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Microplastics in Indian Ecosystems: Environmental Distribution and Human Toxicological Implications

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ABSTRACT

Microplastics (MPs)—plastic particles smaller than 5 mm—have emerged as a pervasive environmental contaminant in terrestrial, freshwater, and marine ecosystems across India. This review synthesises field data from major Indian river systems (Ganga, Yamuna, Cauvery, and Brahmaputra), coastal zones (Bay of Bengal and Arabian Sea shorelines), agricultural soils, and urban air, documenting MP concentrations, polymer types, and spatial distribution patterns. Findings reveal alarming densities of 1,200–8,500 particles/m³ in riverine systems and 340–4,800 particles/kg dry weight in agricultural soils of Punjab and Tamil Nadu. Toxicological pathways examined include ingestion, inhalation, and dermal absorption, with emerging evidence of endocrine disruption, oxidative stress, neurotoxicity, and genotoxic damage in exposed human populations. Priority pollutant polymers—polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET)—serve as vectors for adsorbed heavy metals and persistent organic pollutants (POPs), amplifying cumulative health risks. Regulatory gaps in India's Plastic Waste Management Rules (2016, amended 2022) are evaluated, and evidence-based policy recommendations are proposed to address the growing microplastic burden within the Indian subcontinent.

Keywords: *microplastics, Indian rivers, marine pollution, human toxicology, endocrine disruption, plastic waste policy, environmental contamination*

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1. Introduction

Plastic production has surpassed 400 million metric tonnes annually, and projections indicate this will double by 2040. India is among the top ten plastic-producing nations globally, generating approximately 3.5 million tonnes of plastic waste per year, of which an estimated 40% remains uncollected and enters natural ecosystems. When macro-plastics undergo photodegradation, mechanical abrasion, and microbial fragmentation, they produce microplastics (MPs)—conventionally defined as particles <5 mm in their longest dimension—with nanoplastic fragments (<1 µm) representing an emerging sub-category of even greater toxicological concern.

The ecological significance of MPs was first described in marine contexts, but terrestrial, atmospheric, and freshwater compartments are now recognised as equally critical reservoirs. In India, rapid industrialisation, agricultural intensification relying on plastic mulch films, and inadequate solid-waste infrastructure create a "perfect storm" for widespread MP dissemination. Despite growing global data, systematic nationwide monitoring of MP distribution in Indian ecosystems remains fragmented, and dose-response relationships in human toxicological studies are only beginning to be established.

This paper: (1) synthesises published MP concentration data across major Indian environmental matrices; (2) characterises dominant polymer types and likely source categories; (3) reviews mechanistic toxicological pathways relevant to the Indian population; and (4) appraises regulatory frameworks and proposes actionable mitigation strategies.

2. Scope and Methodology

A systematic literature review was conducted using Web of Science, Scopus, PubMed, and Google Scholar databases, with search terms including "microplastics India," "plastic pollution Indian rivers," "MP soil contamination India," "microplastic human health," and related Medical Subject Headings (MeSH). Studies published between January 2015 and August 2025 were included. Peer-reviewed original research articles, government reports (CPCB, MoEFCC), and international agency assessments (UNEP, WHO) were screened for inclusion. Studies were excluded if they lacked quantitative MP concentration data or credible chain-of-custody documentation.

Data were stratified by environmental matrix (freshwater, marine, soil, air, biota, human tissue), geographic region, collection methodology, and polymer identification technique (FTIR, Raman spectroscopy, pyrolysis-GC/MS). Concentration data were normalised where possible to enable cross-study comparisons. Toxicological evidence was weighted using the Bradford Hill criteria adapted for environmental contaminants.

3. Environmental Distribution of Microplastics in India

3.1 Riverine and Freshwater Systems

Indian rivers represent the primary conduit for MP transport from terrestrial sources to the marine environment. The Ganga basin alone contributes an estimated 72,000 tonnes of plastic to the Bay of Bengal annually. Recent surveys document MP concentrations of 4,640 ± 1,820 particles/m³ in the upper Ganga (Uttarakhand segment) escalating to 8,500 particles/m³ near Kanpur and Varanasi, where textile and tannery effluents introduce synthetic fibres and coloured pellets. The Yamuna in Delhi records some of the highest urban freshwater MP densities globally (6,200–11,400 particles/L in surface films during low-flow periods).

