Stereomicroscope and ATR-FTIR	(N. Singh et al., 2021a)
4	Ganga River (Sahibganj, Patna, Varanasi, Kannauj, Rishikesh and Harsil)	Water samples	Hand-operated bilge pump.	NA	NA	Light microscope and (FTIR)	(Napper et al., 2021)
5	Ganga River, Rishikesh to Farakka	Surface water	manta net with mesh size 300-micron	Fenton	Density Separation using NaCl	Microscope, ATR-FTIR and Raman spectroscopy	(Rajan et al., 2023b)
6	Ganga River, (Rishikesh and Devprayag), Uttarakhand	Surface water Sediment Fish	NA	H_2O_2	Density Separation using NaCl	Microscope, ATR-FTIR	(Badola et al., 2023)
7	Ganga River, Patna	Fish	NA	KOH	Density gradient separation using NaCl	Microscope, ATR-FTIR	(Kumari et al., 2023)
8	Hooghly River, Kolkata	Water samples	Van Dorn water sampler	H_2O_2	NA	Fluorescence microscope	(Ghosh et al., 2021)
9	Jhelum River, Kashmir	Surface water	NA	Fenton	Density Separation using NaCl	Microscope, ATR-FTIR	(Farooq et al., 2023)
10	Netravathi River, Karnataka	Surface water Sediment	Stainless-steel bucket Stainless-steel spoon	Fenton H_2O_2	Density separation using $ZnCl_2$ Double separation using $ZnCl_2$	Microscope, and ATR-FTIR	(Amrutha and Warrier, 2020)
11	Godavari River, Karnataka	Surface water	Stainless-steel buckets	Fenton	Density Separation using NaCl	Microscope, ATR-FTIR	(Sekar and Sundaram, 2023)
12	Godavari River, Maharashtra	Fish	NA	Fenton	NA	Microscope	(Bhalerao, 2020)
13	Alaknanda River, Garhwal, Uttarakhand	Surface water Sediment	100 µm plankton net Grab sampler	H_2O_2	Density separation using NaCl	Stereomicroscope, SEM and EDS	(Chauhan et al., 2021)
14	a. Kosasthalaiyar River, Chennai b. Adyar River, Chennai c. Muthirappuzhayar River, Munnar	Surface water Surface water Surface water	Neuston Net with a mesh size of 335 µm	NA	Oil separation with canola oil	FTIR Spectrometer	(Lechthaler et al., 2021)
15	a. Brahmaputra River (Arunachal Pradesh and Assam) b. Indus River, Ladakh	Sediment	Stainless-steel spoon	H_2O_2	Density separation using Sodium tungstate dihydrate ($Na_2WO_4.2\ H_2O$)	Semi-automated µFTIR and SEM	(Tsering et al., 2021)
16	Vaigai River, Madurai, Tamil Nadu	Sediment samples	NA	NA	NA	FTIR spectroscopy and SEM	(Nanthini Devi et al., 2021)
17	Kaveri River, Tiruchirappalli	Sediment		Fenton	Ultrasound exposure	ATR-FTIR and SEM-EDS	(Maheswaran et al., 2022)
18	South Pennar River, Hosur Tamil Nadu	Surface water	NA	NA	Density separation		(Rajadurai and Roopa, 2008)
19	Sharavathi River, Karnataka	Sediment	Stainless-steel spoon	Fenton	Density separation using $ZnCl_2$	Microscope, ATR-FTIR	(Amrutha et al., 2023)

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Table 1 (*continued*)

S/N	Waterbody/Location	Sample type	Sampling tool	Pre-treatment		Characterization	Reference
				Digestion	Separation Technique		
20	Noyyal River, Coimbatore, Tamil Nadu	Sediment	Ekman grab	H_2O_2	Density separation using $ZnCl_2$ and NaCl	Stereomicroscope ATR-FTIR	(Ayyamperumal et al., 2022)
21	Noyyal River (Tamil Nadu)	Sediment	Stainless-steel shovel	NA	Density separation using NaCl	Optical microscope, ATR-FTIR and SEM	(Crispin and Parthasarathy, 2023)
22	Subarnarekha River, Jharkhand	Surface water Sediment	Stainless-steel mug Stainless-steel scoop	H_2O_2	Density separation using NaCl	Stereomicroscope ATR-FTIR and XRF	(Patidar et al., 2023a)
23	Sabarmati River, Ahmedabad	Sediment	Stainless-steel scoop	NA	Density separation using NaCl	Optical Microscope and SEM	(Ram and Kumar, 2020)
24	Anchar Lake, Kashmir Valley	Sediment samples	Van Veen Grab Sampler	H_2O_2	Density separation using NaCl	Stereo microscope and ATR-FTIR	(Neelavannan et al., 2022)
25	Red Hills Lake, Tamil Nadu	Surface water Sediment	Plankton nets (120 µm) Van Veen grab sampler	Fenton	Density separation using NaCl	Stereomicroscope, ATR-FTIR and SEM-EDX	(K. Gopinath et al., 2020)
26	Veeranam Lake, Tamil Nadu	Surface water Sediment	Nylon Plankton net with a mesh size of 20 µm Van Veen grab sampler	30% H_2O_2	Density separation using $ZnCl_2$	Stereomicroscope and ATR FTIR	(Bharath et al., 2021)
27	Chembarambakkam Lake, Tamil Nadu	Surface water	NA	NA	NA	Optical microscope, SEM-EDX and ATR-FTIR	(Ganesan et al., 2019)
28	Kodaikanal Lake, Tamil Nadu	Surface water	Manta net	H_2O_2	Density separation using $ZnCl_2$	Stereomicroscope ATR-FTIR and SEM	(Laju et al., 2022)
29	Vembanad Lake, Kerala	Sediment	Van Veen grab sampler	H_2O_2	Density separation using NaCl	Micro-Raman spectrometer	(Sruthy and Ramasamy, 2017)
30	Vembanad Lake, Kerala	Surface water	Depth water sampler	H_2O_2	Density Separation using Nacl	Stereomicroscope, ATR-FTIR, Micro-Raman spectrometer	(Anagha et al., 2023)
31	Renuka Lake, Himachal Pradesh	Surface water Sediment	UWITEC water sampler Van-Veen grab sampler	Fenton	Density separation using NaCl	Fluorescent microscope, ATR-FTIR and Raman spectrometer,	(Ajay et al., 2021)
32	Kanke Lake, Jharkhand	Surface water	Manta net	Fenton	Density separation using NaCl	Stereomicroscope and ATR-FTIR	(Singh and Chakraborty, 2021)
33	Kumaraswamy Lake, Tamil Nadu	Surface water	Glass bottles	Fenton	NA	Microscope, FESEM, ATR-FTIR	(Ephsy et al., 2023)
34	Nainital Lake, Uttarakhand	Surface water Sediment	Stainless-steel buckets Sediment sampler	H_2O_2	Density Separation using NaCl	Microscope, ATR-FTIR, SEM-EDX	(Jain et al., 2024)
35	Chilika Lake, Odisha	Surface water Sediment	Glass bottles Van Veen grab, stainless steel scoop	NA	Density Separation using $ZnCl_2$	Microscope, ATR-FTIR	(Singh et al., 2023)
36	Manipal Lake, Karnataka	Surface water	Steel bucket	Fenton	Density separation using NaCl, $ZnCl_2$ and NaI	Stereomicroscope ATR-FTIR and SEM	(Warrier et al., 2022)
37	a. Pangong Lake, Ladakh b. Tsomoriri Lake, Ladakh c. Tsokar Lake, Ladakh	Sediment	Metal spoon	Fenton+Enzymes and Fenton+H_2SO_4	Density separation using Sodium tungstate dihydrate ($Na_2WO_4.2\ H_2O$)	Raman spectroscopy	(Tsering et al., 2022)
38	Rewalsar Lake, Himachal Pradesh	Surface water Sediment	Water sampler Van Veen grab sampler	Fenton	Density separation using $ZnCl_2$	Microscope, Raman spectrometer	(Bulbul et al., 2023)

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Table 1 (*continued*)

S/N	Waterbody/Location	Sample type	Sampling tool	Pre-treatment		Characterization	Reference
				Digestion	Separation Technique		
39	Vellayani Lake, Kerala	Surface water	Plankton nets with a mesh size of 120µ	Fenton	NA	zoom microscope, ATR-FTIR	(Immanuvel David et al., 2023)
		Sediment	Van Veen gab sampler				
40	Punnakayal estuary, Tamil Nadu	Surface water	Teflon pump	Fenton	NA	µFTIR	(Selvam et al., 2021)
41	Ulhas estuary, Maharashtra	Sediment	Shovel and stainless-steel container.	H_2O_2	Density separation using NaCl	Stereo-zoom microscope, SEM-EDS and FTIR	(Kumkar et al., 2021)
		Water	Stainless-steel jug				
		Fishes	NA				
42	Narmada estuary, Gujrat	Sediment	Stainless steel tweezers	H_2O_2	NA	FTIR spectroscopy	(Sharma et al., 2020)
43	Kayamkulam estuary, Alappuzha	Sediment	Van-Veen grab sampler	H_2O_2 followed by HCl	Density separation using $ZnCl_2$	Stereo zoom microscope and ATR-FTIR	(Radhakrishnan et al., 2021)
44	Vellar estuary, Parangipettai, Tamil Nadu	Surface water	Plankton net (330 µm mesh size	H_2O_2	NA	Stereo zoom microscope, ATR-FTIR, and µFTIR	(Nithin et al., 2022)
		Sediment	Van Veen's grab				
45	Mahanadi estuary	Surface water	Stainless-steel mug	Fenton	Density Separation using Nacl	Stereomicroscope, ATR-FTIR	(Patidar et al., 2023b)
		Sediment	shovel				
46	Cochin estuarine System, Kerala	Surface water	Plankton net with mesh size: 200 µm and	H_2O_2	NA	Microscope, ATR-FTIR	(Praved et al., 2024)
		Jellyfish	Hand-held scoop nets				
47	Sita-Swarna estuary, Karnataka	Sediment	Stainless-steel spatula	H_2O_2	Density separation using $ZnCl_2$	Microscope, ATR-FTIR and Raman spectroscopy	(Valsan et al., 2024)
48	Estuarine environment of Tamil Nadu	surface water	Manta trawl net of mesh size 330 micron,	H_2O_2	Density separation using NaI	Microscope, ATR-FTIR	(Jeyasanta et al., 2023)
		Sediment	Van veen Grab				
49	Hooghly estuary	Surface water	Manta net with mesh size 300-micron	Fenton	NA	Microscope, ATR-FTIR	(Rajan et al., 2023a)
50	Different district of Chhattisgarh	Freshwater fish	NA	KOH solution	Density Separation using NaCl	Microscope, fluorescent microscope	(Shukla et al., 2022)
51	Ponds, Chhattisgarh	Surface water	Jars, buckets, or pumps	Fenton	NA	Microscope, ATR-FTIR	(Upadhyay and Bajpai, 2024)
52	East Kolkata Wetland (EKW), West Bengal	Surface water	Steel bucket	H_2O_2	Density separation using $ZnCl_2$	Microscope and ATR-FTIR	(Sarkar et al., 2021)
		Sediment	Grab sampler		NA	Microscope and ATR-FTIR	
		Biological samples	Cast net (10–15 mm mesh)		NA	Fluorescence microscope and ATR-FTIR	

analysed in individual studies. Almost all studies reviewed here have used 5 mm as their upper size limit, but inconsistency exists in the definition of their lower size limit. MP concentrations (as particles per volume of water) for some locations were found to be exceptionally high, such as for instance those reported for the waters of Kosasthlaiyar River (39,200 MPs/m^3; >100 µm) and Godavari River (6500 MPs/m^3; >25 µm) of South Peninsular India, Alakananda (11,320 MPs/m^3; >100 µm) and Jhelam Rivers (2500 MPs/m^3; >75) of northwest India and the downstream part of the Hooghly River of northeast India, with 11,320 (>100 µm) and 2083 MPs/m^3 (>150 µm) found in its surface water, respectively (Priyanka et al., 2023; Sekar et al., 2023; Farooq et al., 2023; Chauhan et al., 2021; Ghosh et al., 2021; Rajan et al., 2023a; Sekar and Sundaram, 2023). In other locations, however, much lower concentrations were

