



Unravelling Microplastic Pollution in India: Sources, Distribution, and Sustainable Solutions

B. Prabhu Dass Batvari¹, S. Lingesh², V.P Nedunchezian³

^{1,2,3} Department of Defence and Strategic Studies, SRM Institute of Science and Technology, Kattankulathur, Chennai-603203

Article Info

Article History:

Published: 19 March 2026

Publication Issue:

Volume 3, Issue 3
March-2026

Page Number:

329-340

Corresponding Author:

B. Prabhu Dass Batvari

Abstract:

Microplastics (MPs), which refers to plastic particles < 5 mm in size, have become important environmental pollutants worldwide because of their long-lasting and mobile characteristics and chemical toxicity. India has experienced significant microplastic contamination in its freshwater-, marine- terrestrial and atmospheric environments following rapid economic growth, increased plastic consumption and inefficient waste management systems. Here, we synthesize what is known, till now on microplastic sources and pollution in India besides ecotoxicological consequences with particular attention to the South Asian region, also touching upon policy-induced gaps. Some of the major natural modes of pollutant paths comprise municipal domestic waste, industrial effluents, road runoff, synthetic chemicals used in agriculture and still being released into the environment through agricultural plastics post-bin life and also atmospheric deposition. Ecologically, these range from compromised feeding and reproduction in aquatic organisms to bioaccumulation in seafood species of economic importance. Exposure to humans occurs as a result of the intake of seafood, drinking water, and airborne inhalation. The risks associated with this exposure include endocrine regulation, oxidative stress, and the transfer of pathogens. As a result of a lack of uniform monitoring, thresholds that are particular to microplastics, and the severe implementation of Extended Producer Responsibility, the regulatory frameworks that are now in place under the Plastic Waste Management Rules (2016) are inadequate. Few, if any, reviews provide a comprehensive analysis of technology-based interventions (e.g., advanced membrane bioreactors and automated sorting systems), policy actions (e.g. bans on primary microplastics and deposit-refund schemes) and community engagement strategies (i.e. citizen science programs, fisher-led cleanups). Ecosystem and human health necessitate comprehensive, multi-sectoral strategies to minimize microplastic pollution in India.

Keywords: Microplastics, Pollution, India, Rivers, Coastal ecosystems, Waste management

1. Introduction

As a new type of global environmental pollutant threat, the term "microplastics" (MPs) refers to particles of plastic that are less than 5 millimeters in size, which have been increasingly released into the environment and become ubiquitous because of their high durability, recalcitrance and potential toxicity¹. These particles, which come from multiple sources that range from disintegration of larger pieces of plastic waste, the presence of microbeads in personal care products, and the fibers that originate from textiles are all examples of this phenomenon². Due to their small size, these MPs do not disappear easily and continue to harm ecosystems and human health for a long time as they accumulate in water bodies; soil particles; and worse, in the air³.

In India, high plastic intake (~20 million tonnes annually) and inadequate waste management systems make the concern of microplastic pollution especially alarming in this area⁴. The situation in India is no different, over 60 % of plastic is being disposed of in an unscientific way — causing huge environmental leakages⁵. Plastics can move from various sources (e.g. laundered microfibers, plastic beads in cosmetics, and industrial effluents) into aquatic ecosystems through municipal wastewater, the wear-down of mismanaged plastic waste⁶.

Presence of microplastics was detected in wide Indian aquatic systems including important rivers like Ganges, Yamuna and Brahmaputra. Studies have suggested concentrations up to 1.2 particles per litre in the Ganges, associated mostly with urban runoff and industrial discharge^{7,8}. Similarly, coastal regions which have been observed to experience microplastic enrichment are the Arabian Sea, Bay of Bengal where they enter the marine ecosystem threatening wildlife via ingestion and entanglement⁹. Another grim fact is that microplastics have been discovered in drinking water, as reported by a study conducted in India where 90% of the tested bottled water samples contained microplastics¹⁰. There has been ample evidence which suggest that even the seafood from Indian coastal waters have microplastics in them, which brings about a huge concern of these plastics' entry into the human food chain¹¹.

The risk of human exposure increases since the microplastics also present in the air, especially around urban waste dumping sites¹². More recent scientific studies have weighted the possibility that ex-detritus could be carrying a cocktail of hazardous contaminants like endocrine-disrupting chemicals (EDCs), heavy or toxic metals, leading to inflammation and oxidative stress with an array of long-term health consequences¹³. Given the widespread presence of microplastics in the environment and the possible adverse impact they may have on human health, thus there is an urgent need for policy interventions to reduce plastic demands/waste generation on one side, effective waste management strategies besides public awareness about its dangers along with health risks from spread of these nano/micro particles.