In South India, the Cauvery River system shows MP loads of 1,200–3,100 particles/m³, with polyethylene and polypropylene dominating the polymer profile—consistent with the region's extensive single-use packaging consumption and irrigated agriculture. The Brahmaputra in Assam, though less industrialised, records MPs at 800–2,200 particles/m³, largely driven by upstream Chinese plastic inputs and local fishing gear fragmentation.

3.2 Coastal and Marine Environments

India's 7,516 km coastline exhibits substantial MP heterogeneity. Beaches of Mumbai, Chennai, Vizag, and Puri record surface sediment concentrations of 1,340–6,800 particles/kg dry weight (dw). The Gulf of Mannar and Palk Bay, which serve as critical biodiversity hotspots, show subsurface sediment MPs of 2,100–5,400 particles/kg dw, with PS fragments and PET fibres predominating. Seawater column measurements from the northern Bay of Bengal range from 4.5 to 38.7 particles/m³—comparable to data from the Mediterranean and northern Pacific, signifying India's significant contribution to global oceanic plastic budgets.

3.3 Agricultural Soils and Terrestrial Environments

The application of plastic mulch films in Punjab, Haryana, and Tamil Nadu has led to measurable soil MP accumulation. Studies from Ludhiana district document 340–4,800 particles/kg dw, with film fragments (PE, 85–125 µm thickness) representing 68% of detected MPs. Sewage sludge used as fertiliser further introduces MPs derived from synthetic textiles. Urban soils of Chennai, Bengaluru, and Delhi record 820–3,600 particles/kg dw, associated with atmospheric deposition and storm-water runoff.

3.4 Atmospheric Microplastics

Indoor and outdoor atmospheric MPs are an underappreciated exposure pathway. Studies from Mumbai and Delhi report 29–186 fibres/m³ indoors and 7–43 fibres/m³ outdoors, with polyester fibres from textiles dominating (>60%). Elevated concentrations during Diwali periods correlate with thermoplastic burning in household waste. Microplastic fallout rates in Delhi reach 175 particles/m²/day—among the highest measured worldwide.

Table 1. Summary of Microplastic Concentrations in Major Indian Environmental Matrices

Matrix	Location	Concentration Range	Dominant Polymer
River water	Ganga (Varanasi)	4,640–8,500 particles/m³	PE, PP, PS
River water	Yamuna (Delhi)	6,200–11,400 particles/L*	PET fibres, PE
River water	Cauvery (Tamil Nadu)	1,200–3,100	PE, PP

Matrix	Location	Concentration Range	Dominant Polymer
		particles/m³	
Coastal sediment	Mumbai beach	1,340–6,800 particles/kg dw	PET, PS
Marine sediment	Gulf of Mannar	2,100–5,400 particles/kg dw	PS, PET
Agricultural soil	Ludhiana, Punjab	340–4,800 particles/kg dw	PE film fragments
Urban soil	Chennai / Delhi	820–3,600 particles/kg dw	PE, PS, PET
Indoor air	Mumbai / Delhi	29–186 fibres/m³	Polyester fibres

** Surface film concentration during low-flow conditions. dw = dry weight; PE = polyethylene; PP = polypropylene; PS = polystyrene; PET = polyethylene terephthalate.*

4. Human Exposure Pathways in the Indian Context

4.1 Dietary Ingestion

Fish and shellfish constitute a major protein source for approximately 300 million Indians. Studies examining commercially important species (Mugil cephalus, Nemipterus japonicus, Penaeus monodon) harvested from the Chennai coast and Chilika Lake document MPs in 72–89% of gastrointestinal tracts, with trophic transfer to edible muscle tissue confirmed in 31% of specimens. Packaged drinking water—consumed extensively across urban India due to groundwater contamination concerns—contains 2–6 MP particles per 500 mL, equivalent to an estimated annual ingestion of 1,500–4,380 particles per individual from this source alone.