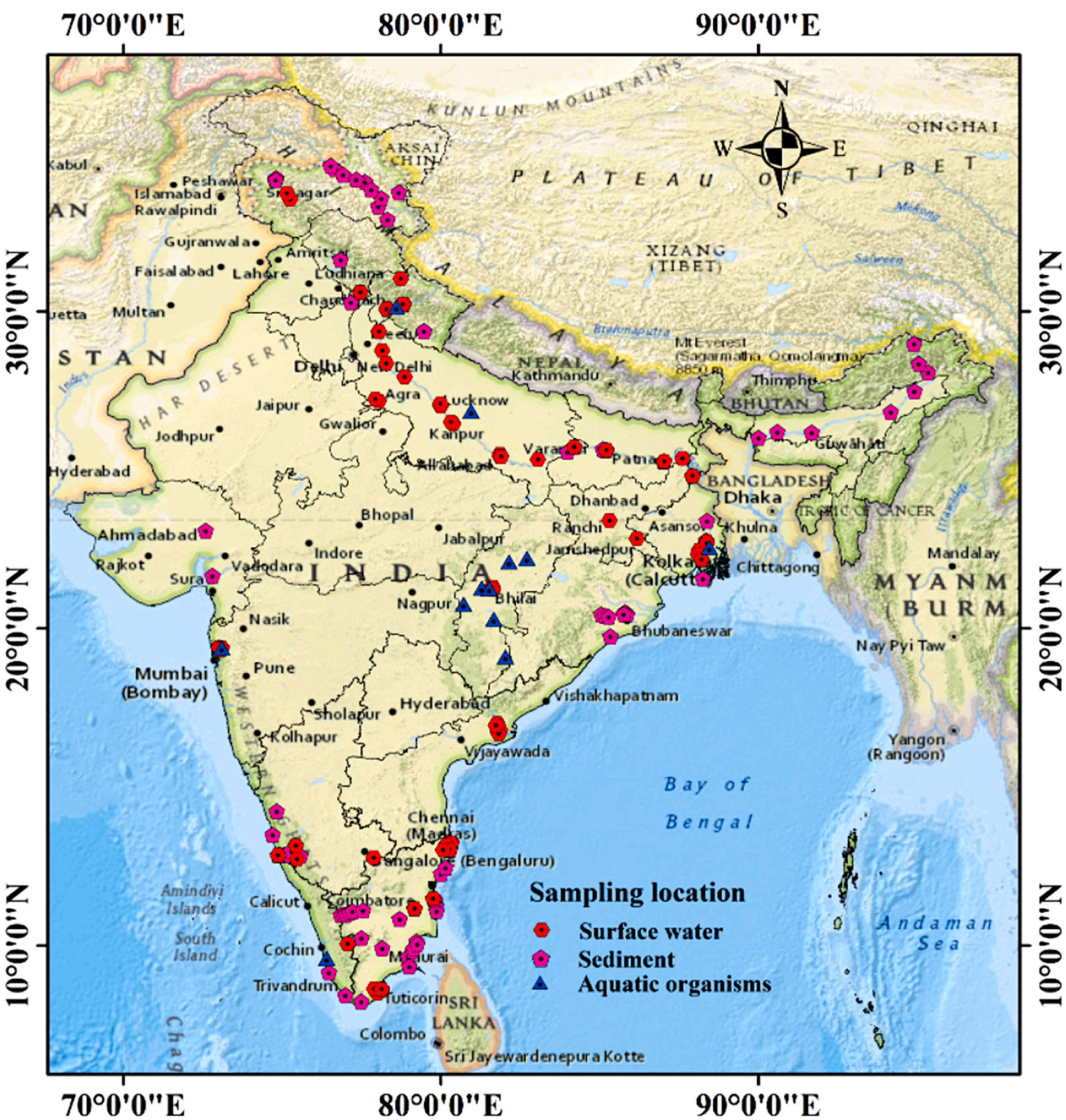

Fig. 2. Spatial distribution of experimental field studies investigating MP pollution in the water column, sediment and aquatic organisms of inland aquatic ecosystems in India. All studies are listed in Table 1.

observed, for example in the Ganga River at Bihar, where concentrations ranged from 0.38 to 18 MPs/m^3 of size > 300 μm (Napper et al., 2021; N. Singh et al., 2021a). At Prayagraj, Yamuna and Ganga as well as the confluence point of the Ganga and Yamuna Rivers, concentrations have been observed as low as 4, 1.47, and 1.23 MPs/m^3 respectively, all in the same size range (NPC 2020). The current information on spatial patterns of MP contamination in Indian freshwater bodies (excluding groundwater) suggests a very heterogeneous geographical distribution that depends upon various factors, including potential differences in the sampling, sample processing and polymer identification techniques (Table S1). Frequently, concentrations of MPs in surface water seem to steadily increase along a downstream trajectory. For example, MP concentrations in the Netravathi River increase in the downstream direction from 56 to 2328 MPs/m^3 (Amrutha and Warrier, 2020). On the other hand, at the river Ganga, higher concentrations of MPs are found in densely populated cities like Varanasi and Rishikesh as compared to Balia, which is further downstream, yet has lower concentrations by two orders of magnitude (Napper et al., 2021; N. Singh et al., 2021a). This can be a result of population density and water management practices along the river Ganga where several barrages exist and water might be rerouted for agricultural or other anthropogenic use, but further studies are required to better understand the evolution of MP concentrations along the Ganga. A recent study has also highlighted the impact of wastewater discharge and anthropogenic activities on MP pollution in river Ganga (Rajan et al., 2023b). They observed that Kanpur, Allahabad and Varanasi have higher MP concentrations than less populated cities downstream, such as Kahalgaon, Sahibganj and Farakka. This underscores the influence of human activities on MP pollution in freshwater bodies, highlighting the need for targeted management strategies to mitigate the impact on aquatic ecosystems. Estuaries such as Mahanadi estuary of central India, Hooghly estuary of northeast India, Punnakayal, Muttukadu and Vellar estuaries of south peninsular India have shown concentrations of 26,000 MPs/m^3 (>0.2 μm), 154 MPs/m^3 (>100 μm), 19,900 MPs/m^3 (>50 μm, Punnakayal), 780 MPs/m^3 (>50 μm) and to 5.14 MPs/m^3 (>330 μm), respectively (Patidar et al., 2023; 2022; Selvam et al., 2021; Jeyasanta et al., 2023). The use of a larger mesh size during sampling as here for the Vellar estuary has most likely led to a considerable underestimation of MPs as been shown to occur for other regions of the world (Kurki-Fox et al., 2023).

It has to be highlighted that the data compared here have been gathered at different times and under different flow conditions (mostly unreported), which introduces an additional level of uncertainty into these types of spatial comparisons. Concentrations could therefore be strongly influenced by local variabilities in discharge as well as larger weather patterns such as monsoonal rainfall. Given the high degree of annual discharge variation of India's typical monsoonal climate (Bookhagen and Burbank, 2010; Bowden et al., 2023), it will be important for future studies to record flow regime and hydrodynamic conditions during sampling in order to ensure comparability of reported concentration data as well as to calculate more accurate MP loads and fluxes towards the oceans.

Similar to the river and estuary environments, most of the studies focusing on lake water have also studied different MP size ranges. For example MP concentrations in the surface water of Indian lakes ranged from 64,000 MPs/m^3 (> 0.2 μm) in Renuka Lake, 56,000 MPs/m^3 (> 0.2 μm) in Nainital lake, 24,420 MPs/m^3 (>250 μm) in Kodaikanal Lake, 11,200 MPs/m^3 (> 0.2 μm) in Kumarswami lake, 9000 MPs/m^3 (>50 μm) in Chembarambakkam Lake, 5900 MPs/m^3 (>125 μm) in Red hills Lake, 4100 MPs/m^3 (>120 μm) in Vellayani lake, 423 MPs/m^3 (>300 μm) in Manipal Lake, and 3 MPs/m^3 (>125 μm) in Kanke Lake (Ajay et al., 2021; Jain et al., 2024; Bharath et al., 2021; Ganesan et al., 2019; K. Gopinath et al., 2020; N. Singh et al., 2021a; Sruthy and Ramasamy, 2017; Warrier et al.,

