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REVIEW ARTICLE

# Microplastics in lentic environments: implications for Indian ecosystems

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## Abstract

The paper focused on occurrence, characterization, and analytical methods of microplastic (MP) pollution in the lentic environment mainly for the Indian scenario. To understand the flow of MP from plastic waste, a material flow diagram was developed using STAN, assigning the transfer coefficients based on existing scientific literature and primary survey from local recycling facilities and industries. The quantity, morphology, and polymers of MP in the water and sediments of the lentic environment were compared for various states from 2011 to 2022. The reasons for the geographical heterogeneity in microplastics may be the migratory routes of MPs in the ecosystems like commercial uses and wastewater characteristics which possibly discharged in lentic system. Factors like particle density, water surface area, water surface depth, wind speed and direction, and water flow size mainly affect MP concentrations in the lentic water body, and mainly PHI and PLI are keys to MP risk analysis. The surface characteristics of MPs reveal that it absorbs many toxic contaminants including heavy metals. The impacts of MP on ecosystem and human health were also discussed. The impacts of socioeconomic conditions on MP concentrations for different states in India were also added. Proposed methods for plastic waste generation control also included which will help for developing policy in future to prevent MP pollution in lentic environments and also motivate future researchers to establish new standardized methods of MP analysis.

**Keywords** Microplastic · Occurrence and material flow · Identification and classification · Ecological risk and human health · Policy of plastic waste management · Indian scenario

## Introduction

In recent years, there has been a lot of focus in India on the distribution and effects of plastic waste, including microplastics (MPs), in various natural environments. Microplastics are little plastic particles having a diameter of 1 $\mu$m–5 mm that have found their way into the aquatic, terrestrial, and atmospheric environments. Microplastic (MP) (smaller than 5 mm) is released into the environment through a variety of sources and entry points, either as primary MPs (smaller than 5 mm) or as secondary MPs (larger pieces of plastic degrading into smaller pieces). The most significant source of MP in fresh water is the fragmentation of plastic waste that has already been disposed of in aquatic environments through various processes such as photodegradation, mechanical degradation, and microbial degradation; however, abrasion of plastic coatings and car tires may also be a greater source. In recent investigations, it has also been discovered that wastewaters contain a large number of MPs. Synthetic textile fibers created during laundry, polyethylene microbeads rinsed out of cosmetics, and disintegrating components of bigger consumer objects flushed down the toilet are all found in wastewater. MPs in the environment come in a variety of sizes and shapes, with the majority of MPs in the environment having irregular shapes, such as pieces, fibers, or films. Though early researchers reported the presence of MPs in nature in the 1970s (Carpenter and Smith 1972; Colton et al. 1974; Gregory 1977), they were not extensively studied until the early 2000s, qualifying them as a contaminant of emerging concern (CEC) (Wagner et al. 2014) due to their potential to cause biosphere threats. MPs have been identified as one of the most important anthropogenic pollution indicators (Waters et al. 2016). It can persist

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in nature for a long period and cause serious environmental pollution due to their sluggish breakdown rates. Due to their association with additives (added or produced during manufacturing), heavy metals, and persistent organic pollutants present in the environment (Rochman et al. 2015), MPs are commonly referred to as a "cocktail of contaminants," and this mixture of contaminants can be bio-available to various aquatic biota, including humans, upon ingestion, inhalation, or physical contact with contaminated materials. It was reported that on an average, global people consume between 39,000 and 252,000 MPs annually (Novotna et al. 2019). MPs have also been reported to have the ability to accumulate hydrophobic organic pollutants such as persistent organic pollutants (POPs), polyaromatic hydrocarbons (PAHs), polycyclic biphenyls (PCBs), and other chemical mixtures such as flame retardants, additives, and plasticizers in their polymer structure (Kwon et al. 2017). Chemical contaminants (Hartmann et al. 2017)(Caruso 2019) and diseases can be disseminated by MPs (Sgier et al. 2016; Wu et al. 2019a). The enrichment of MPs in the human body via the food chain is unavoidable, given their ability to migrate in organisms (Wu et al. 2019b). The possible dangers of digestive system inflammation (von Moos et al. 2012a), poor food absorption (Hurley et al. 2017), and its effects on development and reproduction are all effects of MPs on organisms (Sussarellu et al. 2016).

The majority of MP contamination in India originates on land and is transported by rivers to the ocean. Pollutants (both organic and inorganic) have infiltrated estuarine sediments in India via numerous paths in recent years as a result of fast industrialization, economic development, and climatic change, resulting in lentic, coastal, and marine environmental health concerns (Chakraborty et al. 2014). MPs were found in different fish species, *Rastrelliger kanagurta* and *Epinephelus merra*, that were purchased from the Thirespuram and Punnakayal fish landing sites in Tuticorin (Kumar et al. 2018). MPs (polyethylene (PE) and polypropylene (PP)) were detected in the guts of 33% of landing fish, with microfibers (red, black, and translucent colors) accounting for 80% of the total (Kumar et al. 2018) which will eventually be transferred to human. Therefore, MPs not only have negative impacts on aquatic and terrestrial organisms but also have synergistic effect on environment by combining with other toxic elements.

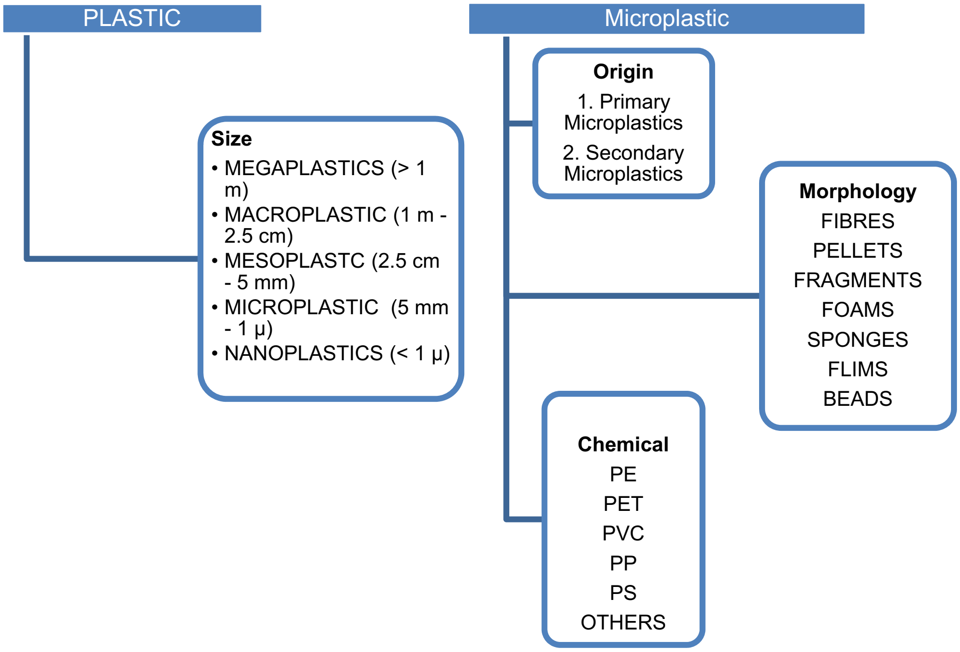
The investigation of occurrence, quantification, analyzation, and characterization and health and environmental effects of MP in the lentic environment in India is the main subject of this review. Though lots of research papers existed on review work of MPs on marine ecosystem, very less research works considered MP in freshwater mainly lentic ecosystem as their subject. Characteristically, the surface water and bottom sediment in a lentic environment are relatively unique compared to other water environments like marine, estuarine, or lotic. Lentic water has relatively lower flow rates, and since the residence time of water is much high, therefore, it can hold water longer than the lotic environment which allows more MP to be stabilized. Contamination detection in a lentic environment is very important since 11% of the total land area of India are covered by lentic system and they are widely distributed over countries. To compare the levels of MP pollution, in the context of India, the origins and abundance of MPs in different stagnant water (Pond, Lake) regions were considered.

Main source of MPs is the degradation of unattended plastic wastes. Recycling is the most suitable method of plastic waste management to reduce the amount of plastic waste to be left unattended in environment and lowering the overall adverse effects of plastics in the environment. Complexity arises due to the different types of plastics, additives, and composites during plastic recycling. Therefore, different countries adopt different recycling strategies depending on their societal acceptance and economic benefits. To delineate the MP concentration in lentic ecosystem of India, the material flow analysis of plastic waste is the prerequisite. Therefore, a material flow diagram (MFD) was developed to determine the amount of plastic waste uncollected and discharged in the environment using STAN. The MFD required a review of the different recovery and recycling initiatives taken by India which are also listed in this paper. The migration pathways of different types of MP in lentic systems were presented. In addition, the possible routes of entry for the MP into the lentic environment and socioeconomic condition of the sampling areas were also discussed which gives a better understanding of reasons of the MP pollution in India. The analytical methods like visual detection, Fourier transform infrared spectroscopy (FTIR), Raman spectroscopy, scanning electron microscopy (SEM), and pyrolysis-gas chromatography-mass spectrometry that have been used so far for characterization and quantification of MP that have been used so far for India were also discussed. The knowledge gap was identified for Indian context and proposed method to reduce MP pollution was also added.

## Classification of microplastics

Microplastics can be categorized in a variety of ways (Fig. 1). On the basis of size, plastic waste obtained in aquatic systems may be classified as megaplastics, macroplastics, mesoplastics, microplastics, and nanoplastics. They are classified as primary or secondary MPs depending on their origin. Plastic particles known as secondary microplastics are produced when bigger plastic debris is broken down in a way that reduces its sizes and volumes. Biodegradation, physical degradation, photodegradation, and chemical degradation produce secondary MPs from plastic deterioration. Primary MPs are discharged directly into the aquatic environment by human activities and

**Fig. 1** Classification of microplastic



refer to the direct use of plastic microbeads in particular cosmetics and other products. Based on morphology, they are classified as fibers, pellets, fragments, films, sponges, beads, and foams. Chemically, they may be classified as polyethylene terephthalate (PET), polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and others.