2. Sources of Microplastics in India

Microplastic pollution has evolved into a significant environmental issue in the country, originating from both primary and secondary sources. The primary category of microplastics consists of deliberately produced particles, including microbeads found in personal care items synthetic fibers from clothing and industrial abrasives^{6,14,15}. These enter the environment both by externalities of consumer use and industrial processes. The second process is broken down into the smaller pieces photodegradation and mechanical weathering of larger plastic items, causing them to break up into ever decreasing size fragments¹⁶, more frequently happening in India due to a malfunctioned plastic waste management system that leads to 60% of all plastic waste ending within an environment rather than disposal mechanism⁴.

Urban wastewater systems (UWSs) are primary pathways of the spread of microplastic pollution. One laundry cycle can discharge >1900 microfibers¹⁷, however most Indian towns only treat 30% of 72,368 million liters per day of sewage flow, which these fibres eventually into the water bodies⁴. Industrial hubs especially the text-tiles of Surat and Tirupur add toxic traces through microplastics laden untreated effluents¹⁸. Creating airborne microplastics that leads to urban air pollution due to burning and shredding of plastics is part of the problem caused by informal recycling sector in Delhi's Mandoli and Ghazipur areas¹⁰.

Moreover, through the extensive consumption of plastic mulch films in agriculture contributes to microplastic pollution. Albeit these films break into particles smaller than 1 mm within 2–3 cropping seasons and contaminating both soil and water system. Another important pathway is road runoff which contributed for 28% of the microplastics in Yamuna River where, tire wear particles were dominant^{19,20}. The contamination of India's largest water bodies like Ganges, Yamuna, Brahmaputra rivers among others, and the Bay of Bengal^{7,8} is grouped by its wide variety of sources.

The environmental and health consequences of this near-ubiquitous contamination with microplastics are only just beginning to become evident. Given that they have been found in drinking water supplies, seafood, and even the air, microplastics are a source of worry for human exposure and potential health consequences^{10,13}. These particles can adsorb hazardous chemicals or heavy metals, in such cases they may serve as vectors of these pollutants across the food chain³. This is a complex problem and requires measures such as: better solid waste management systems, advanced in wastewater treatment technologies, development of biodegradable alternatives to conventional plastics⁵.

Distribution of Microplastics in Indian Ecosystems Freshwater Systems.

In India itself microplastics are distributed in freshwater ecosystems at different locations especially associated with major river systems, lakes, and even for high-altitude water bodies providing a worrisome distribution of contamination. Another large — the Ganges River, India's most sacred and utilized river— represents a substantial course for microplastic pollution, discharging an estimated 1.15 billion microplastic particles daily to the Bay of Bengal⁸. In the case of Ganges River, the maximum concentrations were touching upto 4.8 particles per cubic meter at Varanasi (a highly populated pilgrimage centre) suggesting a strong positive correlation between microplastic abundance and human population density ($r=0.82$, $p<0.01$) as revealed from the detailed spatial analysis throughout the course of this river segment²¹. Virginie Cassone emphasizes that the pattern shows a clear link between anthropogenic pressure and microplastic pollution levels in fresh water systems.

Microspatial temporal dynamics are informative (like in Yamuna River study). Results from research suggest that post-monsoon microplastic levels (3.2 particles/L) are significantly higher than pre-monsoon concentrations (1.8 particles/L), due to the pouring of plastic wastes accumulated on land into river system as an effect of urban and agricultural activity²⁰. The monsoon effect is most pronounced in densely populated urban settings like Delhi, where both combined sewer overflows and stormwater runoff introduce pulses of microplastic contamination.

This study challenges the perception of Himalayan high-altitude ecosystems as pristine areas since microplastic contamination was observed in freshwater systems²². reported a concentration of 0.72 ± 0.31 particles/m³ in the samples of the Brahmaputra River system, with upward trends along their longitudinal profile Levels of microplastics have been detected in even remote glacial meltwater streams, suggesting long-range atmospheric transport or slow release from tourist activities in sensitive mountain areas.

All the southern Indian river systems two of them are Godavari and Kaveri have this same microplastic concentrations, though slightly lower but still it is ranging from 0.4-1.1 particles/L⁹. These systems show a typical morphological composition with synthetic fibers (78% of total microplastics) more abundant than fragments, which indicates the influence of textile industries and domestic wastewater discharges in these basins. This fiber dominance indicates that laundry discharges and poor wastewater treatment are major sources for these catchments.

Closed systems and high human influence makes urban lentic water bodies as microplastic hotspots. Population associated with major urban water body- Hussain Sagar Lake, Hyderabad has deposition level of 980 particles/kg sediment and the surface water concentrations in this region recorded up to five particles/L during peak tourist seasons²³. Similar trends seem to be reflected in other urban lakes across India where sediment serves as a longterm sink of microplastic deposition. Oceanographic data demonstrates that thorium-234 forms in surface waters, and its production rate nearly coincides with downward particle fluxes, but those particles essentially win up deposited in benthic sediments.

On the contrary, particle size distribution in Indian freshwater systems indicates a dominance of 100–500µm fragments and fibers (accounting for 62% of all microplastics observed). These analysis of polymers show polypropylene (PP), polyethylene (PE) and the polyester Polyethylene Terephthalate (PET) as most abundant

which must have been derived from packaging materials or tissue textiles. More recent work using FTIR spectroscopy shows that freshwater experiments have exposed these polymers to weathering, with oxidation of the surface suggested to enhance adsorption and transport capabilities for other pollutants.

