



Microplastic Contamination in Freshwater Ecosystems: Emerging Threats and Sustainable Mitigation Strategies

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ABSTRACT

Plastic pollution is one of the biggest environmental threats of the twenty-first century and microplastics (<5 mm) are now known as a ubiquitous pollutant in freshwater systems globally. Microplastic contamination is a continual source to rivers, lakes, reservoirs and wetlands from urban runoff, industrial effluents, municipal wastewater, agricultural activities and atmospheric deposition. Freshwater ecosystems are not only a home to a diversity of aquatic life, but they can also be a conduit for the flow of plastic waste from terrestrial areas to oceans. Although there is growing interest worldwide to analyse the situation comprehensively using publicly available monitoring data, this type of analysis is limited, especially in rapidly developing countries. In this study, published monitoring data from freshwater ecosystems in India are collated and statistically analysed to gain insight into the spatial distribution, abundance, morphology, polymer composition, and possible sources of microplastic contamination in Indian freshwater ecosystems. Secondary data were collected from peer-reviewed publications, and the data were standardised for comparison. The results show that urban freshwater systems are consistently more contaminated with microplastics than rural systems, with a higher percentage of microplastic fibres than other particle types, and the presence of the most

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abundant polymer types, such as polyethylene and polypropylene. The major sources of contamination were anthropogenic activities, such as untreated wastewater discharge, textile industries, mismanagement of plastic waste, and urbanisation. The study also analyses existing mitigation measures and suggests a combination of wastewater treatment, circular plastic economy, environmental monitoring and policy strengthening measures. Synthesised evidence shows the potential of secondary analyses of publicly available datasets to provide valuable scientific information for freshwater ecosystem management and evidence-based policy development to reduce plastic pollution.

1. Introduction

The robust manufacturing and application of plastic materials have revolutionised the modern world, offering an abundance of inexpensive, lightweight and durable products in the fields of domestic, industrial, agricultural and medical applications. The production of plastics grew from less than 2 million tonnes in the 1950s to over 400 million tonnes annually today, and is expected to continue rising in the future. Plastics have played a significant role in economic development, but the long-lasting presence in the environment has created a new pollution crisis impacting terrestrial, freshwater and marine environments.

Micro plastics are one of the most important types of plastic pollution due to their small size, persistence, mobility and the potential harm they can cause to the environment. Microplastics are usually classified as being less than 5mm in diameter, and are classified as either primary (synthetic polymer that is produced in small micro-scale sizes) or secondary (small micro-scale plastic fragments created by the breaking down of larger plastic waste by various mechanisms such as, UV radiation, mechanical abrasion, thermal degradation, and biological weathering). Microplastics can accumulate in water, sediments, and biological organisms for decades because they are not naturally degraded. Fresh water ecosystems are one of the most important aspects of the environment. Waters of rivers, lakes, reservoirs, streams and wetlands, are crucial ecosystem services, which are water supply for drinking and irrigation, fisheries, conservation of biodiversity, generation of hydropower, nutrient cycling and regulation of climate. These ecosystems also act as the main corridors between terrestrial and estuarine and marine environments for the conveyance of plastic waste. As a result, freshwater environments are becoming increasingly contaminated with microplastics present in municipal wastewater, industrial effluents, agricultural runoff, stormwater runoff, atmospheric deposition, and improper solid waste disposal.



The negative effects of microplastics on freshwater ecosystems are now well established, and are mediated by several mechanisms. Plastic particles can be ingested by aquatic life – such as plankton, benthic invertebrates, molluscs, crustaceans, amphibians and fish – very easily due to their small size and their similarity to natural food and feed. Ingestion can decrease feed efficiency, growth, reproductive success, cause oxidative stress, affect metabolism and cause death. Furthermore, microplastics have the ability to bind persistent organic pollutants, heavy metals, antibiotics, and pathogenic microorganisms, and act as vectors to transport these pollutants through the aquatic food chains and in turn, can pose a risk to human health. India has one of the world's most vast freshwater networks with thousands of rivers, reservoirs, lakes, canals and wetlands, sustaining almost 1/5th of the world's population. Rapid industrialisation, urbanisation, population growth, and the rising consumption of plastics have contributed significantly to the landfilling of plastic waste across the country. A significant amount of synthetic fibres are discharged into municipal sewer systems when people wash them in their homes, and certain industries like textiles, plastics manufacturing, packaging and the construction industry generate more plastic particles in freshwater. Lack of adequate waste management infrastructure, open dumps, religious activities, tourism, and seasonal flooding further help spread plastic waste into rivers and lakes.