### Morphology of microplastic

Plastic pellets, plastic granules, microfibers, foam plastics, films, and other materials are among the most common morphologies of microplastics. Fibers (polyesters) and sheets of film were discovered to be the most important morphotypes of plastic particles. In comparison to other morphotypes such as film and beads, MP contamination emphasizing fibers has lately been addressed (Rodrigues et al. 2019). These fibers in the lotic and lentic sediment could have come from municipal sewage effluents due to garment washing (Lahens et al. 2018). Chemically, MPs may be of polypropylene (PP), polyethylene (PE), polystyrene (PS), polyvinyl chloride (PVC), and polyethylene terephthalate (PET).

Microplastics have a wide range of features and qualities due to their diverse origins, kinds, and degradation processes in the environment, which lead to inconsistencies in separation and identification procedures.

## Methods

### Literature review

Only the relevant literature was chosen for analysis because the data in this study came from references concentrating on MP analysis in India for the years 2011–2022. The references were found using search terms such as “microplastic analysis in India,” “lentic,” “Source and abundance of MPs in lentic ecosystems,” “microplastic analysis in the lentic environment,” “Migration pathway of MPs,” and “Human health and Ecological Risk of MPs” using the search engine Google scholar, Scopus, and Science Direct. Four criteria were used to choose the papers. First, the literature was chosen based on MP measurement units and chemical composition of MP; second, the literature was chosen based on data analysis and MP determination methods; third, the literature was chosen based on morphological classification; and fourth, the literature that gave information on human health and environmental harm as a result of MP contamination levels in a lentic setting of India. Additional information on the prevalence of MPs in surface water and sediment, as well as others, particularly in the lentic system was also analyzed. Data from overseas studies were used to define the current level of understanding of MPs in lentic habitats where information relevant to Indian ecosystems was not available.

### Development of material flow diagram

A material flow diagram (MFD) of India was developed using STAN (2.7.101) (software subSTance flow ANalysis) (Alagha et al. 2022) to depict the flow of plastic waste, extending from the generation, to collection, recovery, recycling, and finally disposal. STAN is based on the principle of conservation of mass, assuming that the mass that enters a system in a MFD either accumulates in the system or completely leave the system (Bureecam et al. 2018). To develop material flow diagram of plastic waste, total solid waste generation as reported by CPCB-2019-20 (CPCB 2020) was considered 150847.1 TPD (for the year 2019–2020). To calculate plastic waste generation, it was considered that 6–8% of all solid waste are plastic waste (Bhattacharya et al. 2018). About 3.5 TPA of plastic waste gets reprocessed/recycled yearly in India, which is 60% of the total plastic waste (PW) formed in the country where 70% of this waste is reprocessed in registered (recognized) facilities, 20% by the informal sector, and the rest 10% is recycled at household level (Shanker et al. 2022). Therefore, these percentages were considered in model development.

## Results and discussions

### Status of current literature

Studies on MP contamination in freshwater systems were gathered for the year 2011 to 2022and are depicted in figure. Figure 2 shows the upward trend in research on MP contamination during the previous 12 years, demonstrating that studies on MPs in Indian lentic ecosystems are receiving increased attention.

Figure 3 summarizes the proportions of publications related to MP concentrations in lentic ecosystem of different states of India. The distribution map was created based on the data gathered from the literature.

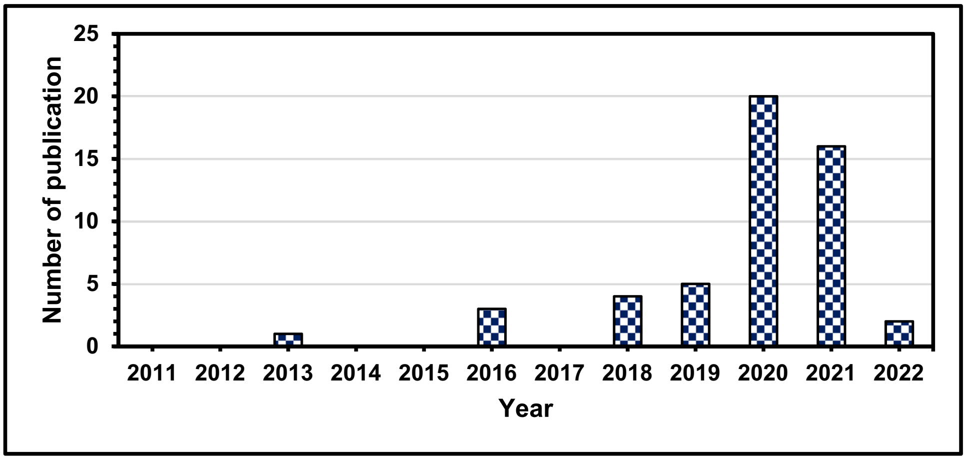
The maximum studies were reported by Tamil Nadu (50%) followed by Kerala (25%), Goa (8.33%), Karnataka and Puducherry (5.56%), Gujarat, Odisha, and West Bengal (2.77%). Maximum publications were obtained from the states adjacent to marine ecosystems and having fishing as one of the major livelihoods. According to Fig. 4, there is far more research conducted on water and sediment than on organisms, seashore sand, soil, snow, and ice. This is demonstrated by the variety of sample matrices used to collect MPs from lentic ecosystems in India.

Figure 5 shows the percentages of studies in different environments regarding MP analysis in India. Most of the studies were performed in the marine ecosystem. Among the lentic ecosystem, all the studies were reported for large lakes used for recreational and fishing purpose, and no studies were reported for ponds mainly used for domestic purposes.

### Sample collections of microplastic and measuring units

The quantity of MPs in water and sediment samples are determined separately for all case studies in India. To quantify microplastics in surface water, the water samples are generally collected using plankton nets (Su et al. 2016; L. Li et al. 2019) or manta trawls (Wang et al. 2017; Jiang et al. 2018). The sediment samples are generally collected using an aluminum foil bag (Patterson et al. 2019), and the shoreline and soil samples are collected using a stainless steel spoon (Sarkar et al. 2019; Jeyasanta et al. 2020). Further information regarding collection of water and sediment samples are described in Table 1.

**Fig. 2** Year wise publication related to MPs in India



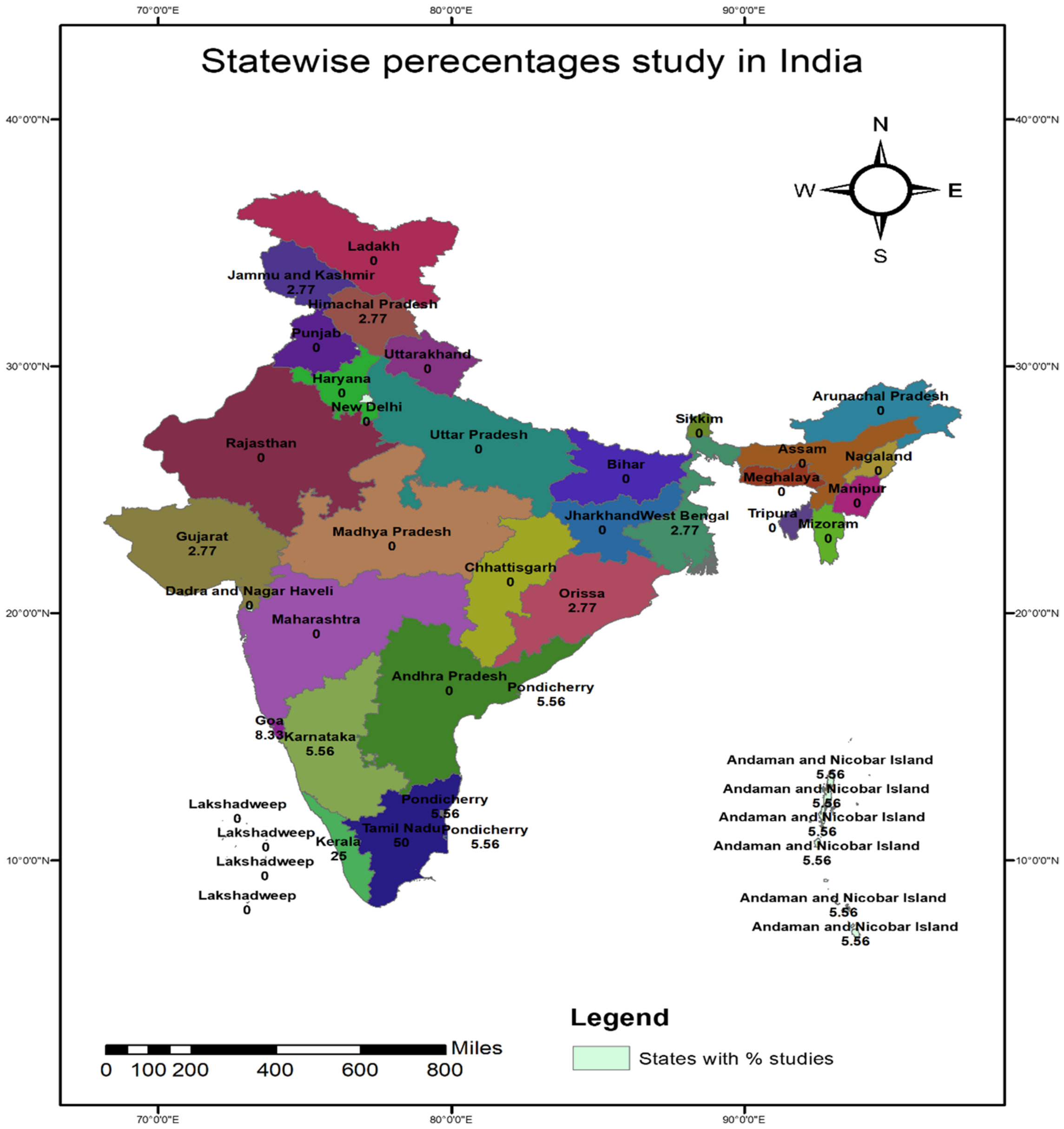


**Fig. 3** State wise percentage studies of microplastic in India

## Microplastic determination methodology in lake environments

The main procedure for analyzing microplastics in still water can generally be divided into three main stages: pretreatment, identification and quantification.