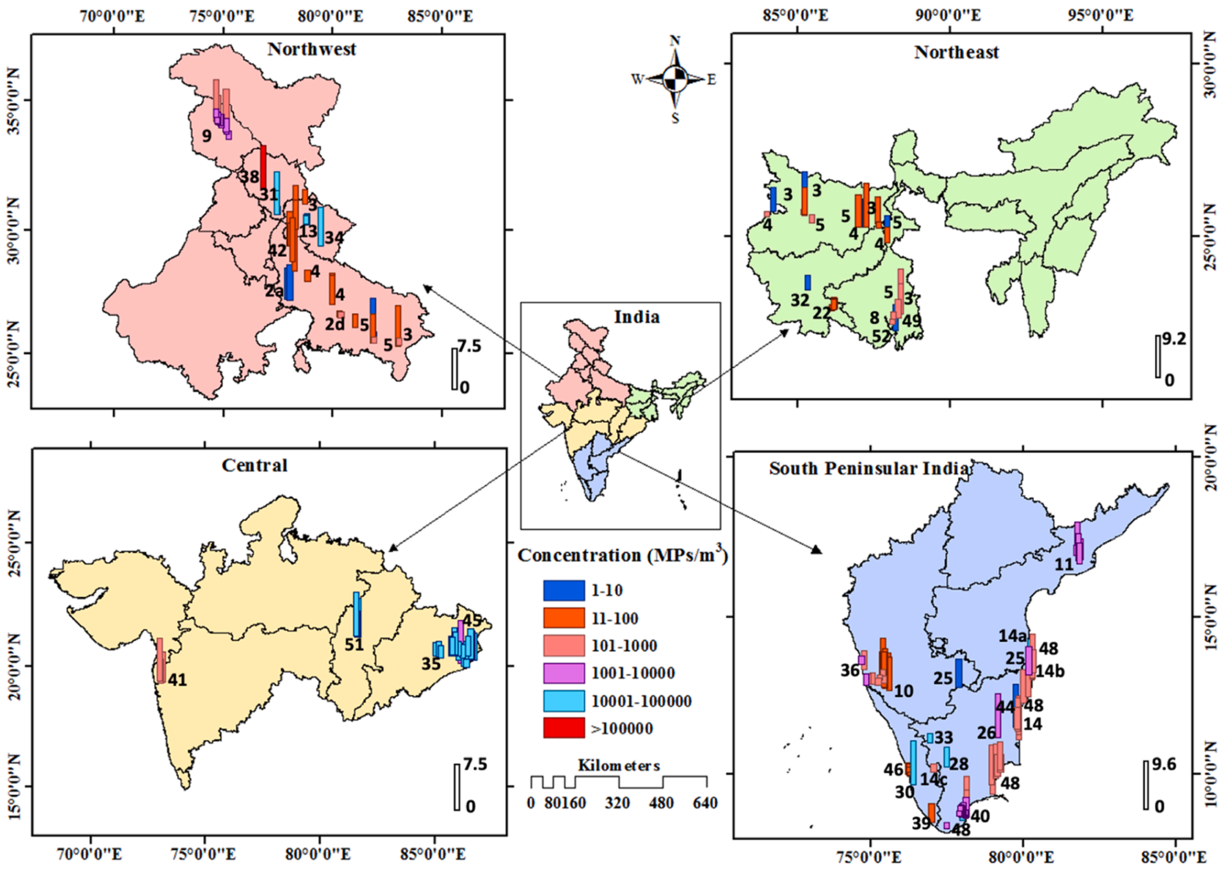

Fig. 3. MPs concentrations in surface water samples of India's inland aquatic ecosystems using different lower size limit (2a. Yamuna River (>300 μm); 2d. Confluence of Ganga and Yamuna(>300 μm); 3. Ganga River (> 330 μm); 4. Ganga River (>300 μm); 5. Ganga River (>100 μm); 8. Hooghly River (>150 μm); 9. Jhelam River (>75 μm); 10. Netravathi River (>300 μm); 11. Govavari River (>0.7 μm); 13. Alaknanda River (>100 μm); 14a. Kosasthalaiyar River (>335 μm); 14b. Adyar River (>335 μm); 14c. Muthirappuzhayar River (>335 μm); 18. South Pennar River (NA); 22. Subarnarekha River (> 125 μm); 25. Red Hills Lake (> 120 μm); 26. Veeranam Lake (> 120 μm); 28. Kodaikanal Lake (>333 μm); 30. Vemband Lake (>1 μm); 31. Renuka Lake (>0.2 μm); 32. Kanke Lake (>125 μm); 33. Kumarswami Lake (>20 μm); 34. Nainital Lake (>20 μm); 35. Chilika Lake (>20 μm); 36. Manipal Lake (>300 μm); 38. Rawalsar Lake (>0.2 μm); 39. Vellayani Lake (>120 μm); 40. Punnakayal estuary (>50 μm); 44. Vellar estuary (>330 μm); 45. Mahanadi Estuary (>0.2 μm); 45. Cochin estuary system (>250 μm); 47. Sita-Swarna estuary (>100 μm); 48. Estuarine system of Tamilnadu (>50 μm); 49. Hooghly estuary (>100 μm); 51. Freshwater Ponds of Chhatisgarh (>50 μm); 52. EKW (>63 μm)).

2022) as shown in Fig. 3. A study conducted by (Nikki et al., 2021) has mentioned 1880 MPs/m^3 (>20 μm) in Vembanand Lake, which is the second largest Ramsar site in India. Intense recreational and heavy tourism activities also represent possible reasons for the high numbers of MPs in these areas (Feng et al., 2020; K. Gopinath et al., 2020; Warrier et al., 2022). In another study, Prapanchan et al. (2023) sampled 44 lakes of the north-western part of Tamil Nadu, reporting elevated MP concentrations in densely populated areas like Chembarambakkam (170,000 MPs/m^3; >0.45 μm) and Mamalla (78,000 MPs/m^3; >0.45 μm) while comparatively lower concentration was observed in Tiger Lily Lake (18,000 MPs/m^3; >0.45 μm), which is less populated. The concentrations of MPs in lake water are often higher than in rivers, with the stagnant lake water representing a terminal endpoint of transported MPs that are up-concentrating from their feeding rivers (Cera and Scalici, 2021; Koelmans et al., 2019). Although those MPs tend to settle out of the lake water column over time, differences in particle shape (fragments, spheres, fibres), size and density can lead to variations in buoyancy, reducing the effect of gravitational settling for some of these particles (Elagami et al., 2022; Kowalski et al., 2016). The shape of particles affects its aerodynamic properties and how it interacts with water currents (Tsuda et al., 2013; Yulan Zhang et al., 2020). Irregularly shaped fragments and fibres may experience increased resistance to settling due to their larger surface area and potential entanglement with other particles (Kowalski et al., 2016; Kumar et al., 2021a,b; Waldschläger and Schüttrumpf, 2019).

MPs with densities lower than water may float or remain suspended in the water column, especially if they are small or possess a shape that enhances buoyancy. The impact of other aspects such as lake stratification or hydrodynamics requires further research (Elagami et al., 2023), while particle deposition is governed by turbulent flow and local pressure differences as found due to instream obstacles or local variation in streambed morphology (Drummond et al., 2022) seem to play an important part in the lakes reviewed here.

Fewer studies have looked at MP concentrations in streambed sediment, with concentrations in the Gangetic basin ranging from 17 to 409.86 MPs/kg (>63 μm), showing an increasing trend in the downstream direction (Sarkar et al., 2019; N. Singh et al., 2021a). A study conducted by Singh et al. (2022) has reported 10,000 MPs/kg (> 45 μm) in sediments of the Ganga River at the downstream side

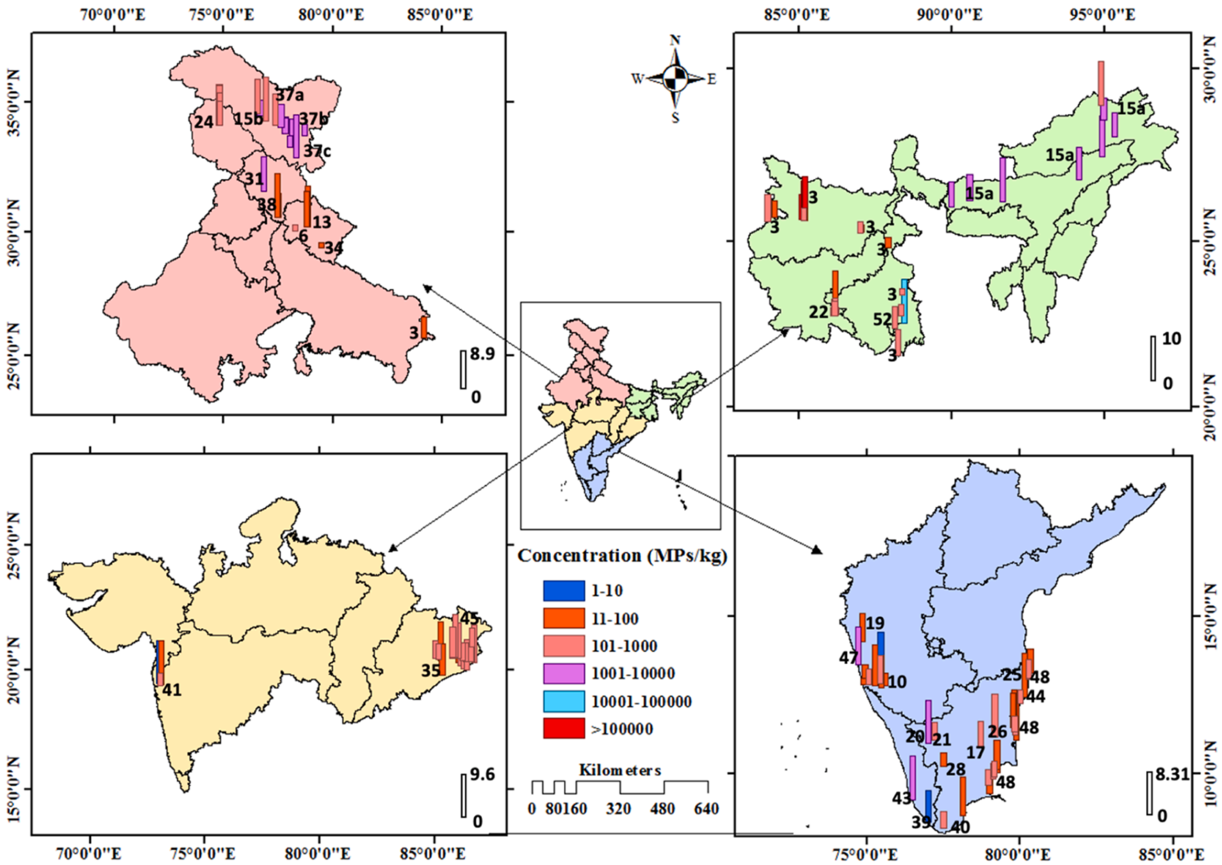

Fig. 4. Concentration of MPs in sediment samples of Indian inland aquatic ecosystems (3. Ganga River (>63 μm); 6. Ganga River (>100 μm); 10. Netravathi River (>300 μm); 13. Alaknanda River (>5 μm); 15[a]. Brahmaputra River (>20 μm); 15b. Indus River (>20 μm); 17. Kaveri River (>0.45 μm); 19. Sharavathi River (>300 μm); 20. Noyyal River (>75 μm); 21. Noyyal River (>75 μm); 22. Subarnarekha River (> 125 μm); 24. Anchar Lake (>300 μm); 25. Red Hills Lake (>300 μm); 26. Veeranam Lake (>300 μm); 28. Kodaikanal Lake (>0.8 μm); 31. Renuka Lake (>0.2 μm); 34. Nainital Lake (>20 μm); 35. Chilika Lake (>20 μm); 37a. Pangong Lake (>20 μm); 37b. Tsokar Lake (>20 μm); 37c. Tsomariri Lake (>20 μm); 38. Rawalsar Lake (>0.2 μm); 41. Ulhas estuary; 44. Vellar estuary (>45 μm); 45. Mahanadi Estuary (>0.2 μm); 47. Sita-Swarna estuary (>100 μm); 48. Estuarine system of Tamilnadu (>50 μm); 52. EKW (>63 μm)).

of Patna (the second most polluted city of India (Kumar et al., 2020)). This study concluded that industries and urbanisation may be responsible for the high concentration of MPs in the area (Kumar et al., 2021a; Singh et al., 2022). The Nethravati River of Indian South Peninsular region has the lowest concentration of MPs (7.5 MPs/kg; >300 μm) so far reported (Amrutha and Warrier, 2020), which coincides with a generally lower population density in the area. In the Kayamkulam estuary on the southwest coast of peninsular India, MP concentrations with a mean of 438.8 MPs/kg were reported, while a modest concentration (43.4 MPs/kg) of MPs has been reported for the Vellar estuary at the south east coast (Nithin et al., 2022; Radhakrishnan et al., 2021) as shown in Fig. 4. The Vellar estuary's data shows a decrease in concentration towards the sea during the winter of 2018 (Nithin et al., 2022). In addition, the Ulhas and Mahanadi estuaries in central India have shown 130 MPs/kg (>45 μm) and 354 MPs/kg (>0.2 μm), respectively (Kumkar et al., 2021). The sediments of EKW have shown MP concentrations ranging from 2124.84 to 6886.76 MPs/kg of size >63 μm (Sarkar et al., 2021).

Sediment MP concentrations in Anchar Lake in the Kashmir Valley that is flanked in the north by the Greater Himalayan and on the south by the Pir-Panjal range, vary from 233 to 1533 MPs/kg (>300 μm) (Neelavannan et al., 2022). Similar to Anchar Lake, some high altitude lakes of northwest India like Pangong Lake (800–1000 MPs/kg), Tsomoriri Lake (1600–3800 MPs/kg) and Tsokar Lake (800–1000 MPs/kg) have also shown a high concentration of MPs of size >100 μm (Tsering et al., 2022), likely indicating the atmospheric deposition of MPs, growing tourist activities and poor local waste management systems. Jain et al. (2024) reported a high concentration of MPs (400–10,600 MPs/kg; > 20 μm) in Naintal Lake, a popular high altitute tourist destination in northwest India (Jain et al., 2024). Similarly, Rawalsar lake has shown a high concentration of MPs ranging from 750 to 3020 particles/kg (Bulbul et al., 2023). Relatively low MP concentrations were observed in Red Hills Lake (28 MPs/kg), situated in the northern part of peninsular India (K. Gopinath et al., 2020), while Veeranam Lake of southern peninsular India has shown concentrations of 309 MPs/kg (Bharath et al., 2021). MP concentrations identified so far in northwest India for a single location are comparatively higher than in the rest of the country, based on the limited number of studies and sites that have been investigated till now. South Peninsular India seems to have high average MP concentrations compared to other regions. Overall understanding of the distribution of MPs requires consideration of regional hydrological variations and the influence of sampling and analysis techniques. In general, high MP concentrations in some locations have at least in parts been attributed to the dense population, increased anthropogenic activities and waste handling practices near to those sampling areas, and the selected lower size limit (Bharath et al., 2021; K. Gopinath et al., 2020; Neelavannan et al., 2022; Tsering et al., 2022) but more evidence is needed to understand how transferable those results are to other parts of India and the world. Additionally, efforts are being made among the scientific community to standardise sampling, sample processing, polymer identification and reporting steps (Cowger et al., 2020) or at least improve the breadth of the information on the techniques used and uncertainties encountered during each of these steps (sampling, processing, enumeration and polymer identification). Some of the discussed studies (Anagha et al., 2023; Immanuvel David et al., 2023; Kumar et al., 2024) clearly provide insufficient information on aspects such as lower size limits of particles identifiable during sampling or polymer identification, typical particle recovery rates during sampling and sample processing, or more specific information on imaging instruments and spectral databases used during polymer identification. As such, comparing MP concentrations across India remains challenging.