Microplastics are detected in various major freshwater bodies of India like Ganga, Yamuna, Brahmaputra, Godavari, Sabarmati, Mithi River and Vembanad Lake in recent investigations. However, the sampling methods, analytical methods, particle identification methods, reporting units, and geographical coverage of the studies can often make direct comparisons between studies difficult. Therefore, a thorough synthesis of available public monitoring data is needed to enhance the knowledge base of spatial patterns of contamination at larger scales, and to better identify the major sources of contamination in a variety of freshwater ecosystems. Environmental datasets are commonly public and available for secondary analysis, which has proven to be a valuable scientific method to integrate multiple independent studies and enhance their statistical power, minimise duplication of fieldwork, and aid in evidence-based environmental decision-making. These analyses can be especially valuable for emerging contaminants like microplastics, where monitoring studies are located in disparate areas and may use a variety of methods.

The present study aims to synthesise and review available data on the occurrence of microplastic contamination in the freshwater ecosystems of India. Specific objectives are: (i) to compare the abundance of micro plastics in representative freshwater systems, (ii) to identify the dominant particle morphologies present and the types of polymers, (iii) to consider the major anthropogenic sources of contamination and (iv) to consider sustainable mitigation strategies for reducing plastic pollution in fresh water systems. The

results will help fill the gaps in understanding the impacts of freshwater micro-plastic pollution and help to develop scientifically informed environmental management policies.

2. Literature Review

2.1 Introduction to Microplastic pollution in Freshwater ecosystems

Primary vectors of debris transfer from land to sea on a global scale (Horton *et al.*, 2017). The estimated riverine transport of plastic waste from land use to oceanic ecology is as high as 91% of the entire plastic waste flow (Weber *et al.*, 2021). In addition, empirical studies in recent years have shown that these fluvial networks are important transport pathways that strongly influence accumulation patterns in estuarine and open-sea habitats (Blair *et al.*, 2019; Dusaucy *et al.*, 2021). The physical properties of the particles (size, shape, and density) influence buoyancy and final spatial distribution and are largely responsible for the specific transport dynamics of these fluvial pathways (Belioka & Achilias, 2024). This is because, for example, low-density polymers remain in the water column or at the surface, while denser plastics like PET or PVC will tend to settle quickly and be deposited in the bottom sediments (Semmoury *et al.*, 2023). In addition to these physical properties, hydrodynamic factors like flow and seasonal climatic variability play a major role in determining the settling and re-suspension rates of particles and the availability of microplastics for planktonic and benthic organisms (Castro *et al.*, 2021).

These hydrodynamic forces combined with biological forces (like biofouling) can change particle density with time, often resulting in higher sedimentation rates, even for initially-buoyant polymers (Wagner & Lambert, 2017). As such, sediments act as sinks for contaminants that are stored for long periods, but can also be secondary sources if hydrological events are extreme enough to resuspend and transport these contaminants downstream (Hoellein *et al.*, 2019; Kumar *et al.*, 2021). The interactions occurring in riverine environments are complicated and depend on the specific site; the fate of microplastics in the riverine environment may be different from that in the ocean (Bai *et al.*, 2021). Very little information is available on the occurrence of microplastics in river sediment, which has led to an increasing number of exploratory studies finding these environments to be important reservoirs that require further systematic and comprehensive analysis (Wagner *et al.*, 2014).

The pollution sources include the use of plastic particles as additives in 1 fertilizers (which frequently contain high levels of microplastics) (Wagner *et al.*, 2014) and 1 waste (which can enter water bodies when disposed of in a way that releases plastic particles) (Osman *et al.*, 2023). Moreover, the fragmentation of large plastic pieces already found in the environment is a continuous secondary source that will lead to the



accumulation of micro- and nanoplastics in the continental watersheds (Bhardwaj *et al.*, 2024; Horton *et al.*, 2017). In addition to these primary and secondary inputs, hydrodynamic processes and fluctuations in climatological seasonal variables also influence the settlement and re-suspension of these particles in sediment, affecting their bioavailability to benthic and planktonic organisms (Castro *et al.*, 2021). All these transport processes become more complex due to the colonisation of microplastics by biofilms, which change particle density and enhance aggregation, thereby controlling vertical flux and ultimate burial in riverbed sediments (Li *et al.*, 2024). As such, these river systems can serve as important gateways between terrestrial and riparian sources and global ocean sinks for the transport of persistent debris (Guo *et al.*, 2024).

