Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 15 May 2026
Revised 14 June 2026
Accepted 02 July 2026

Natural Resources for Human Health 2026, Vol. 6 (4s): 163–189

KEYWORDS:
Polymer composition; Trophic transfer; Bioaccumulation associated contaminants, Surface water and sediments

Microplastics in Indian Freshwater Systems: Sources, Distribution, Characterization and Ecological Risks

Pinaki Prasad Singh[1], Brijendra Pratap Singh[2], Shailly Misra[3], Juhi Kumari[4], Samyak Singh[5]*, Shiv Shankar Yadav[6]

[1]Department of Forestry, Wildlife and Environmental Sciences, Guru Ghasidas Vishwavidyalaya, Bilaspur, Chhattisgarh- 495009, India ppsifs12@gmail.com
[2]Department of Forestry, Wildlife and Environmental Sciences, Guru Ghasidas Vishwavidyalaya, Bilaspur, Chhattisgarh- 495009, India p.brijendra@gmail.com
[3]Department of Botany, University of Lucknow, Lucknow, Uttar Pradesh- 22602, India shailly_misra@yahoo.com
[4]Department of Forestry, Wildlife and Environmental Sciences, Guru Ghasidas Vishwavidyalaya, Bilaspur, Chhattisgarh- 495009, India juhitripathij@gmail.com
[5*] Department of Forestry, Wildlife and Environmental Sciences, Guru Ghasidas Vishwavidyalaya, Bilaspur, Chhattisgarh- 495009, India singhsamyak95@gmail.com
ORCID: 0009-0005-8279-8267
[6]Environmental Science, Chemistry Department, School of Basic Sciences, Babu Banarasi Das University, Lucknow, Uttar Pradesh- 226028, India
drssyprof.unv@gmail.com

ABSTRACT: Microplastic (MP) pollution has emerged as a critical environmental issue in freshwater ecosystems, yet a comprehensive synthesis for Indian freshwater systems remains limited. This review compiles and critically evaluates published studies on the sources, distribution, physicochemical characteristics, and ecological risks of microplastics across rivers, lakes, reservoirs, and wetlands in India. Urban wastewater, industrial discharge, tourism activities, and agricultural runoff are identified as major sources of MP contamination. Reported MP concentrations vary widely among systems, with fibers dominating morphological composition, followed by fragments and films. Polymer analyses using Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy reveal that polypropylene (PP) and polyethylene (PE) are the most prevalent polymers, with additional contributions from polyethylene terephthalate (PET), PVC (Polyvinyl chloride), and polyamide linked to packaging materials, textiles, and fishing activities. Microplastics also function as vectors for heavy metals and plastic additives, enhancing their environmental persistence and toxicity. Evidence of MP ingestion and trophic transfer in fish and other aquatic organisms highlights potential implications for food web integrity and human exposure. Risk assessment indices including Pollution Load Index (PLI), Polymer Hazard Index (PHI), and Potential Ecological Risk Index (PERI) indicate increasing ecological risks in several freshwater systems, particularly in urbanized basins. Despite growing research, key knowledge gaps remain in nanoplastic detection, long-term monitoring, and human health risk assessment, emphasizing the need for standardized methodologies and integrated management strategies to mitigate microplastic pollution in Indian freshwater ecosystems.

1. INTRODUCTION

The global proliferation of plastic materials has resulted in an unprecedented accumulation of plastic debris across terrestrial and aquatic ecosystems. Since the mid-20th century, plastic production has increased dramatically due to its versatility, durability, and low manufacturing costs. Recent global estimates indicate that annual plastic production has exceeded 400 million tonnes, with a substantial fraction eventually entering natural environments through mismanaged waste streams and fragmentation processes (Geyer et al., 2017; OECD, 2022). As larger plastic items degrade through physical, chemical, and biological weathering, they generate smaller particles known as microplastics (MPs), generally defined as plastic fragments smaller than 5 mm (Thompson et al., 2004; Andrady, 2011). Due to their persistence, widespread occurrence, and potential ecological effects, microplastics have emerged as one of the most pressing contaminants of global concern (Rochman et al., 2013; Galloway et al., 2017; Loganathan & Kizhakedathil, 2023; Akinci, 2025). While early research on microplastic pollution primarily focused on marine environments, freshwater ecosystems have recently gained increasing scientific attention as critical reservoirs and transport pathways for plastic debris. Rivers, lakes, and reservoirs function both as sinks and conduits for microplastics, facilitating the transfer of land-based plastic waste from terrestrial environments to coastal and marine systems (Wagner et al., 2014; Eerkes-Medrano et al., 2015). Recent modeling studies suggest that rivers are responsible for transporting several million tonnes of plastic debris to the oceans annually, highlighting their pivotal role in global plastic cycling (Lebreton et al., 2017; Meijer et al., 2021). Consequently, microplastics have now been detected in various freshwater matrices worldwide, including surface waters, sediments, aquatic biota, and drinking water sources (Li et al., 2018; Horton et al., 2017; Wang et al., 2021).

Microplastics enter freshwater systems through multiple anthropogenic pathways, including municipal wastewater discharge, industrial effluents, urban runoff, tourism activities, and atmospheric deposition (Browne et al., 2011; Dris et al., 2017). In addition to primary microplastics, such as microbeads and industrial pellets, secondary microplastics generated from the fragmentation of larger plastic debris represent a major source of contamination in rivers and lakes (Cole et al., 2011). Once introduced into aquatic environments, microplastics exhibit complex environmental behavior due to their variable density, morphology, and polymer composition. These characteristics influence their transport, settling, and accumulation in water columns or sediments (Duis and Coors, 2016). Furthermore, microplastics possess hydrophobic surfaces capable of adsorbing various hazardous contaminants, including heavy metals, pharmaceuticals, and persistent organic pollutants (POPs), thereby acting as vectors for chemical pollutants within aquatic ecosystems (Rochman et al., 2013; Sharma and Chatterjee, 2017). India represents one of the largest producers and consumers of plastic products among developing economies, generating an estimated 26 million tonnes of plastic waste annually (CPCB, 2022). Rapid population growth, urban expansion, industrialization, and insufficient waste management infrastructure contribute significantly to plastic leakage into freshwater ecosystems. Rivers in India serve as vital socio-ecological systems, supporting domestic water supply, agriculture, fisheries, transportation, and cultural activities for hundreds of millions of people. However, increasing anthropogenic pressure has resulted in widespread contamination of these freshwater systems with plastic debris (Hossain et al., 2022; Singh et al., 2021).

Recent investigations have confirmed the presence of microplastics in several major Indian river systems, including the Ganga, Yamuna, Mahanadi, Netravathi, Periyar, and Brahmaputra rivers. For instance, microplastic particles have been reported in surface waters, water columns, and sediments of the Ganga–Yamuna river system, with dominant particle sizes ranging between 300 μm and 5 mm and fibres being the most prevalent morphological type (Gupta et al., 2024). Similarly, studies conducted in the Mahanadi River basin have documented microplastic concentrations ranging from hundreds of particles per cubic meter in water to several hundred particles per kilogram in sediments (Ganie et al., 2024). These findings indicate that Indian freshwater ecosystems are increasingly subjected to microplastic contamination originating from both urban and rural catchments. Among Indian river systems, the Ganga River basin is of particular importance due to its ecological, cultural, and economic significance. The basin covers approximately 26 % of India's geographical area and supports nearly 43 % of the country's population, making it one of the most densely populated river basins in the world (Gupta et al., 2024). Studies have suggested that the Ganga River may rank among the top global contributors of river-derived plastic emissions to the oceans, highlighting the urgency of assessing microplastic pollution within this basin (Lebreton et al., 2017). Seasonal hydrological variations, particularly during the monsoon period, further influence the distribution and transport of microplastics by enhancing runoff and mobilizing plastic debris from urban settlements, agricultural lands, and waste disposal sites. Beyond their physical presence, microplastics pose significant ecological and toxicological risks to freshwater organisms. Numerous studies have documented the ingestion of microplastics by aquatic organisms, including zooplankton, benthic invertebrates, and fish, leading to potential physiological stress, digestive obstruction, oxidative damage, and altered feeding behavior (Au et al., 2015; de Sá et al., 2015; Wang et al., 2021). Moreover, the capacity of microplastics to accumulate and transport toxic chemicals raises concerns about trophic transfer and potential implications for human health through contaminated aquatic food resources (Galloway et al., 2017). In countries like India, where freshwater fish constitute an important source of dietary protein, the presence of microplastics in aquatic food webs represents a growing environmental and public health concern.

Despite the increasing number of studies on microplastic pollution in India, current knowledge remains fragmented, with most investigations focusing on specific rivers or isolated geographical regions. Furthermore, methodological inconsistencies in sampling procedures, extraction techniques, and analytical methods often hinder direct comparisons across studies (Hidalgo-Ruz et al., 2012). Comprehensive synthesis of available literature is therefore essential to better understand the occurrence, sources, and ecological implications of microplastics in Indian freshwater systems. In this context, the present review provides a critical synthesis of existing studies on microplastic pollution in Indian freshwater environments. Specifically, this review aims to (i) identify major sources of microplastic contamination in Indian freshwater systems, (ii) evaluate spatial and temporal distribution patterns of microplastics in water and sediments, (iii) analyze the physical and chemical characteristics of microplastic particles, and (iv) assess their ecological impacts and environmental risks. By integrating findings from recent studies across diverse freshwater ecosystems in India, this review seeks to highlight key research gaps and provide insights that may support future monitoring strategies and pollution mitigation efforts.

2. SOURCES OF MICROPLASTIC CONTAMINATION

2.1 Urban and Municipal Sources

Urban environments are widely recognized as the dominant contributors to microplastic contamination in Indian freshwater systems. Rapid urbanization, high population density, and inadequate waste management infrastructure collectively facilitate the release of plastic debris into rivers and associated aquatic environments. Several studies have identified municipal wastewater discharge, urban drainage channels, and improperly managed domestic waste as major sources of MPs in Indian river systems (Jain et al., 2024; Gupta et al., 2024; Sarkar et al., 2022; Mukhopadhyay & Valsalan, 2024). In particular, major river basins such as the Ganga receive substantial microplastic inputs from urban centers where untreated or partially treated municipal sewage and industrial effluents are discharged directly into river channels. For example, investigations conducted along the Ganga River have reported microplastic concentrations ranging from 1,296 to 2,414 items m^{-3} in highly urbanized regions including Haridwar, Kanpur, and Varanasi, indicating significant anthropogenic pressure in densely populated stretches of the river (Sarkar et al., 2022). Urban drainage networks further intensify this contamination by acting as direct conduits that transport plastic debris and fragmented particles from streets, residential areas, and commercial zones into adjacent freshwater bodies. A recent study from Delhi demonstrated that drainage systems serve as critical pathways facilitating the transfer of microplastics into riverine ecosystems (Vaid et al., 2024).

Recent evidence also suggests that socio-economic events and changes in consumption patterns can significantly influence the magnitude of microplastic pollution. For instance, studies conducted in rivers of Tamil Nadu during the post-COVID-19 period reported elevated microplastic contamination in packaged drinking water, community-stored water, and nearby surface water bodies, reflecting increased plastic consumption and waste generation during the pandemic (Pavithra et al., 2024). In addition to chronic urban inputs, acute contamination events may also contribute to microplastic release into freshwater systems. A notable example is the landfill fire incident in the Brahmapuram waste dumping site in Kerala, which resulted in severe microplastic contamination in surrounding freshwater environments, highlighting the vulnerability of urban water bodies to episodic pollution events associated with improper waste management (Amal and Devipriya, 2024).

2.2 Tourism and Recreational Activities

High-altitude lakes in the Himalayan region provide clear evidence of tourism-related microplastic pollution. Nainital Lake in Uttarakhand has been identified as a microplastic hotspot, where tourism pressure and catchment runoff contribute substantially to plastic inputs. Surface water concentrations at heavily visited sites have been reported to reach up to 88 particles L^{-1}, highlighting the direct influence of tourism activities on microplastic accumulation in this lake ecosystem (Jain et al., 2024). Similarly, Dal Lake in the Kashmir Himalayas receives significant microplastic inputs from tourism-related activities, domestic waste discharge, and urban runoff, with reported surface water concentrations ranging from 140 ± 20 to 846 ± 136 particles L^{-1}, indicating considerable anthropogenic pressure on this freshwater system (Yousuf et al., 2025). In southern India, Kodaikanal Lake, another major tourist destination, has also been reported to experience microplastic contamination largely associated with tourism-generated plastic waste and recreational activities within the catchment area (Laju et al., 2022).

In addition to plastic litter, tourism-related human activities can introduce microplastics through less obvious pathways. Napper et al. (2020) demonstrated that synthetic clothing worn by trekkers and mountaineers can release microplastic fibers during outdoor activities, which subsequently accumulate in high-altitude environments. Frequent trekking expeditions and the establishment of research stations in Himalayan glacier regions, aimed at studying climate change and glacial dynamics, may further contribute to microplastic inputs through the release of synthetic fibers and other plastic materials used in equipment and infrastructure (Bhaduri et al., 2025). Tourism-driven recreational activities also influence microplastic contamination in riverine ecosystems. In the Mandovi River freshwater system of Goa, tourism-related activities and commercial–recreational fishing have been identified as major contributors to microplastic loads, reflecting the combined effects of tourism infrastructure, boating, and fishing operations in the region (Mhapsekar & Kalangutkar, 2026). Fishing activities in particular can significantly contribute to microplastic pollution through the degradation and fragmentation of synthetic fishing gear, ropes, and nets. Wetland ecosystems are especially vulnerable to such inputs. For example, studies conducted in Vembanad Lake, Kerala, revealed a predominance of polyamide (PA) fibers, suggesting that microplastics in this system largely originate from fishing nets and gear used in local fisheries. In addition, domestic laundry wastewater was identified as an additional source contributing synthetic fibers to the lake ecosystem (Anagha et al., 2023).