3.2. Aquatic organisms of inland waters

The majority of Indian MP studies have not attempted to quantify MP numbers in organisms. Less than 10% of the total studies reviewed here have reported MP contamination in inland aquatic organisms, mostly focusing on different fish species of importance with respect to dietary and economic reasons. Seven different species of fin fish and two species of macroinvertebrates/snails have been collected from EKW in a study by Sarkar et al. (2021). Almost all the collected species showed MPs to be present in their gastrointestinal tracts, containing up to 11 MPs/organism in fin fishes (Sarkar et al., 2021), while some other studies found MPs in shellfish (23 MPs/organism) to be higher than in fin fish (15 MPs/organism; Nikki et al., 2021). 37 out of 50 fishes have had MPs in their digestive tracts with 3.75–6.11 MPs/organism (mudskipper fish) collected from the Ulhas River estuary (Kumkar et al., 2021). One study conducted by Pandey et al. (2023) revealed the presence of MPs in commercially valued and dietary-preferred freshwater fish collected from Lucknow, Uttar Pradesh, with the highest concentration being 7.86 MPs/organism in *Channa punctatus* (Pandey et al., 2023). MPs were found in 31 of the 271 fishes that were collected from the Ganga River in Patna. The concentration was 2.5–1.6 MPs/organism (Kumari et al., 2023). Fish can ingest MPs through various pathways, including direct consumption of contaminated water, sediments, or prey items that have already ingested MPs (Alberghini et al., 2023; Badola et al., 2023). The presence of MPs in the surrounding environment increases the likelihood of ingestion by fish during their normal activities (Badola et al., 2023; Kumari et al., 2023). One study conducted by Badola et al. (2023) collected specially targeted fish species with different feeding behaviours (*Tor tor, Schizothorax richardsonii, Labeo dero and Gara gotyla gotyla*) from the upper reaches of the river Ganga. Among these, all the individual fish species, regardless of their specific feeding behaviour, were contaminated with MPs (Badola et al., 2023). Shukla et al. (2022) highlighted that bottom dwelling demersal fish had higher concentrations than surface feeder fishes, attributing this difference to the sediment acting as a sink, accommodating more MPs than surface water.

Most of the existing studies have not put observed MP concentrations into the context of the body weight of the individual organism to describe actual concentrations of MPs in the organism. Factors such as the size and type of MPs, as well as the fish's metabolic rate, can influence the extent of MP accumulation (Bhuyan, 2022; Parolini et al., 2023). Studies on aquatic invertebrates with respect to MP contamination could not be encountered, and studies regarding the impact of bio-accumulative additives contained in plastics on the wider food web are also missing. This knowledge gap should be closed in the future, as MP pollution has been shown to severely impact a wide range of aquatic species, food webs and the wider ecosystem (Krause et al., 2021; Kukkola et al., 2021).

4. Characterisation of MPs found in Indian inland aquatic ecosystems

MPs in Indian inland aquatic ecosystems were found to express widely varying physical and chemical properties with respect to polymer type, shape, colour and size based on their origin and geographic locations, climatic conditions and anthropogenic activities (Shahul Hamid et al., 2018; Vaid et al., 2021; Vanapalli et al., 2021). Understanding the nature and extent of MP pollution in inland aquatic ecosystems would be important for assessing the potential environmental impacts, including effects on the food chain and ecosystem health (Kukkola et al., 2021; Yuan et al., 2019). The following sections provide information on different physicochemical properties of MPs found in Indian inland aquatic ecosystems.

4.1. Polymer types

For this section, 40 papers that describe the chemical composition and polymer type of identified MP particles have been analysed, with 12 papers on sediment, 16 papers on surface water, and 14 papers looking into both media. Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET), polyacetylene (PA) and polyvinyl chloride (PVC) are the six most prevalent polymers that have been reported for Indian inland aquatic ecosystems. Other polymers such as polycarbonate (PC), Ethylene Vinyl Alcohol (EVOH) and PP-PE copolymers made up a minor percentage of the total MPs, as shown in Fig. 5. The PP and PE polymers are extensively used in packaging, manufacturing containers, and care products (Han et al., 2016). As shown in Fig. 5, the analysed surface waters of the river Ganga comprised a polymer composition of PP (36%), PE (30%), PS (26%), and PVC (8%), while the chemical composition of the sediment samples was totally different with PET (39%), PE (30%), PP (19%), and PS (1%) as observed by N. Singh et al. (2021a) and Sarkar et al. (2019). PE (39% and 45%) and PP (45% and 40%) were the most common MP polymers found in the sediments of Brahmaputra (northeast India) and Indus River (northwest India), as reported by Tsering et al. (2021). Similarly, PE (57%- 47%) was the major polymer found in the MPs of surface water samples of Nethravati, Kosasthalaiyar, Adyar, and Muthirappuzhayar rivers of south peninsular India (Amrutha and Warrier, 2020; Lechthaler et al., 2021). Rayon (synthetically altered cellulose fibres) is the dominant polymer found in surface water MPs in the transboundary part of the Ganga River (Napper et al., 2021). Irrespective of other studies, EVOH, PA and PVC seem to be the dominant MPs in the surface water samples of river Ganga and Yamuna at Prayagraj and at their confluence point, which show the influence of anthropogenic activities such as bathing and washing in these places (NPC, 2020). High concentrations of PP are found in the surface water and sediment samples of major estuarine environments in

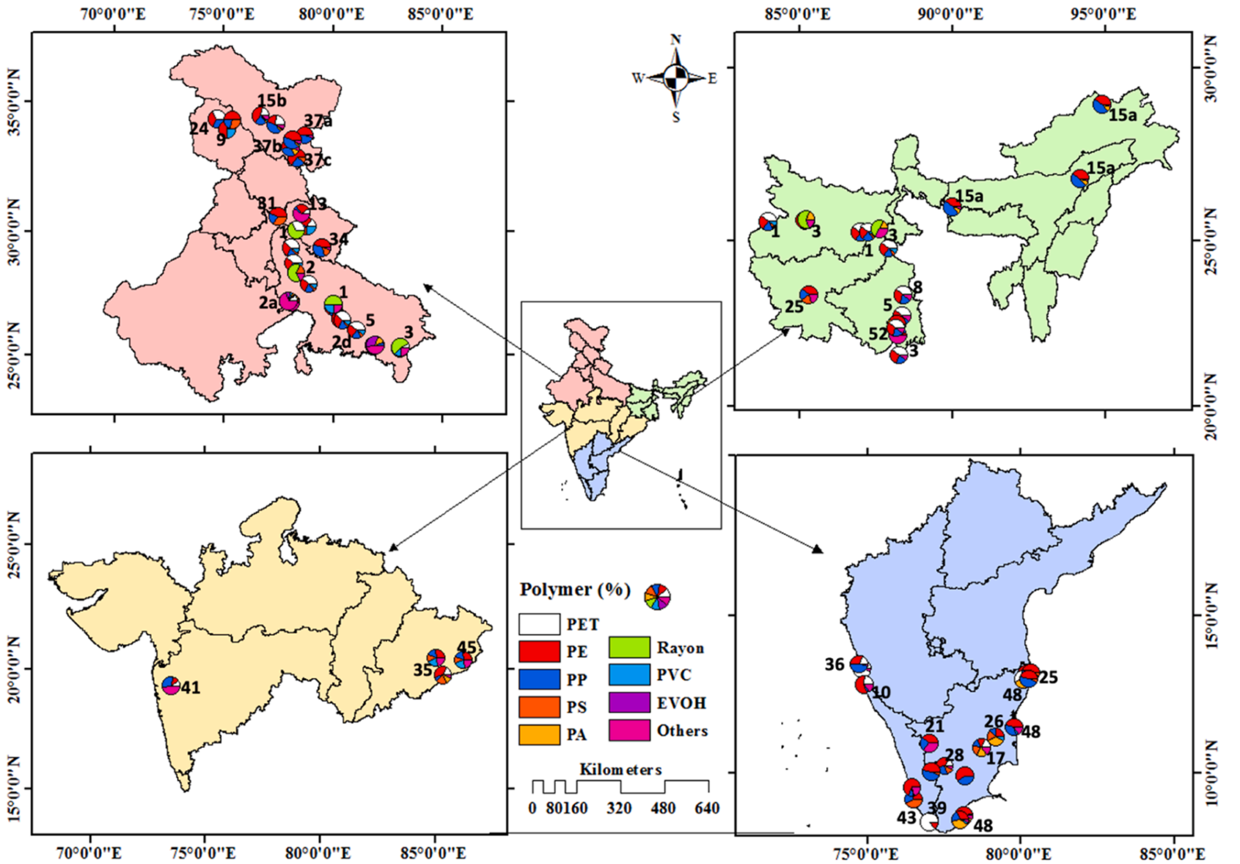

Fig. 5. Composition of polymer types of MPs found in Inland aquatic ecosystems of India.

Tamil Nadu followed by other polymers (Jeyasanta et al., 2023; Kumkar et al., 2021). According to Selvam et al. (2021), PA (38%) is the leading polymer in the surface water samples of Punnakayal estuary, followed by PP (22%).

PA also constitutes the major portion of MPs in sediments from Anchar Lake in northwest India to Veeranam Lake in south peninsular India with a relative concentration of 96% and 35%, respectively (Bharath et al., 2021; Neelavannan et al., 2022), indicating anthropogenic sources like fishing, textiles, automotive and household hygiene products etc. (Cole et al., 2011). Also, Red Hills Lake has a high concentration of PP (53.044%), followed by PE (42.89%) and PS (4.06%) in sediment samples, as reported by K. Gopinath et al. (2020). PA and PP are frequently utilised in textiles, fishing nets and ropes (Europe, 2020) and it seems MPs originating from fishing nets and textile components are the most common MPs found in major Indian lakes and estuaries reported so far. Interestingly, Manipal Lake shows 95.71% of PET MPs in surface water sample, which was mainly derived from the laundry of nearby residential colonies and hostels (Warrier et al., 2022). One study by Badola et al. (2023) also reported PET fragments as a major polymer detected in Gangetic fishes. It should be noted that the extraction and identification methods used to analyse MPs can affect the results not only with respect to encountered concentrations but also polymer types (Kukkola et al., 2023a). For instance, extraction using NaCl may reduce the recovery of high-density polymers such as PET and PS as these materials have densities close to or greater than that of the solution, while zinc chloride ($ZnCl_2$) can effectively extract them. Consequently, the reliability and comparability of MP data across studies may be compromised if extraction methods are not standardised or accounted for in data interpretation. This can lead to differences in results, even for the same area.