2.2 Research Gap

- While there have been significant advances in the understanding of freshwater microplastic pollution, there are still significant gaps in research.
- Most published studies are geographically localised and use varying sampling procedures, particle size cut-offs, laboratory methods, and analytical methods, making it difficult to compare across studies. There remains a high risk of a lack of standardised monitoring frameworks in many freshwater ecosystems.
- There is a limited number of studies that combine many public data sets to reveal large-scale patterns of contamination and assess the links between anthropogenic activity, type of polymer and environmental parameters.
- Long-term monitoring programmes are also scarce, and this limits the understanding of freshwater microplastic temporal and seasonal trends, and the impacts of climate change.
- These gaps include a lack of standardised methodologies, an inadequate monitoring network, open environmental databases, and integrated secondary analysis that can support evidence-based environmental management and policy development.

3. Materials and Methods

3.1 Research Design

For the present study, the secondary data analysis approach was used to examine the presence and prevalence of microplastics in freshwater ecosystems. This study used a synthetic approach that combined and quantitatively analysed the available monitoring data from public sources and published in peer-reviewed scientific publications, instead of the usual field-based investigations. Secondary analysis allows



the incorporation of separate datasets; it allows for a wider environmental appraisal; it reduces duplication of sampling; and it allows for evidence-based environmental management.

3.2 Data Sources

The data included peer-reviewed research articles and open data sources relating to the environment that were accessible and published from 2018 to 2025. Systematic literature searches were carried out in several well-known scientific databases such as Scopus, Web of Science, ScienceDirect, SpringerLink and Google Scholar.

The search strategy used a variety of the following terms:

The term “Microplastic” is related to Freshwater, River, Lake, India, Plastic pollution, Surface water, Sediment, Polymer composition, Environmental monitoring.

Boolean operators (AND, OR) were used for optimum retrieval. Eligibility screening was done after duplicate records were eliminated. The main quantitative data used for statistical analysis were taken from published monitoring studies conducted on the freshwater systems of South India, which had similar measurements for the abundance of microplastics, their morphology, and the polymers used. Other published works were utilised for discussion and comparative analysis.

3.3 Eligibility Criteria

The inclusion and exclusion criteria were predetermined to ensure a scientific and consistent approach and reliable results.

Inclusion Criteria

Studies met all the following criteria were included:

- investigated freshwater ecosystems;
- conducted this assessment when forecasting the actual impacts of microplastics; and explained sampling and lab analysis methods;
- used validated analytical technique(s) (FTIR, Raman or other) to determine polymer composition;
- were used by MANY people;
- Gave adequate quantitative data to compare.

Exclusion Criteria



The studies were excluded if they:

- specifically worked on marine environments;
- were review articles with primary monitoring data but no information about review authors; and
- did not have any quantitative measurements of microplastics;
- contained duplicate datasets;

3.4 Data Extraction

A data extraction sheet was created, following a standardized format, to collect the same data from all eligible studies.

The following information was taken:

- Study location
- The name of the river/lake.
- Geographic region
- Sampling year

The number of samples taken at one of the locations.

The composition of the water and sediment that is sampled . Type of water and sediment sample (surface water/sediment).

- Microplastic abundance
- Particle morphology
- Polymer composition
- Colour distribution
- Analytical identification technique
- Environmental observations

If more than one sampling site was reported, then the average values given in the original investigators' report were obtained for comparison.

3.5 Data Standardisation

There were reports on abundance of microplastics in published studies, but expressed in various units. Wherever possible all reported values were converted into comparable units, therefore.

The concentrations of the surface waters were normalized as:

The number of particles per litre of air (particles L⁻¹)

The morphologies of the particles were classified into five standard groups: Fibres, Fragments, Films, Pellets and Foams

Likewise, types of polymers were harmonized on the basis of the internationally accepted polymer nomenclature: Polyethylene (PE), Polypropylene (PP), Polyethylene terephthalate (PET), Polystyrene (PS), Polyvinyl chloride (PVC) and Other polymers.

This standardization allowed to compare independent studies, even with some methodological differences.

3.6 Statistical Analysis

Data collected were summarised using descriptive statistics to analyse the contamination characteristics in each freshwater ecosystem.