2.3 Industrial and Agricultural Inputs

Industrial activities are an important source of microplastic (MP) contamination in freshwater ecosystems. Industries involved in plastic manufacturing, packaging, textiles, and synthetic polymer processing release microplastics through industrial effluents, atmospheric deposition, and surface runoff (Sharma and Chatterjee, 2017). In addition, accidental losses of industrial resin pellets (nurdles) during production and transport may introduce primary microplastics into aquatic environments. In India, several industrial clusters are located along major river basins such as the Ganga and Yamuna, where industrial discharge contributes to MP pollution. Textile industries are particularly important sources because manufacturing processes release synthetic fibers such as polyester (PES) and nylon that can enter freshwater systems through untreated or partially treated wastewater, resulting in the dominance of fibrous microplastics reported in many studies (Singh et al., 2021). Field investigations further demonstrate industrial influence on riverine contamination. For instance, the Subarnarekha and Kharkai rivers show seasonal MP concentrations ranging from 6.7 ± 0.9 to 22.3 ± 0.4 items L^{-1} in water and 30.3 ± 2.1 to 364.3 ± 3.4 items kg^{-1} in sediments, linked to industrial and anthropogenic pressures within the basin (Patidar et al., 2023a). Similarly, microplastic contamination in the Damanganga and Tapi rivers in Gujarat has been associated with industrial activities, with the Damanganga River reporting 3.53 particles L^{-1} in surface waters (Prasad et al., 2025).

Agricultural activities also contribute to MP contamination through the extensive use of plastic materials such as mulch films, irrigation pipes, fertilizer bags, and greenhouse coverings. These materials degrade into secondary microplastics that accumulate in soils and are transported into rivers and lakes via erosion and surface runoff. Additionally, the application of sewage sludge or organic fertilizers containing microplastics can introduce plastic particles into agricultural soils, which may subsequently enter freshwater systems during rainfall events (Li et al., 2018). Agricultural runoff and drainage inflow have also been linked to MP contamination in lake ecosystems; for example, Kumaraswamy Lake in Coimbatore recorded an average concentration of 8.77 ± 0.27 particles L^{-1}, attributed to runoff and improper waste disposal from surrounding areas (Ephsy and Raja, 2023). Industrial and agricultural activities also influence the polymer composition of microplastics in freshwater systems. Fibrous polymers such as polyester and nylon are commonly associated with textile industries, whereas PE and PP fragments typically originate from plastic packaging and agricultural plastics (Rillig, 2012; Napper & Thompson, 2016).

2.4 Religious and Cultural Practices

Religious and cultural activities represent a distinctive pathway of microplastic contamination in Indian freshwater systems. Practices such as idol immersion, ritual offerings, festival decorations, and waste generated during mass gatherings introduce large quantities of plastic debris into rivers and lakes. These materials subsequently fragment into microplastics, creating localized pollution hotspots and facilitating downstream transport with potential ecological and human-health implications.

Several studies identify religious tourism, ritual practices, and mass gatherings as important contributors to plastic waste entering freshwater bodies (Gosavi and Phuge, 2023; Mishra and Singh, 2025; Singh et al., 2025). In the Ganga River basin, microplastic inputs have been linked not only to municipal and industrial discharges but also to ritual bathing, ceremonial offerings, and tourism-related waste (Sarkar et al., 2022). Such culturally embedded activities represent unique source pathways that are less frequently documented in Western freshwater studies, highlighting the need for culturally appropriate mitigation strategies.

Idol immersion events are widely reported as sources of plastic debris due to non-biodegradable materials used in idols and decorative components, which may fragment into microplastics in lakes and river stretches used for ceremonial immersion (Gosavi and Phuge, 2023; Mishra and Singh, 2025). Similarly, ritual offerings and associated packaging materials deposited at ghats and riverbanks contribute to plastic litter that can enter aquatic environments (Mishra and Singh, 2025; Singh et al., 2025; Shukla, 2025). Festival decorations and single-use disposables used during celebrations and fairs further add to plastic waste loads that degrade into secondary microplastics (Singh et al., 2025; Singh and Verma, 2025). In addition, large pilgrimage events generate substantial pulses of solid waste and sewage inputs, increasing microplastic loading in rivers during and after such gatherings (Rajan et al., 2023; Mishra and Singh, 2025).

Field observations also show higher microplastic concentrations near pilgrimage and recreational riverbank zones. Elevated MP abundance and ecological risk indices have been reported downstream of densely populated and religiously active cities along the Ganga River (Pandey and Rajput, 2026). Similarly, higher concentrations of plastic debris and microplastics have been documented in major pilgrimage centers such as Haridwar and Prayagraj, where intense tourism and ritual activities occur (Gupta et al., 2024). Comparable findings have been reported in other river systems, including the Cauvery River, where cultural practices and human activities are considered potential sources of MPs (Estherrani et al., 2024). Studies from the Hooghly River have also highlighted microplastic hotspots near urban sewage inflows while acknowledging the river's cultural significance as a factor influencing local pollution patterns (Shukla, 2025). Broader regional syntheses similarly emphasize ritual activities, bathing practices, and offerings as pathways through which plastics enter freshwater systems (Raveendran and Geetha, 2023).

3. SPATIAL AND TEMPORAL DISTRIBUTION PATTERNS

3.1 Geographic Distribution Across India

Microplastic contamination is geographically widespread across India, occurring in diverse freshwater environments ranging from Himalayan rivers and high-altitude lakes to peninsular rivers, reservoirs, and urban lakes. Table 1 summarizes reported MP concentrations across major freshwater systems, demonstrating that contamination occurs not only in highly urbanized basins but also in relatively remote and ecologically sensitive environments. In the Himalayan region, significant MP loads have been reported from both rivers and lakes. For instance, Dal Lake in Kashmir recorded surface water concentrations ranging from 140 ± 20 to 846 ± 136 particles L^{-1}, highlighting substantial contamination even in high-altitude systems (Yousuf et al., 2025). Similarly, the Upper Himalayan Ganga basin reported 100.17 ± 16.64 to 1550 ± 257.58 particles L^{-1} in surface waters, indicating considerable MP presence in upstream river stretches (Chaudhary et al., 2025). Other Himalayan rivers, including the Beas and Brahmaputra, further confirm the occurrence of MPs in mountain river systems influenced by local anthropogenic activities and long-distance transport processes (Bhaduri et al., 2025; Tsering et al., 2021).

Major river basins of northern India, particularly the Ganga–Yamuna system, consistently show elevated MP concentrations associated with dense population centers and urban discharge. Surface water concentrations of 14–43 particles L^{-1} have been reported in the Ganga River, with basin-scale studies indicating 4.67–49.50 MPs L^{-1} across multiple sites (Singh et al., 2024; Gupta et al., 2024). Earlier studies also highlighted increasing MP abundance in urban stretches of the Ganga River due to municipal waste discharge, tourism, and industrial activities (Sarkar et al., 2022). Peninsular river systems such as the Godavari, Cauvery, Narmada, and Mahanadi also show widespread MP contamination linked to urban runoff, industrial discharge, and agricultural inputs. For example, the Mahanadi River recorded 337.5 ± 54.4 to 1333.3 ± 557.2 MPs m^{-3} in surface waters (Ganie et al., 2024), while the Cauvery River reported 43–69 particles L^{-1} (Estherrani et al., 2024). Urban rivers and lakes, including the Gomti, Adyar, and Nainital Lake, often exhibit measurable MP contamination associated with wastewater discharge, tourism, and recreational activities (Bhan et al., 2025; Pavithra et al., 2024; Jain et al., 2024).

3.2 Vertical and Spatial Distribution

Within freshwater systems, MP distribution shows strong vertical stratification and spatial heterogeneity, influenced by hydrodynamics, particle characteristics, and localized anthropogenic inputs. Vertical gradients are commonly observed in lakes where microplastics tend to settle toward deeper water layers and sediments. For example, in Vembanad Lake, bottom waters contained 52.70 ± 5.43 items L^{-1}, approximately twice the concentration observed in subsurface waters (26.79 ± 3.74 items L^{-1}), indicating downward transport and accumulation of denser or biofouled particles (Anagha et al., 2023). Such vertical patterns suggest that deeper water layers may act as transitional zones for particle deposition before eventual sediment accumulation. Spatial heterogeneity is also evident within river systems. Pollution hotspots are frequently reported near urban areas, drainage outlets, and recreational zones, where wastewater discharge and human activities increase MP inputs (Jain et al., 2024; Gupta et al., 2024; Mukhopadhyay & Valsalan, 2024). Basin-scale analyses of the Ganga and Yamuna rivers show significant variation between upstream, midstream, and drainage-influenced sites, enabling identification of localized pollution sources (Gupta et al., 2024).

Downstream accumulation trends are commonly observed in many rivers. In the Gola River (Uttarakhand), downstream urban–industrial stretches recorded higher MP abundance (~130 particles L^{-1}) than upstream sections (~90 particles L^{-1}), reflecting increasing anthropogenic influence along the river course (Shifa et al., 2025). A similar pattern was reported in the Mandovi River (Goa), where MP concentrations were highest downstream (4.28 particles L^{-1}) compared with upstream (1.77 particles L^{-1}) and midstream zones (1.27 particles L^{-1}) (Mhapsekar and Kalangutkar, 2026). Spatial heterogeneity has also been observed in the Periyar River, where MP distribution varies across river stretches depending on local pollution sources and land-use characteristics (Mukhopadhyay and Valsalan, 2024). Environmental factors such as particle morphotype, hydrodynamic conditions, pH, and wind patterns may further influence microplastic distribution within freshwater environments (Estherrani et al., 2024).

3.3 Seasonal Variation

Seasonal hydrological dynamics play a crucial role in regulating the abundance, transport, and redistribution of MPs in freshwater systems. In India, the monsoon cycle strongly influences MP fluxes, with several studies reporting elevated concentrations during periods of intense rainfall and high river discharge. In the Ganga River basin, it has been estimated that more than 74.5% of plastic input occurs between May and October, with significantly higher MP transport during the wet season compared to the dry season (Gupta et al., 2024; Sarkar et al., 2022; Varsha et al., 2025). This seasonal pattern is largely attributed to enhanced surface runoff, mobilization of terrestrial plastic debris, and increased river transport capacity during high-flow conditions. Field investigations further confirm strong seasonal variability in MP abundance across Indian rivers. For example, in the Ganga River at Varanasi, water samples contained 17–36 particles L^{-1} during the pre-monsoon period, while higher concentrations were observed at several sites during the post-monsoon season, reflecting the influence of seasonal hydrological processes on MP transport and redistribution (Singh et al., 2024). Similarly, studies in the Mula River (Pune) reported higher MP concentrations during the pre-monsoon season (1808 ± 697 particles L^{-1}) compared to the post-monsoon period (1561 ± 167 particles L^{-1}), indicating that seasonal accumulation and flushing mechanisms can produce varying temporal patterns in different river systems (Verma et al., 2025).

Seasonal trends are also evident in lake ecosystems. In Kumaraswamy Lake, the highest MP concentrations were recorded during the monsoon season, whereas summer exhibited the lowest values, with the outlet zone identified as the most contaminated location (10.70 ± 0.25 particles L^{-1}) (Ephsy and Raja, 2023). Similar patterns have been observed in multiple lakes of Tamil Nadu, where MP concentrations during the monsoon ranged from 16 ± 2 to 130.33 ± 13.52 particles L^{-1} in water and 26.66 ± 5.03 to 159.45 ± 11.68 particles kg^{-1} in sediments, exceeding those reported during the summer season (Laju et al., 2023). River systems in eastern India also show pronounced seasonal variation. The Subarnarekha and Kharkai rivers exhibit fluctuations in MP abundance linked to changes in hydrological conditions and anthropogenic inputs across seasons (Patidar et al., 2023a). Similar observations have been reported from the Periyar River, where the highest MP abundance occurred during the monsoon season (124.95 items L^{-1}), followed by the post-monsoon and pre-monsoon periods (Mukhopadhyay and Valsalan, 2024). Increased MP concentrations during the monsoon are commonly attributed to enhanced runoff, stormwater discharge, and erosion processes that transport plastic debris from terrestrial environments into aquatic systems (Amrutha et al., 2023).

3.4 Accumulation in Sediments and Biota

Sediments are widely recognized as major sinks for MPs in freshwater ecosystems because particles transported through the water column eventually settle through gravitational settling, aggregation, and biofouling processes. Numerous studies from Indian freshwater systems show that sediment concentrations frequently exceed those in overlying waters, indicating long-term accumulation in benthic environments. For example, Dal Lake sediments contain 2,616 ± 1,016 to 12,966 ± 496 particles kg^{-1}, far higher than surface water concentrations, confirming sediments as long-term reservoirs of MPs (Yousuf et al., 2025). Similarly, sediments of Nainital Lake contain 0.4–10.6 particles g^{-1}, with localized hotspots near areas of intense human activity (Jain et al., 2024). Comparable accumulation has been reported in other lacustrine systems, including Anchar Lake (606 particles kg^{-1}) and Veeranam Lake (92–604 particles kg^{-1}), highlighting the capacity of lake sediments to retain MPs over extended periods (Neelavannan et al., 2022; Manikanda et al., 2021).

