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A Comprehensive Review of Microplastic Pollution in Inland Aquatic Ecosystems of India: Sources, Distribution, Ecological Risks, And Policy Interventions

Natalya V. Popova
Department of Chemistry, Lomonosov Moscow State University, Moscow, Russia

Minh H. Nguyen
Faculty of Science, Vietnam National University, Hanoi, Vietnam

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ABSTRACT

Introduction: Microplastic (MP) pollution poses a substantial and rapidly escalating threat to global aquatic ecosystems. In India, the vast network of inland aquatic systems (IAS), critical for both ecology and human sustenance, faces unique challenges due to high population density and inconsistent waste management. This comprehensive review synthesizes the current knowledge on MP contamination within Indian IAS, focusing on sources, distribution, ecological risks, and the efficacy of current policy interventions. Methods: A systematic literature review was conducted, synthesizing data on MP occurrence from major Indian rivers (e.g., Ganga, Yamuna) and lakes. The review standardized heterogeneous sampling and quantification data to identify consistent trends. Results: MP concentrations in Indian IAS demonstrate a strong correlation with urbanization density, often registering high levels dominated by Polyethylene (PE) and Polypropylene (PP) fragments and fibers, linked to single-use plastics and domestic effluent. The primary source is identified as diffuse land-based pollution and inadequate wastewater treatment. Ecologically, MPs serve as vectors for adsorbed contaminants and have been documented in various Indian aquatic biota, suggesting potential for trophic transfer. Discussion and Conclusion: While national policies, such as the Plastic Waste Management Rules, are established, a critical implementation deficit at the local governance level hinders effective control. Future efforts must focus on decentralized, technology-driven waste solutions, standardized national monitoring, and rigorous enforcement of Extended Producer Responsibility to effectively mitigate the growing peril of MP pollution in India's vital freshwater resources.

KEYWORDS

Microplastic, Inland Waters, India, River Pollution, Wastewater, Policy Implementation, Ecological Risk.

INTRODUCTION

1.1 Background and Global Context of Plastic Pollution

The advent of plastics has fundamentally reshaped modern society, yet their remarkable durability, combined with escalating production and insufficient waste management, has culminated in a planetary-scale pollution crisis. Since the early 2000s, global plastic production has accelerated, with billions of metric tons produced to date. A considerable fraction of this material is improperly disposed of, ultimately leading to the ubiquitous presence of plastic debris across marine, terrestrial, and freshwater environments.

A particular concern is the emergence of microplastics (MPs), defined as plastic particles generally less than 5 mm in size. MPs originate either as primary microplastics (manufactured to be small, e.g., microbeads in cosmetics) or, more predominantly, as secondary microplastics resulting from the fragmentation and weathering of larger plastic debris in the environment. These particles, due to their small size, persistence, and propensity to sorb environmental contaminants, are recognized globally as significant emerging pollutants. Initial scientific attention primarily focused on marine ecosystems, revealing vast accumulation zones. However, contemporary research increasingly highlights the pivotal role of inland aquatic systems (IAS)—rivers, lakes, and reservoirs—as critical conduits and ultimate sinks for MPs, transporting them from terrestrial sources to the oceans, while simultaneously posing localized ecological threats.

1.2 Significance of Inland Aquatic Systems in India

India possesses one of the world's most extensive and hydrologically crucial networks of IAS. Major river systems like the Ganga, Yamuna, Godavari, and their numerous tributaries not only sustain vast populations through irrigation, drinking water, and sanitation but also hold immense cultural and religious significance. Similarly, a myriad of lakes, reservoirs, and wetlands forms the backbone of regional biodiversity and water security.

The vulnerability of these systems to pollution is magnified by several factors inherent to the region: extremely high population densities along riparian zones, rapid and often unplanned urbanization, and severe infrastructural deficiencies in solid waste management (SWM) and wastewater treatment. Initial studies in India, such as the first report on MPs in the Vembanad Lake and estuarine sediments in Kerala, signaled an alarming level of contamination comparable to international hotspots. This is compounded by the heavy reliance on single-use plastics and pervasive open dumping practices. A comprehensive synthesis focusing specifically on the unique challenges and data emerging from India's IAS is thus imperative.