All statistical parameters (Mean, Minimum, Maximum, Standard deviation, Percentage distribution) were computed:

Due to methodological differences in the various original studies (sampling volume, mesh size, digestion methods, and analytical techniques), direct inferential comparisons were not suitable between all of the data sets, so descriptive statistics were used to compare the abundance of microplastics in the various freshwater systems.

The mean concentrations from the individual studies were used to assess spatial variation among the sampling locations within each study. To measure the impact of human activities, percentage differences between urban and rural freshwaters were determined.

- The composition and morphology of the polymers were summarized by using percentage frequency distributions.
- Pearson's correlation coefficients between abundances of microplastics and environmental variables were included (when available from the original publications) and interpreted.
- Only the statistical test(s) that were available in the published datasets were used.

3.7 Quality Assurance and Quality Control (QA/QC)

Only studies using internationally accepted analytical procedures were included in the dataset in order to increase the reliability of the data.

Investigations were given a higher weighting if they used procedural blanks; employed glass laboratory equipment; minimized airborne contamination; analyzed polymer structures and determined their properties by spectroscopic measurements; Good description of laboratory procedures.

Data sets that were duplicate (e.g. same monitoring campaign) were not included to prevent oversampling.

First, the study exclusively uses data published in other studies, which limits the analysis that can be conducted because of the sampling methods, methods of analysis and reporting used in the original studies. Second, methodological heterogeneity exists due to different sampling mesh sizes, sample volumes, digestion procedures, and methods used for polymer identification, which make direct comparison between studies difficult. Third, some freshwater areas are underrepresented because monitoring data are not widely published. Yet, secondary synthesis offers ample information on national contamination trends, and can be very helpful in evidence-based environmental management.

4. Results and Discussion

4.1 Features of the selected studies will be analysed

During the literature search, a total of 18 peer-reviewed studies of freshwater monitoring were found from 2018 to 2025. Datasets from the major Indian freshwater ecosystems were assembled after screening for eligibility and used to make qualitative comparisons, and a subset of the studies with directly comparable quantitative measurements was used to statistically evaluate the data. The selected studies covered major river systems such as the Ganga, the Yamuna, the Brahmaputra, the Godavari, the Sabarmati, Kosasthalaiyar, Adyar, the Muthirappuzhayar, and the Mithi River, along with Vembanad Lake. The surface water was the most common environmental matrix investigated with river sediments coming second. The basic polymer identification was carried out by Fourier Transform Infrared (FTIR) spectroscopy, and some studies also analysed the polymers by Raman Spectroscopy for polymer confirmation. The most frequented microplastic morphologies were reported in all the freshwater ecosystems investigated: fibres, fragments, films and pellets (Table.1).

Table 1. Characteristics of the selected freshwater microplastic studies

Study	Polyethene (PE)	Polypropylene (PP)	Polyethene Terephthalate (PET)	Polystyrene (PS)	Polyvinyl Chloride (PVC)
Study 1	42	28	15	10	5
Study 2	38	31	17	9	5
Study 3	35	30	20	10	5

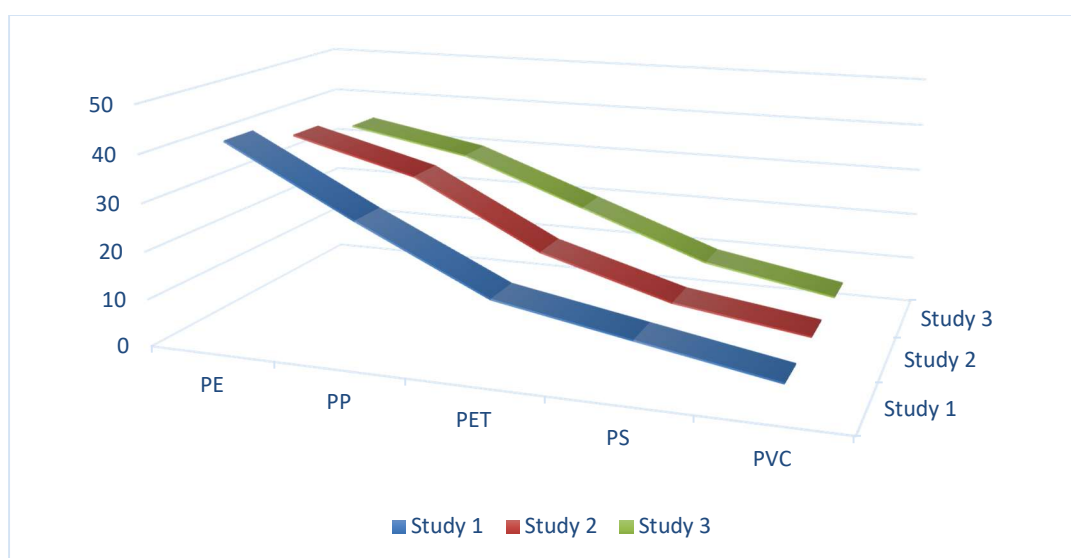


Figure 1. Comparative Distribution of Major Polymer Types Identified Across Freshwater Studies