High sediment loads have also been documented in major river systems across India. In the Upper Ganga basin, sediment concentrations range from 7,200 to 16,400 particles kg^{-1}, among the highest reported values for Indian freshwater sediments (Nayal and Suthar, 2022). Basin-wide studies across the Ganga and Yamuna rivers report sediment concentrations ranging from 633 to 5,266 particles kg^{-1}, reflecting strong anthropogenic inputs in densely populated regions (Gupta et al., 2024). Other investigations along the Ganga River recorded 152–514 particles kg^{-1}, while earlier work documented 99.27–409.86 particles kg^{-1}, indicating persistent accumulation in riverine sediments (Singh et al., 2024; Sarkar et al., 2019). Similar patterns are observed in peninsular rivers, including the Mahanadi River (14.7 ± 3.7 to 69.3 ± 10.1 particles kg^{-1}) and the Narmada River (119.4 ± 39.6 particles kg^{-1}) (Ganie et al., 2024; Patidar et al., 2024). Other systems such as the Subarnarekha and Kharkai rivers also exhibit notable sediment loads ranging from 30.3 ± 2.1 to 364.3 ± 3.4 particles kg^{-1}, further demonstrating the role of sediments as repositories of microplastics transported from upstream catchments (Patidar et al., 2023a).

Beyond sediment storage, MPs can enter freshwater food webs through ingestion by aquatic organisms. Several studies from Indian freshwater systems report the presence of MPs in fish tissues and gastrointestinal tracts, indicating trophic transfer within aquatic ecosystems. In Loktak Lake, approximately 91% of examined fish contained microplastics, with fragments accounting for nearly 82% of detected particles (Borah et al., 2024). Investigations in the Mahanadi River similarly documented MP transfer across the water–fish continuum, suggesting the potential for bioaccumulation and human exposure through fish consumption (Ganie et al., 2024). Additional studies from the upper Ganga River have detected MPs in multiple fish species including *Tor tor*, *Schizothorax richardsonii*, *Labeo dero*, and *Garra gotyla*, with abundances ranging from 12.63 ± 5.93 to 53.13 ± 63.77 particles per individual, indicating widespread ingestion within riverine fish communities (Badola et al., 2023). Evidence of MP ingestion has also been reported in fish from Deepor Beel, a Ramsar wetland ecosystem, highlighting ecological risks associated with microplastic contamination in freshwater biota (Saikia et al., 2024).

4. PHYSICAL AND CHEMICAL CHARACTERIZATION

4.1 Size Distribution

The size distribution of MPs reported from Indian freshwater systems is dominated by small-sized particles, typically within the submillimeter range (<1 mm). This pattern reflects both the progressive fragmentation of larger plastic debris under environmental weathering and the analytical detection windows used in most studies. Table 1 summarizes the dominant size ranges of MPs reported across major freshwater systems in India. Several investigations indicate that smaller microplastics are consistently more abundant than larger particles in both surface waters and sediments. In the Hirakud Reservoir, the majority of detected MPs occurred within the 53–300 µm size range, suggesting extensive degradation of larger plastic materials into secondary microplastics (Patra & Baitharu, 2024). The dominance of these smaller particles is of particular ecological concern because particles within this size range can be readily ingested by a wide range of aquatic organisms, including zooplankton, benthic invertebrates, and fish, facilitating trophic transfer through freshwater food webs (Patra & Baitharu, 2024).

Similar patterns have been reported from several river systems across India. Studies in the Ganga River basin have documented a predominance of MPs smaller than 500 µm, indicating that extensive fragmentation processes occur during riverine transport and environmental exposure (Gupta et al., 2024; Sarkar et al., 2022). Investigations along the Upper Himalayan Ganga also reported a higher proportion of particles within smaller size classes, reflecting continuous mechanical breakdown of plastics through hydrodynamic processes and sediment abrasion (Chaudhary et al., 2025). Likewise, MP particles in the Subarnarekha and Kharkai rivers were dominated by smaller size fractions, further demonstrating the importance of secondary microplastic formation in freshwater environments (Patidar et al., 2023a). Lake ecosystems also exhibit similar size distribution trends. In Nainital Lake, smaller MPs constituted a substantial proportion of detected particles in both water and sediment samples, indicating continuous fragmentation of plastic debris introduced through tourism and urban runoff (Jain et al., 2024). Comparable observations have been reported from Kodaikanal Lake and other freshwater lakes of Tamil Nadu, where particles within the smaller size ranges were widely distributed across sampling locations, reflecting persistent breakdown of plastic materials within lacustrine environments (Laju et al., 2022; Laju et al., 2023).

4.2 Morphological Characteristics

Fibers consistently dominate microplastic (MP) morphology across Indian freshwater systems, followed by fragments, films, foams, and beads. Multiple studies report a strong prevalence of fibrous particles in both water and sediment matrices, reflecting common sources such as textile fibers, fishing gear degradation, and synthetic fabric usage. For example, fibers constituted 69.6–80.4% of MPs in the Subarnarekha and Kharkai rivers (Patidar et al., 2023a), while in the Beas River they accounted for 84% of MPs in water and 66% in sediments, followed by films (14% in water and 21% in sediments) (Bhaduri et al., 2025). Similarly, in the Netravathi River, fibers represented 51.59% of MPs in water samples, followed by films (34.92%) (Amrutha and Warrier, 2020). In the Ganga River basin (Doon Valley), fibers dominated water samples (41%), whereas fragments were relatively more abundant in sediments (38%) (Nayal and Suthar, 2022). A similar dominance of fibrous particles has been reported in other freshwater systems. In the Gola River, fibers accounted for 79.29% upstream and 85% downstream, reflecting both natural weathering processes and increased urban inputs (Shifa et al., 2025). In the Mandovi River, fibers comprised 91.55% of MPs, followed by fragments (6.50%), foam (1.02%), and films (0.93%) (Mhapsekar and Kalangutkar, 2026). Reservoir and lake systems show comparable patterns; fibers represented 46.21% of surface water MPs and 44.86% in sediments in Hirakud Reservoir (Patra and Baitharu, 2024), while more than half of the MPs detected in subsurface and bottom waters of Vembanad Lake were fibrous (Anagha et al., 2023). Earlier studies from Vembanad Lake also reported notable occurrences of films and foams (Sruthy and Ramasamy, 2017).

However, morphological composition may vary depending on local anthropogenic activities and hydrological conditions. In the Mula River (Pune), films dominated at sites such as Wakad and Bopodi, whereas foam particles were more prevalent at Aundh during the pre-monsoon period, while microbeads remained the least abundant morphotype (Verma et al., 2025). In Gangasagar Pond (Darbhanga), fibers ranged from 12–56 m^{-3}, followed by films (10–38 m^{-3}) and fragments (8–22 m^{-3}) (Kumari, 2024). In contrast, fragments dominated MPs detected in fish from Loktak Lake (~82%), suggesting selective ingestion or retention of certain particle types in aquatic organisms (Borah et al., 2024). Color characteristics also provide clues about MP sources and degradation pathways. Blue and black fibers are particularly common in the Ganga and Yamuna rivers (Gupta et al., 2024), whereas transparent particles dominate in Hirakud Reservoir (Patra and Baitharu, 2024). Overall, the widespread dominance of fibrous microplastics highlights the significant role of textile fibers, fishing gear, and domestic wastewater inputs in shaping MP morphology in Indian freshwater environments.

4.3 Polymer Composition

Chemical characterization of MPs in Indian freshwater systems has predominantly been carried out using spectroscopic techniques such as FTIR, Attenuated Total Reflectance–Fourier Transform Infrared Spectroscopy (ATR-FTIR), µFTIR, Raman spectroscopy, and µ-Raman, which allow reliable identification of polymer types. Analysis of available studies (Table 1) shows that PP and PE are the dominant polymers, followed by PET, high-density polyethylene (HDPE), PVC, and PA, while polymers such as ethylene-vinyl acetate (EVA) and ethylene vinyl alcohol (EVOH) are rarely reported (Figures 1 & 2). Their widespread occurrence reflects the extensive use of these polymers in packaging materials, plastic bags, food containers, and other consumer products. PE and PP dominate in several major river systems including the Ganga, Brahmaputra, Netravathi, Periyar, Subarnarekha, and Mahanadi rivers, indicating strong inputs from urban waste, degraded plastic packaging, and domestic plastic consumption (Sarkar et al., 2022; Nayal and Suthar, 2022; Ganie et al., 2024; Mukhopadhyay and Valsalan, 2024). Similar dominance of PE and PP has also been reported in multiple lake and reservoir systems such as Nainital Lake, Vembanad Lake, Kolavai Lake, Kumaraswamy Lake, and Kodaikanal Lake, highlighting the influence of tourism, urban runoff, and domestic waste disposal in freshwater pollution (Jain et al., 2024; Anagha et al., 2023; Thandavamoorthy et al., 2023; Ephsy and Raja, 2023; Laju et al., 2022).

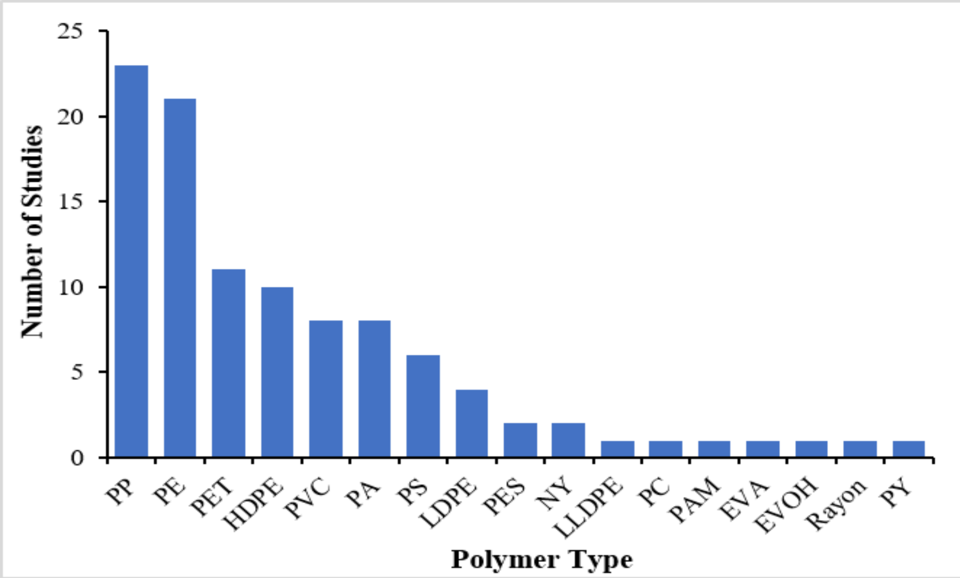

Figure 1. Frequency of polymer types reported in freshwater microplastic studies across India (2017–2026).

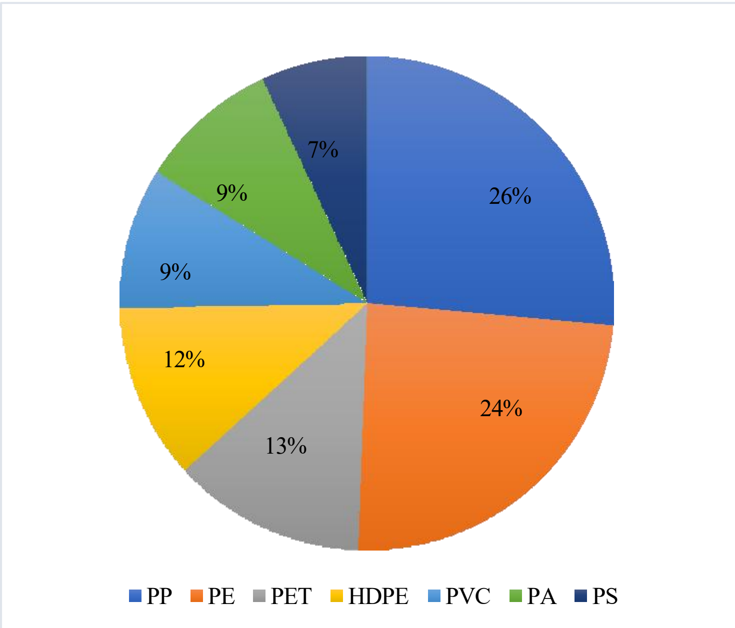

Figure 2. Proportional composition of dominant polymer types reported in Indian freshwater ecosystems based on recent studies.

Other commonly detected polymers include PET, PA, PVC, and polystyrene (PS). PET particles are often associated with beverage bottles and packaging materials and have been reported from several river systems including the Ganga, Sharavathi, and Zuari rivers (Sarkar et al., 2022; Amrutha et al., 2023; Kalangutkar et al., 2024a). Polyamide, frequently occurring in fibrous form, is commonly linked to fishing nets, ropes, and synthetic textiles and has been identified in water and sediment samples from Vembanad Lake, Mandovi River, and Dal Lake (Anagha et al., 2023; Mhapsekar and Kalangutkar, 2026; Yousuf et al., 2025). PVC and PS fragments have also been detected in several river systems, including the Mahanadi, Subarnarekha, and Narmada rivers, suggesting contributions from construction materials, industrial plastics, and packaging waste (Patidar et al., 2023a; 2023b; Patidar et al., 2024). In addition to these dominant polymers, some studies have reported less common polymer types such as HDPE, low-density polyethylene (LDPE), EVA, polyethylene sulfone, and EVOH. These polymers are typically associated with multilayer packaging materials, agricultural plastics, or specialized industrial products. For example, EVOH has been reported in peninsular river systems including the Kaveri, Thamirabarani, Adyar, and Cooum rivers, likely originating from multilayer food packaging and industrial plastic products (Pavithra et al., 2024).

4.4 Polymer Hazard Assessment

Recent studies increasingly apply polymer hazard scoring frameworks to evaluate the ecological risks associated with microplastics in freshwater environments. These assessments integrate polymer-specific toxicity scores with microplastic abundance to estimate environmental risk levels. In Nainital Lake, a mixture of low-risk polymers such as PP and moderate-risk polymers including PE resulted in classification of the system within low-to-high hazard categories depending on polymer composition (Jain et al., 2024). Similarly, investigations in the Ganga and Yamuna rivers detected hazardous polymers with hazard scores exceeding 1,000, suggesting potential ecological and human health risks in the densely populated Indo-Gangetic Plain (Gupta et al., 2024).