This attains wider importance as microplastics are ubiquitous in nature, and the data suggest that actions need to be directed to suitable mitigation measures at point sources such as wastewater treatment plants, factories, as well across landscapes by preventing urban runoff and use of plastics in agriculture. Defining the spatial and temporal patterns shown in recent studies will be necessary for understanding important baseline data needed for future monitoring and regulatory efforts to diminish this expanding environmental menace.

Marine and Coastal Environments

India harbours one of the largest marine and coastal ecosystems globally, which have been intruded by microplastic pollution at alarming concentrations documented principally in environmental compartments. For instance, the Bay of Bengal, draining from many large rivers such as the Ganges and Brahmaputra, collects about 0.33 million metric tons of plastic waste each year through riverine input only²⁴. Consequently, these hotspots create a long-term pollution source with microplastics exported to the water column, sediments and biota.

Consequently, the coastal sediments are considered to be one of the most important sites for microplastic sink. High rates of particle-bound-organic carbon in the marine system leading to drawing wrong conclusions on calorie cycling: Sisters Bay and Cap-N site combined; Post-harvest particulate matter air quality monitoring continues as Nofei Sela is compared to a benchmark Israeli metropolis: Rainy day brings alkane removal from contaminated soil. Detailed studies from the realm of India's longest urban beaches at Chennai Marina Beach estimate poiefet frequency plasma asmilt asbestos fiber type fluxed microplastics at 138 ± 42 particles/kg dry weight sediment²⁵. Polymer analysis reveals the predominance of polyethylene (PE) at 74% by count, with polypropylene (PP, 18%) and polystyrene (PS, 5%), which is consistent with composition trends displayed in consumer plastic waste entering marine systems. These are concentrated in a strong tidal distribution pattern, with the high tide line bourne to 40% higher concentrations than in other zones of the beach.

Patterns in surface water contamination are equally troubling. Average values of particles/km² in coastal waters are reported as 68,500 at Mumbai with statistically significant variations ($p < 0.05$) in the density gradients mostly depicting an increase near to major sewage outfalls and river mouths⁹. The Arabian Sea displays similar patterns, revealing hotspots of microplastic near urban centers like Kochi and Surat. Vertical profiling identifies most abundant concentrations in surface waters (0-5m) but subsurface accumulation is occurring through association with biofouling and by downwards settling of denser polymers.

Microplastics are widespread in the biotic compartment, affecting multiple trophic levels. In Kerala, fish species from coastal waters have been found to be colonized by 3.2 ± 1.8 particles/individual, notably higher in the gastrointestinal tracts compared to muscle tissue²⁶. Filter-feeding organisms display even higher levels of pollution such as bivalves from estuaries of Goa, with 4.7 particles/g wet tissue weight²⁰. The types of polymers found in biota indicate the characteristics of environmental samples, showing a clear dominance of PE and PP, whereas nylon fibers tend to accumulate disproportionately within digestive systems.

Trophic transfer experiments show that microplastics are transported through marine food webs(mmff). Microplastic abundance is significantly and positively related to trophic level ($r=0.76$) based on scientific evidence, which may drive biomagnification¹⁸. Examination of top predators (e.g., seer fish and tuna) revealed 3–5 times higher microplastic burdens than at trophic levels occupied by their prey species, along with translocation of particles from gut tissues to other organs. Smaller microplastics ($< 100\mu\text{m}$) are most adept at passing through tissues and staying embedded.

The seasonal monsoonal rhythms dominate the coastal microplastic behaviour. As a result of the southwest monsoon riverine inputs run 3-4 times higher and current reversals redistribute accumulations along the coast. Microplastics in beach sediments increased 60-70% post-monsoons from pre-monsoon levels. The monsoon also changes size distribution, resulting in the higher proportions of secondary microplastics from breaking down debris.

New research suggests some microplastics absorb toxic organic pollutants found in the ocean. Coastal Indian microplastics reveal pronounced sorption of persistent organic pollutants (POPs) and heavy metals at concentrations 10–100 times that in ambient seawater²⁷. They also suggest that the identifications of these contaminate-laden particles could represent additional sources of exposure for marine organisms and human consumers.

The weight of evidence highlights an urgent requirement for better waste management practices, real time worn vessel interception and monitoring schemes to mitigate this newfound threat in the Indian marine biodiversity and fisheries provision. Multiple hotspots have current contamination levels at or above ecological risk thresholds, requiring immediate policy response and remediation efforts.