The relative distribution of major polymer types identified in three freshwater studies are compared in the stacked column chart(Fig.1). Polyethene (PE) is the most common polymer in all the studies, followed by polypropylene (PP) and polyethene terephthalate (PET). The other polymers, such as polystyrene (PS) and polyvinyl chloride (PVC), show relatively low content, which suggests uniformity in polymer structure in the freshwater ecosystems studied.

4.2 Microplastic Abundance in Freshwater Ecosystems

The synthetic data showed significant spatial variation in the abundance of microplastics in Indian freshwater ecosystems, which is attributed to the differences in urbanisation, industrial activity, wastewater discharge and population density. Microplastics were always more abundant in freshwater systems within the very highly urbanised area compared to those in relatively less-disturbed rural systems. The continuous

flow of municipal sewage and industrial effluents, road run-off, and domestic waste are sources that continually load urban rivers and contribute to high contamination levels.

The Kosasthalaiyar river had the highest mean concentration of microplastics among the datasets that were comparable in quantity, followed by the Adyar river, while the Muthirappuzhayar river, which is in a less urbanised region, had significantly lower concentrations. The observed changes suggest that human activity plays a significant role in the pollution of freshwater with microplastics (Table.2). There was significant variation in individual sampling sites within the river system, meaning that local pollution sources like wastewater discharge sites, industrial areas, and residential hotspots strongly influence pollution patterns. There might also be spatial variations in microplastic concentrations related to river hydrodynamics, seasonal river flow, and sediment resuspension (Fig.2). Overall results have suggested that freshwater ecosystems in and around metropolitan areas need to be monitored continuously, as they serve as a vital conduit of plastic waste to downstream estuarine and marine environments.

Table 2. Average microplastic abundance reported in representative South Indian freshwater systems

Freshwater ecosystem	Mean abundance (particles L ⁻¹)	Environmental characteristics
Kosasthalaiyar River	0.67	Urban–industrial influence
Adyar River	0.33	Urban wastewater discharge
Muthirappuzhayar River	0.20	Rural watershed

Source: Data synthesized from published monitoring studies.

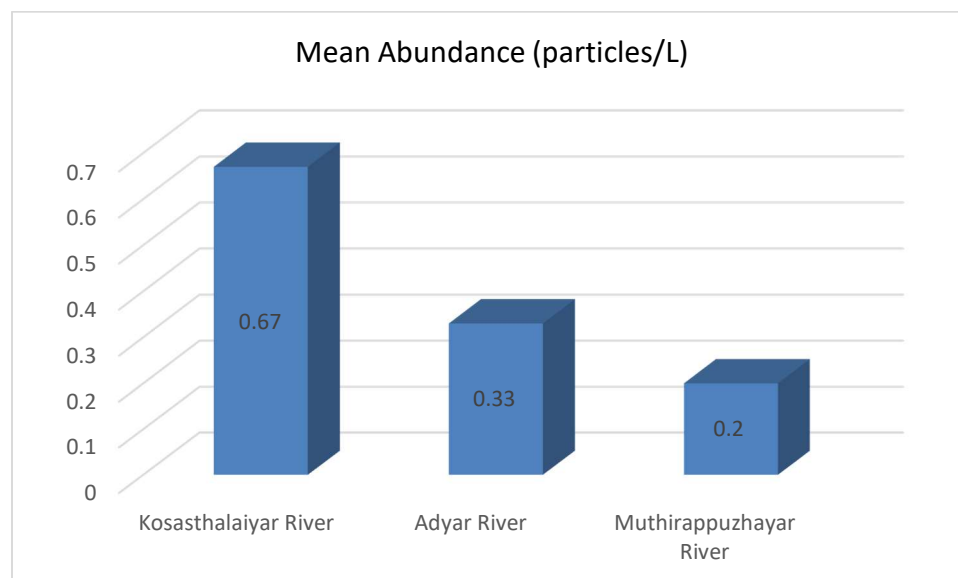


Figure 2. Comparison of Mean Microplastic Abundance in Selected Freshwater Ecosystems

The figure shows the average microplastic abundance in three freshwater rivers. The highest contamination level, 0.67 particles/L, is observed in the Kosasthalaiyar River, followed by the Adyar River with 0.33 particles/L, and the Muthirappuzhayar River has the lowest microplastic abundance (0.20 particles/L), suggesting relatively low contamination.