### Pretreatment

The pretreatment method can generally be categorized into two main processes: density separation (Sruthy and Ramasamy 2016; Gopinath et al. 2020) and oxidation. In density separation, substances like NaCl (CAS NO: 7647-14-5) (Masura et al. 2015) or other chemicals are employed to isolate microplastics from other materials, while oxidation methods, using $H_2O_2$(CAS NO: 7722-84-1) or similar chemicals, aim to eliminate natural organic matter (Park and Park 2021). The sequence of density separation and oxidation can vary, depending on the sample type and the extent of contamination. In cases involving highly contaminated microplastic samples, a pretreatment procedure is essential to minimize interference with the measurement of inorganic particles before the instrumental analysis.

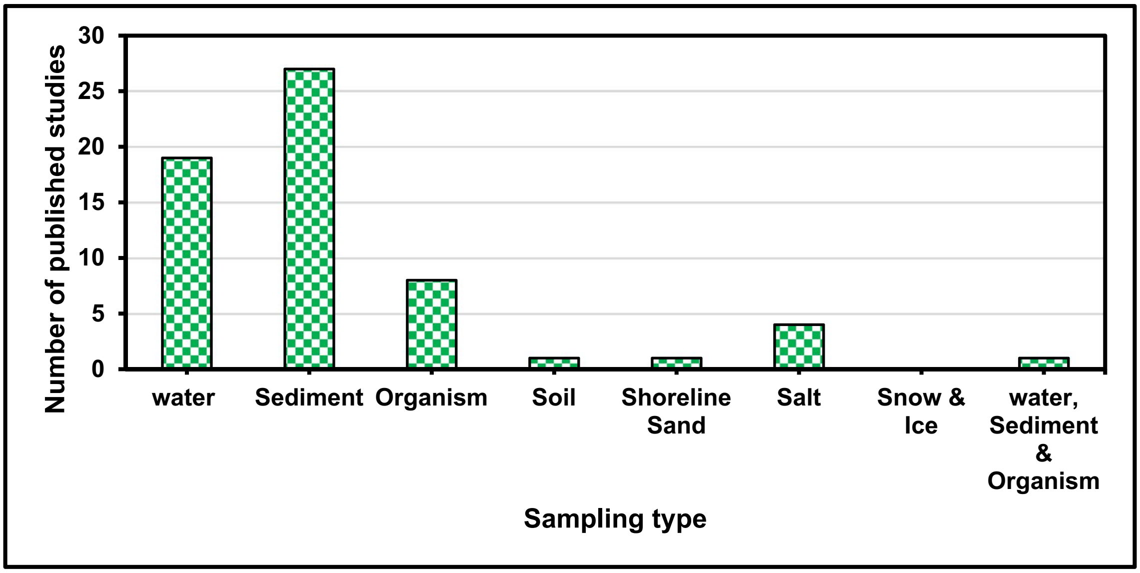
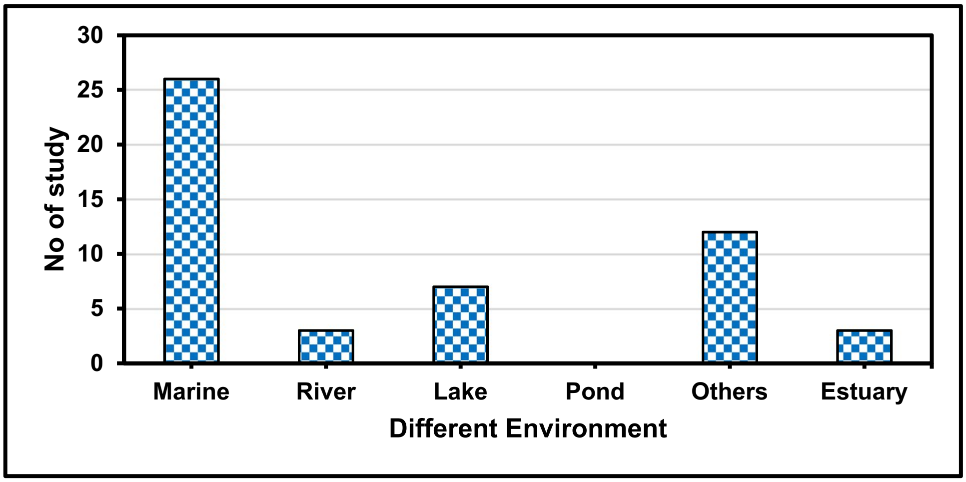


**Fig. 4** Number of published studies of different sampling for microplastic in Indian scenario

**Fig. 5** Percentages of studies in different environment for microplastic in Indian scenario



## Identification

The identification and quantification of microplastics are predominantly achieved through visual inspection, often supplemented with subsequent chemical characterization. Among reviewed studies on water and sediment, 80% employed methods based on Fourier-transform infrared spectroscopy (FTIR), 5% relied on visual inspection and 10% utilized Raman spectroscopy. Each of electron microscopy and gas chromatography-mass spectroscopy (GC-MS) were employed in 5% of the studies. It is worth noting that electron microscopy was used in three additional studies alongside FTIR. Furthermore, pyrolysis-gas chromatography e mass spectrometry (Pyro-GC-MS), Thermoextraction and desorption coupled with gas chromatography-mass spectroscopy (TED-GC-MS) combines a thermogravimetric analysis (TGA), Liquid chromatography, X-ray fluorescence (XRF) and Scanning electron microscope (SEM) have also been employed to gather data on the morphology and chemical composition of microplastics (Prata et al. 2019).

## Quantification

In water, microplastic abundance is quantified in items/km$^2$, items/m$^2$, or items/m$^3$ (Masura et al. 2015). But in sediment, the usual unit is items/m$^2$, or items/kg of dry weight. This approach is recommended to mitigate variations associated with moisture content. NOAA advises using 400 grams (wet weight) of sediment per replicate, followed by drying and weighing to normalize the results (Masura et al. 2015).

**Table 1** Approaches for gathering samples from water and sediment (Prata et al. 2019)

| Sample | Type | Advantages | Disadvantage |
|---|---|---|---|
| Water | Neuston and Manta nets | User-friendly, capable of sampling significant water volumes, widely adopted (ideal for cross-location comparisons), yields substantial quantities of microplastics for subsequent analysis | Costly machinery, necessitates a boat, time-intensive, risk of contamination from vessel and tow ropes, minimum detectable limit is 333 millimeters |
| | Plankton net | User-friendly, achieves a minimal detection limit of 100 millimeters, rapid in operation, collects samples of moderate water volumes | Costly apparatus, boat-dependent, Static sampling necessitates water flow, prone to clogging or breakage, samples smaller water volumes compared to the Manta trawl |
| | Sieving | No need for specialized equipment or boats, simple sample collection process | Demanding and time-intensive, collects moderate water volumes, involves manual water transfer using buckets |
| | Pumps | Collects substantial water volumes, requires minimal effort, permits the selection of mesh size | Equipment-dependent, relies on energy for operation, susceptible to contamination from the apparatus, challenging to transport between sampling sites |
| | Filtration or sieving ex situ | Simple sample collection process, provides a predetermined water volume, offers the option to select mesh size | Collects small sample volumes, necessitates the transportation of water samples to the laboratory, risk of contamination from the apparatus, time-consuming, when considering mesh size |
| Sediment | Beach sediment collection | Straightforward to execute, swift sample acquisition, permits the collection of significant sample volumes or replicates | Dependent on the sampled area and depth |
| | Seabed collection (grab sampler, box corer, gravity core) | User-friendly, potential for replicates | Costly machinery, boat-dependent, sensitive to variations in sampled area and depth, sampling may disrupt the sediment surface |

Based on analysis of water sampling studies, it was observed that nets were the most frequently employed method, followed by pumps and sieves. The total amounts of MPs in lentic systems were generally determined using the method proposed by National Oceanic and Atmospheric Administration (NOAA). This method is a manual for quantifying MP in the environment in a laboratory setting. NOAA recommends the use of manta nets in conjunction with sieving (0.3 mm) and filtration (0.3 mm) (Masura et al. 2015).

## Challenges faced by available sampling and analysis methods for microplastic detection

Initially, MPs and nano plastics (NPs) were primarily regarded as a concern limited to aquatic environments. However, the focus has now shifted from purely environmental issues to growing concerns about their impact on human health. The majority of analytical instruments available in research laboratories were not originally designed for the precise analysis of micro-sized and submicron-sized particles, posing a significant obstacle to their accurate identification and quantification. Another substantial encounter arises from the uneven distribution of plastic debris in both natural environments and the samples collected for laboratory analysis. Consequently, the specific fraction of a sample or dust filter chosen for analysis can have a significant impact on the final count of MPs and NPs. Additionally, the low concentrations of MPs and NPs found in the environment make reliable measurement a daunting task (Adhikari et al. 2022).

The quantification of MPs and NPs often necessitates substantial high-concentration from large volumes of air and water, thereby heightening the risk of sample contamination and the potential for reporting misleading or erroneous results. Another significant challenge in the measurement of MPs and NPs arises from their diverse range of shapes and sizes, which can result in preferential attachment and detection, leading to somewhat arbitrary reporting. In fact, each MP detected can vary considerably in size, sometimes differing by several orders of magnitude in mass. This variability also holds true for NPs. Additionally, most plastics exhibit buoyancy and density similar to that of water, which limits the effectiveness of density separation methods. This limitation introduces biases in detection and quantification. Furthermore, NPs and MPs interact with environmental constituents, including their propensity to attract and accumulate other environmental pollutants on their surfaces. This interaction not only alters their size, appearance, and surface characteristics but also complicates the accuracy of risk assessments. Although there has been notable progress in collecting data on MPs in various environmental matrices, such as solids, liquids, and the air, comparable data for NPs remain largely elusive. Moreover, the detection and quantification of plastic debris in human biofluids and tissues are lagging behind. Collecting MPs and NPs can be particularly challenging, especially in atmospheric samples and tissues from humans and animals. Typically, active and passive sampling techniques are employed for particle collection in the atmosphere. However, these techniques cannot capture all MPs and NPs present, leading to inherent biases in the samples. When mass reporting detection methods like Pyr-GC–MS and polymer digestion followed by LC–MS/MS are utilized, they may yield the same accurate mass results for samples that exclusively contain MPs or a significantly larger quantity of NPs only. Without accompanying information on particle count, geometry, and size, the collected data may ultimately have limited value in evaluating risk (Adhikari et al. 2022).