4.2. Particle type and shape

The shape of a MP particle can be regarded as an indicator of its general origin and helps us better understand its fate under specific environmental conditions (Wu et al., 2019). As shown in Fig. 6, the Gangetic basin of northwest India (Patna, Varanasi, Kannauj, Anushar, and Rishikesh) shows high concentrations of MP fibres (80–90%) followed by fragments and other types of MPs in their surface water samples (Napper et al., 2021). Similarly, Kosasthaliyar, Adyar, and Muthirappzhayar Rivers of south peninsular India have 64% fibres in water samples as reported by Lechthaler et al. (2021). The concentration of fibres is also high in the surface water of the Godavari River in northwest India and the Kosasthalaiyar River in the south peninsular region (Priyanka and Govindarajulu, 2023; Sekar and Sundaram, 2023). It has been speculated that, as pilgrims and tourists tend to bathe close to the coast where they also wash their clothes, these practises might cause fibres from their clothes to become detached and be released into the surface water (Kumar

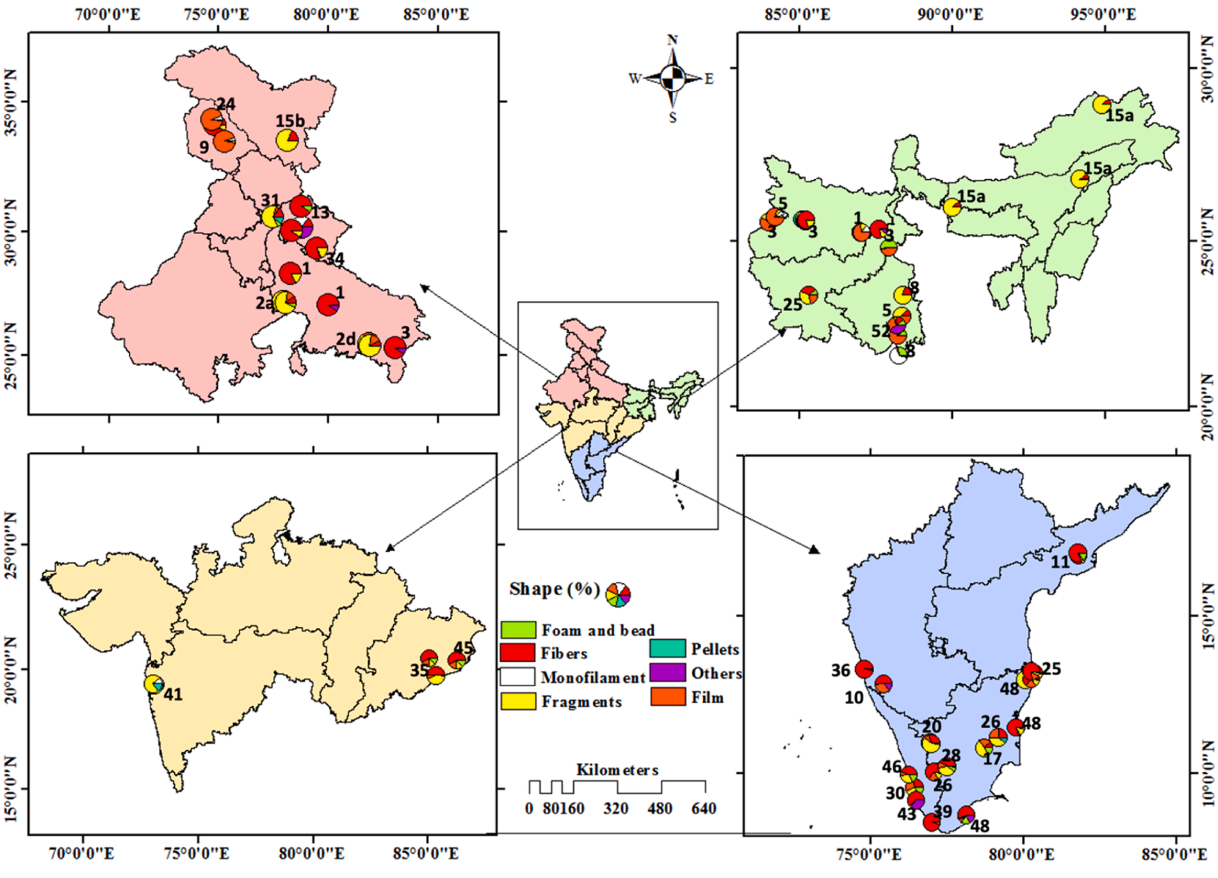

Fig. 6. Differences in the dominant shapes of MPs found in surface water and sediment of India.

et al., 2021a; Napper et al., 2021). The sediments of the Brahmaputra and Indus River show high concentrations of fragments (89%), followed by fibres (Tsering et al., 2021). MPs at the Hooghly River are varying in their shape and form along the river with a dominance of fragments in Digha (Upstream) that is decreasing towards Mashidghat (downstream), as reported by Ghosh et al. (2021). Interestingly, the Netravathi River shows a high concentration of fibres (52%) in surface water samples, while fragments are dominant in its sediment samples (Amrutha and Warrier, 2020), indicating that MP particles accumulating in the streambed sediment do not necessarily derive from local sources only, with deposition, transport and resuspension being controlled also by the hydrodynamic regime. Due to their lower buoyancy, fragments tend to settle more quickly out of the water column than fibres (Waldschläger and

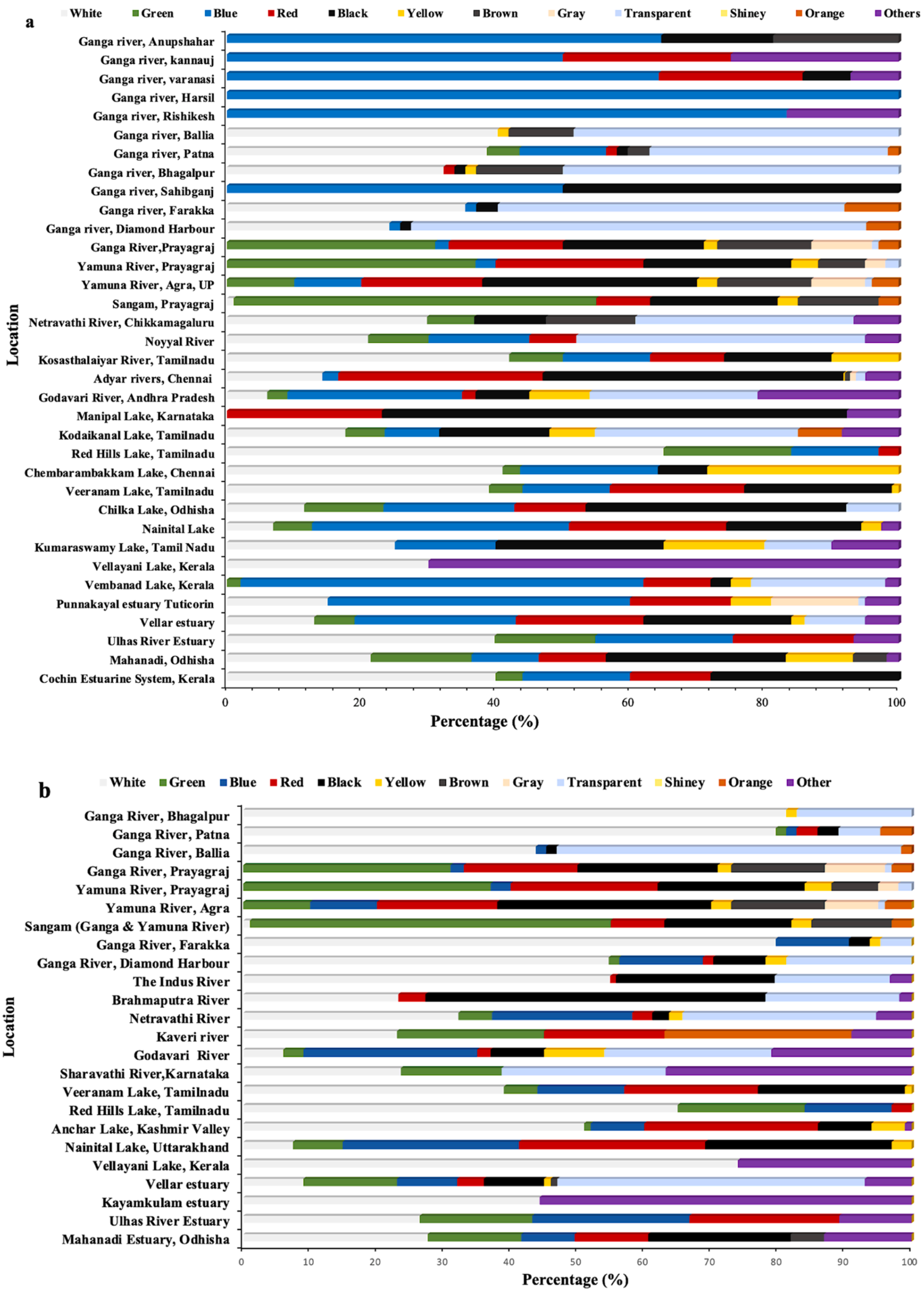

Fig. 7. Colour and size distribution of MPs in (a, c) surface water and (b, d) sediment of inland aquatic ecosystems of India.

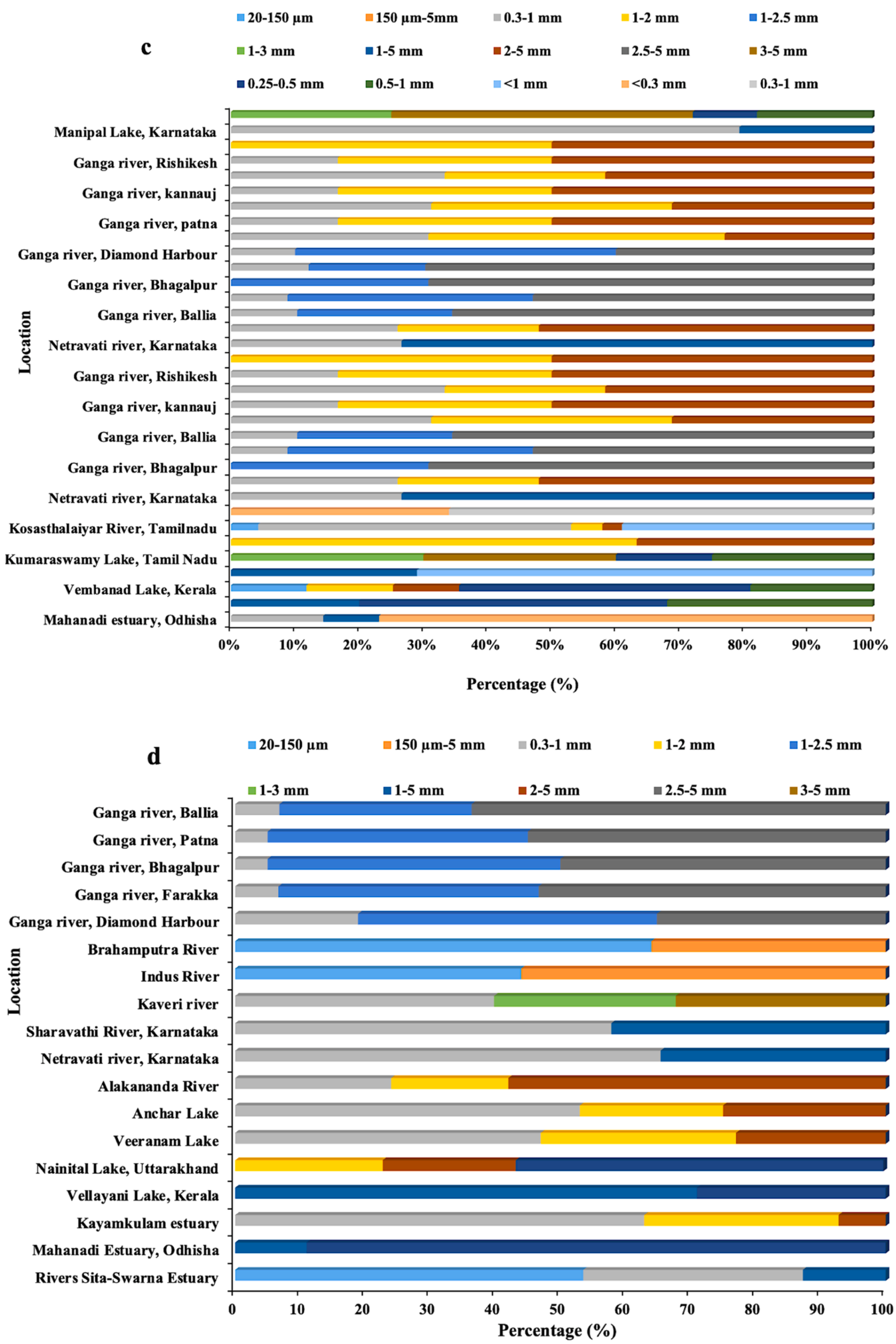

Fig. 7. (*continued*).