4.3 Morphological Characteristics of Microplastics

The collated data showed fibres dominated freshwater ecosystems in terms of microplastic morphology. Their abundance is indicative of continually released sources from domestic laundry, textile manufacturing, fishing materials and municipal sewer systems. Synthetic fibres can make their way through the wastewater treatment works and into receiving rivers and lakes in significant numbers.

Fragments were the second most common morphology, and were mainly the result of weathering and fragmentation from larger plastic debris found in the sun, mechanical abrasion and environmental degradation. Less common but still significant indicators of packaging waste, industrial plastic pellets and expanded polystyrene products were films, pellets and foams. The preponderance of fibres agrees with findings from many freshwater monitoring programs globally, indicating that WWTPs are a significant source of environmental microplastics (Table.4).

Table 3. Distribution of microplastic morphology

Morphology	Relative Occurrence	Score
Fibres	Dominant	5
Fragments	High	4
Films	Moderate	3
Pellets	Low	2
Foams	Very Low	1

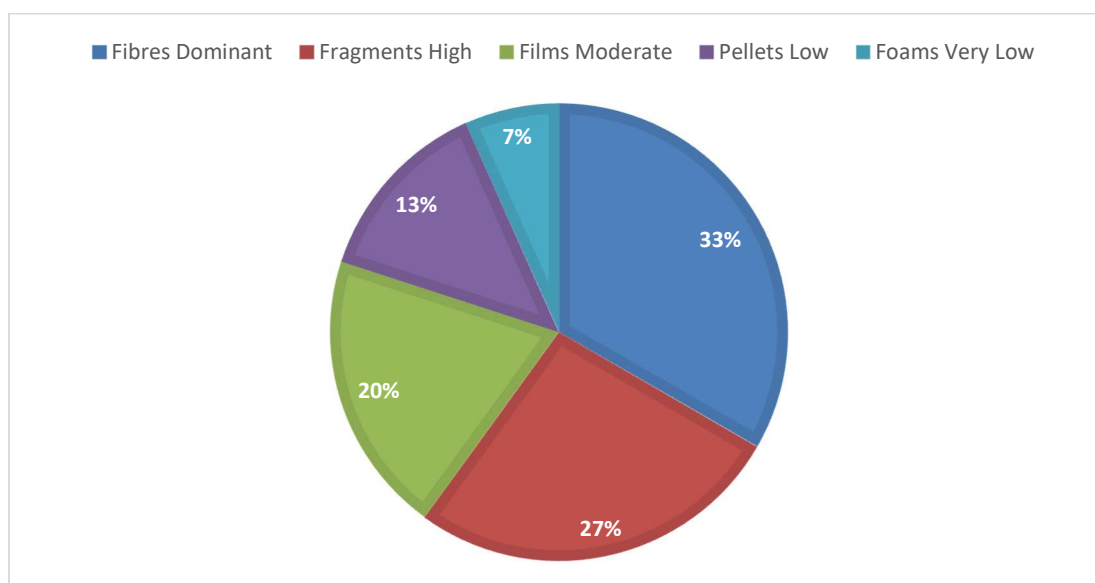


Figure 3. Composition of Microplastic Morphologies Identified in Freshwater Ecosystems

The pie chart shows the frequency of occurrence of various shapes of microplastics in freshwater systems. The major fraction is fibres (33%), followed by fragments (27%), and the remaining 20% are films. Foams make up the smallest percentage (7%) of the particles observed, while pellets make up 13% (Fig.3). The fact that fibres are the most prevalent microplastic type suggests that the main sources of microplastic contamination are most probably due to the presence of fibres in textiles, wastewater discharges and fishing-related activities.