The absence of a universally accepted gold standard analytical technique adds further complexity to the interpretation of findings across various studies. Currently, the NOAA method is commonly employed for the analysis of marine water and sediment. However, the absence of standardized methods has recently resulted in mounting frustration when attempting to analyze water samples for MPs mainly for drinking purpose.

## Material flow analysis of plastic waste

From the material flow analysis using STAN, the plastic waste generation was obtained 4405,142.61 ± 4000 tons. According to the CPCB annual report 2019–2020 on the implementation of the Plastic Waste Management (PWM) rules 2016 (CPCB 2021), information provided by 35 states and Union territories (UTs) estimated that 3,469,780 TPA of plastic waste generated on average during the years 2019–2020. Of this total model obtained, plastic waste 2,081,429.88 ± 1890 tons of waste is collected of which 1,457,000.92 ± 1323 tons was recycled and reprocessed by formal sector. And 416,285.98 ± 378 tons of waste is recycled by informal sector and rest 208,142.99 ± 189 tons at household level. As per MFD (Fig. 6), average 1,387,619.92 TPA plastic waste remains uncollected resulting pollution of land, fresh waterbodies, air, and oceans and can be sustained very long time in the environment since the degradation rate of plastic waste is slow and might take up to 50 or more years for fully decomposed (Webb et al. 2012)(Mohanan et al. 2020). The United Nations Environment Programme reported that India dumped nearly 0.6 million tons of plastic waste into the marine environment annually (N. Sathish et al. 2019b).

## Source of microplastic in lentic environment

The identification of sources (Fig. 7) of MPs is a crucial first step in regulating their pollution. Depending on the entering pathways, these sources can be classified as either land-based or wind and runoff-based (Veerasingam et al. 2016). Pellets, powder plastics, and microbeads in cosmetics are easily obtained since they are commercially available and widely employed in industrial processes. The fragmentation and disintegration of macroplastics exposed to UV or physical abrasion in the environment are secondary sources of microplastics (Bhan 2021). The sources, weathering patterns, climatic characteristics, and hydrodynamic conditions could all influence the deposition of MP in the lake environment (Zhao et al. 2015). Road runoff, storm and rain-related

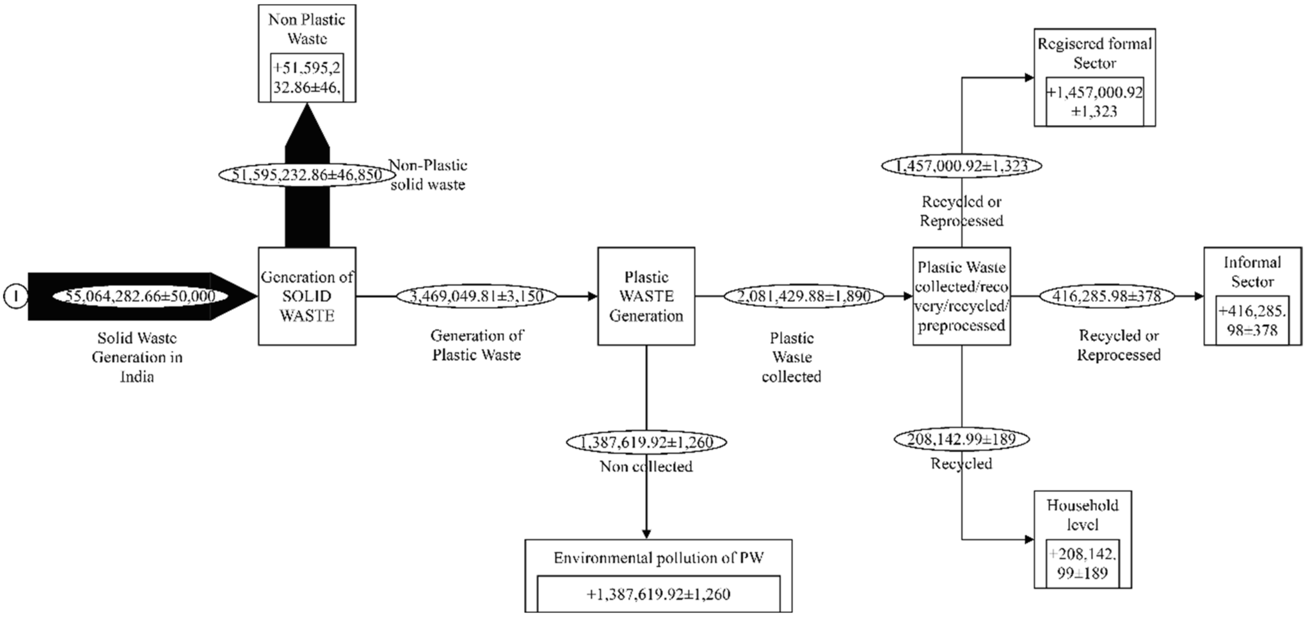


**Fig. 6** Model of material flow analysis for plastic waste in India

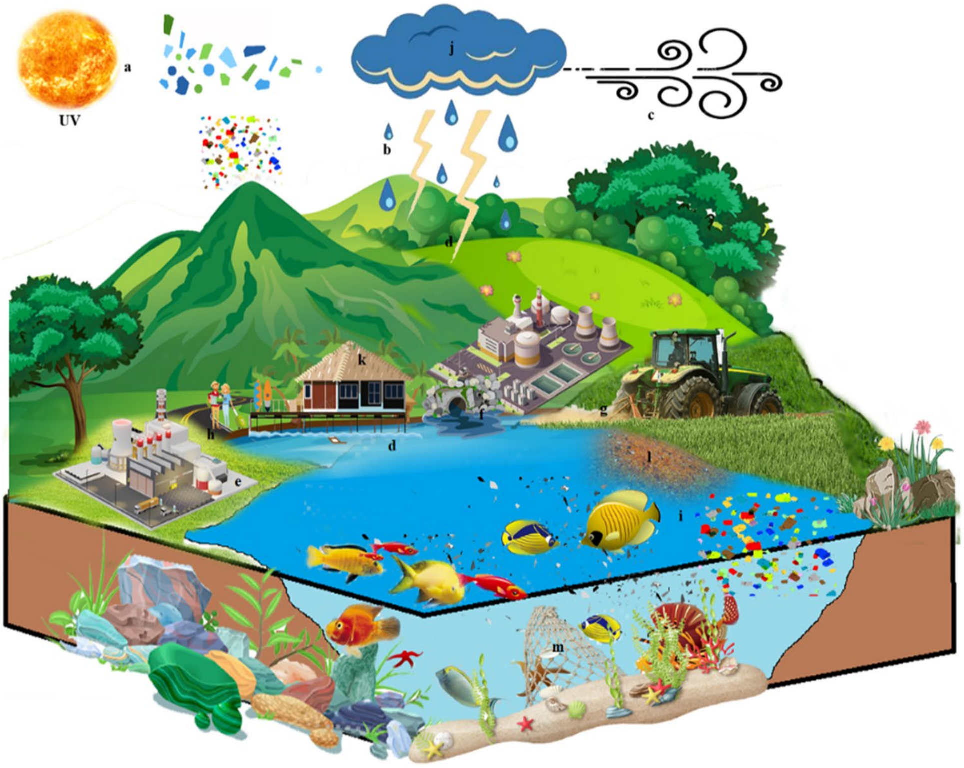


**Fig. 7** Sources and factors of microplastic in Lentic environment in Indian scenario: **a** UV, **b** rainfall, **c** storm, **d** hydrodynamic condition, **e** industrial process, **f** waste water discharge, **g** agricultural soil runoff, **h** road runoff, **i** weathering pattern, **j** climate condition, **k** tourist spot, **l** plastic packets with flower, **m** ghost net

events, agricultural soil runoff, wastewater discharge (Ballent et al. 2016), and lake tributaries (Bretas Alvim et al. 2020) are the primary sources of MP in the lakes. MP abundance is higher during storm events as reported by some researchers (Gündoğdu et al. 2018; Veerasingam et al. 2016). Non-point source contaminants such as silt, fertilizers, and pathogens are mobilized by rain and storm events. Similar processes are thought to be engaged in the mobilization and transportation of MPs. High atmospheric transport, according to Evangeliou et al. (2020), is a primary pathway for MP to reach isolated regions such as the polar regions where the mobilization and transportation of MPs are governed by comparable processes. In the lake environment, wastewater could also be a substantial source of MP (Bretas Alvim et al. 2020); (Cao et al. 2020). Textile fibers are the major constituents of MP in wastewater, according to numerous experimental studies. The prevalence of MPs in Indian lakes was recently investigated, and fragmentation of macroplastic debris was discovered as a major source of these synthetic polymers (Sruthy and Ramasamy 2017; Gopinath et al. 2020; Bharath et al. 2021a). Leakage of primary MPs from personal care items or industries, riverine conveyance of MPs, runoff activities due to rainfall, and dry deposition could all be the contributing factors.

## Abundance of microplastic in lentic environment

### Comparison of microplastic abundance in lentic environment

The amount of microplastic contamination in the lentic environment depends on population characteristics, urbanization, consumption patterns cultural habits, and policies present to manage plastic waste (Sruthy and Ramasamy 2017)(Vaughan et al. 2017). Table 2 summarizes the limited number of studies that reported MP abundance in the still water environment in India to date.