1.3 Scope and Objectives of the Review

This comprehensive review aims to bridge the current gap in understanding the full extent and implications of MP pollution across the diverse inland aquatic ecosystems of India. The review's objectives are four-fold:

1. To systematically identify and characterize the primary sources and transport pathways of MPs entering Indian IAS.

2. To synthesize and comparatively analyze the available data on the spatial and temporal distribution and occurrence of MPs (concentration, polymer type, morphology) across India's major rivers and lakes.

3. To critically assess the documented and predicted ecological and human health risks associated with MP contamination in the Indian context.

4. To evaluate the efficacy and implementation challenges of the existing national policy and management frameworks designed to mitigate plastic pollution in India.

Ultimately, this work seeks to provide a robust, evidence-based foundation for policymakers and environmental scientists, guiding future research and informing effective, targeted remediation strategies.

1.4 Key Insights to Guide the Narrative

An overarching theme of this analysis is that Microplastic concentration in major Indian river systems is strongly correlated with urbanization density and ineffective solid waste management in riparian zones, often surpassing levels reported in highly industrialized Western rivers. This suggests that the problem is predominantly driven by high waste input rates rather than slower degradation and accumulation processes. Furthermore, analysis of the available literature indicates that the most frequently detected polymer types are Polyethylene (PE) and Polypropylene (PP), primarily fragments and fibers, suggesting a significant contribution from single-use plastics and domestic sewage/laundry effluent. Crucially, the review concludes that current legislative and policy frameworks in India, such as the Plastic Waste Management Rules, 2016/2021, are structurally robust but face significant implementation deficits at the local governance level, creating an urgent need for decentralized, technology-driven waste solutions to bridge this policy-practice gap.

2. METHODOLOGY (Review Structure)

2.1 Search Strategy and Selection Criteria

The methodology adopted a systematic approach to ensure a comprehensive and unbiased review of the literature. Key academic databases, including Scopus, Web of Science, and Google Scholar, were queried using specific search terms related to both the contaminant and the geographical area: "microplastic," "nanoplastic," "plastic debris," combined with "India," "river," "lake," "freshwater," "aquatic ecosystem," and "sediment." The search was limited to peer-reviewed original research articles, review papers, and authoritative technical reports published up to the present. Inclusion criteria prioritized studies that reported quantitative data on microplastic occurrence (concentration, size, polymer type) from Indian freshwater or estuarine IAS. Exclusion criteria involved studies focused solely on marine environments distant from Indian estuaries, theoretical modeling without empirical data, or papers that did not specify a geographically relevant sampling site.

2.2 Data Extraction and Synthesis

A primary challenge in synthesizing microplastic literature is the heterogeneity of sampling and analytical methods, which often results in non-standardized units. Data extracted for each included study comprised: sampling location (river/lake name, region), matrix (water, sediment, biota), reported concentration and unit (e.g., particles/L, particles/kg dry weight), dominant shape (fiber, fragment, film), and polymer composition. For quantitative analysis, data were grouped by major river basin or system. A qualitative synthesis approach was applied to policy and risk assessment literature, grouping findings into common themes, such as 'management failure points' or 'observed ecotoxicological effects.'

2.3 Classification of Microplastics

To maintain consistency, this review adhered to the generally accepted definition of microplastics as plastic particles with a diameter less than 5 mm. Classification by shape focused on four main categories: fragments (irregular shapes from the breakup of larger objects), fibers (threads from textiles and ropes), films (thin plastic sheets, e.g., from packaging), and beads (spherical particles, e.g., microbeads). Polymer identification, where reported, was categorized by major commercial types, with a focus on Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl Chloride (PVC), and Polyethylene Terephthalate (PET).

3. RESULTS: Occurrence and Distribution in Indian IAS

3.1 Sources and Pathways of Microplastics into IAS

The influx of microplastics into India's IAS is multifaceted, stemming predominantly from land-based activities.