Risk assessments in Tamil Nadu rivers using the Polymer Risk Index (PORI) categorized the Adyar and Thamirabarani rivers as moderate risk (Category II), while the Kaveri and Cooum rivers were classified as considerable risk (Category III) due to the presence of higher-hazard polymers (Pavithra et al., 2024). In the Godavari River, despite relatively low PLI values (1–2), elevated PHI scores at sites dominated by polycarbonate (PC), PVC, and nitrile polymers indicated that polymer toxicity, rather than microplastic concentration alone, governs ecological hazard potential (Sekar and Sundaram, 2025). Likewise, urban lakes in Tamil Nadu exhibited PHI values up to 1204.84, corresponding to hazard levels IV–V, further demonstrating the influence of polymer-specific toxicity on ecological risk (Laju et al., 2023). In the Upper Himalayan stretch of the Ganga River, PLI-based assessments classified Zones I–II under hazard category I and Zone III under category II, indicating increasing microplastic contamination downstream (Chaudhary et al., 2025). Similarly, post-disturbance monitoring in the Kadambrayar and Chitrapuzha rivers (Kerala) reported elevated Microplastic Pollution Index (MPI) values (4.14–7.38 in water) and increased Risk Quotient (RQ) scores following a landfill fire event, highlighting intensified polymer-associated ecological risk in affected zones (Amal and Devipriya, 2024). The relative hazard ranking of commonly reported polymers in Indian freshwater systems is summarized in Figure 3.

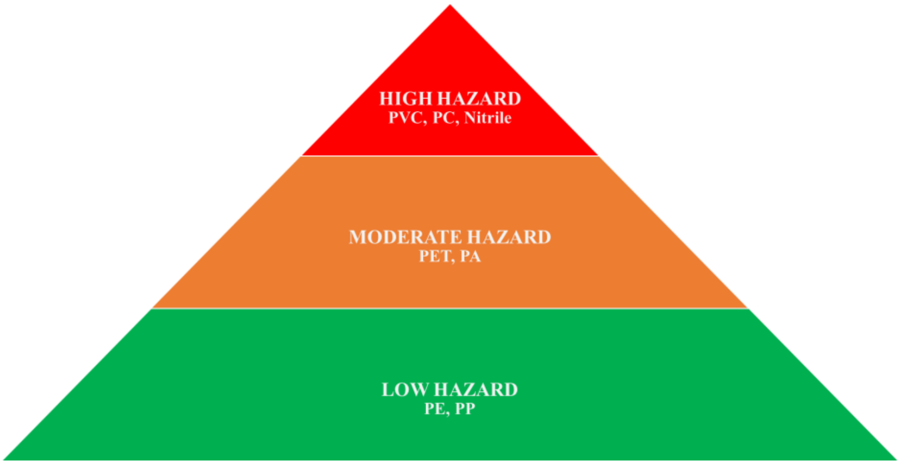

Figure 3. Polymer Hazard Classification in Indian Freshwater Systems

4.5. Associated Contaminants

Microplastics in freshwater systems can act as vectors for associated contaminants, including heavy metals and plastic additives. This "vector effect" results from their high surface-area-to-volume ratio and hydrophobic surfaces, which facilitate contaminant adsorption and transport within aquatic food webs (Pandey et al., 2021). Several studies from Indian freshwater systems report the presence of heavy metals adsorbed on microplastic surfaces. Elemental analyses using techniques such as Energy Dispersive Spectroscopy (EDS), X-ray Fluorescence (XRF), Scanning Electron Microscopy–Energy Dispersive Spectroscopy (SEM–EDS), and Inductively Coupled Plasma–Mass Spectrometry (ICP–MS) have identified a wide range of metals associated with MPs. For instance, investigations in the Subarnarekha and Kharkai rivers detected metals including Pb, Cu, Zn, Fe, Cr, and Ni adhered to microplastic particles (Patidar et al., 2023a). Similar findings have been reported in other freshwater systems, suggesting that MPs may act as carriers of contaminants derived from industrial discharge, urban runoff, and wastewater inputs. In the Ganga River, Rahman et al. (2025) reported the concentration sequence Fe > Cr > Cu > Ni >

Pb > Zn > Mn > Cd, with increasing levels of Cr, Fe, and Cu corresponding to higher MP concentrations, indicating a positive relationship between microplastic abundance and metal contamination. High-risk metals such as Pb, Cr, and Cd have also been reported on MPs in the Ganga, Subarnarekha, and Yamuna rivers, reflecting the influence of industrial and urban pollution sources (Patidar et al., 2023a; Vaid et al., 2022; Rahman et al., 2025). Other metals frequently associated with MPs include Cu, Zn, and Ni, often linked to urban wastewater and industrial discharges, as observed in the Subarnarekha and Sabarmati rivers (Patidar et al., 2023a; Ram and Kumar, 2020). Naturally occurring elements such as Fe and Mn may also accumulate on MP surfaces through redox processes in freshwater environments (Bagde et al., 2023; Saha et al., 2025), while toxic elements such as Hg and As have been reported in agricultural and industrial watersheds in Andhra Pradesh, where their occurrence correlates with MP abundance (Savitha et al., 2026).

Freshwater lakes also demonstrate significant metal–microplastic interactions. In Manasbal Lake (Kashmir), SEM–EDS analysis detected eleven metals, including Bi and Hg on MP surfaces, indicating that the lake functions as a sink for both MPs and associated metal loads (Kumar et al., 2023; Kumar et al., 2025). Similar observations have been reported in Loktak Lake, where multiple inorganic elements were detected on MPs in biota-rich ecosystems (Borah et al., 2024). Evidence from other systems further supports the role of MPs in contaminant transport. In the Chapora River (Goa), EDS analysis identified metals such as Zn, Al, Cu, Fe, Mn, and Co associated with MPs, sediments, and *Crassostrea* spp., suggesting metal–microplastic interactions (Bhutia et al., 2023; Kalangutkar et al., 2024b). Studies from Gujarat rivers also reported that weathering and oxidation processes enhance the sorption capacity of MP surfaces (Prasad et al., 2025), while SEM–EDX analyses from the Markanda River identified metals including Mn, Ni, Cr, Zn, As, Se, and Cu, with higher concentrations in downstream areas influenced by agricultural and urban land use (Kumar et al., 2024). The adsorption of contaminants onto MPs is strongly influenced by surface aging and weathering processes, which generate cracks and oxygen-containing functional groups that enhance the affinity of plastics for metal ions and organic pollutants (Mishra et al., 2023). In addition to metals, MPs may also carry plastic additives such as phthalate esters (PAEs). A study from a Lesser Himalayan lake reported a strong positive correlation between MP abundance and PAE concentrations in sediments, with dibutyl phthalate (DBP) and di(2-ethylhexyl) phthalate (DEHP) detected at concentrations of 6–357 ng g^{-1} dry weight (Kumar et al., 2021).

5. ECOLOGICAL IMPACTS AND RISK ASSESSMENT

5.1 Bioaccumulation and Trophic Transfer

Evidence of microplastic bioaccumulation in aquatic organisms has been widely reported across Indian freshwater systems, indicating potential trophic transfer through aquatic food webs. In Loktak Lake, about 91% of sampled fish contained MPs, with fragments dominating (~82%) (Borah et al., 2024). Similarly, studies from the Mahanadi River reported MP concentrations in water ranging from 337.5 ± 54.4 to 1,333.3 ± 557.2 MPs m^{-3}, with evidence of MP accumulation in fish tissues, suggesting transfer from water to biota (Ganie et al., 2024). In the Ganga River (central Himalaya), MP accumulation varied among fish species, with the highest abundance recorded in *Tor tor* (53.13 ± 63.77 particles individual^{-1}), followed by *Schizothorax richardsonii*, *Labeo dero*, and *Garra gotyla gotyla*. Diverse polymers including PET, PP, PE, PVC, PS, PA, and PC were detected in fish guts, indicating possible trophic transfer and potential human health risks through fish consumption (Badola et al., 2023). Likewise, freshwater fishes from the Cyprinidae and Channidae families in Lucknow showed MP ingestion, with the highest abundance in *Channa punctatus* (7.86 ± 2.0 items individual^{-1}) followed by *Labeo rohita*, *Labeo bata*, *Salmostoma bacaila*, and *Puntius amphibius* (Pandey et al., 2023).

Microplastics may also cause physiological and histopathological effects in fish. In Gangasagar Pond, MPs detected in the gill chamber and buccal cavity of *Labeo rohita* were associated with impaired feeding and swimming behavior, oxidative stress, and tissue alterations in gills and digestive organs (Kumari, 2024). Particle size further influences ingestion dynamics; in Hirakud Reservoir, smaller MPs (53–300 µm) facilitate ingestion across trophic levels, enhancing bioaccumulation and biomagnification potential (Patra and Baitharu, 2024). In Vembanad Lake, MPs and associated contaminants pose risks to aquatic organisms and the food web, with implications for communities dependent on fish and mussels (Anagha et al., 2023). Polymer composition and seasonal inputs may further influence ecological risk. Sites dominated by high-toxicity polymers exhibited higher Risk Index (RI) values, suggesting greater potential for additive-mediated bioaccumulation (Sekar and Sundaram, 2025). Similarly, elevated PHI and PERI values during the monsoon indicate increased runoff-driven inputs of hazardous polymers and enhanced trophic transfer potential (Laju et al., 2023).

- **Risk Assessment Indices**

Several studies have applied quantitative risk assessment indices to evaluate microplastic pollution in Indian freshwater systems. The PLI is widely used to assess contamination levels. In the Subarnarekha and Kharkai rivers, overall PLI indicated risk level I, although some sediment sites reached risk level II, suggesting localized contamination (Patidar et al., 2023a). Similarly, Tamil Nadu rivers (Kaveri, Thamirabarani, Adyar, and Cooum) showed PLI values >1, with the Pollution Risk Index (PRI) trend CR > AR > KR > TR, indicating spatial variability in pollution intensity (Pavithra et al., 2024). In contrast, Kumaraswamy Lake exhibited relatively low contamination with PLI <10 (risk category I) (Ephsy and Raja, 2023), while MP pollution in Gujarat rivers was generally classified as marginal based on PLI, with the Damanganga River identified as the most vulnerable site (Prasad et al., 2025).

However, concentration-based indices alone may underestimate ecological risks associated with polymer composition. In the Beas River (western Himalayas), although the PLI reached 4.99, indicating low pollution levels, the PHI exceeded 1000, placing the system in the highest hazard category, and the PERI reached 13,761, indicating extreme ecological risk in some locations (Bhaduri et al., 2025). Advanced approaches such as the Species Sensitivity Distribution (SSD) method have also been used. In Hirakud Reservoir, the Predicted No-Effect Concentration (PNEC) was 3,954 particles m^{-3}, with RQ values of 0.02073–0.04122, indicating negligible ecological risk for freshwater species (Patra and Baitharu, 2024). Hazard classification based on MP concentrations placed Dal Lake in hazard category II, with surface water concentrations of 140 ± 20–846 ± 136 particles L^{-1} and sediment concentrations of 2,616 ± 1,016–12,966 ± 496 particles kg^{-1} (Yousuf et al., 2025).

Polymer toxicity indices further reveal elevated ecological risks in several freshwater systems. In the Chapora River (Goa), PLI suggested low ecological risk, but the presence of PET, HDPE, PP, and PS resulted in a PHI value of 1006 (hazard category V) (Kalangutkar et al., 2024b). Similarly, the Mandovi River showed a PLI of 1.71 with PHI indicating hazard level V and high PERI values, suggesting considerable ecological risk (Mhapsekar and Kalangutkar, 2026). In the Mahanadi estuary, PLI indicated partial contamination (hazard category I), whereas PHI levels (III–V) suggested higher polymer-related ecological risks (Patidar et al., 2023). Extremely high hazard levels were also reported in the Mahananda River and nearby urban ponds (Malda, West Bengal), where PHI >1000 and PERI >1200, with the highest hazard recorded in pond sediments (PHI = 11,591) (Mandal et al., 2025).

- **Impacts on Aquatic Organisms**

Microplastics can affect aquatic organisms through both physical and chemical pathways, leading to a range of ecotoxicological impacts across freshwater ecosystems. Their small size allows ingestion by organisms at multiple trophic levels, where they may cause digestive obstruction, reduced nutrient uptake, oxidative stress, immune dysfunction, and tissue damage (Khalid et al., 2021; Rodríguez et al., 2024; Pathak et al., 2026). In addition to these physical effects, MPs can act as vectors for plastic additives, heavy metals, and POPs, which may leach into tissues and disrupt physiological processes.

Several studies have documented direct biological impacts of MPs on freshwater organisms. Physical effects such as intestinal blockage, histological alterations, and behavioral changes have been reported in fish, mussels, and other invertebrates exposed to MPs (Ephsy and Raja, 2023). Experimental observations also indicate that MP ingestion can induce oxidative stress and inflammatory responses, affecting vital organs and tissues in fish (Kumari, 2024). In addition, MPs may disrupt feeding behavior by causing gut blockage and reduced food intake, which can ultimately influence organismal growth and survival, prolonged exposure may also affect growth and reproductive processes, particularly through the leaching of toxic additives and adsorbed contaminants from MP surfaces (Sarkar et al., 2022). These effects can contribute to chronic toxicity within freshwater food webs, potentially impacting broader ecosystem health (Ephsy and Raja, 2023).