The maximum number of MP reported for the sediment of Vembanad Lake (Kerala) may be due to abrasion of the fishing net. MP concentration in lake water varies from 2 to 64 items per liter which are quite high for other Asian countries (1.81 to 34,000 items/m$^3$ for China, 700–9000 items/m$^3$ for Saudi Arabia) as reported by Yang et al. (2022). In Europe, the plastic concentration in lake water is very low which is 0.0377–23.12 items/m$^3$. In Africa, though MP concentration is less for lakes in Kenya 1.56–5.38 items/m$^3$, but for Nigeria, it is very high (around 3701.6 items/m$^3$). Lake waters of North America contain less microplastic concentration (0.028–19.1 items/m$^3$) compared to lake waters of South America (100–180 items/m$^3$). Compared to surface water, sediments were reported to have the maximum amount of MPs. For Asia, MP concentration in sediment ranges from 11 to 1150 items/kg; for Europe, this value ranges from 0.77 to 486.5 items/kg. Anchar Lake of India reported more concentration than Asian concentration. North America shows a relatively high concentration of MPs in sediment (32.9 to 6229 items/kg) compared to surface water. Similarly, the sediment of Victoria Lake of Africa which is known to be the largest lake of freshwater reported on MP concentration of 0–1102 items/kg. The precipitation of microplastic from surface water to sediment in a lentic environment may be attributed to the MP composition, density, and energy of the transporting medium. Microplastic concentrations in Asia and Africa are much high compared to developed countries suggesting that developing countries require much more stringent policies to minimize plastic waste pollution. The sampling methods, depth of the collection, mesh sizes, distance from shoreline and turbulence of tributary input, and wave energy also govern the concentration of microplastics.

### Comparison of microplastic morphologies and polymer in lentic environment

In this study, the diverse kinds of microplastic found in lentic systems from different areas were compiled. Microplastics observed in lakes may be separated into two types based on shape and polymer types (Yang et al. 2022). The first group contains fibers, films, fragments, pellets, and foams, whereas the second group includes polyethylene (PE), polyethylene terephthalate (PET), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), and polyamides (PA, nylon) (Wagner et al. 2014; Sighicelli et al. 2018). The other types of MPs that are common are beads, granules, and sheets. Table 3 summarizes the state wise common morphology and polymer that were reported by various studies in India for the lentic ecosystem.

**Table 2** Summary of the MP related studies in lentic system in India

| Location | Sample type | Microplastic concentration | Reference |
|---|---|---|---|
| Vembanad Lake (Kerala) | Sediment | 252.8 particles/m$^2$ (average) | (Sruthy and Ramasamy 2016). |
| Red Hills Lake (Tamil Nadu) | Water and sediment | 5.9 particles/L and 27 particles/kg | (Gopinath et al. 2020) |
| Renuka Lake (Himachal Pradesh) | Water and sediment | 2 to 64 particles/L and 15–632 particles/kg | (Ajay et al. 2021) |
| Veeranam Lake (Tamil Nadu) | Water and sediment | 13 to 54 items/km$^2$ (mean 28 items/km$^2$) and 92 to 604 items/kg (mean 309 items/kg) | (Bharath et al. 2021) |
| Anchar lake (Northwest Himalaya, Jammu Kashmir) | Sediment | 233 to 1533 particles/kg (mean 606 particles/kg) | (Bharath et al. 2021) |
| Lake Manipal (Karnataka) | Water | Monsoon season (0.423 particles/L) and post-monsoon (0.117 particles/L) | (Warrier et al. 2022) |
| Kodaikanal Lake (Tamil Nadu) | Water, surface sediment, and core sediment | 24.42 ± 3.22 items/L, 28.31 ± 5.29 items/kg, and 25.91 ± 7.11 items/ kg | (Laju et al. 2022) |

**Table 3** State wise morphology and polymer obtained in India

| State | Location | Morphology | Polymer |
|---|---|---|---|
| Kerala | 9°36′06″N/76°23′35″E | Fragment, sheet, film, foam, fiber/line, and pellet | HDPE, LDPE, PP, PS |
| Tamil Nadu | 7°19′15″N/79°32′44″E | -- | Nylon (39%), polyethylene (23%), polystyrene (19%), polypropylene (15%), and polyvinyl chloride (4%) |
|  | 13°09′00″N/80°11′05″E | Fibers (37.9%), fragments (27%), films (24%), and pellets (11.1%) | - |
|  | 10°14′3.84″N/77°29′10.68″E | In water, fibers (36.42%), fragments (28.34%), foams (22.46%), and films (12.78%), whereas in surface sediment, fragments (48.47%), films (13.94%), foams (10.38%), and fibers (9.52%) | For water and sediment: polyethylene (44.71 and 46.01%), polypropylene (16.22 and 17.35%),polystyrene (17.03 and 13.84%), polyethylene terephthalate (13.18 and 7.02%), polyvinyl acetate (0 and 10.42%), and polyether urethane (8.86 and 5.36%) |
| Jammu and Kashmir | 34°08′38″N/74°47′13″E | Fibers (91%), fragments/films (8%), and pellets (1%) | Polyethylene terephthalate (PET, 1.4%), polyamide (PA, 96%), polyvinyl chloride (PVC), polystyrene (PS), and polypropylene (PP, 0.7%) |
| Himachal Pradesh | 30°35′43″N/77°28′22″E | - | - |
| Karnataka | 13°20′32.9″N/74°47′9.5″E | 96% of fibers, small amount of fragments, pellets, films, and foams | PET |

For the Indian lentic system, fiber is the most dominant form followed by fragment, film, and pellet. This findings are similar with the morphological characteristics of average Asian countries [fibers (64.5%) > fragments (22.6%) > films (12.1%) > pellets (0.8%)] as reported by Yang et al. (2022). America also reported similar distribution as Asia (fibers (56.2%) > fragments (28.8%) > foam (8.1%) > films (5.6%) > pellets (1.3%). But Europe reported maximum concentration of fragment (68.8 %) followed by fibers (22.1%), with only 7.2% foams, 1.1% films, and 0.8% pellets. For Africa, pellet (75.7%) reported largest portion followed by fragments (13.0%), films (6.0%), and fibers (5.3%). Fiber with less than 5 mm length with biofilm growth on the surface may be attributed to the cultural practice of bathing and washing clothes in a lentic system. The significant portion of fragments may be due to the fragmentation of larger plastics by weathering actions that are deposited in water bodies due to mismanaged plastic waste and the cultural practice of throwing flowers from worshipping wrapped in plastic bags. India is an agriculture-dominated country; therefore, coverings of greenhouses, mulching of soil, etc. may be the source of films in a lentic environment. Food packaging and disposable diapers also added the film to aquatic bodies. Microplastic morphology in the lentic environment is influenced by a variety of causes. Fragments result from the disintegration of a larger products (Meng et al. 2020). Thermal and sound insulation materials, as well as foam, are developed from food packing (Yin et al. 2019)(Hendrickson et al. 2018). PVC foams are derived from building and transportation products (Driedger et al. 2015a). Garbage and shopping bags, as well as greenhouse construction and packaging, are all sources of films (Mohamed Nor and Obbard 2014). Fibers originate from the production of textiles (Meng et al. 2020), pellets from the production of plastic, and beads from the production of personal care products, water purification systems, or sandblasting (Meng et al. 2020).

Efficient plastic management policies and sewage treatment before discharge in surface water can reduce significantly the MP concentration since literature reported approximately 40–99.9% of microplastics can be reduced during secondary water treatment (Yang et al. 2022).

Based on polymer type, the common polymer in the lentic system in Jammu and Kashmir of India is polyamide, whereas for Tamil Nadu, it is nylon. For Asian lentic system, the most common polymer is PP (25.0%) followed by PET (22.6%), PE (19.0%), PA (9.7%), PS (8.1%), PVC (1.3%), and others (14.4%) as reported by Yang et al. (Yang et al. 2022). Here, "others" include polymethylmethacrylate (PMMA) and polyurethane (PU). For Europe, PP (50.0%) > PS (27.3%) > PE (15.5%) > others (5.8%) > PET (1.3%) > PVC (0.2%). For America, the most common polymer is PP (33.8%) followed by 25.1% PE, 11.9% PS, and 10% PVC in surface water. For Africa, the largest contribution is from PVC (44.5%) followed by PET (40.9%), PE (5.4%), others (5.1%), PP (3.4%), and PA (0.7%). The different distribution of polymer was observed for lake sediment attributed to unevenly distributed concentration, polymer characteristics including density, and transport pattern. For example, for Asia, the distribution of polymers are as follows: PET (40.4%) > PE (20.1%) > PP (11.0%) > PS (11.7%) > others (8.2%) > PVC (5.6%) > PA (3.0%). For Europe, for lake sediment, maximum contribution is from PA (79.9

%), whereas for America, it is PE (67.7%), and for Africa, it is PVC (61.9%). The most common polymer types of MP worldwide in the lentic system are PET, PVC, PP, and PE which are consistent with global plastic production as PE (36%) > PP (21%) > PVC > PET > PS.

## Surface characteristics of microplastics

Scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) were frequently used to investigate the surface element compositions of microplastics in India. Metals such as Al, Fe, Mg, Ca, Na, Si, Ti, K, and Cl were found to be absorbed by the microplastic. In comparison to other metals, Al, Fe, Si, and Ca are abundant in all samples (Gopinath et al. 2020). Polypropylene, polyethylene, polyamide, polyvinyl chloride, and cellulose pellets were tested for their ability to absorb arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), and zinc (Zn). As, Cd, Cr, Cu, Pb, Mn, and Zn adsorption capabilities were higher in polypropylene, while Mn adsorption capacity was higher in polyamide (Selvam et al. 2020). According to the EDAX analysis, fiber-type microplastics comprise Ca, K, Cl, O, Mg, Fe, Si, Na, Al, S, and Ti; film-type microplastics contain C, O, Cu, Zn, Ca, K, Cl, Mn, Fe, Si, Mg, S, Al, Ni, and Na; and fragment-type microplastics contain C, O, Cr, Fe, Cl, Ca, Hg, SI, Pb, Sr, Al, Cu, and As (Jeyasanta et al. 2020).