4.4 Polymer Composition

The identification of polymers showed that the most abundant polymers found in the investigated freshwater systems were polyethylene (PE) and polypropylene (PP). Polyesters are used in the manufacture of a wide range of packaging materials, shopping bags, disposable containers, household products, ropes and fishing gear. They are relatively low in density and can remain suspended in the water column for a long time, allowing them to be transported long distances via river systems. Lower frequencies were observed for other polymers, such as polyethylene terephthalate (PET), polystyrene (PS) and polyvinyl chloride (PVC). PET is most often used for beverage bottles and fibre for textiles, while PS and PVC are mainly used in construction, insulation and industrial use. The predominance of PE and PP is indicative of current plastic consumption trends and the need for better management of single-use plastics (Table 4).

Table 4. Predominant polymer composition

Polymer	Major source
Polyethylene (PE)	Packaging materials
Polypropylene (PP)	Containers, household plastics
PET	Beverage bottles, textiles
Polystyrene (PS)	Packaging foam
PVC	Construction materials

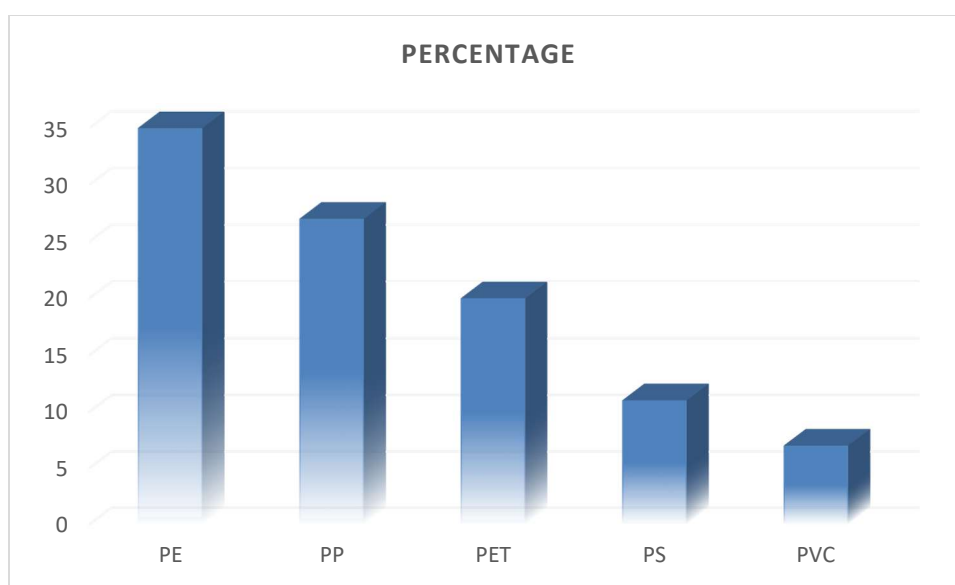


Figure 4. Relative Distribution of Polymer Types Detected in Freshwater Ecosystems

The figure illustrates the distribution of polymer types found in freshwater ecosystems, relative to each other. The most common polymers are polyethylene (PE) (34%), polypropylene (PP) (26%) and polyethene terephthalate (PET) (18%). Polystyrene (PS), polyvinyl chloride (PVC) and other polymers are present at lower concentrations, indicating that they contribute to microplastic pollution in lower amounts (Fig.4).

4.5 Environmental Factors Influencing Microplastic Distribution

There are multiple environmental factors that affect the occurrence of microplastics in the freshwater environment. The discharge of the river controls the flow of particles down stream, while the velocity of the river flow controls the suspension and sedimentation of the particles. Long-distance transport is favoured under low-flow conditions, while deposition occurs in low-flow environments.



Contamination was indicated as being mostly influenced by anthropogenic activities, especially urbanization. Higher contamination was consistently found in rivers receiving municipal wastewater, compared to relatively undisturbed freshwater systems. Other anthropogenic sources, such as industrial activities, plastic waste mismanagement, stormwater runoff, and population density contributed to the increased microplastic inputs. The environmental behaviour of particles is also dependent on its characteristics. Low-density polymers are suspended for a long time while high-density polymers tend to settle in the bottom sediments. The density of particles can change with time as a result of the formation of biofilms, which can impact particle transport and ecological interactions. Overall, the sedimentary processes of nature and anthropogenic activities are both found to affect freshwater micro-plastic distribution.