Microplastics also act as carriers of hazardous chemicals, including plastic additives such as phthalates and bisphenol A, as well as POPs and heavy metals adsorbed from surrounding water. These substances may be released after ingestion, leading to endocrine disruption, metabolic disturbances, and other physiological effects in exposed organisms (Bagde et al., 2023; Rebecca et al., 2024). The ecological impacts of MPs vary among organism groups depending on habitat and feeding strategies. Pelagic organisms tend to interact with buoyant microplastics suspended in the water column, whereas benthic invertebrates are more likely to ingest denser particles accumulated in sediments, resulting in differential exposure across ecological niches (Sarkar et al., 2022). Larger freshwater fauna may also be affected. For example, in the Ganga River, the endangered Gangetic dolphin faces significant risks from plastic ingestion and entanglement, representing a serious conservation concern (Sarkar et al., 2022). Freshwater ecosystems are particularly vulnerable to MP pollution because rivers and lakes often function as sinks for land-derived plastic debris. Once ingested, MPs can cause physiological stress, gastrointestinal blockage, reduced feeding efficiency, and inflammatory responses, while also facilitating the transfer of associated contaminants through aquatic food webs (Rajan et al., 2023).

- **Human Health Implications**

Microplastics (MPs) can move through aquatic food webs from lower to higher trophic levels, ultimately reaching humans through the consumption of contaminated food and water. Once ingested or inhaled, MPs may induce oxidative stress, inflammation, endocrine disruption, cytotoxicity, and genotoxic effects, posing potential risks to respiratory, metabolic, and gastrointestinal health (Jin et al., 2021; Lee et al., 2023; Winiarska et al., 2024; Vogel et al., 2024; Pathak et al., 2026). The presence of MPs in fish and other aquatic organisms consumed by humans has raised increasing public health concerns. For example, studies in Loktak Lake reported MP ingestion in approximately 91% of sampled fish, with particles often carrying heavy metals, indicating potential exposure through dietary pathways (Borah et al., 2024). Similarly, investigations in the Mahanadi River documented MP bioaccumulation in aquatic organisms, highlighting possible risks associated with human consumption of contaminated fish (Ganie et al., 2024).

Human exposure may also occur through drinking water and other freshwater resources. In Nainital Lake, the detection of MPs in tube-well and drinking water indicates direct exposure pathways for local populations, emphasizing the need for mitigation strategies (Jain et al., 2024). Likewise, elevated PHI and PERI values reported in certain sections of the Beas River suggest potential health risks for communities living near highly urbanized areas (Bhaduri et al., 2025). Additional evidence from Tamil Nadu revealed MPs in packaged drinking water, community-stored water, and groundwater following the COVID-19 pandemic, indicating multiple routes of human exposure (Pavithra et al., 2024). Chronic exposure to MPs may also lead to bioaccumulation of plastic particles and associated contaminants in the human body, potentially triggering toxicological responses. Studies from Gangasagar Pond suggest that prolonged exposure to MPs may contribute to DNA damage and increase the risk of carcinogenic effects (Kumari et al., 2024). Furthermore, research in the Ganga and Yamuna rivers highlights that MPs containing hazardous polymers may pose risks to the densely populated Indo-Gangetic Plain, where millions depend on river water and fish resources for daily consumption (Gupta et al., 2024).

- **Ecosystem-Level Concerns**

At the ecosystem scale, microplastic (MP) pollution poses significant threats to the ecological integrity of freshwater habitats, including protected wetlands and biodiversity hotspots. In Loktak Lake, a Ramsar wetland and the world's only floating lake, MP contamination highlights the need for comprehensive management strategies to safeguard ecosystem functioning and biodiversity (Borah et al., 2024). Similar concerns have been reported for other Ramsar sites such as Deepor Beel and Vembanad Lake, where MP accumulation may threaten wetland ecology and associated aquatic communities (Saikia et al., 2024; Anagha et al., 2023).

River ecosystems also show increasing vulnerability to MP pollution. In the Valvanti River (Goa), microplastics have been identified as emerging hazardous contaminants, with surface analyses indicating elevated ecological risk in the riverine environment (Mhapsekar et al., 2025). Likewise, studies from rivers in the Western Ghats, a UNESCO World Heritage biodiversity hotspot, report MP contamination in sediments, raising concerns about potential impacts on aquatic biodiversity and ecosystem stability (Amrutha et al., 2023). Overall, the occurrence of MPs in ecologically sensitive regions underscores the broader implications of plastic pollution for freshwater ecosystem health, biodiversity conservation, and long-term ecological resilience.

Table 1. Summary of reported microplastic polymer composition, sampling locations, freshwater system types, and analytical methods across Indian freshwater ecosystems.

Water Body	Location	System Type	Surface Water (particles L^{-1})	Sediment (particles kg^{-1} or g^{-1})	Dominant Size Range (µm)	Dominant Polymers	Analytical Method	Reference
Vembanad Lake	Kerala	Ramsar site	-	252.80 ± 25.76 m^{-2}	100–200	LDPE	µ-Raman	(Sruthy & Ramasamy, 2017)

Natural Resources for Human Health
eISSN: 2583-1194

Ganga River	Bihar	Major Himalayan River	-	99.27–409.86	NA	PET, PE	FTIR	(Sarkar et al., 2019)
Netravathi River	Southern Karnataka	Mountainous/High-Gradient River	0.29	96	300–1000, 1000–5000	PE, PET	FTIR-ATR	(Amrutha & Warrier, 2020)
Kosasthalaiyar River	Chennai, Tamil Nadu	Ephemeral river	0.67	-	335 µm to 5 mm			
Adyar River		Seasonal river	0.33	-	336 µm to 5 mm			
Muthirappuzhayar River	Munnar, Kerala	Tropical mountain river	0.2	-	337 µm to 5 mm	PE, PP	FTIR	(Lechthaler et al., 2021)
Veeranam lake	Tamil Nadu	Urban reservoir	13 to 54 km^{-1}	92–604	300–1000	PE, PVC	ATR-FTIR	(Manikanda et al., 2021)
Ganga River	Eastern India	Major Himalayan River	380–684 items 1000 m^{-3}	17–36	2.5–5 mm	PE, PS	ATR-FTIR	(Singh et al., 2021)
Brahmaputra River	Arunachal Pradesh, Assam	Major Himalayan River	-	551–325	20–150			
Indus River	Ladakh	Major Himalayan River	-	585–2092	20–150	PP, PE	µFTIR	(Tsering et al., 2021)
Noyyal River	Coimbatore, Tamil Nadu	Seasonal Peninsular River	-	500– 6500 n m^{-3}	330–1000	PP	ATR-FTIR	(Ayyamperumal et al., 2022)
Kodaikanal Lake	Tamil Nadu	Man-made Reservoir	24.42 ± 3.22	28.31 ± 5.29 (Surface) to 25.91 ± 7.11 (Core)	3–5 mm	PE, PP	ATR-FTIR	(Laju et al., 2022)
Upper Ganga River	Doon valley	Major Himalayan River	2800–4200	7200–16400	-	PP, PE	ATR-FTIR	(Nayal & Suthar, 2022)
Anchar Lake	Kashmir Valley	high-altitude lake	NA	606 ± 360	300–1000	PA	ATR-FTIR	(Neelavannan et al., 2022)
Ganga River	Multiple states	Major Himalayan River	1.30–2.42 m^{-3} (1,296–2,414 urban)	99.27–409.86	63 µm to 5 mm	PE, PP, PET	FTIR	(Sarkar et al., 2022)

Water Body	Location	System Type	Surface Water (particles L^{-1})	Sediment (particles kg^{-1} or g^{-1})	Dominant Size Range (μm)	Dominant Polymers	Analytical Method	Reference
Ulhas River	Mumbai	Perennial, west-flowing River	NA	40–600	-	LDPE, HDPE	FTIR-ATR, μ-Raman	(Verma et al., 2022)
Sharavathi River	Karnataka	westward-flowing river	NA	6.39 (± 5.17) to 14.82 (± 13.10)	300–1000	PE, PET	ATR-FTIR	(Amrutha et al., 2023)
Vembanad Lake	Kerala	Ramsar wetland	26.79±3.74 (subsurface); 52.70±5.43 (bottom)	-	100–500	PA, PP	μ-Raman	(Anagha et al. 2023)
Ganga River	Uttarakhand	Major Himalayan River	118.5 ± 49.65 L^{-1000}	131.5 ± 53.60	100–1000	PE, PP, PET	FTIR	(Badola et al., 2023)
Vellayani Lake	Kerala	tropical freshwater lake	4.1	5.4	<1000	PY, PP, PE	FTIR	(David et al., 2023)
Kumaraswamy Lake	Tamil Nadu	Urban lake	8.77±0.27	-	5–3 mm, 3–1 mm, 1–0.5 mm, 0.5–1 μm	LLDPE, HDPE, PP	FTIR	(Ephsy & Raja, 2023)
Tamil Nadu lakes	Tamil Nadu	Multiple lakes	16 ± 2.69 to 118.17 ± 22.17	19.50 ± 4.75 to 156.23 ± 36.41	<500, 500–1000	PE, PP	FTIR-ATR	(Laju et al., 2023)
Subarnarekha & Kharkai Rivers	Eastern India	Rain-fed peninsular river	6.7±0.9 to 22.3±0.4	30.3±2.1 to 364.3±3.4	125–355	PVC, PP, PET	FTIR	(Patidar et al., 2023a)
Mahanadi River	Odisha	Major Peninsular River	16.6 ± 5.2 to 15.1 ± 5.4	164.6 ± 76.9 to 197.3 ± 5.4	<1000	PE, PVC	ATR-FTIR	(Patidar et al., 2023b)
Ganga River	Multiple state	Major Himalayan River	92.85 ± 50.69 m^{-3}	-	100-2000	PET, PA	FTIR-ATR, μ-Raman	(Rajan et al., 2023)
Godavari River	Andhra Pradesh	Major Peninsular River	2.2 to 6.2	-	-	PP	ATR-FTIR	(Sekar & Sundaram, 2023)

Kolavai Lake	Tamil Nadu	Perennial Freshwater Reservoir	6.1 ± 2.5	-	<0.1 to 300	PE, HDPE	ATR-FTIR	(Thandavamoorthy et al., 2023)
Kadambrayar and Chitrapuzha rivers	Kerala	Urban freshwater industrial river	25.79 ±5.62 to 44.86±8.20	589.96 ± 89.20 to 874.125 ± 221.39	11.80 to 4998.57 (surface water), 11.67 to 4983.59 (sediment)	LDPE, HDPE, PP	Raman-AFM	(Amal & Devipriya, 2024)
Cauvery River	Tamil Nadu	Major Peninsular River	43-69	-	-	NY, HDPE	FTIR	(Estherrani et al., 2024)
Mahanadi River	Peninsular India	Major Peninsular River	337.5±54.4 to 1,333.3±557.2 m^{-3}	14.7 ± 3.7–69.3 ± 10.1	<0.500	PP, PE	FTIR-ATR, μ-Raman	(Ganie et al., 2024)

Water Body	Location	System Type	Surface Water (particles L^{-1})	Sediment (particles kg^{-1} or g^{-1})	Dominant Size Range (μm)	Dominant Polymers	Analytical Method	Reference
Ganga & Yamuna Rivers	Multiple states	Major Himalayan River	4.67–49.50	633.33–5266.67	300–1000	PAM, PA, PVC	FTIR/Raman	(Gupta et al., 2024)
Nainital Lake	Uttarakhand	High-altitude lake	8.6 to 56.0	0.4–10.6 g^{-1}	20–1000	HDPE, PP	FTIR-ATR	(Jain et al., 2024)
Zuari River	Goa	Monsoon-driven tidal estuary	0.28 ± 0.35	-	300–1000	PET, HDPE, PP	FTIR	(Kalangutkar et al., 2024a)
Chapora River	Goa	Tidal River	0.25± 0.13	-	100–300	PET, HDPE	FTIR-ATR	(Kalangutkar et al., 2024b)
Periyar River	Kerala	Perennial, west-flowing River	120.5−124.95	-	100–200	PE, PP	FTIR	(Mukhopadhyay & Valsalan, 2024)
Kollidam River	Tamil Nadu	Deltaic river	2.42 particles m^{-3}	1580 ± 705	1–2.5 mm, 0.01–1 mm	PP, PE	FTIR	(Nagalakshm et al., 2024)
Narmada River	Madhya Pradesh	Major Peninsular River	6.3 ± 3.8	119.4 ± 39.6	<1000	PES, PVC, PP, PS	ATR-FTIR	(Patidar et al., 2024)

Hirakud Reservoir	Odisha	Reservoir	82–89	159–163	53–300	PP, HDPE, LDPE, PS	FTIR	(Patra & Baitharu, 2024)
Kaveri River		Major Peninsular River	2.15 ± 1.9	-				
Thamirabarani River		Perennial Peninsular River	1.1 ± 0.99	-				
Adyar River		Seasonal Peninsular River	5.25 ± 1.15	-				
Cooum River	Tamil Nadu	Tidal River	4 ± 2.65	-	<1000	PA, PP, PE, EVOH, PVC	μFTIR, μRaman	(Pavithra et al., 2024)
Ganga River	Varanasi, Uttar Pradesh	Major Himalayan River	14-43	152-514	2.5–5 mm	PET, Rayon	ATR-FTIR	(Singh et al., 2024)
Beas River	Himachal Pradesh	Perennial Himalayan River	112.27 ± 12.43	319.47 ± 49.25	<1000	PE	FTIR-ATR	(Bhaduri et al., 2025)
Gomti River	Lucknow, Uttar Pradesh	Perennial river	39−82	320−1160	150-4500	PA, PE	SEM–EDS, FTIR	(Bhan et al., 2025)
Upper Himalayan Ganga River	Uttarakhand	Major Himalayan River	100.17 ±16.64 to 1550 ±257.58	50.33 ± 6.62 to 1300.33 ±233.96	500–5000, 250–500	PE, PA, PS, PVC	FTIR-ATR	(Chaudhary et al., 2025)
Manasbal Lake	North-western Himalaya	Natural freshwater	13−89	840−4020	<200	PP, PE, PS	Raman	(Kumar et al., 2025)
Mahananda river & Pond	West Bengal	Rain-fed Himalayan River & fresh water pond	59–100	167–193 particles g^{-1}	300 and 1180, 1180 and 5000	PA, PE	FTIR	(Mandal et al., 2025)