Carbonyl index (CI), which was computed using the conventional equation for polyethylene and polypropylene, corroborated the MPs' weathering trend.

$$CI = A1715/A2870$$

where *A1715* is the carbonyl group (-CO-) absorption and *A2870* is the methylene group ($CH_2$-) absorbance, symmetric stretching vibration (N. Sathish et al. 2019). The CI values of MPs reported for five beaches of Tamil Nadu varied from 0.20 to 3.30 for PP and from 0.07 to 0.70 for PE with highest values for Chennai beach. Different CI values obtained for different beaches indicated that the parent plastics underwent different degrees of weathering even though they were derived from similar sources. However, no such study was reported for weathering of plastic for lentic environment for India.

## Migration of microplastic from external emerged water system

Generally speaking, different MP morphologies originate from various sources. Fragments are usually produced when bigger items, such as paint and tires, break down (Meng et al. 2020). Foams are derived from thermal and acoustic insulation materials as well as food packaging (Hendrickson et al. 2018; Yin et al. 2019). PVC foam often derives from building and transportation supplies (Driedger et al. 2015a); They are mostly made from the supermarket and trash bags, the building of greenhouses, abandoned agricultural films, mulching in agricultural fields (Mohamed Nor and Obbard 2014); fibers are from textiles (Meng et al. 2020); packaging (Meng et al. 2020), fishing gear, fishing lines (Timmers et al. 2005); Pellets come from the plastic production process, whereas beads come from sandblasting, personal care products, or water purification systems (Meng et al. 2020). The two principal migration mechanisms for microplastics to lentic systems are air transport and surface runoff. Regional differences in weather, hydrological conditions, and lentic habitats are blamed for the varied distribution of microplastics in water and sediment from the same lake (Yang et al. 2022).

There is extensive information available regarding the transport of MPs and nanoplastics (NPs) in porous media. Such particles are commonly employed as model colloids for evaluating fundamental transport and filtration mechanisms (Yu and Flury 2021). In the majority of these studies, researchers have utilized pristine spherical polystyrene particles, including primary NPs and MPs, with varied sizes and surface characteristics, along with porous media such as sand or glass beads. Further, despite considering three different sizes of plastic particles (1 μm and 2 μm MPs and 0.2 μm NPs), the studies focused exclusively on assessing the transport and retention behaviors of polystyrene spherical plastics, which constitute a single plastic type and shape. Furthermore, other information's regarding size and shape of the plastic particles to impact with porous medium environment are depicted in Table 4.

## Factors influencing the distribution and transportation of MPs in lentic environment

### Physical factors

Particle density, water surface area, water surface depth, wind speed and direction, and water flow size are all elements that influence microplastic movement in lentic ecosystems (Fischer et al. 2016). Wind transports microplastics over large distances in the atmosphere. Bergmann et al. (2019), Wright et al. (2020), and Dris et al. (2016) discovered microplastics on plant leaves, and Li et al. (2020a) and Grayling et al. (2018) predicted another mode of microplastic transportation and microplastics travel downward through soil, and fibers penetrate the lentic environment. Microplastics can also enter the lentic system by a rainwater runoff, with the season having a significant impact on the outcome (Horton et al. 2017; Liu et al. 2021). Storms, being one of the major producers of microplastics, typically generate seasonal fluctuations in precipitation runoff, resulting in

**Table 4** Mechanisms governing the transport of NPs and MPs in porous media with size and type (Yu and Flury 2021)

| Type of plastic | Mechanism of transport | Condition of flow | Porous medium | Size of plastic (μm) |
|---|---|---|---|---|
| Polystyrene | Primary and Secondary minimum deposition | Saturated | Sand/glass-bead column | 0.02–5.7 |
| | Surface heterogeneity | | | 0.02–10 |
| | Blocking, ripening | | | 0.239–21 |
| | Straining, wedging | | | 0.45–4.25 |
| | Size exclusion | | | 0.05–3 |
| | Flow rate | | | 0.03–40 |
| | Structure heterogeneity | | | 1–90 |
| | Interaction with air–water interface | Unsaturated | | 0.02–6 |
| | Film straining | | | 0.014–0.97 |
| | Transient flow | Saturated/unsaturated | | 0.1–2 |
| | Nonspherical particles | | | 0.2–6.1 |
| | Cotransport | | | 0.05–2.6 |
| | Tracer | | | 0.23–1.35 |
| Polyethylene, polypropylene, polyethylene terephthalate, polylactic acid, polyamide, styrenebutadiene-rubber | Infiltration, travel distance | Unsaturated | | 21–5000 |
| Secondary MPs and NPs | Transport | Saturated | Soil column | 0.422–0.487 |

microplastic flow into the lentic system (Horton et al. 2017), (de Jesus Piñon-Colin et al. 2020) . In sewage treatment facilities, cleaned sewage still includes some microplastics, which may be discharged into receiving waters after treatment. It is worth noting that sewage treatment plant sludge contains a larger concentration of microplastics. In agriculture, sludge is used as a source of fertilizer. As a result, some microplastics from sludge may find their way into the soil (Meng et al. 2020).

## Socioeconomic condition and livelihood

It was believed that socioeconomic status of people had an impact on the microplastic contamination's occurrence (Gunawan et al. 2021). The average plastic footprint of Kochi's residential areas is 4.25 $m^2$ per person. Highest plastic waste generation was observed for households having incomes between 10,000 and 15,000, followed by 20,000, 5,000–10,000, and 15,000–20,000. During festive season, the plastic waste generation is highest followed by the dry and wet seasons. Individual plots, low rise buildings, and row housing units produce the least amount of plastic garbage, followed by high rise structures (Ravi and Vishnudas 2016). Household having door-to-door waste disposal option generates more plastic waste compared to household having community level waste disposal option. Since major source of MPs is degradation and fragmentation of plastic waste; therefore, the concentration of MPs may have direct relation with plastic waste generation. The livelihood of people also has implications on morphology of MPs. For example, Sathish et al. (2019b) reported correlation of MP concentrations of beach sediments collected from five coastal sites of Tamil Nadu, with a range of common coastal activities such as land use, ritual, fishing, and recreational. The commonly obtained MP were fiber, fragments, and foam. Fishing gear and wastewater discharge may be responsible for the fiber-type MP in coastal areas. The sizes varied from 0.5 to 3 mm. They were of PE, PP, NY, and polyester (PES) types. Dowarah et al. (2020) also reported the significant correlation of MP concentrations with the fishing and recreational activities of Puducherry coast. The sediments collected from Vembanad Lake (Sruthy and Ramasamy 2016) showed the presence of fragments, films, foam, and fiber/line of mostly LDPE type which is commonly used polymer in plastic bags, housewares, films, and milk cartons. Microbeads were not observed in Vembanad Lake suggesting that they are less frequently used in this region. Mean abundance of 252.80 ± 25.76 (96–496 items) $m^{-2}$ of MPs in the sediment may be due to discharge from the commercial capital of Kerala, Kochi City, and the industrialized area of Eloor which are located north of TM bund. The lake receives about 21,900 $Mm^3$ of water annually through riverine discharge passing through the urban and rural areas of this region. Improper solid waste management facilities in this region may also result in abundant plastic waste that are being flushed into the lake. Sediment and water samples collected from the Veeranam lake ecosystem in Cuddalore district, Tamil Nadu (Bharath et al. 2021), also showed the presence of maximum fiber of nylon which is highly correlated with the fishing as the major livelihood of that area and use of single use plastic. Mean concentration of 5.9 particles/L MPs in water and 27 particles/kg in sediment were reported for Red Hills Lake of Chennai city, Tamil Nadu. The main types of microplastics observed in water and sediment samples were reported as fibers (37.9%) followed by fragments (27%), films (24%), and pellets (11.1%). The lake is surrounded by residential area in southeastern part, water treatment plant, and central prison on the eastern part of the reservoir. Outlet of the reservoir is surrounded by garbage and sewage outlet from the residential area. Therefore, major sources of MPs pollution in water and sediment of Red Hills Lake may be due to fishing activities, flow of raw sewage from the residential encroachment near the Lake bed, dry deposition, waste accumulation around the reservoirs, and waste burning near the lake. PE and polypropylene were the major plastic polymers recovered in both water and sediment, which is the main plastic material used in fishing net and packaging. MP concentration was reported by Lakshmanna et al. (2022) (Himalayan lakes can potentially become long-term sinks of microplastics| India Water Portal) for shore sediment of three high-altitude lakes in Ladakh of the Indian Himalayas, namely, Pangong Lake, Tsomoriri Lake, and Tsokar Lake. The concentration was reported as 160–1000 MP/kg dw in Pangong Lake, 960–3800 MP/kg dw in Tsomoriri Lake, and 160–1000 MP/kg dw in Tsokar Lake. Surface runoff caused by the melting of snow washing away plastic litter by rain, anthropogenic activities, including tourism such as trekking, vehicles, clothes with synthetic fibers, tents, disposal of plastics litters like drinking water bottles and food packaging and cleaning of vehicles along the shore particularly in Pangong Lake and Tsomoriri Lake could add MPs into the Lakeshore sediment.