3.1.1 Terrestrial Runoff and Waste Dumping (Primary Source)

The most significant pathway is the direct disposal and runoff of macroplastic waste from surrounding areas. India’s informal and often unregulated SWM infrastructure leads to massive accumulation of plastic debris in open dumpsites and along riverbanks. During the monsoon season, this macroplastic litter breaks down and is subsequently mobilized as MPs via surface runoff and stormwater drains into the nearest water body. The high concentrations reported in rivers flowing through densely populated urban centers strongly suggest that diffuse urban runoff and mismanaged waste are the overriding primary sources. This finding underpins the core argument: MP levels are strongly associated with urbanization density and SWM efficacy.

3.1.2 Wastewater Treatment Plants (WWTPs) and Sewage Discharge

A major, non-diffuse source of microplastic fibers and fragments is the discharge from Wastewater Treatment Plants (WWTPs) and, more critically, the direct release of untreated domestic sewage. In India, many urban centers lack comprehensive sewage collection and treatment, meaning vast volumes of wastewater are often dumped directly into rivers and lakes. Even where WWTPs exist, they are primarily designed for conventional pollutant removal, and their efficiency in removing small plastic particles is highly variable. While advanced tertiary treatments can achieve high removal rates, basic or primary/secondary treatment is often the norm, acting as a consistent conduit for MPs, particularly synthetic textile fibers from laundry effluent, into the aquatic environment.

3.1.3 Atmospheric Deposition and Industrial Effluent

Less dominant, but increasingly recognized, are pathways involving atmospheric deposition and specific industrial point sources. Microplastics, particularly lightweight fibers and fragments, have been shown to be transported significant distances via air. The high incidence of fibers in IAS, even in relatively remote locations, suggests that atmospheric fallout from urban areas, potentially including domestic dust and vehicle tire wear, contributes to the total MP burden. Furthermore, industrial effluent from plastic manufacturing units, textile industries, and other plastic-processing facilities represents a localized, high-concentration point source in certain regions.

3.2 Spatial and Temporal Distribution Patterns

3.2.1 Major River Systems (Ganga, Yamuna, Godavari)

Studies across India's major river basins consistently report high levels of MP contamination, particularly in stretches traversing large cities. The Yamuna River, for instance, exhibits elevated concentrations in and around the National Capital Region (NCR), a finding which supports the correlation between MP concentration and urbanization density. Similarly, segments of the Ganga River are characterized by high concentrations downstream of major population centers, demonstrating a gradient that mirrors population density and industrial activity. Research on the Gomti River, a tributary of the Ganga, further showed seasonal variations linked to urban input. The high concentrations observed in these systems, particularly when standardized for comparable matrices, indeed suggest that inputs from Indian urban areas are often substantial, underscoring the severity of the challenge.

3.2.2 Lakes, Reservoirs, and Estuaries

In enclosed and semi-enclosed systems, such as Vembanad Lake in Kerala and numerous urban lakes, the dynamics shift from transport to accumulation. These systems function as long-term sinks where water movement is restricted, allowing MPs to settle and concentrate in the sediments. Studies in these lentic environments frequently report higher sediment concentrations compared to lotic (flowing) rivers, with the sediment acting as a major environmental reservoir. Estuarine regions, where river flow meets the sea, exhibit complex dynamics driven by tidal forces, salinity, and flocculation, leading to high concentrations in the mixing zones.

3.2.3 Seasonal Variations

Seasonal variations are a defining feature of MP distribution in India's IAS, largely governed by the intense monsoon cycle. Studies have noted that high-flow periods during the monsoon often lead to a flushing effect, transporting accumulated MPs from riverbanks and catchment areas into the main channel, resulting in higher measured concentrations in the water column. Conversely, during the dry season, lower flow rates can result in increased settling and higher concentrations of MPs observed in riverbed sediments. This hydrological control emphasizes the need for year-round monitoring and suggests that the annual MP load exported by rivers is substantial.

3.3 Polymer Types and Morphologies

The composition analysis across multiple Indian IAS studies reveals a consistent pattern. The most prevalent polymer types are Polyethylene (PE) and Polypropylene (PP). This dominance is directly linked to their widespread use in single-use plastic items, such as shopping bags (PE), packaging films (PP), and bottles (PET, although less dominant than PE/PP fragments).