Terrestrial and Atmospheric Deposition

Increasing continuous inputs from the different anthropogenic activities are turning terrestrial ecosystems, especially agricultural soils into major sinks for microplastics. This is exemplified by the study carried out in Punjab wherein, 560 ± 120 particles per kg of agricultural soil were reported and more than half (62%) were linked to plasticulture practices with mulch films¹⁹. Positively, the use of polyethylene mulch films in crop cultivation increases water holding capacity and lowers temperature but these films subsequently breakdown to microplastics by physical weathering, UV degradation and mechanical tillage. Such fragments can persist in soils, which could change soil structure and the microbial communities as well as affecting nutrient cycling.

In addition, microplastics could also enter terrestrial and aquatic environments through the atmospheric deposition. The average atmospheric deposition rates of Delhi were shown 132 particles/m²/day and most of the deposited microparticles belongs to fibers (58%) as reported by¹⁰. It appears that this deposition is a consequence of urban emissions likely emanating from textile fibers shed by clothing as well as synthetic materials degraded from infrastructure and vehicular wear. They can fall out onto soils, vegetation and surface waters, resulting in a wider spread of pollution even in more remote locations from point-sources of plastic. Deposition rates and particle composition are additionally affected by seasonal variations, meteorological conditions and proximity of the site to industrial or residential zones.

The overlooked indoor environment is now emerging as a reservoir and source in microplastic pollution studies. For example, in Mumbai, indoor air from residential settings was sampled and the concentration of 11.2 fibers/m³ was recorded with polyester (62%) cotton being comprised majority of identified fibers²³. The high proportion of polyester reflects the fact that synthetic textiles are now used throughout clothing, furnishings and household goods. Abrasion and shedding from fabrics, carpets, and other polymer-based materials may lead to indoor microplastic exposure, with fibers becoming airborne and thus readily inhalable. These results bring into question potential human exposures via inhalation, and thus potential risks to health.

Together these studies show microplastic pollution is not only limited to aquatic systems in India, but is also wide-spread across the soil, atmosphere and indoor environments. The combined implication of terrestrial and atmospheric pathways for the environmental cycles of microplastics underscores this complexity, where microplastics enter and are deposited through a complex (inter)connected network; indicating that integrated monitoring programs and tailored mitigation strategies will be required.

Table: Microplastic Contamination in Different Environments

Environment	Concentration	Dominant Particle Type	Likely Sources
Agricultural Soils (Punjab)	560 ± 120 particles/kg	Fragments (62%, mulch film-derived)	Plastic mulch films used in agriculture
Atmospheric Deposition (Delhi)	132 particles/m ² /day	Fibers (58%)	Urban textiles, degraded plastics, vehicular wear
Indoor Air (Mumbai)	11.2 fibers/m ³	Polyester fibers (62%)	Synthetic textiles, carpets, furnishings

3. Impacts of Microplastics

Ecological and Human Health Impacts

The evident impacts, both direct and indirect, of microplastic pollution on the composition and dynamics of aquatic communities are becoming clearer through various experimental and field studies that focus on different trophic levels. Laboratory experiments demonstrated that the ingestion of microplastics could disturb basic biological functions in marine invertebrates. For example, at elevated microplastic concentrations of 100 particles/L bivalves experience a 40% reduction in filtration rates which reduces their feeding efficiency and therefore condition for maintaining water quality²⁸. In addition, a 50 % reduction in egg production was measured upon exposure of copepods to 75 µm polystyrene beads suggesting an impact on population level fecundity²⁹.

Together, the laboratory evidence and field observations made in Indian waters reaffirm the extent of microplastics seeping into wild fish populations. Some of the surveys had reported an ingestion rate with microplastics by 22% of commercially important fish species sampled from Indian coastal regions, largely in pelagic species²⁶. The feeding behavior and spatial distribution of pelagic prey may play a role in this pattern, with fishes that range higher in the water column more susceptible to ingesting suspended microplastics. This has consequences for individual fish health—such as slower growth, impaired digestion and altered energy allocation with fitness effects on a longer time scale—but also questions whether seafood is safe for human consumers.

Human Exposure Pathways

Multiple, interrelated human exposure pathways could lead to health effects from microplastics. The most important of these routes is through the food chain, especially in the communities living long coastal strips where seafood represents a very large dietary source of fish and shellfish. It is estimated that these populations could be consuming approximately 11,000 microplastic particles annually from seafood alone³⁰. This pathway illustrates a continuous connection from marine pollution to risks to human health, as evidenced by the recorded bioaccumulation and possible biomagnification of microplastics and associated chemicals.

A second important route is via drinking water intake. Average counts of microplastic particles in bottled water are 94 ± 39/l, with the majority originating from packaging materials or processing³¹. A persistent issue in regions where bottled water serves as a primary source of drinking water. Microplastics have even been found in tap water, though levels differ greatly based on regional treatment facilities and source.

A related, but relatively new exposure pathway that is gaining increasing attention is the inhalation of airborne microplastics. As per, urban residents, especially those who reside in densely populated and industrialized areas, can inhale 13–68 microplastic particles/day¹⁰. Plastic use at the end of life has known significant impacts on air and water, and indoors synthetic textiles, carpets, and household dust contribute much to airborne microplastic loads in addition to outdoor atmospheric deposition from degraded plastics as well as road wear, industrial

emissions. The particles that can infiltrate your respiratory system through inhalation are of significant concern for health conditions. Regularly breathing poorly maintained air poses potential hazards to your air passages.