Natural Resources for Human Health
eISSN: 2583-1194

Water Body	Location	System Type	Surface Water (particles L⁻¹)	Sediment (particles kg⁻¹ or g⁻¹)	Dominant Size Range (µm)	Dominant Polymers	Analytical Method	Reference
Valvanti River	Goa	Perennial, west-flowing River	2.91 ± 1.69	-	100–300, 300–850	PP, PA, PET	FTIR	(Mhapsekar et al., 2025)
Sutlej River	Punjab	Antecedent river	3.6 to 19.0 MPs/L	-	100–500	PP, HDPE	ATR-FTIR	(Nagendra et al., 2025)
Surface water bodies	Rohtak, Haryana	-	16–28 particles/L	-	0.61–4.87 mm	PE, PP	FE-SEM, ATR-FTIR	(Narwal & Katyal, 2025)
Godavari River	Andhra Pradesh	Major Peninsular River	6.7	-	<500 µm, 500–1000 µm, 1000–1500 µm	PC, Nylon, PVC, PP	FTIR-ATR, µ-Raman	(Sekar & Sundaram, 2025)
Gola River	Uttarakhand	Spring-fed river	0.321 ± 0.004 (upstream), 0.436 ± 0.004 (downstream)	-	200-300, 150-200	PE, PP	SEM–EDS, FTIR	(Shifa et al., 2025)
Ganga River	Bihar	Major Himalayan River	-	1017.5 ± 214.3 $kg^{-0.5}$	<1000 µm	LDPE, HDPE, PVC, PP	FTIR	(Varsha et al., 2025)
Mula River	Pune	Monsoon-fed freshwater river	1350 ±426 to 1972 ±572	-	25–100	EVA	FTIR	(Verma et al., 2025)
Dal Lake	Kashmir	High-altitude lake	140±20 to 846±136	2,616±1,016 to 12,966±496	<500 µm	PE, PP	FTIR	(Yousuf et al., 2025)
Mandovi River	Goa	Coastal plain estuary	2.37 ± 3.11	-	100–300	PA, PET	SEM–EDS, FTIR	(Mhapsekar & Kalangutkar, 2026)

6. GAPS IN CURRENT KNOWLEDGE

Despite the growing body of research on MPs in Indian freshwater systems, several critical knowledge gaps remain. First, toxicological evidence is still limited. While bioaccumulation in aquatic organisms has been documented, information on chronic toxicity thresholds, population-level effects, and species-specific sensitivities remains scarce. Only a few studies, such as the histopathological investigation from Gangasagar Pond, provide direct evidence of physiological impacts, highlighting the need for broader ecotoxicological assessments. Second, source apportionment remains poorly resolved. Although urban, industrial, and agricultural inputs have been identified as major sources, quantitative source identification techniques such as polymer fingerprinting or isotopic analysis have rarely been applied. This limitation restricts the ability to design effective source control and mitigation strategies. Another important gap relates to temporal monitoring. Most existing studies are based on short-term or single-time assessments, providing limited understanding of seasonal variability, long-term trends, or the effectiveness of management interventions. Long-term monitoring programs are therefore required to evaluate the evolution of MP pollution in freshwater systems.

The nanoplastic fraction also remains largely unexplored. Current analytical methods primarily detect MPs larger than 50–100 µm, while smaller nanoplastics (<1 µm), which may pose greater toxicological risks due to their ability to penetrate biological membranes and enter cells, are rarely quantified in Indian freshwater environments. In addition, food web dynamics are insufficiently understood. Although ingestion of MPs by fish and other organisms has been widely reported, comprehensive studies tracing MP transfer from primary producers to higher trophic levels are limited. Understanding how MPs influence trophic interactions, energy flow, and ecosystem functioning remains an important research priority. Finally, human exposure and health risk assessments remain inadequate. Despite the detection of MPs in fish, drinking water, and other freshwater resources, quantitative exposure estimates, dietary intake assessments, and epidemiological studies are largely lacking. Addressing these gaps is essential for developing robust risk assessment frameworks and informing policy interventions aimed at protecting both ecosystem and human health.

7. FUTURE DIRECTIONS AND RECOMMENDATIONS

7.1 Research Priorities

Standardization of methods: Develop and adopt standardized protocols for MP sampling, extraction, identification, and quantification to enable reliable comparisons across studies. Harmonization of size thresholds, analytical techniques, and reporting units is essential.

Long-term monitoring networks: Establish basin-scale monitoring programs across major rivers, lakes, and wetlands to evaluate temporal trends, identify pollution hotspots, and assess the effectiveness of mitigation measures. Integration with existing water quality monitoring frameworks is recommended.

Ecotoxicological research: Conduct comprehensive toxicity studies to determine species-specific sensitivity, chronic exposure effects, and combined impacts of MPs with associated contaminants such as heavy metals and POPs, prioritizing native freshwater species.

Source apportionment studies: Apply advanced analytical approaches including polymer fingerprinting, stable isotope techniques, and machine learning-based source tracking to quantitatively identify major sources of MP contamination.

Nanoplastic characterization: Develop improved analytical methods to detect and quantify nanoplastics (<1 µm), which remain largely uncharacterized but may pose higher toxicological risks due to their ability to penetrate biological membranes.

Human health risk assessment: Implement comprehensive exposure assessments integrating dietary intake, drinking water consumption, and inhalation pathways, along with epidemiological studies to better understand potential health risks associated with MP exposure.

7.2 Policy and Management Recommendations

Source control measures: Implement targeted interventions to reduce major MP sources, including upgrading wastewater treatment plants with microplastic removal technologies, improving stormwater management to limit urban runoff, regulating plastic use in tourism zones, strengthening waste management infrastructure, and promoting alternatives to single-use plastics in cultural and religious activities.

Regulatory framework: Develop microplastic-specific water and sediment quality standards to establish regulatory benchmarks. Integration of MP monitoring into existing national water quality assessment programs (e.g., the National Water Quality Monitoring Programme) should be mandated.

Protected area management: Strengthen conservation strategies for Ramsar wetlands and other protected freshwater ecosystems by establishing buffer zones to reduce external MP inputs, implementing visitor management in tourism-dependent areas, and adopting adaptive monitoring programs to track MP contamination trends.

Public awareness and education: Promote awareness campaigns highlighting the sources, impacts, and mitigation strategies for microplastic pollution. Incorporating plastic pollution topics into school and community education programs can encourage long-term behavioral change.

Waste management infrastructure: Increase investment in solid waste management systems, particularly in urban and peri-urban regions, to prevent plastic leakage into freshwater systems. Strengthening extended producer responsibility (EPR) frameworks for plastic products is also essential.

International collaboration: Enhance participation in global research networks and data-sharing initiatives to facilitate knowledge exchange, capacity building, and access to advanced analytical tools for microplastic monitoring and assessment.

7.3 Technological Innovations

MP removal technologies: Develop and implement cost-effective microplastic removal technologies in wastewater treatment plants and stormwater systems, along with in-situ remediation approaches for rivers and lakes. Nature-based solutions, such as constructed wetlands and biofilters, may provide sustainable and scalable alternatives for reducing MP loads.

Advanced monitoring tools: Utilize remote sensing, artificial intelligence, and automated image analysis to improve the efficiency and spatial coverage of microplastic monitoring. The development of portable and field-deployable analytical instruments would also enable rapid and real-time assessment of MP contamination.

Biodegradable alternatives: Encourage research and development of biodegradable and environmentally safer plastic alternatives tailored to Indian climatic conditions and waste management systems, thereby reducing future inputs of microplastics into freshwater ecosystems.

8. CONCLUSION

This comprehensive review demonstrates that microplastic contamination is a pervasive and growing threat to Indian freshwater ecosystems. MPs are widely distributed across diverse freshwater environments, ranging from Himalayan headwaters to peninsular rivers and lakes in southern India, with reported concentrations ranging from 0.2 to 4200 particles L^{-1} in surface waters and 5 to 16,400 particles kg^{-1} in sediments. Fibers dominate the morphological composition (41–91%), predominantly within the submillimeter size range (100–1000 μm). Among polymer types, PP, PE, PVC, and PA are most frequently reported. Urban runoff, tourism activities, industrial discharge, and municipal wastewater are identified as the primary sources of MP contamination, with pronounced seasonal variations showing elevated loads during monsoon periods due to enhanced runoff and hydrological transport. Ecological risk assessments indicate low to considerable risk levels across systems, with clear evidence of bioaccumulation in aquatic organisms (up to 91% incidence in fish) and increasing recognition of MPs as vectors for heavy metals and other contaminants. The occurrence of MPs in edible fish and drinking water sources highlights potential human health risks.

Despite growing research efforts, significant knowledge gaps persist, including limited toxicological data, lack of quantitative source apportionment, absence of long-term monitoring, and insufficient characterization of nanoplastics. Addressing these gaps requires standardized methodologies, long-term monitoring frameworks, advanced ecotoxicological investigations, and integrated human health risk assessments. Effective mitigation of MP pollution in Indian freshwater systems demands a multi-pronged approach, including source control, strengthened regulatory frameworks, improved waste management infrastructure, public awareness, and technological innovations. Given the dependence of over 1.4 billion people on freshwater resources and the ecological significance of these systems, urgent and coordinated action is essential. This review provides a scientific foundation for evidence-based policy and management strategies aimed at safeguarding freshwater ecosystems and associated human well-being under accelerating urbanization and environmental change.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Declarations

Ethical approval: All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

Competing interests: The authors declare no competing interests.

REFERENCES

[1] Akinci, G. (2025). *Mikroplastiklerin Ekosistem Ve Biyoçeşitlilik Üzerine Etkileri*. 351–382. https://doi.org/10.53478/tuba.978-625-6110-33-5.ch15

[2] Amal, R., & Devipriya, S. P. (2024). Severe microplastic pollution risks in urban freshwater system post-landfill fire: A case study from Brahmapuram, India. *Environmental Pollution*, *352*, 124132. https://doi.org/10.1016/j.envpol.2024.124132

[3] Amrutha, K., & Warrier, A. K. (2020). The first report on the source-to-sink characterization of microplastic pollution from a riverine environment in tropical India. *Science of the Total Environment*, *739*, 140377. https://doi.org/10.1016/j.scitotenv.2020.140377

[4] Amrutha, K., Shajikumar, S., Warrier, A. K., Sebastian, J. G., Sali, Y. A., Chandran, T., ... & Unnikrishnan, V. (2023). Assessment of pollution and risks associated with microplastics in the riverine sediments of the Western Ghats: a heritage site in southern India. *Environmental Science and Pollution Research*, *30*(12), 32301-32319. https://doi.org/10.1007/s11356-022-24437-z

[5] Anagha, P. L., Viji, N. V., Devika, D., & Ramasamy, E. V. (2023). Distribution and abundance of microplastics in the water column of Vembanad Lake–A Ramsar site in Kerala, India. *Marine Pollution Bulletin*, *194*, 115433. https://doi.org/10.1016/j.marpolbul.2023.115433

[6] Andrady, A. L. (2011). Microplastics in the marine environment. *Marine pollution bulletin*, *62*(8), 1596-1605. https://doi.org/10.1016/j.marpolbul.2011.05.030

[7] Au, S. Y., Bruce, T. F., Bridges, W. C., & Klaine, S. J. (2015). Responses of Hyalella azteca to acute and chronic microplastic exposures. *Environmental toxicology and chemistry*, *34*(11), 2564-2572. https://doi.org/10.1002/etc.3093

[8] Badola, N., Sobhan, F., & Chauhan, J. S. (2023). Microplastics in the River Ganga and its fishes: Study of a Himalayan River. *Science of the Total Environment*, *901*, 165924. https://doi.org/10.1016/j.scitotenv.2023.165924

[9] Bagde, P. S., Mathew, R., Jose, R., Ranjeet, K., & Nikhil, V. G. (2023). Characteristics and risk assessment of microplastic mediated heavy metal transport in black clam Villorita cyprinoides from a Ramsar wetland of South India. *Journal of Hazardous Materials Letters*, *4*, 100092. https://doi.org/10.1016/j.hazl.2023.100092

[10] Bhaduri, R. N., Sinha, S., Guererro, A. M., Jackson, S. L., Alemán, E. A., & Chatterjee, S. (2025). Microplastic contamination and environmental risks in the Beas River, western Himalayas. *EnvironmentalPollution*, *365*,125387. https://doi.org/10.1016/j.envpol.2024.125387

[11] Bhan, C., Jadaun, S., & Kumar, N. (2025). Distribution and characterization of microplastics present in the water and sediments of River Gomti, India. *Environmental Sustainability*, 1-15. https://doi.org/10.1007/s42398-025-00398-0

[12] Bhutia, T., Nasnodkar, M. R., & Nayak, G. N. (2023). Speciation of metals in sediments and their bioaccumulation by edible bivalves (Cassosstrea spp. and Polymesoda spp.) in the aquatic bodies of Goa, west coast of India. *Arabian Journal of Geosciences*, *16*(6), 386. https://doi.org/10.1007/s12517-023-11488-w

[13] Borah, P., Kshiar, N., Reang, D., Nath, A. J., & Baruah, K. K. (2024). Incidence of microplastic contamination in fishes of the Ramsar Wetland, Loktak–The world's only floating lake from the Indian Himalayan region. *Journal of Environmental Management*, *358*, 120928. https://doi.org/10.1016/j.jenvman.2024.120928

[14] Browne, M. A., Crump, P., Niven, S. J., Teuten, E., Tonkin, A., Galloway, T., & Thompson, R. (2011). Accumulation of microplastic on shorelines woldwide: sources and sinks. *Environmental science & technology*, *45*(21),9175-9179.https://doi.org/10.1021/es201811s

[15] Chaudhary, M., Rawat, S., & Suthar, S. (2025). Microplastic in upper Himalayan Ganga river: Occurrence, seasonal dynamics and ecological risk. *Science of the Total Environment*, *967*, 178824. https://doi.org/10.1016/j.scitotenv.2025.178824

[16] Cole, M., Lindeque, P., Halsband, C., & Galloway, T. S. (2011). Microplastics as contaminants in the marine environment: a review. *Marine pollution bulletin*, *62*(12), 2588-2597.

https://doi.org/10.1016/j.marpolbul.2011.09.025

[17] CPCB (2022). Annual Report on Plastic Waste Management, Central Pollution Control Board, India.