In terms of morphology, fragments and fibers consistently dominate the particle count across both water and sediment samples. Fibers are strongly associated with laundry and sewage effluent, while fragments are the product of macroplastic litter breakdown. The high ratio of fragments and fibers reinforces the conclusion that the majority of MPs originate from the secondary breakdown of ubiquitous consumer plastics and wastewater discharge, thereby linking MP types directly to the region's prevalent SWM and consumption habits.

4. DISCUSSION: Ecological and Human Health Risks & Management

4.1 Ecological Consequences in IAS

Microplastic contamination in India’s IAS is not merely an aesthetic issue; it presents tangible ecological consequences for endemic aquatic life.

4.1.1 Ingestion and Trophic Transfer

The risk of ingestion is particularly high for filter feeders and detritivores, who often mistake MPs for natural food sources. Indian studies have begun to document the presence of MPs in the gastrointestinal tracts of various aquatic organisms, including commercially important fish species and invertebrates. Once ingested, MPs can cause physical harm, including blocking the digestive tract, reducing feeding stimulus, and leading to false satiation and energy depletion.

The small size of MPs facilitates their trophic transfer across the food web. While the evidence for significant biomagnification (increasing concentration with trophic level) remains contested globally, the accumulation of MPs at lower trophic levels (e.g., zooplankton) inherently exposes higher-level consumers, including fish and potentially humans, to the particles.

4.1.2 Carrier Effect of MPs

Microplastics possess a high surface-area-to-volume ratio and are typically lipophilic, enabling them to effectively adsorb hydrophobic organic contaminants (HOCs) and heavy metals from the ambient water, a phenomenon often termed the carrier effect. In India’s highly polluted urban waterways, this effect is critical. MPs act as shuttles, concentrating pollutants like PCBs, pesticides, and flame retardants far above the surrounding water concentration. When ingested by aquatic organisms, these MPs can desorb the hazardous chemicals, potentially leading to toxicological effects such as hepatic stress and endocrine disruption. Moreover, MPs can also harbor pathogenic microorganisms, forming a 'plastisphere' that can contribute to the spread of disease, though this area requires further investigation in the Indian context.

4.1.3 Impacts on Ecosystem Function

Beyond direct effects on individual organisms, MPs can modify ecosystem functions. The accumulation of MPs in river and lake sediments alters the physical properties of the substratum, which is vital habitat for benthic invertebrates. Furthermore, the presence of MPs can influence microbial community structure and function. In terrestrial-aquatic interfaces, the use of sewage sludge as fertilizer, which often contains high MP loads from WWTPs, acts as a pathway for MP contamination of agricultural soils adjacent to IAS, creating a complex cross-ecosystem threat.

4.2 Potential Risks to Human Health

The human population in India is intrinsically linked to the health of its IAS, utilizing these waters for drinking, bathing, and food. The presence of MPs in these waters thus translates to potential human exposure pathways.

4.2.1 Drinking Water Exposure

Many large Indian cities draw their raw water from rivers and lakes that are known to be contaminated with microplastics. While municipal water treatment processes are generally efficient in removing larger particles, the presence of MPs in raw water dictates a high initial exposure load. Studies have confirmed the presence of MPs in finished drinking water globally, suggesting that current filtration and disinfection methods are not entirely effective, although data specific to treated water quality across Indian cities remain a significant knowledge gap.

4.2.2 Seafood Consumption

Given the documented ingestion of MPs by fish and shellfish in Indian aquatic systems, the consumption of aquatic produce represents a direct pathway for human exposure. While the bioaccumulation and transfer kinetics are not fully understood, the chronic ingestion of MPs, and the associated chemicals they carry, presents a long-term, non-trivial public health concern.

4.2.3 Airborne Inhalation

The air we breathe, particularly in densely populated urban centers, contains microplastic fibers. Research indicates that the highest concentration of fibers often corresponds to indoor environments, but outdoor atmospheric deposition is also a confirmed pathway. The proximity of urban populations to open waste sites and the high concentration of textile fibers from domestic sources suggest that inhalation of airborne MPs is a potentially significant route of exposure in India.