Schüttrumpf, 2019), which may provide one explanation for the encounter of more fragments in sediment samples than fibres (Eriksen et al., 2013; Lechthaler et al., 2021; Napper et al., 2021). However, the deposition and accumulation of MPs in sediment is a multi-faceted process and is influenced by various factors beyond buoyancy alone. Flow velocity, sediment characteristics, and the size and shape of MP particles all play crucial roles in shaping the spatial distribution of MPs within aquatic environments (discussed in Section

7).

A high abundance of fibres (65%) has been found in the surface water samples of the Punnakayal estuary of south peninsular India, followed by foam (12.4%) and fragments (3%) (Selvam et al., 2021), while the Ulhas river estuary of central India shows a majority of fragments (66–74%) in sediment samples, succeeded by pellets (15.37–17.24%) and filaments (10–21%) (Kumkar et al., 2021). Similarly, the sediments of Veeranam Lake demonstrate a high content of MP fragments (27%), followed by film and fibres (24%) (Bharath et al., 2021). A high proportion of MP fragments (64% and 63% respectively) has been found in both water and the sediment samples of Renuka Lake (Ajay et al., 2021), while Anchar Lake of northwest Himalaya and Kodaikanal Lake of south peninsular India have a high percentage of fibres (92%, 41.14%) in sediments followed by fragments (7.82%, 36.72%) (Laju et al., 2022; Neelavannan et al., 2022). Mostly fibres (95.71%) were reported in the surface water of Manipal Lake of south peninsular India (Warrier et al., 2022).

In general, most of the surface water samples indicate that fibres were the dominant MP shape, while fragments were found to be the dominant shape in most sediment samples, most likely due to their higher density (Eriksen et al., 2013; Gerritse et al., 2020). Several studies in other parts of the world have also reported that fibres have a significantly lower settling velocity than fragments (Hoellein et al., 2019a; Waldschläger and Schüttrumpf, 2019). One study conducted by Sruthy and Ramasamy. (2017) has found the majority to be film (31%), followed by fibres (27.07%), fragments (23.07%), and foam (18.9%) in the sediment samples of Vembanad Lake Kerala, hinting towards a significant breakdown of carry bags and thin plastic films of packaging material. Some extraction methods, particularly those involving harsh chemical treatments or mechanical processing, can cause fragmentation or degradation of MPs. These alterations in particle size and morphology can pose challenges during the analysis and interpretation of results. Fragmented or degraded particles may be misclassified or overlooked, affecting estimates of MP concentrations and characteristics. Furthermore, the variability introduced by extraction methods can hinder the comparability of data between studies, complicating efforts to understand the extent and impact of MP pollution in the environment.

4.3. Particle colour

As MPs are manufactured into different products or originate from the breakdown of larger plastic items, a wide range of different colours has been observed across the reviewed studies. Various types of plastics are manufactured for different needs, such as colourful nylon for clothing, transparent bottles and colourful packing, resulting in different colours of MPs (Giese et al., 2021; Muhib et al., 2023; Richards, 2015). Sometimes photooxidation also plays a role in changing the colours of MPs (Martí et al., 2020) during their aging process. In general, reporting MP colour can be rather subjective (Delgado-Gallardo et al., 2021), although the parameter can be helpful when studying the preferential uptake of MPs by certain aquatic fauna as these colourful particles mimic their preferred food source (Roch et al., 2020).

However, information on MP colours is only reported in 54% of the papers reviewed here. Of those, 40% papers focus on surface water and 25% on sediment, while 35% reported findings on both water and sediment. Figs. 7a and 7b depict the colours of MPs reported in those studies. Eight different MP colours have been identified in the sediment and surface water of the lower Ganga stretches such as Ballia, Patna, Bhagalpur, Farakka, and Diamond Harbour with an abundance of white and transparent MPs in most of the places, which signifies the loss of pigments and other dyes in the environment due to the effects of anthropogenic factors and sunlight during matrix degradation (N. Singh et al., 2021a). Similarly, the fractions of transparent and white MPs were high in both sediments and surface water samples of the Netravathi River (Amrutha and Warrier, 2020). The Ganga and Yamuna Rivers exhibit high concentrations of green, black, and red MPs at their confluence in Prayagraj, potentially because of distinct pollution sources from the two rivers. Specifically, the Yamuna River flows through heavily urbanized and industrialized regions before joining the Ganga River (Sengupta., 2006), which may introduce more coloured MPs into the Ganga. Various chemicals, including dyes, pigments, organic compounds, and industrial chemicals interact with MPs along river courses, leading to the introduction of coloured MPs (Campanale et al., 2020; H. Deng et al., 2020; X. Zhao et al., 2022). Thus, the MPs in each river could have different origins and properties, leading to the differences in colour observed at their confluence point (NPC, 2020). Black (30.8%) and white coloured (14.19%) MPs are also dominant in the surface water of minor rivers (Kosasthalaiyar, Adyar, and Muthirappuzhayar River) studied nearby Chennai (Lechthaler et al., 2021). Apart from these, Kaveri River has shown a high percentage of orange MPs (28%), followed by white (23%), green (22%), red (18%) and others (9%), demonstrating a high variability of coloured plastic debris from industries and urban wastewater entering the river (Maheswaran et al., 2022). Estuaries like Punnakayal and Vellar show an excess of blue coloured (45% and 24% respectively) MPs in their surface water samples, most likely linked to the extensive use of ropes and fishing gear (Kumkar et al., 2021; Nithin et al., 2022). Other than these, most of the estuaries and lakes reviewed for this study were dominated by MPs of white colour (Bharath et al., 2021; Ganesan et al., 2019; K. Gopinath et al., 2020; Neelavannan et al., 2022; Radhakrishnan et al., 2021; Selvam et al., 2021). The prevalence of light coloured MPs (white, transparent, off-white) could be attributed to environmental influences such as aging and fading induced by factors like temperature variations, UV radiation exposure, and oxidation processes (Martí et al., 2020;). These environmental stressors can contribute to the alteration of the original colouration of plastic items over time, resulting in the production of lighter-coloured MPs in aquatic ecosystems.

4.4. MPs size distribution

Despite the fact that MPs are widely described as plastic debris with a length of 1–5000 μm, there is still significant variation in their size distributions in the natural environment, particularly for the lower sizes (Hartmann et al., 2019). Almost all the research reviewed in this study has used a 5 mm upper size limit to define MPs. However, the approaches used to collect (e.g., by using a trawl net or by sieve-filtering water), extract (e.g., type of density separation), and identify MPs from environmental samples have a big impact on the smallest identifiable size of MPs recorded in a specific study. In India, MPs have been found in a wide range of sizes, which is not surprising due to their diverse sources and degradation in different environmental conditions. Fifteen different size classes of MPs are reported in the reviewed literature as shown in Figs. 7c and 7d. For example, N. Singh et al., (2021a) reported MPs in three categories of 0.3–1 mm, 1–2.5 mm and 2.5–5 mm in Ganga River, while 0.02–0.15 mm, and 0.15–5 mm has been used to account for MPs in the Brahmaputra and the Indus rivers in India (Tsering et al., 2021). This inconsistency continues to make the size comparison of MPs very challenging. More than 50% of the studies in India have used around 0.3 mm as their lower limit for size classification of MPs (Figs. 7c and 7d.), indicating that most studies may have overlooked substantial amounts of MPs that would be expected to be present as rather small particles. For example, the smaller size (20–150 μm) of MPs is more abundant in concentration in the sediments of the Brahmaputra and Indus River than the larger size (0.15–5 mm), as reported by Tsering et al. (2021).

In general, smaller sized MPs have been predominantly reported in most of the Indian lakes and rivers, e.g., the Alakananda River as reported by Chauhan et al. (2021) or the Kaveri River sediment (Maheswaran et al., 2022). However, in a few studies, larger MP particles have been found in higher number concentrations than smaller ones such as in surface water of the Ganga River in the transboundary area and in its lower section in the states of Bihar and West Bengal (Napper et al., 2021; N. Singh et al., 2021a) or the Nethravati River (Amrutha and Warrier, 2020). For most studies, it was found that the MPs in water samples were substantially smaller than those in sediment samples (Amrutha and Warrier, 2020; Radhakrishnan et al., 2021). Smaller MP particles have a higher likelihood of remaining suspended in water and being transported over longer distances through hydrodynamic forces (Ballent et al., 2012; Wu et al., 2024). Conversely, larger particles tend to settle and deposit on the surface sediment due to their greater density (Talbot, Chang. 2022a; Wu et al., 2024). It is important to note that earlier studies have focused predominantly on larger MP size ranges that can be identified more easily with standard microscopy techniques, without fluorescent dyes and in most lab settings, while smaller particles although anticipated to dominate (in numbers) in many environmental samples are much harder to extract, isolate and identify with a sufficient degree of certainty (Nel et al., 2019).

5. MP detection and quantification approaches used in India

Despite the fact that research on MP pollution has been undertaken for more than two decades, the procedures and methods applied for sample collection, sample processing, polymer identification and MP quantification are diverse and not standardised (Li et al., 2018; Silva et al., 2018). As such, findings in different studies with respect to MP size, shape, composition, and polymer type can vary greatly, which makes a direct comparison of the results often challenging (Van Cauwenberghe et al., 2015). As can be seen in Table 1, the articles reviewed in this study reiterate this diversity in field, lab and analysis methods.

Uncertainties in the analysis of MPs arise from a range of different factors including: i) field sampling techniques and the initial sample size, (ii) lab procedures and techniques used to dry, sieve, and filter samples to extract and isolate MPs, as well as sample storage, (iii) differences in counting and measuring techniques and technology used during MP enumeration and polymer identification, and (iv) inconsistent units used in MPs quantification and reporting (Cowger et al., 2020; Ivleva et al., 2017).