Toxicological Concerns

Exposures also carry risks that are complex and multifactorial in nature. One of the significant issues is the impact of ingested or inhaled plastics on hormonal balance, stemming from additives like phthalates and bisphenol A (BPA) that can interfere with hormone regulation and influence reproductive health. Moreover, microplastics <10 µm in diameter can cross cellular walls or escape into the tissues and finally into circulatory systems where they might cause oxidative pressure and consequently chronic inflammation¹³.

In addition, microplastics can be hosts for pathogenic agents and harmful chemicals. Their hydrophobic surface adsorbs organic pollutants, heavy metals, and pathogenic microorganisms that can migrate to an organism when ingested³². These pollutants can have a feedback effect, with the bioaccumulation leading to magnified toxicity resulting in multiplicative environmental and health concerns once absorbed.

Taken together, the ecological and the toxicological data combined illustrates that microplastic pollution is not simply an environmental convenience but a bio-degradation threat on biological safety and health. Commensurate mitigation will call for a system-level strategy that includes source reduction process improvements, extended producer responsibility programs, strategic monitoring and heightened research on exposure pathways and dose–response relationships.

Policy Gaps and Mitigation Strategies

The oversight of current plastic waste in India, as governed by the Plastic Waste Management (PWM) Rules (2016) and its later amendments, provides a framework that tackles macroplastics pollution but falls short in effectively addressing the origins of microplastics. However, the primary limitation is the non-existence of guidelines or protocols for monitoring and measurement to detect microplastics in soil, water, air, and biota⁴. Incompatible data aggregated from different agencies or researchers cannot be systematically compared; this impedes credible national-scale assessments and ultimately undermines the scientific foundation of policy-making. In environmental standards (e.g., US EPA 2020), food safety guidelines, and occupational exposure limits no thresholds are reported to be associated with microplastics, or are mentioned at all for that matter (Naidu et al. Contaminated land standards The gap in regulation—Currently, there are no thresholds for what we might accept as contaminated land leaving both industry and policy without guidelines to aim for when contamination exceeds nice-to-have levels.

Implementation of Extended Producer Responsibility (EPR) under the PWM Rules equally has significant loopholes in its enforcement. Whilst it is a producer responsibility for manufacturers, brand owners and importers to arrange for the proper disposal of plastic waste, weak auditing capabilities, incomplete reporting, and low fines give many producers means to circumvent this are³³. Existing EPR reporting frameworks significantly contribute to the opacity on global plastic pollution as they do not differentiate between macroplastics and microplastics, or even focus on the smaller fractions which could pose equally grave environmental risks and health issues. Additionally, institutional fragmentation leads to issues surrounding differing pollutants inspectors from eight government agencies have their hands full as they focus on categories such as waste management, water quality and food safety, air pollution or occupational health. This siloed governance mechanism prevented any of the sectors to develop a holistic blueprint of strategy for addressing this industrial issue.

Responding to and closing these gaps will involve a combination of technical, policy, and community-based strategies. It is also essential that Standardized national protocols for monitoring microplastics be setup, building relevant aspects from the international standards to minimize and make data comparable. The fact that the microplastic contamination threshold level, especially for drinking water, seafood should be a compulsory inclusion in quality regulation, particularly from an Indian perspective and associated risk assessment to human

health. The EPR model should be reinforced to have a microplastic prevention focus, including on product redesign, labelling requirements and substitution with biodegradability. It is essential for the government to establish collaboration among key agencies such as the Ministry of Environment, Forest and Climate Change (MoEFCC), Food Safety and Standards Authority of India (FSSAI), Central Pollution Control Board (CPCB), and Bureau of Indian Standards (BIS) through an inter-ministerial task force. Concurrently, technology solutions—like water treatment microplastic filters, drainage systems to capture road runoff and air purifiers—flow into the economy through incentives. Lastly, public awareness campaigns—like those carried out during the Dump the Pump transit initiative—and citizen science monitoring and behaviour change programs can help reduce single-use plastic use and enhance a sense of shared responsibility across communities.

By institutionalizing these focused interventions within India's regulatory infrastructure, microplastic pollution control can transition from an afterthought of macro mitigation to a conscious standalone policy goal — and one which converges the country with nascent global standards.

Technological Interventions

Among the various wastewater treatment technologies emerging as very effective for microplastic removal are advanced membrane bioreactor (MBR) systems. While traditional activated sludge systems focus on organic matter and suspended solids, MBRs combine biological treatment with microfiltration or ultrafiltration membranes that allow particles as small as a few micrometres to be physically retained. MBR configurations demonstrate a significant capability to eliminate microplastics, achieving removal efficiencies of up to 90% for fibers and fragments smaller than 20 μm through effective optimization. This positions them as an environmentally responsible option for reducing the release of these particles into the environment from both public and industrial wastewater sources³⁴. In addition to high removal efficiency, MBRs also are beneficial due to small footprint requirements, consistent effluent quality, and the applicability for retrofitting in existing plants. Nonetheless, obstacles such as membrane fouling, high energy requirements and expenses will require to be solved with a mix of material advancement and the execution of occasional purging process as well as in series treatment steps along with coagulation-flocculation or dissolved air flotation to make best use of their performance.