4.3 Policy Landscape and Management Challenges in India

4.3.1 Review of Current Frameworks

India has acknowledged the plastic crisis through progressive, national-level environmental policy. The Plastic Waste Management (PWM) Rules, 2016, and their subsequent amendments, notably in 2021, represent the country's primary legislative framework. Key provisions include: a defined Extended Producer Responsibility (EPR) for producers, importers, and brand owners; the regulation of multilayered plastic; and most recently, a comprehensive, phased ban on Single-Use Plastics (SUP) with low utility and high littering potential (e.g., specific categories of plastic bags, cutlery, packaging films) enacted from July 2022. These rules are structurally sound, aiming to internalize the cost of waste management and reduce the source of the most common polymer types found in IAS (PE and PP fragments and films).

The EPR mechanism under the PWM Rules mandates that the responsibility for the final, environmentally sound disposal of plastic packaging waste shifts from the local government and waste collection systems to the producers, importers, and brand owners (PIBOs) who introduce the plastic into the market. This principle is a cornerstone of modern global waste policy. In the Indian context, the EPR framework requires PIBOs to meet mandatory recycling and resource recovery targets on a yearly basis. However, the system's effectiveness is predicated on the robustness of the monitoring and reporting infrastructure, which necessitates a transparent digital platform for tracking the movement of plastic waste from collection to certified recycler. The structural ambition of the Indian EPR rules is commendable, particularly the inclusion of post-consumer plastic waste generated across the country. Yet, the sheer scale and complexity of the supply chain, involving millions of small retailers and a deeply fragmented collection system, introduce significant challenges to verification, which can lead to superficial compliance without real on-the-ground reduction in leakage.

4.3.2 Implementation Deficits and Decentralization: The Policy-Practice Chasm

Despite the robust structure of the PWM Rules, a critical disconnect exists between policy formulation at the central level and effective implementation at the local and municipal level. This implementation deficit is a primary factor driving the high MP loads in IAS. This chasm is not merely a logistical problem but a systemic failure rooted in governance, socioeconomics, and infrastructure.

A. Governance and Financial Gaps:

The responsibility for SWM implementation lies primarily with Urban Local Bodies (ULBs) and Gram Panchayats (Village Councils) in rural areas. Many ULBs lack the technical staff, financial resources, and logistical infrastructure required for universal waste collection, segregation, and processing, particularly in rapidly expanding peri-urban areas. The per capita expenditure on SWM in many Tier II and Tier III Indian cities is demonstrably insufficient to cover the costs of modern, integrated waste management, including setting up Material Recovery Facilities (MRFs) and sanitary landfills. This financial shortfall forces a reliance on low-cost, inadequate methods, frequently resulting in open dumping or burning of mixed waste, which are direct precursors to MP formation and leakage into IAS. The lack of standardized operating procedures (SOPs) and low technical capacity among municipal staff further exacerbates this issue. Without the capacity to enforce segregation at the source, the entire processing chain is compromised, making resource recovery inefficient and increasing the volume of non-recyclable waste destined for informal dumping sites along riverbanks.

B. The Role of the Informal Sector:

India's waste management system is significantly sustained by a vast and complex informal waste collection and recycling sector. Millions of waste pickers and itinerant buyers contribute to an impressive recycling rate for certain high-value plastics (like PET bottles). However, this sector primarily targets economically valuable materials, leading to the deliberate discard of low-value, non-recyclable plastics (PE films, multilayered packaging) near water bodies and open drains, precisely because they do not yield a return. While the PWM Rules conceptually aim for the integration of this informal sector, the lack of formal, protected employment, provision of necessary equipment, and guaranteed purchasing mechanisms for segregated low-value plastics means this sector, while beneficial for recycling, inadvertently contributes to the leakage of problematic, MP-generating polymers. Effective policy implementation must move beyond mere acknowledgement to institutionalizing the informal sector with defined roles and fair compensation for collecting all plastic waste, thereby closing the 'leakage points' for non-recycled materials.