[18] de Sá, L. C., Luís, L. G., & Guilhermino, L. (2015). Effects of microplastics on juveniles of the common goby (Pomatoschistus microps): confusion with prey, reduction of the predatory performance and efficiency, and possible influence of developmental conditions. *Environmental pollution*, *196*,359-362. https://doi.org/10.1016/j.envpol.2014.10.026

[19] Dris, R., Gasperi, J., & Tassin, B. (2017). Sources and fate of microplastics in urban areas: a focus on Paris megacity.In *Freshwater microplastics: emerging environmental contaminants?* (pp. 69-83). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-61615-5_4

[20] Duis, K., & Coors, A. (2016). Microplastics in the aquatic and terrestrial environment: sources (with a specific focus on personal care products), fate and effects. *Environmental Sciences Europe*, *28*(1), 2. https://doi.org/10.1186/s12302-015-0069-y

[21] Eerkes-Medrano, D., Thompson, R. C., & Aldridge, D. C. (2015). Microplastics in freshwater systems: a review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water research*, *75*, 63-82.https://doi.org/10.1016/j.watres.2015.02.012

[22] Ephsy, D., & Raja, S. (2023). Characterization of microplastics and its pollution load index in freshwater Kumaraswamy Lake of Coimbatore, India. *Environmental Toxicology and Pharmacology*, *101*, 104207. https://doi.org/10.1016/j.etap.2023.104207

[23] Estherrani, J. R. B. T., Jeyakumar, S. S. L., Merlin, J. P., Christopher, J. J., Rajalakshmi, E., Sivanantham, D., & Ponniah, J. M. (2024). Presence of microplastics during high rainfall events in the Cauvery River (South India): Ecological risk and cultural practices. *Environmental Monitoring and Assessment*, *197*(1),38. https://doi.org/10.1007/s10661-024-13421-4

[24] Galloway, T. S., Cole, M., & Lewis, C. (2017). Interactions of microplastic debris throughout the marineecosystem. *Nature ecology & evolution*, *1*(5), 0116. https://doi.org/10.1038/s41559-017-0116

[25] Ganie, Z. A., Mandal, A., Arya, L., Talib, M., & Darbha, G. K. (2024). Assessment and accumulation of microplastics in the Indian riverine systems: Risk assessment and implications of translocation across the water-to-fish continuum. *Aquatic Toxicology*, *272*, 106944. https://doi.org/10.1016/j.aquatox.2024.106944

[26] Geyer, R., Jambeck, J. R., & Law, K. L. (2017). Production, use, and fate of all plastics ever made. *Scienceadvances*, *3*(7),e1700782. https://www.science.org/doi/10.1126/sciadv.1700782

[27] Gosavi, S. M., & Phuge, S. K. (2023). First report on microplastics contamination in a meteorite impact Crater Lake from India. *Environmental Science and Pollution Research*, *30*(23), 64755-64770. https://doi.org/10.1007/s11356-023-27074-2

[28] Gupta, P., Saha, M., Naik, A., Kumar, M. M., Rathore, C., Vashishth, S., & Thukral, H. (2024).

[29] A comprehensive assessment of macro and microplastics from Rivers Ganga and Yamuna: Unveiling the seasonal, spatial and risk factors. *Journal of Hazardous Materials*, *469*, 133926. https://doi.org/10.1016/j.jhazmat.2024.133926

[30] Hidalgo-Ruz, V., Gutow, L., Thompson, R. C., & Thiel, M. (2012). Microplastics in the marine environment: a review of the methods used for identification and quantification. *Environmental science & technology*, *46*(6), 3060-3075.

[31] https://doi.org/10.1021/es2031505

[32] Horton, A. A., Walton, A., Spurgeon, D. J., Lahive, E., & Svendsen, C. (2017). Microplastics in freshwater and terrestrial environments: Evaluating the current understanding to identify the knowledge gaps and future research priorities. *Science of the total environment*, *586*, 127-141. https://doi.org/10.1016/j.scitotenv.2017.01.190

[33] Hossain, R., Islam, M. T., Shanker, R., Khan, D., Locock, K. E. S., Ghose, A., & Sahajwalla, V.

[34] (2022). Plastic waste management in India: Challenges, opportunities, and roadmap for circular economy. *Sustainability*, *14*(8), 4425. https://doi.org/10.3390/su14084425

[35] Jain, Y., Govindasamy, H., Kaur, G., Ajith, N., Ramasamy, K., RS, R., & Ramachandran, P. (2024). Microplastic pollution in high-altitude Nainital lake, Uttarakhand, India. *Environmental Pollution*, *346*, 123598. https://doi.org/10.1016/j.envpol.2024.123598

[36] Jin, M., Wang, X., Ren, T., Wang, J., & Shan, J. (2021). Microplastics contamination in food and beverages: Direct exposure to humans. *Journal of Food Science*, *86*(7), 2816-2837. https://doi.org/10.1111/1750-3841.15802

[37] Kalangutkar, N., Mhapsekar, S., MM, A., & Pednekar, P. (2024a). Microplastic pollution in the surface waters of the Zuari River, Goa, India. *Environmental Monitoring and Assessment*, *196*(11), 1007. https://doi.org/10.1007/s10661-024-13181-1

[38] Kalangutkar, N., Mhapsekar, S., Redkar, P., Valsan, G., & Warrier, A. K. (2024b). Microplastic pollution in the Chapora River, Goa, Southwest India: Spatial distribution and risk assessment. *Environmental Monitoring and Assessment*, *196*(5), 409. https://doi.org/10.1007/s10661-024-12587-1

[39] Khalid, N., Aqeel, M., Noman, A., Khan, S. M., & Akhter, N. (2021). Interactions and effects of microplastics with heavy metals in aquatic and terrestrial environments. *Environmental Pollution*, *290*, 118104. https://doi.org/10.1016/j.envpol.2021.118104

[40] Kumar, A., Behera, D., Bhattacharya, S., Mishra, P. K., Yadav, A., and Ambili, A. (2021). Distribution and characteristics of microplastics and phthalate esters from a freshwater lake system in Lesser Himalayas. *Chemosphere*, *283*,131132. https://doi.org/10.5194/egusphere-egu22-251

[41] Kumar, S., Ajay, K., Behera, D., Yaseen, A., Karthick, B., Prasad, S., & Anoop, A. (2025). Co-occurrence of microplastics and heavy metals in a freshwater lake system in Indian Himalaya: Distribution and influencing factors. *Emerging Contaminants*, *11*(1), 100394. https://doi.org/10.1016/j.emcon.2024.100394

[42] Kumar, S., Ajay, K., Diptimayee, B., Yaseen, A., Balasubramanian, K., Bhat, S. U., & Ambili,A. (2023). Quantifying Microplastics Abundance and Their Implications as Vectors for Heavy Metal Adsorption in Freshwater Aquatic System of Kashmir Himalaya. In *IMOG 2023* (Vol. 2023, No. 1, pp. 1-1). European Association of Geoscientists & Engineers. https://doi.org/10.3997/2214-4609.202333254

[43] Kumar, S., Behera, D., Ajay, K., Karthick, B., Dharia, C., & Anoop, A. (2024). Microplastics and heavy metal contamination along a land-use gradient in a Himalayan foothill river: Prevalence and controlling factors. *Journal of Contaminant Hydrology*, *266*, 104411. https://doi.org/10.1016/j.jconhyd.2024.104411

[44] Kumari, R. (2024). Chronic toxicity of microplastics on fish (Labeo Rohita) and their impact on the freshwater ecosystem: a case study of gangasagar pond, Darbhanga, India. *Uttar Pradesh Journal of Zoology*, 45(10),135-143. https://doi.org/10.56557/upjoz/2024/v45i104057

[45] Laju, R. L., Jayanthi, M., Jeyasanta, K. I., Patterson, J., Asir, N. G. G., Sathish, M. N., & Edward, J. P. (2022). Spatial and vertical distribution of microplastics and their ecological risk in an Indian freshwater lake ecosystem. *Science of the Total Environment*, *820*, 153337. https://doi.org/10.1016/j.scitotenv.2022.153337

[46] Laju, R. L., Jayanthi, M., Jeyasanta, K. I., Patterson, J., Bilgi, D. S., Sathish, N., & Edward, J. P. (2023). Microplastic contamination in Indian rural and urban lacustrine ecosystems. *Science of the TotalEnvironment*, *895*,165146. https://doi.org/10.1016/j.scitotenv.2023.165146

[47] Lebreton, L. C., Van Der Zwet, J., Damsteeg, J. W., Slat, B., Andrady, A., & Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature communications*, *8*(1), 15611. https://doi.org/10.1038/ncomms15611

[48] Lee, Y., Cho, J., Sohn, J., & Kim, C. (2023). Health effects of microplastic exposures: current issues and perspectives in South Korea. *Yonsei medical journal*, *64*(5), 301. 10.3349/ymj.2023.0048

[49] Li, J., Liu, H., & Chen, J. P. (2018). Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection. *Water research*, *137*, 362-

[50] 374. https://doi.org/10.1016/j.watres.2017.12.056

[51] Loganathan, Y., & Kizhakedathil, M. P. J. (2023). A review on microplastics-an indelible ubiquitous pollutant. *Biointerface Res. Appl. Chem*, *13*(2),126. https://doi.org/10.33263/BRIAC132.126

[52] Mandal, M., Roy, A., & Sarkar, A. (2025). Comprehensive study of the microplastic footprint in the urban pond and river of Eastern India. *Scientific Reports*, *15*(1),8645.https://doi.org/10.1038/s41598-025-87452-3

[53] Manikanda Bharath K., Srinivasalu, S., Natesan, U., Ayyamperumal, R., Kalam, N., Anbalagan, S., Sujatha, K., & Alagarasan, C. (2021). Microplastics as an emerging threat to the freshwater ecosystems of Veeranam lake in south India: A multidimensional approach. *Chemosphere*, *264*,128502. https://doi.org/10.1016/j.chemosphere.2020.128502

[54] Meijer, L. J., Van Emmerik, T., Van Der Ent, R., Schmidt, C., & Lebreton, L. (2021). More than 1000 rivers account for 80% of global riverine plastic emissions into the ocean. *Science advances*, *7*(18), eaaz5803. https://doi.org/10.1126/sciadv.aaz5803

[55] Mhapsekar, S., & Kalangutkar, N. G. (2026). Assessing Microplastic Contamination and Associated Risks in the Surface Waters of the Mandovi River: Upstream-to-Sink Study from Freshwater to Estuarine Mouth in Goa, India. *Water, Air, & Soil Pollution*, *237*(2), 1-28. https://doi.org/10.1007/s11270-025-08742-0

[56] Mhapsekar, S., Kalangutkar, N., & Joshi, N. (2025). Microplastic contamination and ecological risk in a riverine system: A case study from the Valvanti River, Goa, India. *Environmental Monitoring and Assessment*, *197*(6), 706. https://doi.org/10.1007/s10661-025-14168-2

[57] Mishra, A. K., Singh, J., & Mishra, P. P. (2023). Microplastics in freshwater ecosystem: A serious threat for freshwater environment. *International Journal of Environmental Science and Technology*, *20*(8), 9189-9204. https://doi.org/10.1007/s13762-022-04489-x

[58] Mishra, R., & Singh, N. (2025). Regulating Plastic Rivers: A Study of Microplastic Pollution and Regulatory Deficits in India's Freshwater Systems. *Revija za kriminalistiko in kriminologijo/Ljubljana*, *76*(4), 359-367.

[59] Mukhopadhyay, P., & Valsalan, S. A. (2024). Seasonal variation, spatial distribution and risk assessment of microplastics in surface waters of Periyar River, Kerala, India. *Environmental Monitoring and Assessment*, *196*(7),679. https://doi.org/10.1007/s10661-024-12820-x

[60] Napper, I. E., & Thompson, R. C. (2016). Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Marine pollution bulletin*, *112*(1-2), 39-45. https://doi.org/10.1016/j.marpolbul.2016.09.025

[61] Napper, I. E., Davies, B. F., Clifford, H., Elvin, S., Koldewey, H. J., Mayewski, P. A., & Thompson, R. C. (2020). Reaching new heights in plastic pollution—preliminary findings of microplastics on Mount Everest. *One Earth*, *3*(5),621-630. https://doi.org/10.1016/j.oneear.2020.10.020

[62] Nayal, R., & Suthar, S. (2022). First report on microplastics in tributaries of the upper Ganga River along Dehradun, India: Quantitative estimation and characterizations. *Journal of Hazardous Materials Advances*, *8*, 100190. https://doi.org/10.1016/j.hazadv.2022.100190

[63] Neelavannan, K., Sen, I. S., Lone, A. M., & Gopinath, K. (2022). Microplastics in the high-altitude Himalayas: Assessment of microplastic contamination in freshwater lake sediments, Northwest Himalaya (India). *Chemosphere*, *290*,133354. https://doi.org/10.1016/j.chemosphere.2021.133354

[64] OECD (2022), *Global Plastics Outlook: Policy Scenarios to 2060*, OECD Publishing, Paris, https://doi.org/10.1787/aa1edf33-en.