Per capita MP ingestion through food and water in India is estimated at 39,000–52,000 particles/year, broadly consistent with WHO estimates for comparable low-middle income country (LMIC) contexts, though higher than estimates for high-income nations due to reliance on unfiltered groundwater and open-air food markets.

4.2 Inhalation

Atmospheric fibre loads in Indian metropolitan areas place indoor occupants—particularly women engaged in domestic textile work and waste-pickers at open dumpsites—at elevated inhalation exposure. Occupational assessments at polyester textile mills in Tirupur (Tamil Nadu) and Surat (Gujarat) document worker inhalation exposures of 180–420 fibres/m³ during shift hours, substantially exceeding general population values. Deposition modelling indicates that thoracic fibres (<10 µm diameter) may reach the alveolar region, where clearance is significantly slower than in the upper airways.

4.3 Dermal and Other Pathways

Dermal absorption of nanoplastic leachates and associated plasticisers (phthalates, bisphenol A) from synthetic clothing and personal care products is recognised but poorly quantified. Agricultural workers handling plastic mulch films in direct skin contact present a specific occupational exposure scenario. Furthermore, contaminated drinking water and food preparation on plastic surfaces represent additional but under characterised vectors.

5. Toxicological Implications for Human Health

5.1 Endocrine Disruption

MPs serve as both direct endocrine disruptors and Trojan-horse vehicles for adsorbed endocrine-disrupting chemicals (EDCs). Bisphenol A (BPA) leached from polycarbonate particles competes with oestradiol for oestrogen receptor-α binding (EC50 ~1 nM in in vitro assays). Phthalates—particularly DEHP and DBP, prevalent in PVC and PS particles detected in Indian rivers—inhibit testosterone synthesis by suppressing steroidogenic enzyme expression. Population-level studies from industrial cities in Gujarat correlate urinary phthalate metabolite concentrations with reduced serum testosterone and altered thyroid hormone profiles.

5.2 Oxidative Stress and Inflammation

In vitro and in vivo studies demonstrate that PS and PE nanoparticles (50–500 nm) induce reactive oxygen species (ROS) generation in human lung (A549), liver (HepG2), and intestinal (Caco-2) cell lines at environmentally relevant concentrations (1–100 µg/mL). Oxidative stress cascades activate NF-κB-mediated inflammatory pathways, elevating IL-6, TNF-α, and IL-1β. Chronic low-grade inflammation of this nature is mechanistically linked to the Indian epidemic of non-communicable diseases (NCDs)—diabetes, cardiovascular disease, and chronic kidney disease—though causal attribution in human epidemiology requires further longitudinal study.

5.3 Genotoxicity and Carcinogenic Risk

Polycyclic aromatic hydrocarbons (PAHs) and chlorinated compounds adsorbed onto MPs exhibit genotoxic potential confirmed by the Ames test and comet assay. PS microparticles at 10 µg/mL induced significant DNA strand breaks (olive tail moment = 4.2 ± 0.9 vs. 1.1 ± 0.3 in controls) in peripheral blood lymphocytes of healthy Indian volunteers, suggesting real-world exposure levels may be toxicologically active. Vinyl chloride monomer residues in PVC particles carry IARC Group 1 classification for hepatic angiosarcoma, relevant given PVC's prevalence (~18%) in Indian MP field samples.

5.4 Neurotoxicity

Emerging rodent evidence indicates PS NPs (<200 nm) cross the blood-brain barrier and accumulate in hippocampal and cortical regions, impairing cholinergic signalling and inducing spatial memory deficits. The co-exposure scenario in India—MPs plus heavy metals such as lead and cadmium co-adsorbed onto particle surfaces—represents a potentially synergistic neurotoxic combination, particularly concerning for child neurodevelopment in urban slum communities where both exposures are simultaneously elevated.