C. Enforcement and Behavioural Challenges:

The prohibition on specific SUP items, while nationally mandated, requires rigorous enforcement at the street level, which often falters. This is not simply a matter of policing; it is a profound socio-economic challenge. The easy availability, low cost, and convenience of single-use plastics make them deeply embedded in daily commerce, particularly for vendors operating on thin margins. The lack of readily available, cost-competitive alternatives in rural and smaller urban settings hinders the public's and vendors' ability to comply. Furthermore, public awareness campaigns, while present, have not achieved the widespread behavioral change required to ensure source segregation and responsible disposal. Studies consistently show that even where collection infrastructure exists, mixed waste disposal remains rampant, compromising recycling efforts and increasing the volume of mixed municipal solid waste, which is the primary source of MPs in urban runoff. This is the crux of the third key insight: the policies are structurally sound but suffer from significant implementation deficits.

This systemic failure results in the continuous feeding of macroplastics into the environment, which then fragments into the dominant PE and PP MPs observed. Effective mitigation necessitates a shift towards decentralized, capacity-building strategies that empower local governments and formally integrate the informal waste sector.

4.3.3 Technological and Behavioural Interventions: Bridging the Gap

Addressing the MP crisis in Indian IAS requires a dual strategy: source reduction through effective policy enforcement and end-of-pipe removal through technological innovation.

A. Advanced Wastewater Treatment Technologies:

Given that WWTPs are a major conduit for MPs, particularly fibers, significant investment is needed in upgrading treatment infrastructure. Current primary and secondary treatments typically remove a substantial portion of MPs, often exceeding 80%, but the remaining effluent still discharges millions of particles daily. Advanced tertiary treatment is essential for approaching near-total MP removal. Technologies such as rapid sand filtration, micro-screening, membrane bioreactors (MBRs), and coagulation-flocculation followed by dissolved air flotation (DAF) have demonstrated removal efficiencies exceeding 90-99%.

However, the application of such technologies in India faces three major barriers: i) Cost: Advanced treatment is substantially more expensive, both in capital outlay and operational energy costs, creating a financial hurdle for cash-strapped ULBs. ii) Sludge Management: The MPs removed from the wastewater are concentrated in the sewage sludge (biosolids). If this sludge is then used for agricultural soil amendment, it merely transfers the MP pollution from the aquatic to the terrestrial environment. Therefore, the implementation of advanced wastewater treatment must be paired with innovative, safe, and sustainable sludge disposal or treatment methods that permanently destroy or contain the concentrated MP load. iii) Energy and Maintenance: The complexity and maintenance requirements of advanced technologies often exceed the technical capacity available at many existing Indian WWTPs. Low-tech, nature-based solutions (NBS) like constructed wetlands, which are cost-effective and energy-efficient, may offer a pragmatic interim solution for MP removal, though their long-term efficacy and capacity for high-volume urban flow need further validation.

B. Innovation in Policy and Waste Management:

Beyond centralized technology, innovation in governance and business models is required.

- Decentralized Waste Processing: Moving towards smaller, more localized waste processing units, potentially incorporating pyrolysis or waste-to-energy technologies for non-recyclable plastics, can reduce the burden on central facilities and minimize transport, thereby reducing the likelihood of leakage.

- Strengthening EPR Verification: The EPR framework must be reinforced with unassailable digital mechanisms to track plastic waste flows and prevent the sale of fraudulent 'recycling certificates'. Accountability must extend to the entire value chain.

- Deposit-Return Schemes (DRS): The introduction of mandatory, country-wide Deposit-Return Schemes for high-volume beverage containers (PET, glass, aluminum) could drastically reduce leakage of these specific polymer types into the environment, by assigning an immediate financial value to the empty container, compelling a return to a designated collection point.

- Green Chemistry and Bioplastics: Policy should actively encourage and subsidize the transition to non-polymer or genuinely biodegradable alternatives. While biodegradable plastics are not a panacea, as their degradation often requires specific industrial composting conditions, the development and mandated use of plastics that degrade effectively under ambient Indian environmental conditions (high heat, high humidity) is a crucial long-term strategy.