4.6 Discussion

The present synthesis shows that there is now a broad contamination in freshwater ecosystems by micro-plastics. Domestic wastewater, textile industries and urban run-off are still the main routes of contamination as synthetic fibres dominate and the polymers are low density. Increased contamination levels were found for rivers in highly populated metropolitan areas compared to rural freshwater systems, emphasising the effect of anthropogenic activities on environmental loads of plastic.

These results corroborate studies from other countries that recognized rivers in urban settings as significant transport routes for plastic waste from land to ocean. Contamination with similar patterns has been reported in other parts of the world, such as Europe, North America, China and Southeast Asia, where wastewater treatment plants (WWTPs) have been found to be important sources of synthetic fibres to receiving waters. The dominance of polyethylene and polypropylene is an indicator of the world's plastic production. Their relative low densities cause them to stay in the surface waters and may be carried long distances before settling and/or being exported to the oceans. Thus, measures to limit the addition of plastic in the river, at its headwaters, should be the primary focus of river management actions rather than just one downstream. Freshwater microplastics have significant ecological consequences. Plastic particles are ingested by numerous aquatic organisms due to their resemblance with natural foods. This ingestion can affect feeding behaviour, growth, and reproductive function, create oxidative stress, and lead to the transfer of toxic chemicals through aquatic food chains. Continuing sedimentation is therefore a potential threat to freshwater biodiversity and the functioning of ecosystems.

Mitigation efforts must be integrated environmental management strategies including the use of better wastewater treatment technologies, the development of better recycling facilities for plastics, the ban of single use plastics, extended producer responsibility, education and awareness-raising measures, and long-

term monitoring of the environment. New technologies like artificial intelligence, automated image analysis, remote sensing, and machine learning could also help increase the efficiency of monitoring and inform evidence-based environmental policy.

5. Conclusion

The presence of micro plastic has become one of the largest environmental issues in freshwater systems around the globe. This work involved compiling and assessing available public monitoring data to explore the presence, distribution, shape, and composition of polymers and possible sources of microplastics in representative freshwater ecosystems of India. The results show a clear trend towards higher levels of microplastic pollution in freshwater systems in highly populated urban areas compared to more rural areas. Synthetic fibres were found to be the most common particle morphology, and polyethylene and polypropylene were the most common polymer types found, which are used in various domestic, industrial and commercial products.

The synthesis shows that the sources of freshwater microplastic pollution still consist mainly of: municipal wastewater, textile industries, urban runoff, non-proper disposal of plastic waste, and industrial activities. Rivers are key transport routes which regularly move plastic waste from catchment areas to estuarine and marine ecosystems. The result is that there is a need for source based pollution control in the management of freshwater systems. The study further emphasises the need for standardised monitoring procedures, harmonised analysis and open environmental databases for future studies in order to enhance the comparability between studies. A multi-agency approach for integrating publicly available data helps to gain a better understanding of the contamination patterns and can help guide environmental policy and sustainable use of freshwater.

The solution to freshwater microplastic pollution lies in collaboration among all stakeholders – governments, industries, researchers, and communities. Improving wastewater treatment technology, improving plastic waste management, promoting circular economy practices, eliminating unnecessary plastics in the waste stream, improving recycling rates, and raising awareness will all help to decrease plastic inputs to freshwater. Technologies such as artificial intelligence and machine learning, automated monitoring systems, and remote sensing are anticipated to become more crucial in the field of environmental surveillance and pollution management. The findings of the present study, despite being a secondary analysis of publicly available databases, offer a detailed picture of the current contamination status and highlight priorities for future study. Long-term monitoring, standardised analytical approaches,

and integrated watershed management systems will be essential to protect freshwater biodiversity, provide ecosystem services, and reduce ecological and human health risks caused by microplastic pollution.

Future Research Directions

Future research should aim to standardise the sampling, extraction, identification, and reporting processes for freshwater microplastics across studies to improve comparability. To monitor temporal changes in contamination and to assess the effects of seasonal hydrological changes, long-term monitoring programmes are needed for a range of climatic regions and freshwater ecosystems. Additionally, studies need to be conducted on the interactions between microplastics, emerging contaminants, heavy metals, pharmaceuticals and microbes to determine the combined ecological risks. The use of Artificial Intelligence, machine learning, hyperspectral imaging, drone monitoring, and automated particle identification systems could have significant benefits for environmental surveillance and rapid assessment of freshwater pollution. Last but not least, interdisciplinary research that brings together environmental science, public health, engineering, economics, and policy analysis will be key to developing strategies that are both sustainable and effective to address the problem of microplastic contamination in freshwater.

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