[65] Pandey, D., Singh, A., Ramanathan, A., & Kumar, M. (2021). The combined exposure of microplastics and toxic contaminants in the floodplains of north India:A review.*Journal of Environmental Management*,*279*,111557.https://doi.org/10.1016/j.jhazmat.2024.133926

[66] Pandey, K., & Rajput, J. (2026). cxsPlastic Footprints in Sacred Waters: Assessing Microplastic Presence in the Himalayan Ganga River Ecosystem. In *Reimagining Indian Rivers for Sustainability* (pp. 443-464). Cham: Springer Nature

Switzerland. https://doi.org/10.1007/978-3-032-04754-0_10

[67] Pandey, N., Verma, R., Patnaik, S., & Anbumani, S. (2023). Abundance, characteristics, and risk assessment of microplastics in indigenous freshwater fishes of India. *Environmental Research*, *218*, 115011. https://doi.org/10.1016/j.envres.2022.115011

[68] Pathak, H. K., Gandhi, K., & Singh, R. P. (2026). Potential Impact of Heavy Metals and Microplastics in River Ecosystem on Aquatic Organisms and Human Health, and Sustainable Mitigation Approaches. *Water, Air, & Soil Pollution*, *237*(4), 199. https://doi.org/10.1007/s11270-025-08844-9

[69] Patidar, K., Ambade, B., Mohammad, F., & Soleiman, A. A. (2023a). Microplastics as heavy metal vectors in the freshwater environment: distribution, variations, sources and health risk. *Physics and Chemistry of the Earth, Parts a/b/c*, *131*, 103448. https://doi.org/10.1016/j.pce.2023.103448

[70] Patidar, K., Mahato, D. K., & Ambade, B. (2024). Microplastics pollution in Narmada River water and sediments: characterization, source distribution and risk assessment. *International Research Journal of Environmental Sciences, 13(3), 1-10.*

[71] Patra, K. B., & Baitharu, I. (2024). Assessment of microplastics and associated ecological risk in the Hirakud Reservoir, Odisha, India. *Journal of water and health*, *22*(6), 1017-1032. https://doi.org/10.2166/wh.2024.393

[72] Pavithra, K., Vairaperumal, T., Mukhopadhyay, M., Malar, P., & Chakraborty, P. (2024). Microplastics in packaged water, community stored water, groundwater, and surface water in rivers of Tamil Nadu after the COVID-19 pandemic outbreak.*Journal of Environmental Management*, *356*, 120361. https://doi.org/10.1016/j.jenvman.2024.120361

[73] Prasad, G., Mohanty, S., Chakraborty, P., & Bharat, G. K. (2025). Microplastics in the rivers of Gujarat (India) to the Arabian Sea: assessment of the sources, distribution, and associated environmental risk. Integrated Environmental Assessment and Management, 21(4), 843-857. https://doi.org/10.1093/inteam/vjaf011

[74] Rahman, M. O., Mostafa, M. G., Islam, M. S. U., & Zaman, S. (2025). Assessment of Heavy Metals, Microplastics Abundance, Pollution Level, and Contamination Risk in the Ganges

[75] Downstream. *Sustainable Environmental Insight*, *2*(2),124-140. https://doi.org/10.53623/sein.v2i2.767

[76] Rajan, K., Khudsar, F. A., & Kumar, R. (2023). Urbanization and population resources affect microplastic concentration in surface water of the River Ganga. *Journal of Hazardous Materials Advances*, *11*, 100342. https://doi.org/10.1016/j.hazadv.2023.100342

[77] Ram, B., & Kumar, M. (2020). Correlation appraisal of antibiotic resistance with fecal, metal and microplastic contamination in a tropical Indian river, lakes and sewage. *NPJ Clean Water*, *3*(1), 3. https://doi.org/10.1038/s41545-020-0050-1

[78] Raveendran, A., and A, Geetha. (2023). River Resuscitation From Ritualistic Practices Through Strategical Planning Approaches. In *Proceedings of the 7th Biennial International Conference On Emerging Trends in Engineering, Science &Technology (ICETEST 2023)*.http://dx.doi.org/10.2139/ssrn.4494860

[79] Rebecca Cathrine Jayakumari D., Deborah Anne Rose N., Sheeba Anitha Nesakumari C., Mahesh T.C., Saravanan R. and Thirunavukkarasu N. (2024). Microplastic pollution in India's marine and inland environmental matrices: A comprehensive review. Intern. J. Zool. Invest. 10(1): 1050-1069. https://doi.org/10.33745/ijzi 2024.v10i01.109

[80] Rillig, M. C. (2012). Microplastic in terrestrial ecosystems and the soil?. *Environ. Sci. Technol.* 46, 12, 6453–6454. https://doi.org/10.1021/es302011r

[81] Rochman, C. M., Hoh, E., Kurobe, T., & Teh, S. J. (2013). Ingested plastic transfers hazardous chemicals to fish and induces hepatic stress. *Scientific reports*, *3*(1), 3263. https://doi.org/10.1038/srep03263

[82] Rodríguez, A. M., Kratina, P., & Jones, J. I. (2024). Microplastic pollution and nutrient enrichment shift the diet of freshwater macroinvertebrates. *Environmental Pollution*, *359*, 124540. https://doi.org/10.1016/j.envpol.2024.124540

[83] Saha, A., Saikia, K. K., & Handique, S. (2025). Distribution characteristics of microplastics and potentially toxic

elements as co-contaminants in groundwater in mid-Brahmaputra Valley, northeastern India. *Environmental Monitoring and Assessment*, *197*(7),818.https://doi.org/10.1007/s10661-025-14266-1

[84] Saikia, K. K., & Handique, S. (2024). Microplastics abundance and potential ecological risk assessment in sediment, water and fish of Deepor Beel—a Ramsar Wetland of the Brahmaputra plain, India. *Environmental Monitoring and Assessment*, *196*(10), 977. https://doi.org/10.1007/s10661-024-13138-4

[85] Sarkar, D. J., Sarkar, S. D., Das, B. K., Manna, R. K., Behera, B. K., & Samanta, S. (2019). Spatial distribution of meso and microplastics in the sediments of river Ganga at eastern India. Science of the Total Environment, 694,133712.https://doi.org/10.1016/j.scitotenv.2019.133712

[86] Sarkar, D. J., Sarkar, S. D., Kumar, S. A. N. T. H. A. N. A., Kundu, S. O. U. R. A. V., & DASa, B.

[87] K. (2022). Microplastic pollution in Ganga: present status and future need. *Science and Culture*, *88*(11–12). https://doi.org/10.36094/sc.v88.2022.Microplastic_Pollution_in_Ganga.Sarkar.400

[88] Savitha, C., Sekar, V., Talari, R., & Sundaram, B. (2026). Assessing the impacts of land use and land cover on occurrence, spatial distribution of microplastics and heavy metals in an agricultural watershed, Tadepalligudem, Andhra Pradesh, India. *Environmental Research*, *294*, 123848. https://doi.org/10.1016/j.envres.2026.123848.

[89] Sekar, V., & Sundaram, B. (2025). Investigation of microplastic pollution index in the urban surface water: A case study in west Godavari district, Andhra Pradesh, India. *Journal of Environmental Management*,374,124098.https://doi.org/10.1016/j.jenvman.2025.124098

[90] Sharma, S., & Chatterjee, S. (2017). Microplastic pollution, a threat to marine ecosystem and human health: a short review. *Environmental Science and Pollution Research*, *24*(27), 21530-21547. https://doi.org/10.1007/s11356-017-9910-8

[91] Shifa, S., Sathish, K., & Saraswat, S. (2025). Assessment of upstream and downstream surface water microplastic pollution in Lower Himalayan Gaula River, Uttarakhand, India. *Bulletin of Environmental Contamination and Toxicology*, *114*(6), 85. https://doi.org/10.1007/s00128-025-04061-6

[92] Shukla, S. (2025). A comprehensive analysis of microplastic pollution in Sangam. *Ecosystem Dynamics of Prayagraj*, 55.

[93] Singh, M., & Verma, K. L. (2025). An invisible threats: A review of microplastics in Indian waters and their implications–the case of "the Ganges". *Marine Biodiversity and Pollution: A Scientific and Ethical Enquiry*, 90.

[94] Singh, N., Mondal, A., Bagri, A., Tiwari, E., Khandelwal, N., Monikh, F. A., & Darbha, G. K. (2021). Characteristics and spatial distribution of microplastics in the lower Ganga River water and sediment. *Marine Pollution Bulletin*, *163*,111960. https://doi.org/10.1016/j.marpolbul.2020.111960

[95] Singh, P. K., Singh, A., Srivastava, A. K., Chauhan, R., Basniwal, R. K., & Chauhan, A. (2025). Microplastic pollution in the Ganga River: A state-of-the-art review of pathways, mechanisms,and mitigation. *Water Supply*, *25*(2),249-267. https://doi.org/10.2166/ws.2025.009

[96] Singh, P. K., Singh, A., Tripathi, K., Basniwal, R. K., Chauhan, R., & Chauhan, A. (2024). Insights into the seasonal variation, distribution, composition and dynamics of microplastics in the Ganga River ecosystem of Varanasi City, Uttar Pradesh, India. *Environmental Monitoring and Assessment*, *196*(11), 1134. https://doi.org/10.1007/s10661-024-13307-5

[97] Sruthy, S., & Ramasamy, E. V. (2017). Microplastic pollution in Vembanad Lake, Kerala, India: the first report of microplastics in lake and estuarine sediments in India. *Environmental pollution*, *222*, 315-322. http://dx.doi.org/10.1016/j.envpol.2016.12.038

[98] Thandavamoorthy Rajeswari, I., Iyyanar, A., & Govindarajulu, B. (2023). Microplastic pollution in Kolavai Lake, Tamil Nadu, India: quantification of plankton-sized microplastics in the surface water of lake. *Environmental Science and Pollution Research*, *30*(41), 94033-94048. https://doi.org/10.1007/s11356-023-29078-4

[99] Thompson, R. C., Olsen, Y., Mitchell, R. P., Davis, A., Rowland, S. J., John, A. W.,& Russell,A. E. (2004). Lost at sea: where is all the plastic?. *Science*, *304*(5672), 838-838. https://doi.org/10.1126/science.1094559

eISSN: 2583-1194

[100] Tsering, T., Sillanpää, M., Sillanpää, M., Viitala, M., & Reinikainen, S. P. (2021). Microplastics pollution in the Brahmaputra River and the Indus River of the Indian Himalaya. *Science of the Total Environment*, *789*, 147968. https://doi.org/10.1016/j.scitotenv.2021.147968

[101] Vaid, M., Mehra, K., Sarma, K., & Gupta, A. (2022). Investigations on the co-occurrence of microplastics and other pollutants in the River Yamuna, Delhi. *Water Supply*, *22*(12), 8767-8777. https://doi.org/10.2166/ws.2022.408

[102] Vaid, M., Sarma, K., & Gupta, A. (2024). Urban drainage channels as a pathway for microplastics in riverine systems: A case study of Delhi, India. *Water Science & Technology*, *90*(2), 563-577. https://doi.org/10.2166/wst.2024.181

[103] Varsha, Ranjan, R., Dass, A., Singh, S. K., & Singh, T. (2025). Microplastics assessment in the lower stretch of the Ganga River sediment from East Indian region: Influence of land use and rainfall patterns. *Chemosphere*, *385*,144530.https://doi.org/10.1016/j.chemosphere.2025.144530

[104] Verma, M., Singh, P., Pradhan, V., & Dhanorkar, M. (2025). Spatial and seasonal variations in abundance, distribution characteristics, and sources of microplastics in surface water of Mula river in Pune,India. *Environmental Pollution*,373, 126091.https://doi.org/10.1016/j.envpol.2025.126091

[105] Vogel, A., Tentschert, J., Pieters, R., Bennet, F., Dirven, H., van den Berg, A., ... & Haase, A. (2024). Towards a risk assessment framework for micro-and nanoplastic particles for human health. *Particle and Fibre Toxicology*, *21*(1), 48. https://doi.org/10.1186/s12989-024-00602-9

[106] Wagner, M., Scherer, C., Alvarez-Muñoz, D., Brennholt, N., Bourrain, X., Buchinger, S., & Reifferscheid, G. (2014). Microplastics in freshwater ecosystems: what we know and what we need to know. *Environmental Sciences Europe*, *26*(1),12. https://doi.org/10.1186/s12302-014-0012-7

[107] Wang, T., Hu, M., Xu, G., Shi, H., Leung, J. Y., & Wang, Y. (2021). Microplastic accumulation via trophic transfer: can a predatory crab counter the adverse effects of microplastics by body defence?. *Science of the Total Environment*, *754*,142099. https://doi.org/10.1016/j.scitotenv.2020.142099

[108] Winiarska, E., Jutel, M., & Zemelka-Wiacek, M. (2024). The potential impact of nano-and microplastics on human health: Understanding human health risks. *Environmental research*, *251*, 118535. https://doi.org/10.1016/j.envres.2024.118535

[109] Yousuf Dar, J., Mukhopadhyay, R., Bhat, I., Kumar, S., and Yadav, R. K. (2025). Lake sediments act as a sink of microplastics in the High-Altitude Himalayan Dal Lake, India, EGU General Assembly 2025, Vienna, Austria, EGU25-214. https://doi.org/10.5194/egusphere-egu25-214