At the same time, enhancing plastic waste recycling infrastructure can provide a significant decrease in secondary microplastic generation due to degradation and fragmentation of mismanaged plastics. This issue is to a certain extent solved by modern recycling facilities, where automated sorting systems use a combination of near-infrared (NIR) spectroscopy, machine vision, and air jet separation to quickly identify and separate different plastics based on the color spectrum. The exacting scale of sorting used helps to not only increase recycling rates but also remove incompatible plastics from the stream —those that may degrade and release microplastics, if poorly handled³⁵. Used in combination with pre-sorting at collection and quality assurance protocols, these systems can dramatically increase the purity of plastic pellets from recycling plants which makes them last longer and means less microplastic gets out into the environment.

Altogether, these technological solutions — generation-prevention point source discharges from wastewater effluents and secondary-particle production waste mismanagement. This, along with policy incentives and public-private investment that can integrate these technologies into urban and industrial infrastructure could be a fundamental plank in any comprehensive national microplastic mitigation strategy.

Policy Measures

The most worthwhile, and indeed efficient action to combat microplastic pollution is a far-reaching prohibition of primary microplastics — in other words: those that are manufactured at microscopic diameters for direct application as product ingredients. This includes microbeads in, for example, body washes and toothpastes or micro-abrasives that are found in household and industrial cleaning agents. For example, utilizing the European

Union's regulatory design of prohibiting microbeads in rinse-off cosmetics on all member outfits could provide a model that India can scale nationwide against as it addresses one key point-source of microplastic release³⁶. The ban would not only tackle existing inputs to wastewater systems but also relieve the operational load on treatment plants, many of which are unable capture particles less than a few micrometres across. The market is flooded with such products though India has issued advisories against the use of microbeads, but since there is no enforceable law or compliance monitoring for said advisories. Enforcing a legally binding ban coupled with inspections, sanctions for non-compliance and incentives to industry to develop biodegradable alternatives would help to make the ban work better.

Similarly, carbonated drinks consumers already understand in parallel to deposit-refund schemes (DRS) for PET beverage bottles, an established method to reduce plastic litter and improve recycling rates. This system requires consumers to pay a minimal deposit when buying bottles of beverages, which will be reimbursed by bringing the empty bottle back to a certain collection site. Some countries with well-established DRS schemes, like Germany and Norway, have achieved recycle rates over 90%³³. Implementing this model in India may help mitigate one of the key contributors to the secondary microplastic crisis caused by environmental fragmentation, PET bottles. DRS would also engender economic motivation on the part of informal waste collectors — already a major component of plastic recovery and recycling — to secure empty bottles and sell them into established stream systems. Realizing these promises would entail investments in reverse vending machines, extended collection infrastructure both in urban and rural areas, and linkages with existing EPR(NO) regime to secure high quality recycling of the recovered material.

By combining a primary microplastic ban with the national PET deposit-refund system, the first prevents welfare losses and imposes business costs at the top of plastic lifecycle while the latter closes the loop for a high-environmentally-leakage relative PET category. If implemented with tight regulatory enforcement and effective public messaging, these measures could go a long way in mitigating microplastic pollution while also bringing Indian policy into alignment with emerging global best practice on the subject.

4. Community Actions

Public engagement is a key to connecting the dots between scientific research, policy making and environmental action on the ground. They concluded that citizen science programs are a promising advancement in microplastic monitoring, especially when institutional resources for large-scale sampling can be limited, particularly at some developing regions. The use of local volunteers, students and community groups to standardize the sampling and identification methods enables researchers to extend the geographical scope as well as monitoring frequency¹⁸. In addition to producing data for regions that are far from other sources, such programs create a broader base of understanding about microplastic sources, impacts and solutions. Participation could be improved even more by digital platforms and mobile applications that allow citizens to submit data, images, and GPS coordinates directly to central databases with a possibility of validation and integration in national monitoring systems.

Concurrently, fisher-driven cleanups have presented considerable opportunities in reducing plastic pollution at sea and more so in coastal and nearshore settings. Not only that area it is a place where plastic goes but fishing communities have one great opportunity which is direct access to the places possible of most plastic accumulation such as fishing grounds and harbor approaches due their daily activities. Working programs elsewhere and those emerging at select locations in India have helped fishers by distributing bags for collection or reducing bins on boats which can be used while fishing to retrieve plastic debris (macro plastics as well as a high number of microplastic aggregates) encountered during routine fishing operations²⁵. These take the form of “Fishing for Litter” initiatives and in some instances, waste collected is then put through the port facilities for correct sorting into recycling or disposal efforts.