## Biomagnification of microplastic in lentic environment

Biomagnification occurs when a contaminant moves forward at high concentrations via the food chain (Fig. 8). Light weight MP floats on the surface of the water, while dense weight MP settles on the bed (Woodall et al. 2014). Denser MP can also be found in the water column, according to Lenaker et al. (2019). Small plastic particles are easily ingested by aquatic creatures of various nutritional levels, enriching the food web in the process (Ivleva et al. 2017). MPs in water may be entangled with algae and ingested by aquatic insects and medium-sized plankton. Macroplankton such as *Daphnia* can take up medium plankton, aquatic insects, or algae that contain microplastics. Fish may consume MPs directly by mistake or through aquatic insects and macroplankton that contain MPs (López-Rojo et al. 2020) (Yuan et al. 2019)(Peters and Bratton 2016). Researchers found that the percentage of white plastic in fish samples (16.7%) was much greater than that in water (1.8%) and sediments (9.3%) in a study of microplastics in the Lake (Yuan et al. 2019). The biomagnification process in the food chain is influenced by polymer type of MP. Polyethylene (PE; 38.46 percent), cellulose (CE; 23.08 percent), rayon (RY; 15.38 percent), polyester (PL; 15.38 percent), and polypropylene (PP; 7.69 percent) are the most commonly found MP in the intestine of fish obtained from stagnant water such as lakes, ponds, and other bodies of water, according to Robin et al. (2020). MPs were found in 41.1 percent of the fish's inedible tissues, although just 7% of the fish's edible tissues included MPs (Daniel et al. 2020). In water, the abundance of MPs ranged from 3.1 ± 2.3 to 23.7 ± 4.2 items $L^{-1}$, 0.11 ± 0.06 to 3.64 ± 1.7 items/individual, and 0.0002 ± 0.0001 to 0.2 ± 0.03 items/g gut weight of fish (M. N. Sathish et al. 2020). MPs pose particular dangers to individual organisms in lentic environments because of their capacity to absorb other dangerous substances or to settle harmful microorganisms (McCormick et al. 2014). In addition, MPs in lake sediments can be ingested by crustaceans, mollusks, clams, and flatworms. Sobhani et al. (2021) proofed the decreasing reproductive behavior in earthworms in the presence of perfluoroalkyl-loaded polyvinyl chloride microplastics. Researchers also found that this type of microplastic served as enhanced transport vector to transfer perfluoroalkyl substance to earthworms. MPs can increase an organism's inflammatory response (von Moos et al. 2012), block the digestive tract and impair nutrient absorption (Azzarello and Van Vleet 1987), reduce predation effectiveness, and encourage organism development (Au et al. 2015a). When the concentration of MPs in the aquatic environment exceeds

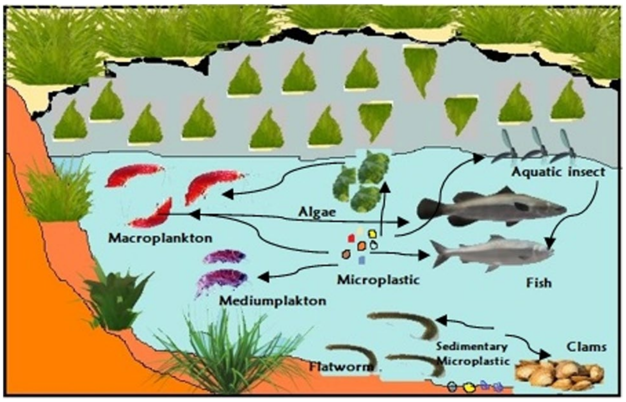


**Fig. 8** Transfer of microplastic into living organism in lentic environment

a given concentration, it becomes neurotoxic to fish (Oliveira et al. 2013). It may reduce predation efficiency (de Sá et al. 2015) and hinder the growth of organisms (Au et al. 2015b). Annually 31,650 tons of clams are harvested from the Vembanad lake (Sruthy and Ramasamy 2016) for local consumption along with prawns, crabs, and fishes which are also staples of the local diet leading to potential health consequences related to ingestion of MPs and associated toxins. As many water birds visit the lakes, the spread of MPs from the lake to terrestrial habitats may possible via bird scat.

## Ecological risks of microplastic

Microplastic accumulation and harmful chemical composition have an impact on human health and the ecosystem, as well as the bay organism, due to continual MP discharge into fresh water (Ajay et al. 2021). Because of its persistent nature, ease of transit, and bioaccumulation property in the trophic level of aquatic ecosystems, MP is extremely difficult to remove from the environment (Arthur et al. 2009). The ingestion of MP by aquatic organisms can contaminate the aquatic food web (Jeong and Lee 2022). Because of their low density, MP can travel a long distance with pollutants, preventing the settling of plastic particles when compared to other suspended materials. MPs absorb waterborne contaminants such as heavy metals and persistent, bio-accumulative, and toxic (PBT) compounds due to their large surface-to-volume ratio and chemical make-up. Phthalates, which are frequently used as plasticizers to soften plastic, pose a serious threat to the environment. Humans may be exposed to greater quantities of this pollutant due to the use of PAEs in common items including children's toys, medical equipment, cosmetics, personal care products (PCPs), pharmaceutical nutritional supplements, and dietary supplements (Kelley et al. 2012) (Gong et al. 2015). The vast distributions of MPs and PAEs, as well as their unfavorable impacts, have piqued the scientific community's interest (Ajay et al. 2021). For risk assessment analysis of MP contamination in lake systems, the pollutant load index (PLI), potential ecological risk index (PERI) and polymer hazard index (PHI) values are utilized. Based on PHI values, the total threat posed by MP contamination in lake sediments was categorized as hazard category IV to V for Anchar Lake, Kashmir. The PHI values were obtained greater than 1000 in some sampling points due to presence of MP obtained from PVC. Sediments in the lakes have PLI values less than 10, indicating hazard level I, which means low MP risk for sediment sample (Neelavannan et al. 2022). Kodaikanal Lake showed high PHI values (> 1000) for sediments due to MPs with high hazard score polymers (PS and PEU), whereas the PLI values (1.33 < 10) indicate low level of ecological risk due to MP (Laju et al. 2022). PHI scores of 19.53 and 32.54 were estimated for HDPE and LDPE respectively for different freshwater fish species collected from Lucknow, Uttar Pradesh (Pandey et al. 2023). The PHI values due to the presence of HDPE and LDPE are indicating very high risks (hazard category III). Based on MP abundance, the PLI for all the fish species obtained less than 10, indicating minor risk.

## Toxicity of MPs

MPs are primarily underfed by aquatic species or accompanied by trophic grade stepwise enrichment, which can have hazardous consequences on aquatic creatures and plants, as well as people in the long run. Because it is simpler for small-sized MPs to penetrate the bodies of aquatic animals, which are primarily made of fibers and fragments, large-sized MPs are less common. Furthermore, colored MPs are more readily ingested by aquatic organisms. Most of the case show how colored and black MPs predominate in the organisms whereas transparent and white MPs are scarce (Pan et al. 2023). The primary food source in lake ecosystems is algae (Cardinale et al. 2011). According to Rani-Borges et al. (2021), MPs now obstruct algal photosynthesis and growth primarily through their light shielding impact, increased medium turbidity, cell internalization processes, and adherence to cell walls. By varying the concentrations of charged PS microbeads in the algal growth medium, Bhattacharya et al. (2010) conducted a study on the consumption of carbon dioxide, confirming that PS adsorption on Chlorella prevents light from reaching the photosynthetic center and may interfere with the passage of light through the cell wall into the cell interior. In their study, Sighicelli et al. (2018)b conducted exposure experiments on microalgae using charged polystyrene (PS) microbeads. Despite the high concentration of microplastic particles (MPs), which reduced the light intensity available to the microalgae, it had limited impact on the photosynthesis of the MPs themselves. This finding confirmed that uncharged PS microbeads had an inhibitory effect on the growth of microalgae. Furthermore, this inhibitory effect was influenced by both the size and concentration of the MPs. Specifically, higher concentrations of MPs, coupled with smaller particle sizes, resulted in a more pronounced inhibition of microalgae growth. In a separate study by Wu et al. (2019b), they investigated the effects of PP and PVC MPs on chlorophyll and the photosynthetic activity of freshwater algae. Their research revealed that both PP and PVC exerted varying degrees of inhibition on the photosynthesis of algae. The chloride ion present in PVC may be responsible for its stronger ability to obstruct photosynthesis, although higher concentrations of MPs clearly inhibited algal growth. Kalčíková et al. (2017) showed that PE microbeads greatly obstruct the mechanical growth of Lemna minor phytoplankton roots. Aquatic and terrestrial plant growth was hindered by various MP kinds (PP, PS, PVC, PE, and PET) to varying degrees (Ge et al. 2021). In freshwater environments, MPs can injure both fish and algae, and the severity of the harm is based on the MPs' dose and particle size. When MPs are present in water at attentions between 1 and 100 g/L, PS is frequently employed to investigate their adverse effects on aquatic life. Higher concentrations cause biological death and cause severe damage.

## Impact of microplastic on microorganisms

MPs are obligated to have some effect on the physical and chemical characteristics as well as the biological environment when they reach the water or soil environments. The addition of MPs has no appreciable effect on the diversity of the soil itself as far as the influence on the soil microbial community is concerned, but there is a distinct structure of microbial community colonization on the surface of MPs (Huang et al. 2019). According to Wang et al. (2020), the presence of MPs in soil ecosystems may cause a quick succession of soil bacterial communities. MPs, such as PLA (polylactide), have minimal effects on the diversity and composition of bacterial communities as a whole, as well as on ecosystem-related processes and functions (Chen et al. 2020). However, they can have an impact on interactions between constituent species. Additionally, the addition of PVC and PE will decrease the diversity and abundance of bacterial populations by stimulating the activities of urease and acid phosphatase and inhibiting the activity of luciferin diacetate hydrolase (Fei et al. 2020). PS may have a deleterious impact on soil enzyme activity (Huang et al. 2019). MPs may potentially have an impact on the soil's nitrogen cycle (Huang et al. 2019). Microorganisms and MPs interacting in the aquatic environment, MPs will speed up the rate at which organic, hazardous compounds diffuse to the surface, having an indirect impact on the aquatic environment (Wu et al. 2017). The concentration of microorganisms on MPs will cause the MPs to bowl when the microbial film mentioned in the previous article is generated, which will alter the bottom habitat (Basili et al. 2020). It is confirmed that additional research into the role of plastic as a carrier of pathogenic germs is necessary by the discovery of possible pathogens on the surface of plastic, which represents the level of microbial contamination in the water environment (Basili et al. 2020). Because MPs are widely dispersed in the aquatic environment, they are easily ingested by aquatic organisms and build up in the gastrointestinal tract (particularly in the intestine), which has an impact on the intestinal microbial community. These three factors can be used to analyze this influence. In the beginning, MPs can disturb the balance of flora in an animal's intestines, potentially harming the organism (Li et al. 2020b). When microplastics (MPs) enter the intestinal tract of organisms, they have the potential to be absorbed and accumulate. For instance, zebrafish liver cells have demonstrated a high efficiency in absorbing PS MPs, which tend to accumulate primarily within lysosomes. Additionally, there is evidence of a synergistic effect on virus and immune gene expression when MPs accumulate in the intestine and pancreas, as reported by Brandts et al. (2020), thereby possibly having an impact on human health.