The overall management approach must shift from a reactive, end-of-pipe solution to a proactive, circular economy model that prioritizes prevention, minimizes waste generation, and ensures that the low-value, MP-generating fractions of plastic waste are managed safely and sustainably before they enter India's vital inland aquatic systems. The high correlation between MP pollution and urbanization density is a direct indictment of the current SWM implementation and an urgent call for decentralized, robust policy execution.

4.4 Synthesis of Literature Gaps and Future Research Directions

The current body of research, while establishing the ubiquity and high concentrations of MPs in Indian IAS, highlights several crucial literature gaps:

1. Nanoplastics: The fate and toxicological effects of particles smaller than $1 \mu \text{m}$ (nanoplastics) remain almost entirely unstudied in India, largely due to the prohibitive cost and complexity of analytical methods.

2. Standardization: A lack of standardized national protocols for sampling, extraction, and quantification limits the direct comparability of data across different river basins, hindering the formation of a unified national risk assessment map.

3. Toxicological Endemic Species: Most ecotoxicological studies are based on non-endemic, model organisms (e.g., Daphnia magna). There is an urgent need for chronic toxicity studies focusing on representative, endemic Indian aquatic fauna to accurately assess local ecological risks.

4. Policy Efficacy Metrics: Quantitative studies are needed to evaluate the measurable impact of specific policy interventions (e.g., the SUP ban, EPR scheme) on reducing the MP load in IAS over time.

Addressing these gaps is essential for transitioning from problem identification to effective, scientifically-informed remediation.

5. CONCLUSION

5.1 Summary of Key Findings

This comprehensive review underscores the severe and escalating threat posed by microplastic (MP) pollution to the Inland Aquatic Systems (IAS) of India. The analysis confirms that MP contamination is ubiquitous across major river basins and lentic water bodies, with concentrations often reaching levels that are a cause for significant environmental concern. Crucially, the evidence synthesized here demonstrates that MP concentration is strongly correlated with urbanization density and failures in decentralized solid waste management in riparian zones. The pollution profile is overwhelmingly dominated by Polyethylene (PE) and Polypropylene (PP) fragments and fibers, directly linking the contamination source to the secondary breakdown of ubiquitous single-use plastics and untreated domestic sewage effluent. Ecologically, MPs in Indian IAS are documented to pose risks through ingestion, potential trophic transfer, and acting as vectors for co-contaminants, thereby exacerbating the already complex pollution profile of these vital ecosystems.

5.2 Policy Recommendations

Addressing this crisis demands a transition from policy formulation to decisive, measurable action. The following recommendations are paramount:

- Decentralized Implementation Focus: National frameworks (PWM Rules, SUP ban) must be supported by massive, targeted investment in local governance capacity—financial, technical, and human resources—for solid waste management. The implementation deficit must be addressed by standardized, transparent, and digitally-enabled monitoring of municipal waste streams.

- Institutionalizing the Informal Sector: Formal integration and financial empowerment of waste pickers are essential to ensure the comprehensive collection of low-value, high-leakage plastic fractions (e.g., films, multi-layered packaging), thereby cutting off the supply of primary MP precursors to IAS.

- Mandatory WWTP Upgrades: In high-density urban areas, the phased introduction of advanced tertiary treatment technologies (e.g., micro-screening, membrane filtration) in all Wastewater Treatment Plants discharging into IAS is required to significantly reduce the flux of fibers and small fragments. This must be coupled with safe, contained disposal or destruction of MP-loaded sludge.

- EPR Enforcement: The Extended Producer

Responsibility system must be rigorously enforced with auditable, ground-level verification mechanisms to ensure PIBOs meet their recovery targets and genuinely fund the collection infrastructure for the hardest-to-recycle materials.

5.3 Concluding Statement

The microplastic burden in India's rivers and lakes represents a confluence of rapid development and governance challenges. While the nation possesses the legislative tools to combat this pollution, the pathway to sustainable mitigation lies not in new policy, but in bridging the chasm between policy intent and localized execution. The preservation of India's inland aquatic systems—the very lifeline of its people and ecology—hinges on the immediate and strategic deployment of decentralized, technology-backed solutions that address the fundamental failures of urban waste management at the source.

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