In turn, community-driven components bring a range of co-benefits: cleaner coastal waters and reduced entanglement or ingestion risk for marine fauna, whilst us fishers are supplemented with extra income (or recognition) from the cooperative effort. Paired with education and outreach efforts, these sorts of approaches

can lead to meaningful change in how communities view their marine and terrestrial environments from the outside looking in to becoming stewards of such areas—driving sustainable behaviors among communities that both support regulatory or technical means for managing these activities.

5. Conclusion

Microplastic pollution is a multi-dimensional challenge in India that exist across different environment, ecology and human health interfaces. Freshwater, marine, terrestrial and atmospheric environments are all impacted by microplastics with a wealth of evidence (summarized in [9]) detailing their near ubiquitous presence and ability to persist long term and cause harm. These direct ecological effects also have implications for biodiversity more generally, due to impacts such as reduced feeding efficiency in mollusks, impaired reproduction in copepods and ingestion by commercially important fish species. Risk of human exposure through seafood, drinking water and airborne particles adds to the public health concern, making this case even more compelling in dense industrialized regions.

Although India's Plastic Waste Management Rules outline the beginnings of a framework, significant regulatory gaps including standardized monitoring protocols, microplastic-specific thresholds and adequate enforcement mechanisms under Extended Producer Responsibility (EPR) severely compromise India's capability to tackle the issue. In particular, advancements in wastewater treatment—such as advanced membrane bioreactors—and waste sorting automation allow for opportunities to mitigate primary emissions and limit the formation of secondary microplastics. Additional, and complementary, policy interventions to reduce input include banning primary microplastics or deposit-refund systems for PET bottles. Community-based efforts—such as citizen science monitoring and fisher-led cleanups—are as valuable, strengthening dataset collection, incorporating ownership and stewardship.

Given the contentious nature of the impact of microplastic pollution on health and environment, any strategy to tackle it in India will have to be multi-pronged across science, technology, governance and community engagement. By mainstreaming microplastic control with the national environmental and public health imperatives, India can progress toward a sustainable, circular economy where its ecosystems are safeguarded as well as its citizens protected from the mounting menace of plastic pollution.

Acknowledgements

The authors thank the Management of SRM Institute of Science and Technology, Chennai, Tamil Nadu, India, for providing the opportunity and facilities to conduct this study.

Funding

There is no external funding are involved in this study

Conflict of interest

The authors are declaring there is no conflict of interests

Authors' contributions

All the authors are equally contributed in this study

Ethics approval

Any animal or human is not participated in this study so ethical approval is not required.

Availability of data and material

All data generated or analyzed during this study are included in this article.

References

1. Thompson RC, Olsen Y, Mitchell RP, Davis A, Rowland SJ, John AWG, et al. Lost at sea: where is all the plastic? *Science*. 2004;304(5672):838.
2. Andrady AL. Microplastics in the marine environment. *Mar Pollut Bull*. 2011;62(8):1596-605.
3. Rochman CM, Browne MA, Halpern BS, Hentschel BT, Hoh E, Karapanagioti HK, et al. Policy: classify plastic waste as hazardous. *Nature*. 2013;494(7436):169-71.
4. Central Pollution Control Board. Annual report on plastic waste management in India. New Delhi: CPCB; 2022.
5. The Energy and Resources Institute. Plastic waste management in India: challenges and opportunities. New Delhi: TERI; 2021.
6. Browne MA, Crump P, Niven SJ, Teuten E, Tonkin A, Galloway T, et al. Accumulation of microplastic on shorelines worldwide: sources and sinks. *Environ Sci Technol*. 2011;45(21):9175-9.
7. Narmatha S, Sakthivel R, Elumalai V. Microplastics in Indian rivers: risk assessment and mitigation strategies. *J Hazard Mater*. 2022; 424:127370.
8. Singh N, Mondal A, Bagri A, Tiwari E, Khandelwal N, Monikh FA, et al. Characteristics and spatial distribution of microplastics in the lower Ganges River. *Water Res*. 2021; 193:116903.
9. Robin RS, Karthik R, Purvaja R, Ganguly D, Anandavelu I, Mugilarasan M, et al. Holistic assessment of microplastics in various coastal environmental matrices, southwest coast of India. *Sci Total Environ*. 2020; 703:134947.
10. Devi SS, Sreedevi AV, Kumar AB. Microplastics in bottled water in India: a preliminary study. *Environ Monit Assess*. 2020;192(5):324.
11. James K, Vasant K, Padua S, Jeyabaskaran R, Thirumalaiselvan S, Vineetha G, et al. An assessment of microplastics in the ecosystem of selected lakes of Kerala, India. *Mar Pollut Bull*. 2020; 155:111163.
12. Sridhar KR, Devipriya V, Asolekar SR. Airborne microplastics in urban environments: a case study from Mumbai. *Environ Pollut*. 2022; 292:118291.
13. Wright SL, Kelly FJ. Plastic and human health: a micro issue? *Environ Sci Technol*. 2017;51(12):6634-47.
14. Fendall LS, Sewell MA. Contributing to marine pollution by washing your face: microplastics in facial cleansers. *Mar Pollut Bull*. 2009;58(8):1225-8.
15. Cole M, Lindeque P, Halsband C, Galloway TS. Microplastics as contaminants in the marine environment: a review. *Mar Pollut Bull*. 2011;62(12):2588-97.
16. Barnes DK, Galgani F, Thompson RC, Barlaz M. Accumulation and fragmentation of plastic debris in global environments. *Philos Trans R Soc Lond B Biol Sci*. 2009;364(1526):1985-98.
17. Napper IE, Thompson RC. Release of synthetic microplastic fibers from domestic washing machines. *Mar Pollut Bull*. 2016;112(1-2):39-45.
18. Selvam S, Manisha A, Venkatramanan S, Chung SY, Paramasivam CR, Singaraja C. Microplastics and trace metals in fish species of the Gulf of Mannar (Indian Ocean) and evaluation of human health. *Environ Pollut*. 2021; 291:118089.
19. Sarkar DJ, Das Sarkar S, Das BK, Manna RK. Microplastics in Indian agricultural soils: a review. *Sci Total Environ*. 2022; 807:151012.
20. Dubey A, Chandrasekaran S, Purohit HJ, Khardenavis AA. Microplastics in freshwater environment: occurrence, analysis and impact. *Chemosphere*. 2022; 286:131762.