5.1. Sample collection

More than 80% of the literature reviewed for this study has documented sampling procedures, tools and techniques. Neuston and Plankton nets have been used for most of the surface water sampling but not all studies provide sufficient information on volume filtered through the net during sample collection. A Neuston net with a mesh size of around 300 μm has been used to collect surface water samples from rivers like Yamuna, Ganga and the confluence point of the Yamuna and Ganga, while a mesh size of 335 μm has been used for Kosasthalaiyar, Adyar and Muthirappuzhayar river (Lechthaler et al., 2021; NPC 2020). Similarly, plankton nets with different mesh sizes have been used to collect surface water samples of different Indian lakes and river. A plankton net with a mesh size of 20 μm has been used in Veeranam Lake, while other studies used 100 μm in river Alaknanda, 120 μm in Red Hills Lake and Vellayani Lake, 200 μm is used in Cochin Estuarine System and 300 μm in Vellar estuary and the central and lower stretch of the Ganga River (Bharath et al., 2021; Chauhan et al., 2021; K. Gopinath et al., 2020; Immanuvel David et al., 2023; Nithin et al., 2022; Suresh et al., 2020). A stainless steel spoon has been used to collect sediment samples of the Netravathi, Sabarmati,Sharavathi, Brahmaputra, Indus River and also for lakes like Pangong, Tsomoriri and Tsokar (Amrutha and Warrier, 2020; Ram and Kumar, 2020; Tsering et al., 2021). Grab sampling to collect sediments has been employed in Anchar, Red Hills, Veeranam, Vembananad, Vellayani, Nainital, Kodaikanal, Noyyal and Renuka Lakes, as well as some estuary studies, such as Vellar and Kayamkular estuaries and major estuarine system of Tamilnadu (Ajay et al., 2021; Ayyamperumal et al., 2022; Bharath et al., 2021; K. Gopinath et al., 2020; Nithin et al., 2022; Radhakrishnan et al., 2021; Sarkar et al., 2021; Sruthy and Ramasamy, 2017). Napper et al. (2021) have used a hand operated bilge pump to collect their water samples from the transboundary region of Ganga River while Van Dorn water samplers have been used to collect the water samples from a depth of 15 cm of river Hooghly (Ghosh et al., 2021). In some of the cases, only stainless steel containers have been used to collect water and sediments samples (Kumkar et al., 2021; Sarkar et al., 2021), while some other studies have used pumps for sample collections (Napper et al., 2021; Selvam et al., 2021). Cast nets of mesh size 10–15 mm have been used to collect organisms from EKW as reported by Sarkar et al. (2021). Some studies have not specified any sampling techniques (Table S1).

Most of the studies looking at water samples have used a standard sampling unit of per volume, while one study conducted in Tamilnadu (Veeranam Lake) has used an area (km^{-2}) as a sampling unit (Bharath et al., 2021). For sediments, mostly weight (kg^{-1}) has been used as a sampling unit. Even though the reporting of MP concentrations depends to a large degree on the selected sampling tools, mesh size, sample depth and remoteness from the centre of anthropogenic activity (Qiu et al., 2016) and this has been brought to the attention of the scientific community (Cowger et al., 2021, 2020b; Kurki-Fox et al., 2023), efforts are still lacking to define/develop more standardized sampling procedures making a comparison between studies complicated. Time, location, and duration of sampling should also be carefully studied to ensure collected samples are most representative for the conditions they are reporting on.

5.2. Sample processing

Almost all environmental samples contain some impurities (organic, inorganic, and detritus) in different forms (Prata et al., 2019), which might be confused as MPs during counting and polymer identification. Therefore, removal of organic matter by digestion might be required. Different digestion methods are briefly summarised in Table 1. Hydrogen peroxide (H_2O_2) has been used in most of the studies to digest the organic matter present in the samples (Bharath et al., 2021; Chauhan et al., 2021; Kumkar et al., 2021; Neelavannan et al., 2022; Sarkar et al., 2021, 2019; Sharma et al., 2020; Sruthy and Ramasamy, 2017; Anagha et al., 2023; Jain et al., 2024; 2020), at times using only heat as a catalyst, while in other studies ferrous iron (Fe^{2+}) is used as catalyst via Fenton's reagent (Ajay et al., 2021; Amrutha and Warrier, 2020; K. Gopinath et al., 2020; Maheswaran et al., 2022; N. Singh et al., 2021a). The latter is able to degrade organic matter at a much faster rate (Hurley et al., 2018) albeit at potentially higher temperatures. As such, when using Fenton's reagent, care must be taken to control the temperature of the reaction as previous studies have found that at higher temperatures a degeneration of polymers can more likely occur (Munno et al., 2018). However, temperature control measures have not always been discussed sufficiently in all studies reviewed here. Sarkar et al. (2021) have used 30% H_2O_2 to digest gastrointestinal tracts of the aquatic organism to detect MPs. Radhakrishnan et al. (2021) have used 30% H_2O_2 solution followed by 2 N HCl to treat sediment samples of the Kayamkulam estuary. Another study suggests that the shape of MPs may be destroyed by using acids for digestion purposes (Claessens et al., 2013). In the enzymatic breakdown, samples collected for MP analysis are treated with a variety of enzymes such as cellulase, amylase, proteinase, lipase, and chitinase (Cole et al., 2015; Eerkes-Medrano et al., 2015). Since the enzymes are expensive and their reaction temperature must be controlled during storage, the method has not been followed widely in the studies discussed here. Formalin has been added to degrade the organic substances present in the surface water samples of the Yamuna and Ganga rivers (NPC (2020). Another digestion technique utilizes Sodium Hypochlorite (NaClO), which efficiently breaks down organic components in the samples. However, it is essential to note that while effective, this method may have adverse effects on certain types of MPs ((Lv et al., 2021; Mushtak et al., 2024).

Aside from organic matter digestion, density separation might be required to separate the MPs from the respective environmental matrices. The method used for density separation can have a profound impact on number concentrations. For example, more than 60% of the studies have used NaCl for density separation due to its non-toxic nature, wide availability and ease-of-use (Ajay et al., 2021; Chauhan et al., 2021; K. Gopinath et al., 2020; Kumkar et al., 2021; Neelavannan et al., 2022; N. et al., 2021; Sruthy and Ramasamy, 2017). Often, density separation was only required to extract MPs from sediment. However, NaCl solution (density of about 1.2 g/cm^3) have low efficiency in separating the higher density MPs such as polyformaldehyde, polyethylene terephthalate and polyvinyl chloride (Ivleva et al., 2017; Nuelle et al., 2014). Consequently, some researchers have used Zinc chloride ($ZnCl_2$, density of 1.4–1.6 g/cm^3) to extract MPs more effectively (Amrutha and Warrier, 2020; Laju et al., 2022; Radhakrishnan et al., 2021; Sarkar et al., 2019). However, $ZnCl_2$ is less environmentally friendly as compared to other commonly used salts (X. Zhang et al., 2018), it must be recovered and reused (Prata et al., 2019). Nonetheless, it is commonly used in combination with so-called Sediment-MPs Isolation (SMI) units as demonstrated by Bharath et al., (2021). Tsering et al. (2022), (2021) have used sodium tungstate dihydrate ($Na_2WO_4.2\,H_2O$, 1.4 g/cm^3) solution to separate MPs from the sediments of rivers (Indus and Brahamputra) and lakes (Pangong, Tsomoriri and Tsokar) because of its high density. Sodium tungstate dihydrate is easy to use and relatively safe to handle (Joyce et al., 2023; Pagter, 2018a; Pagter et al., 2018b). Other salt-based density separation techniques such as that outlined by (X. Zhang et al., 2020) have not been applied in an Indian context. Lechthaler et al. (2021) tested an interesting and low-cost separation technique based on canola oil to separate MPs from surface water samples of Kosasthlaiyar, Muthirappuzhayar and Adyar Rivers.

5.3. Characterisation techniques

After purification and density separation, suspected MP particles have to be identified and properly quantified. The most frequently used approach for MP enumeration (with respect to number concentration, shape, colour and size) is to first analyse particles by using optical or fluorescent microscopy or even the naked eye in the case of large MPs. This step is usually followed by confirmation (polymeric analysis) using Fourier transform infrared spectroscopy (FTIR) or Raman spectroscopy. Generally, most studies reviewed here followed this approach by determining shape, colour and abundance using microscopy, while the chemical characterisation and composition are confirmed using FTIR or Raman spectroscopy (Amrutha and Warrier, 2020; Bharath et al., 2021; Neelavannan et al., 2022; Selvam et al., 2021; Kumkar et al., 2021; Radhakrishnan et al., 2021; Sarkar et al., 2019; N. Singh et al., 2021a). Sometimes, these instruments are coupled with microscopy for a better understanding of the results. Tsering et al. (2021) used semi-automated μFTIR to analyse the MPs in sediment samples of Brahmaputra and Indus River. Similarly, in the Vellar estuary, the MPs present in surface water and sediment samples have been identified by FTIR -ATR and μFTIR (Nithin et al., 2022). Raman spectroscopy was used by (Tsering et al., 2022) to characterise the MPs present in sediment samples of Pangong, Tsomoriri and Tsokar Lake. Ram and Kumar (2020) used an optical microscope of 50x magnification and scanning electron microscopy to analyse MPs in sediment samples of the Sabarmati River. Out of 52 studies reviewed here, around 55% report the use of microscopes for visual analysis of MPs (Table 1). For the biological samples (aquatic organisms), Nile Red staining has been applied before using florescence microscopy (Sarkar et al., 2021).

It should be noted that the method of microscopy can have a potential impact on results. For example, it has been shown that Nile

Red, a fluorescent dye used for staining MPs prior to fluorescent microscopy might not stain well certain polymers (especially fibres) such as PET (Araujo et al., 2018; Wiggin and Holland, 2019). Subsequently, these MPs would express a lower pixel brightness and might be missed during counting where fluorescent microscopy is the sole method applied, which is why recent studies suggest combining fluorescent with bright field microscopy (Kukkola et al., 2023a). On the other hand, the use of Raman spectroscopy or microFTIR for polymer identification is based on matching measured particle spectra to recorded spectra (mostly of pristine standard particles) in a database. The matching threshold for both spectra (e.g., at least 70%), as well as other post-processing methods that might have been applied such as signal smoothing and/or peak picking are often not reported in the studies discussed here, which can lead to uncertainty in the accuracy of the reported results.

6. MP pollution in India as part of a global trend

MP particles are contaminating inland aquatic ecosystems around the world, with concentrations varying substantially in space and time (González-Pleiter et al., 2020). Due to variations in sampling techniques, applied analytical methods, and reporting standards, it should be emphasised that the ability to draw comparisons from previously published research remains limited. Undoubtedly, India is home to some inland water bodies that are heavily polluted with MPs. For example, MPs have been found in the entire Ganga River from its source to sink with a maximum concentration of 10,000 MPs/kg for particles > 5 μm (R. Singh et al., 2021b) at Masjid Ghat, Patna, which is comparable to other major rivers in the world polluted with MPs. For instance, Wang et al. (2022) found 300 MPs/kg in the Yangtze River, while Wen et al. (2018) reported MP concentrations ranging between 270 and 867 MPs/kg in the urban water sediments of Changsha, using the same lower size limit. The lower limit of observed MP concentrations in water and sediment samples has a great impact when drawing conclusions from the reviewed Indian data in comparison to data from other regions. For example, (Frei et al., 2019) reported the highest MP concentration (~30,000 particles per kg dry weight) in Roter Main River, Germany by looking at particles between 20–50 μm. Some other studies have used 63 μm as their lower size limit during analysis. For example, a high concentration of MPs has been reported in the River Rhine, Germany (4000 MPs/kg, > 63 μm, (Klein et al., 2015)) and a concentration of 165 MPs/kg was reported in the heavily urbanised catchment of the River Tame, UK (Tibbetts et al., 2018). The Gallatin River, USA (1–67500 MPs/m^3; Barrows et al., (2018)) has shown concentrations greater than the Indian river Alaknanda (11320 MPs/m^3(Chauhan et al., 2021)) for a similar size range (>100 μm).

While some recent riverine studies showed that MP concentrations in densely populated areas were higher than those in sparsely populated ones and elsewhere in the world (Duis and Coors, 2016; Mani et al., 2015), other studies from the Indian Himalayas show that rivers and river sections in rather remote areas can also be heavily polluted with MPs, in spite of less intensive human activities (Tsering et al., 2022, 2021). Often, data on surface water MP concentrations alone are not enough to fully understand the local sources, transport and downstream export of MPs. Estuaries are important entry points for MPs into the ocean. The Pannakayal estuary of southern India has shown high MP concentrations of 19,900 MPs/m^3 in its surface water (Selvam et al., 2021), which is greater than the Pearl River estuary (8902 MPs/m^3; Yan et al., (2019)) and Yangtze estuary China (500–10,200 MPs/m^3; Zhao et al., (2014)) when looking at similar particle sizes (>50 μm and >32 μm, respectively). Similarly, benthic sediment MP concentrations reported for the Changjiang estuary, China (121 ± 9 particles/kg; (Peng et al., 2017)), is about three to four times lower than the concentration found in the sediment of Kayamkulam estuary of coastal Tamilnadu (433 MPs/kg; (Radhakrishnan et al., 2021)). In case of lake MP pollution, the concentrations observed at Renuka Lake (Ajay et al., 2021) are comparable with other lakes of the world like Taihu Lake, China (3400–25,800 MPs/m^3;Su et al., 2016), Poyang Lake, China (500–34,800 MPs/m^3;Yuan et al., 2019), Sassolo Lake Switzerland (2600 MPs/m^3; Velasco et al., 2020), and Lake Baikal, Russia (1065 MPs/m^3; Karnaukhov et al., 2020). In general, in India as well as in other parts of the world, MPs with a size <1 mm seem to be more common in freshwater ecosystems than larger MPs, with decreasing trend as size increases (Bharath et al., 2021; Corcoran et al., 2015; K. P. Gopinath et al., 2020; Neelavannan et al., 2022).