## Impact of microplastic on human health

The main ways that plastic impacts human life are either through the chemicals used in its manufacture or through handling and prolonged use (Fig. 9). Several compounds used in the production of plastics have been identified as hazardous (Ragaert et al. 2017). When landfills occur as a result of the mixing of plastic garbage with other solid waste, hazardous liquids and gases are released, posing a threat to the surrounding area (Chidambarampadmavathy et al. 2017). An extensive evaluation of a living organism's exposure to contaminants from many sources is provided by the biomonitoring approach. This technique has shown that

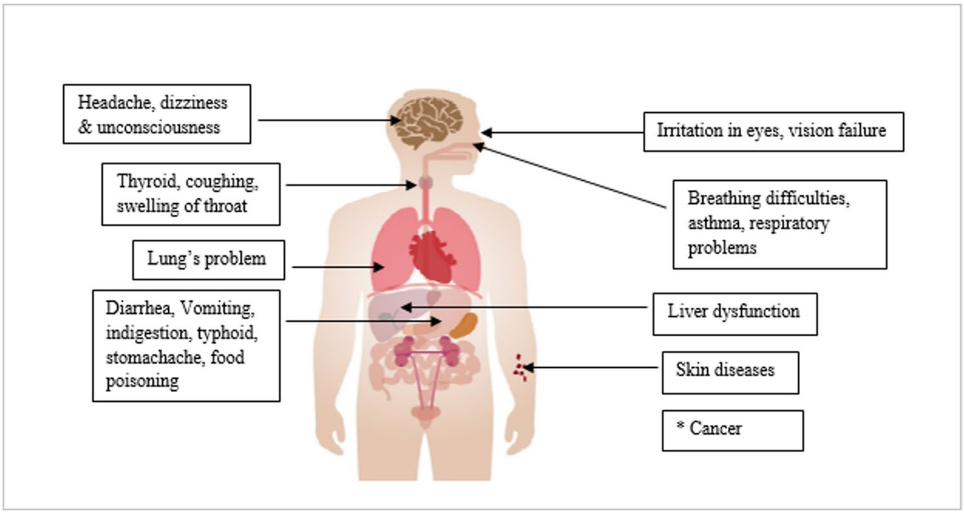


**Fig. 9** Effects of microplastic on human health

the human body contains compounds used in the production of plastics, regulating metabolism, continual exposure, and excretion of the compounds found there (North and Halden 2013). In today's world of widespread plastic use, there is no such organization dedicated to examining the impact of low-level exposures on human health. From conception to death, everyone is exposed to some degree. Bisphenol-A (BPA) and di-2ethylhexylhexyl phthalate are two key compounds used in the plastics industry that is harmful to humans. According to a study, persons in the USA had 95 percent of BPA in their urine (Vandenberg et al. 2007). Various sea creatures, such as mussels, oysters, crabs, sea cucumbers, and fish, consume microplastic, which can have negative health consequences for humans throughout the food chain (Chaudhry and Sachdeva 2021). PE microplastic particles can be found in face washes, hand cleaners, toothpaste, and dental care products, as well as face pack peelings and shower products. Microplastic is absorbed into tissues and caused skin damage as a result of continued usage of this product (Duis and Coors 2016). Toothpaste microplastic and microbead particles can be covertly grasped and injected into the gastrointestinal tract (Ustabasi and Baysal 2020). Infertility, obesity, and cancer are all linked to microparticles (Campanale et al. 2020). Breast cancer in women can be caused by an estrogen-like substance (Van Cauwenberghe and Janssen 2014). The ability of microplastic to accumulate in secondary organs can harm the immune system of the human body. Plastic's hydrophobic surface is carcinogenic due to pulmonary arterial hypertension (PAH) (Selvam et al. 2020).

## Knowledge gap and future research opportunities

The literature review clearly indicated that very limited reliable data are available on the occurrence of MPs in lentic system of India. The lakes at riparian areas around major rivers and metropolitan areas are not studied properly. It is important to note that information on MP pollution at lentic ecosystem along the southeast and west coast of India is mostly restricted to the states of Tamil Nadu, Puducherry, and Kerala. The vast, largely unexplored lakes of the east coast states like West Bengal and Orissa are particularly impressive. Future studies should concentrate on the MP concentration of lakes of Karnataka, Maharashtra, and Gujarat along the western coast. For hilly area, MP concentrations of lentic systems were reported for Kashmir and Ladakh only. Therefore, an in-depth research is required to monitor the spatiotemporal variations of MPs of lentic systems present across India. Different sample collection and analytical methods were used for the extraction, identification, and quantification of polymers in water and sediments collected from lentic systems. The current manual sampling method causes many errors with high analysis cost. Consistent mechanical sampling method and standardized analytical methods are required to be established to assess and compare the spatiotemporal variations of MPs in water and sediments collected from lentic systems around the globe and associated health and ecological risks. Little investigation related to MP concentration in different organisms collected from lentic systems was reported with compare to MP concentration in water and sediment. Correlation between water quality indicators such as salinity, DO, TSS, DIN, and $PO_4^{-3}$-P (Vibhatabandhu and Srithongouthai 2022) and DO, pH, nitrate, and nitrite (Xiong et al. 2022) with MP were reported, but there may be other water quality parameters which may have significant correlation with MP concentration. Correlations between socioeconomic conditions and livelihood were not reported with MP concentrations for Indian lentic systems. Future studies may also examine the seasonal variations in MP concentrations to assess the danger of contamination and determine the quality and safety of human food, as well as the relationship between these variables and water quality measures. There is a study gap in the exact source and quantity of MP in different environments. In this study, an attempt was made to determine the plastic waste generation of India using material flow analysis. Background concentrations of MP along with polymer type play vital role for determining ecological risks due to MP in lentic systems in terms of PHI and PLI. The MPs are derived from several anthropogenic activities; therefore, setting up of reference background value for ecological risk assessment due to MP concentration is a crucial task. Very few studies only reported polymer types using FTIR or Raman spectroscopy. Therefore, accurate quantification of MPs and associated polymer types using machine learning approaches is important for planning investigations relevant to toxicology related to MP and linking the gap between field and laboratory analyses of potential health and ecological risk. Future research may thus focus on tracking the spread of microplastics via tropical food chains and the lentic environment across India, which will provide a thorough evaluation of the pollution' exposure and danger. Carbonyl index also is required to be determined for assessing the degree of weathering of parent plastic for lentic environment. The present paper did not discuss mitigation methods of MP from lentic environment. Extensive effort should be provided for designing and development of novel mitigation methods of MP from lentic system adopting photocatalysis, advanced oxidation, filtration process, etc. The contribution of microbial communities as well as enzymatic biodegradation process of MP from aquatic media and sediment may be the promising and sustainable future trend of research.

## Proposed methods to control microplastic concentration of lentic systems

(a) Since most common source of MP in lentic ecosystems is the disintegration of plastic wastes, surface runoff, and disposal of domestic or industrial wastewater, therefore, proper management plan is required to minimize the generation of plastic waste and treatment of domestic and industrial waste water before being discharged to lentic systems.

(b) Public awareness and incentive-based utilization of alternatives of plastics may reduce plastic waste generation so as micro plastic concentration.

## Conclusion

This study examined the presence of microplastics in the lentic environment (both water and sediment) of several Indian states and regions. Based on the current studies, Tamil Nadu and Kerala are encountering the most serious levels of MP analysis as compared to other states in India. The maximum number of literature was published in the year 2020. Most of the MP analysis has been done in the Marine environment as compared to other environments. In water, MP abundance is measured in items/km$^2$, items/m$^2$, or items/m$^3$, but in sediment, the usual unit is items/m$^2$ or items/kg in a lentic environment. The possible sources of primary MP in a lentic environment are cosmetics, where secondary MP may come from the wastewater discharge in surface water and effluent from the textile industry. In addition, the two main migration routes for MPs into lentic systems are air transport and surface runoff. The most common MP reported in the lentic environment for India is fiber followed by fragment, film, and pellet which is similar to the morphological characteristics of the lentic environment of average Asian countries. The most dominant polymer for Jammu and Kashmir is polyamide, whereas for Tamil Nadu, it is nylon. The polymer types of different regions depend on the generation and consumption pattern of plastic as it is anthropogenically originated. Polypropylene, polyethylene, polyamide, polyvinyl chloride, and cellulose pellets were tested for their ability to absorb arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), lead (Pb), manganese (Mn), and zinc (Zn). As, Cd, Cr, Cu, Pb, Mn, and Zn adsorption capabilities were higher in polypropylene, while Mn adsorption capacity was higher in polyamide. Microplastics may be consumed directly by fish or indirectly through aquatic insects and macroplankton because microplastics cannot be consumed by bacteria or others in any lentic environment. Factors affecting MP in a lentic environment are water surface dimensions, water depth, wind speed and direction, water flow size, water particle density, etc. For risk assessment analysis of microplastic contamination in lake systems, the pollutant load index (PLI) and polymer hazard index (PHI) values were generally utilized. Consumption of microplastics by Humanvia the food chain causes various diseases like respiratory problems, Infertility, obesity, cancer, and negative impact on the immune system. Policies for reducing this pollution are developing in India, but research in the lentic environment is still needed to fully understand the causes, incidence, movement, destiny, potential effects, and potential remedies of MPs.

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## Declarations

**Ethical approval** The authors are declaring that during the data collection and preparation of paper, no human/animal was harmed, and in the future, also no human/animal will be harmed. The authors are responsible for correctness of the statements provided in the manuscript.

**Consent to participate** All the authors actively participated during preparation and revision of the manuscript.

**Consent for publication** All the authors hereby are providing consent for the publication of the manuscript detailed above, including any accompanying images or data contained within the manuscript. We understand that this information will be freely available online and accessible to the general public.

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

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