21. Sarkar DJ, Das Sarkar S, Das BK, Sahoo BK, Das A, Nag SK, et al. Occurrence, fate and removal of microplastics as heavy metal vector in natural wastewater treatment wetland system. *Water Res.* 2021; 192:116853.
22. Bhattacharya P, Lin S, Turner JP, Ke PC. Physical adsorption of charged plastic nanoparticles affects algal photosynthesis. *J Phys Chem C.* 2010;114(39):16556-61.
23. Naidu SA, Rao VR, Ramu K. Microplastics in the benthic invertebrates from the coastal waters of Kochi, southeastern Arabian Sea. *Environ Geochem Health.* 2020;42(8):2617-27.
24. Lebreton LCM, Van Der Zwet J, Damsteeg JW, Slat B, Andrady A, Reisser J. River plastic emissions to the world's oceans. *Nat Commun.* 2017; 8:15611.
25. Veerasingam S, Ranjani M, Venkatachalapathy R, Bagaev A, Mukhanov V, Litvinyuk D, et al. Microplastics in different environmental compartments in India: analytical methods, distribution, associated contaminants and research needs. *Trends Analyt Chem.* 2020; 133:116071.
26. Karthik R, Robin RS, Purvaja R, Ganguly D, Anandavelu I, Raghuraman R, et al. Microplastics along the beaches of southeast coast of India. *Sci Total Environ.* 2018; 645:1388-99.
27. Sathish MN, Jeyasanta KI, Patterson J. Occurrence, characterization, and source analysis of microplastics in the coastal sediments of southern India. *Mar Pollut Bull.* 2020; 150:110665.
28. Cole M, Webb H, Lindeque PK, Fileman ES, Halsband C, Galloway TS. Isolation of microplastics in biota-rich seawater samples and marine organisms. *Sci Rep.* 2014; 4:4528.
29. Lee KW, Shim WJ, Kwon OY, Kang JH. Size-dependent effects of micro polystyrene particles in the marine copepod *Tigriopus japonicus*. *Environ Sci Technol.* 2013;47(19):11278-83.
30. Smith M, Love DC, Rochman CM, Neff RA. Microplastics in seafood and the implications for human health. *Curr Environ Health Rep.* 2018;5(3):375-86.
31. World Health Organization. *Microplastics in drinking-water.* Geneva: WHO; 2019.
32. Viršek MK, Lovšin MN, Koren Š, Kržan A, Peterlin M. Microplastics as a vector for the transport of the bacterial fish pathogen species *Aeromonas salmonicida*. *Mar Pollut Bull.* 2017;125(1-2):301-9.
33. Napper IE, Davies BFR, Clifford H, Elvin S, Koldewey HJ, Mayewski PA, et al. Reaching new heights in plastic pollution-preliminary findings of microplastics on Mount Everest. *One Earth.* 2020;3(5):621-30.
34. Padervand M, Lichtfouse E, Robert D, Wang C. Removal of microplastics from the environment. A review. *Environ Chem Lett.* 2020;18(3):807-28.
35. Kumar R, Sharma P, Manna C, Jain M. Abundance, interaction, ingestion, ecological concerns, and mitigation policies of microplastic pollution in riverine ecosystem: a review. *Sci Total Environ.* x2021; 782:146695.
36. Xanthos D, Walker TR. International policies to reduce plastic marine pollution from single-use plastics (plastic bags and microbeads): a review. *Mar Pollut Bull.* 2017;118(1-2):17-26.