PE, PP, PS, PET, PA and PVC were the main polymers reported for MP pollution across the world (Alvarez-Vazquez et al., 2004; Talbot, Chang. 2022b; Vaid et al., 2021; Vivekanand et al., 2021). Similar to India, PE and PP are the most common MPs found in parts of China (K. Zhang et al., 2018), South America (Ardusso et al., 2021), and Bangladesh (Islam et al., 2022). For example, the Yangtze River of China has shown a high abundance of PE and PP polymers similar to River Ganga. Currently, there is no clear understanding of the reasons of the discrepancies in polymer composition in inland aquatic ecosystem. More studies are needed to determine if a predominant polymer group is found in the contaminated zone and whether the composition varies depending on sample location and distance travelled by the particles (Eerkes-Medrano et al., 2015; Fahrenfeld et al., 2019; Hartmann et al., 2019).

The global issue of MP pollution in aquatic environments and its implications for both the environment and public health have spurred widespread concern. 88% of freshwater fishes are found contaminated with MPs in Chhattisgarh, India, comparable to prevalence levels reported in other parts of the world such as Serra Talhada, Brazil (83%), Lake Michigan, USA (90%) and Thames England (75%) ((McGoran et al., 2017; McNeish et al., 2018; Shukla et al., 2022; Silva-Cavalcanti et al., 2017). Discrepancies in prevalence could be attributed to using varied analytical methods, lack of standardized identification methods, local plastic pollution levels, and diverse feeding habits. These uncertainties need further exploration to understand the specific factors contributing to elevated MP levels in these regions.

7. Integrating hydrology into the study of MPs in Indian inland aquatic ecosystems

The existing literature on MPs in India has predominantly focused on their occurrence, spatial distribution, and environmental effects. However, the hydrological conditions, which may play a crucial role in the fate and transport of MPs, have so far been largely overlooked. Yet, understanding how MPs interact with water bodies, their transport mechanisms, and the role of hydrological processes is essential for a comprehensive understanding of MP pollution (Das and Jain, 2023; Gupta et al., 2024; Kye et al., 2023; Waldschläger et al., 2022). Incorporating this information into MP research can lead to a more accurate prediction of MP transport patterns and pollution hotspots (Hoellein et al., 2019a; Waldschläger et al., 2022).

Most of the studies reviewed here have provided evidence of MPs in water and sediment at a certain location and certain time (snapshot-sampling). However, similar to other dissolved or particulate contaminants as well as suspended sediments, MP concentrations vary in space and time. For India, this spatio-temporal variability needs to be better linked to hydrological parameters as is being done more frequently now for other regions of the world. These hydrology-related parameters could include discharge or flow rates (Kumar et al., 2021a,b; Lu et al., 2023; Yadav et al., 2022), streambed morphological conditions (Hoellein et al., 2019a) or hyporheic exchange (Drummond et al., 2020). For examples, an enhanced understanding of discharge in subsequent downstream sections has allowed (Kukkola et al.,2023b) to improve downstream MP load estimates for parts of Boulder Creek, USA and the authors found that large amounts of MP particles were rerouted through the catchment together with river water abstracted for agriculture purposes. Such water (and MP particle) redistribution across Indian catchments is very likely, as in many areas river water is a major water source for agriculture, horticulture and livestock (Brown et al., 2021; Dilshad et al., 2019; Rasul, 2010; Srivathsa et al., 2023). Yet, data on catchment-wide and river-corridor MP transport as well as MP export across catchments in India is lacking. However, this data is needed to consider rivers as more than just conduits with respect to downstream MP transport.

Hydrological parameters such as discharge can significantly vary in space and time, for example, due to changing streambed conditions or because of seasonal weather patterns, with the monsoon as one of the most prominent ones in India. However, less than 20% of the studies discussed here have looked at seasonal weather effects on MP transport. Most of the studies reported higher concentrations of MPs during the post-monsoon season (Ephsy and Raja, 2023; Jeyasanta et al., 2023; Nithin et al., 2022; Warrier et al., 2022;). For instance, Warrier et al. (2022) observed a twofold increase in MPs during the monsoon season compared to the post-monsoon period at Lake Manipal. Similarly, Ephsy and Raja. (2023) found elevated MP concentrations in the monsoon period (12410 MPs/m^3) compared to both pre-monsoon (11160 MPs/m^3) and post-monsoon periods (3330 MPs/m^3) at Kumaraswamy Lake. Heavy rainfall plays a pivotal role in this phenomenon by intensifying surface runoff erosion on land, facilitating the transport of plastic materials from terrestrial environments to water bodies, including rivers (Amrutha et al., 2023; Das et al., 2022; Haque and Fan, 2023). Episodes of heavy rainfall, storm surges, and floods can significantly augment plastic concentrations mobilized by rivers (Amrutha et al., 2023; Bhat et al., 2023; Crispin and Parthasarathy, 2023; Haque and Fan, 2023). Contrary to the elevated MPs concentration in water during the monsoon, sedimentary dynamics exhibit a different pattern, with higher concentrations observed during the pre-monsoon season compared to the post-monsoon period (Amrutha et al., 2023; Nithin et al., 2022). Crispin and Parthasarathy. (2023), observed a high concentration of MPs in stream sediment during monsoon, while the opposite was observed for lake and reservoir sediment. This pattern may be attributed to the substantial influx of MPs carried by freshwater inflow, settling at the sediment bottom before the onset of the dry season (Cordova et al., 2022; Nithin et al., 2022). The observed seasonal variations in MP concentrations highlight the complex and multifaceted interactions between hydrological processes, sediment dynamics and MP transport mechanisms. To obtain a comprehensive understanding of MP pollution, further studies are needed to investigate the interactions between MPs and weather dynamics. Additionally, intermediate to long-term changes in hydrometeorological conditions should also be considered as they may lead to further changes in discharge patterns due to alternating rainfall length and intensity. The current status of plastic pollution in India's groundwater resources remains less known, requiring further investigation and detailed exploration to assess the extent and impact of this environmental compartment. However, activities such as managed aquifer recharge as well as agricultural practices such as mulching or the use encapsulated seeds, fertilizer and pesticides to allow for delayed release have been shown to potentially pollute groundwater resources with plastic particles and it is largely unknown so far under which conditions these plastic particles can be transported towards freshwater bodies such as lakes or rivers (Moeck et al., 2023).

8. Conclusions

Studies related to the presence of MPs in Indian inland aquatic ecosystems are limited, in spite of the intense exposure of a large part of the world's population to these environments. Based on our systematic review, we can conclude that MPs have been found in almost all inland water systems of the country. This includes the holy river Ganga and its tributaries which have been found to be polluted by MPs in all samples analysed. Additionally, studies on MP uptake by various aquatic species showed that particle ingestion is common, including in commercially important fish species and mussels, highlighting the risk for entrance into our food chain. The use of diverse size categories in the assessment of MP quantities adds complexity to cross-study comparisons and requires careful consideration of the methodologies employed in future. Additionally, the presence of MPs in the sediment during summer and in the water during the monsoon highlights the complicated relationship between weather conditions and the fate of MPs in aquatic ecosystems. These relationships between hydrological parameters, seasonal variations, and MP transport warrant closer scrutiny, especially considering the potential impact on both aquatic life and human well-being. It has been observed from the previous studies that Hydrological processes, including river flow, currents, and tides, significantly influence the transport of MPs. These processes also play a critical role in the sedimentation and resuspension of MPs. Changes in water flow, sedimentation rates, and turbulence can impact the vertical distribution of MPs in aquatic environments within water columns and sediment beds. By incorporating these considerations, researchers can enhance the comprehensiveness and applicability of their findings, contributing to a more holistic understanding of the intricate interactions between MPs and aquatic environments.

The majority of the studied sites (Fig. 2) is located in the Northern and Southern parts of the Indian sub-continent while vast areas in Western and Central India have a limited number of studies with respect to MPs despite their richness in aquatic ecosystems. While it is prudent to assume that aquatic ecosystems in those under- and unstudied regions are also contaminated with MP, future studies should focus on closing this knowledge gap by providing data from those areas. While the current studies have provided ample qualitative and semi-quantitative examples of MP contamination in water bodies and first research has been carried out with respect to the spatial distribution of MP particles in river water column and sediment future studies should focus their efforts away from pure snap-shot sampling. We argue that for monitoring programmes to be established in the future, repeat-sampling at identified hot-spots is crucial and spatial information on MP pollution needs to be linked to the hydrological processes governing catchment-wide transport. This will provide researchers and managers with a better understanding of where within the river networks MP particles actually end up.

9. Future prospective

Future research should focus on better understanding the potential impact of MP pollution on soil and groundwater resources, as these compartments are in constant interaction with aquatic ecosystems such as rivers, lakes or glaciers. Atmospheric transport and deposition patterns with respect to MPs are also largely unknown, yet atmospheric deposition has been shown to be an important input factor, especially in areas with comparably little human exposure.

The studies reviewed show that most MP researchers in India use widely accepted analytical tools (such as Raman spectroscopy or microFTIR) and laboratory techniques. However, future efforts should focus on improving reporting standards. For example, exact instrument configurations, post-processing software and algorithms used, particle extraction techniques in the lab as well as investigated particle size ranges were not always reported yet are crucial for a good comparison of results across regions as well as the design of follow-up studies. The differences in applied extraction, digestion and density separation techniques in the lab are likely to contribute to some of the variations in concentration observed between different studies and future efforts could be undertaken to establish a more standardized lab protocol that can then be followed in large-scale monitoring studies to achieve a good comparability among different sites.

In order to better identify local sources of MP input into aquatic ecosystems future studies could also be focused on agricultural practices to understand whether mulching and encapsulated seeds or fertilizers are important MP contributors. Additionally, local wastewater treatment efficiency with respect to MP removal needs to be better understood. Furthermore, local residential and commercial practices (e.g., textile washing in rivers, discharge of untreated wastewater) might need to be studied further in certain regions in terms of their impact on local aquatic ecosystems.

Authors statement

In the course of conducting this study and preparing the accompanying manuscript, the authors employed various tools and software applications to facilitate data analysis and visualization. Notably, ArcGIS tools were utilized for mapping purposes, while Microsoft Excel and Origin Pro were employed for data plotting and analysis.

The authors hereby confirm that throughout the entire research process and manuscript preparation, no AI tools were utilized for report generation or any aspect of manuscript composition. The authors affirm that the content of this paper is a result of meticulous research, data analysis, and interpretation carried out using traditional analytical methods and software applications.

We appreciate the opportunity to contribute our research to the Journal of Hydrology Regional Studies and remain dedicated to maintaining the highest standards of academic integrity in our scientific endeavours.

CRediT authorship contribution statement

Brijesh Kumar Yadav: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Jaswant Singh:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Stefan Krause:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition. **Uwe Schneidewind:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation.

Declaration of Competing Interest

The authors of this study state that they do not have any known conflicting financial or personal interests that might have impacted the findings of this research.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2024.101798.

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