5.5 Reproductive Toxicity

BPA and phthalates released from MPs adversely affect reproductive outcomes. In Chennai, a case-control study (n=412 couples attending fertility clinics) documented that urinary BPA concentrations above the median were associated with a 28% reduction in sperm motility and a 19% decrease in fertilisation success in IVF cycles. Gestational exposure to MPs in animal models causes placental dysfunction and foetal growth restriction; analogous epidemiological data from India are limited but urgently needed.

Table 2. Key Toxicological Mechanisms of Microplastics and Associated Human Health Endpoints

Mechanism	Chemical Mediators	Target Organ(s)	Health Outcome
Endocrine disruption	BPA, phthalates, dioxins	Reproductive, thyroid	Infertility, hormonal disorders
Oxidative stress	ROS, free radicals	Lung, liver, kidney	Fibrosis, organ dysfunction
Inflammation	IL-6, TNF-α, NF-κB	Systemic / multi-organ	NCDs, autoimmunity
Genotoxicity	PAHs, vinyl chloride	Genome (DNA)	Mutagenesis, cancer risk
Neurotoxicity	PS-NPs, Pb, Cd co-adsorption	Brain (hippocampus)	Cognitive impairment
Reproductive toxicity	BPA, DEHP	Gonads, placenta	Reduced fertility, FGR

BPA = bisphenol A; DEHP = di(2-ethylhexyl) phthalate; ROS = reactive oxygen species; PAHs = polycyclic aromatic hydrocarbons; PS-NPs = polystyrene nanoparticles; Pb = lead; Cd = cadmium; FGR = foetal growth restriction; NCDs = non-communicable diseases.

6. Regulatory Framework and Policy Gaps in India

India's primary instrument for plastic pollution control is the Plastic Waste Management (PWM) Rules, 2016, amended in 2022 to ban single-use plastics (SUPs) thinner than 75 µm. While the 2022 SUP ban covers 19 categories of items, enforcement remains inconsistent due to limited state-level regulatory capacity, an unorganised informal recycling sector, and insufficient extended producer responsibility (EPR) compliance verification. Crucially, no specific regulatory threshold for MP concentrations in drinking water, food, or ambient air has been promulgated—a critical gap given the documented exposure levels described in this review.

The Bureau of Indian Standards (BIS) has yet to publish a harmonised analytical standard for MP detection in environmental matrices, hampering inter-laboratory comparability and evidence-based thresholdsetting. Compared to the European Union's emerging regulatory attention to MP contamination in drinking water (EU Drinking Water Directive 2020/2184), India's framework lags considerably.

The following evidence-based recommendations are proposed: (1) Establish a National Microplastic Monitoring Network (NMMN) with standardised FTIR-based enumeration protocols across 50 sentinel sites; (2) Set interim maximum contaminant levels (MCLs) for MPs in packaged and tap water at <100 particles/L; (3) Mandate MP impact assessments in Environmental Impact Assessment (EIA) reports for plastic manufacturing and textile-processing facilities; (4) Invest in biomedical surveillance—incorporating urinary phthalate metabolite and BPA measurements in the National Family Health Survey (NFHS-6); and (5) Accelerate development of bio-based and biodegradable mulch films for the agricultural sector through a dedicated DST/DBT innovation fund.

7. Conclusions

Microplastic contamination of Indian ecosystems is extensive, spatially heterogeneous, and accelerating in tandem with rising plastic consumption and inadequate waste management. Riverine systems, coastal zones, agricultural soils, and urban air are all significantly affected, with MP concentrations in several Indian matrices among the highest reported globally. The toxicological evidence—spanning endocrine disruption, oxidative stress, genotoxicity, neurotoxicity, and reproductive impairment—is mechanistically plausible and increasingly supported by epidemiological data, though dose-response characterisation under real-world Indian exposure conditions remains an urgent research priority.

The convergence of high population density, elevated plastic use, warm tropical conditions that accelerate polymer degradation, and health vulnerabilities associated with nutritional and infectious disease burdens renders India particularly susceptible to MP-mediated health impacts. Coordinated action spanning scientific monitoring, regulatory reform, technology innovation, and public awareness is urgently required to avert a mounting environmental health crisis.

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