

Microplastics in Aquatic Ecosystems: Sources, Pathways, Biological Impacts, and Mitigation Strategies — A Comprehensive Review

SUNITA ARYA¹, RANJIT SINGH²

¹Professor, Department of Zoology, Dayanand Girls PG College, Kanpur (U.P.)

²Associate Professor, D.S.N. College, Unnao (U.P.)

Abstract- Microplastics (MPs), defined as plastic particles less than 5 mm in diameter, have emerged as ubiquitous and persistent contaminants across global aquatic ecosystems. Their widespread distribution, bioavailability, and capacity to adsorb toxic substances pose significant threats to aquatic organisms across all trophic levels. This review synthesizes current knowledge on the sources, transport pathways, ecological distribution, and biological impacts of microplastics on aquatic fauna, highlighting physiological, behavioral, and ecosystem-level consequences. Originating from both primary sources such as microbeads in cosmetics and industrial abrasives and secondary sources resulting from the environmental degradation of larger plastic debris, microplastics are now detected across oceans, rivers, lakes, polar ice cores, and urban freshwater systems. Their persistence and ubiquitous distribution pose a grave threat to aquatic biodiversity and water quality. A broad range of marine and freshwater organisms, including fish, shellfish, plankton, and cetaceans, ingest these particles, resulting in physical blockages, reduced energy intake, oxidative stress, endocrine disruption, and toxic exposure to co-contaminants such as heavy metals and persistent organic pollutants (POPs). These toxins bioaccumulate through food chains, potentially reaching human consumers via seafood and drinking water. Microplastics also settle into sediments, disrupting benthic habitats and altering microbial communities essential to nutrient cycling. Environmental monitoring highlights the role of mechanical degradation and its interaction with physico-chemical stressors in freshwater systems. Evidence further indicates that MP exposure impairs reproduction, growth, and behavior in aquatic species while facilitating the dispersal of invasive microbes and antibiotic-resistant pathogens. Their small size renders detection and removal technically challenging, necessitating advanced analytical technologies and standardized monitoring protocols. Solutions demand integrated waste management, reductions in primary plastic production, biodegradable material substitution, and enforceable global policy frameworks. The impact of microplastics on aquatic ecosystems is multifaceted and far-reaching, demanding

urgent, coordinated interdisciplinary action to protect biodiversity, ecosystem services, and public health from long-term harm.

Keywords: Aquatic Ecosystems, Bioaccumulation, Endocrine Disruption, Microplastics, Organic Pollutants, Sediment Contamination, Trophic Transfer

I. INTRODUCTION

The dramatic escalation of global plastic production since the mid-twentieth century has generated unprecedented environmental contamination, with microplastics (MPs) now recognized as a pervasive and persistent pollutant in virtually every compartment of the aquatic environment. Global plastic production exceeded 359 million metric tons in 2020, with a substantial fraction entering marine and freshwater systems through direct discharge, fragmentation, atmospheric deposition, and terrestrial runoff (Chaukura *et al.*, 2021). Once released, plastics undergo physicochemical and biological weathering, fragmenting progressively into micro- and nano-scale particles that resist conventional remediation (Wright *et al.*, 2013).

Microplastics originate from two broad categories of sources: primary MPs, manufactured at the micro-scale for industrial or consumer applications, and secondary MPs, formed through the environmental degradation of larger plastic items (Mehra *et al.*, 2020). The environmental fate and ecological risks of MPs are compounded by their physicochemical heterogeneity—they encompass diverse polymer types (polyethylene, polypropylene, polystyrene, polyethylene terephthalate, polyvinyl chloride), morphologies (fragments, fibers, films, pellets, beads), and size ranges each influencing bioavailability,

ingestion likelihood, and toxicological profiles differently.

Due to their small size, MPs are readily ingested by aquatic organisms ranging from zooplankton to large marine mammals, frequently causing adverse physiological and ecological effects. Their surfaces adsorb persistent organic pollutants (POPs), heavy metals, and microbial pathogens, further exacerbating their intrinsic toxicity (Pal *et al.*, 2024). The degradation of water quality in river systems, such as the Ganga, reflects the broader burden of anthropogenic pollution on freshwater biodiversity and underscores the need for robust environmental assessments (Arya and Dubey, 2017; Naqash *et al.*, 2020; Hemaprabha and Arya, 2025).

This review aims to provide a comprehensive, evidence-based analysis of the influence of microplastics on aquatic organisms and ecosystems, integrating insights on sources, transport pathways, distribution, physiological and behavioral effects, bioaccumulation dynamics, and emerging mitigation strategies.

II. SOURCES AND PATHWAYS OF MICROPLASTICS IN AQUATIC ENVIRONMENTS

2.1 Primary Sources

Primary MPs are intentionally manufactured at microscopic scales for specific industrial and consumer applications. Major categories include synthetic textiles (contributing ~35% of environmental MPs through washing), tire abrasion (~28%), city dust (~24%), microbeads in cosmetics (~2%), road markings (~7%), marine coatings (~3.7%), and plastic resin pellets (~0.3%) (Landrigan *et al.*, 2023).

2.1.1 Cosmetics and Personal Care Products

Microplastics are deliberately incorporated into a wide range of cosmetic and personal care products to serve as abrasives, emulsifiers, film-forming agents, and viscosity regulators. Common applications include facial scrubs, body washes, toothpaste, shampoos, and makeup products such as foundation and mascara. Microbeads composed of polyethylene (PE) or polypropylene (PP) are widely used as exfoliants,

while glitter particles made from metalized polyethylene terephthalate (PET) add optical effects to cosmetics.

Because of their small size and water-insolubility, these particles readily bypass conventional wastewater treatment infrastructure, entering rivers, lakes, and oceans where they persist indefinitely. In aquatic ecosystems, they are ingested by marine organisms and accumulate through trophic webs, carrying adsorbed toxic chemicals including heavy metals and POPs (Verma, 2019; Prakash and Shukla, 2021; Prakash, 2023). Regulatory responses have emerged; the European Union enacted Regulation EU 2023/2055 phasing out intentionally added microplastics in cosmetic formulations. Biodegradable alternatives including cellulose microbeads, sugar-based exfoliants, and polylactic acid (PLA) particles are increasingly being explored as substitutes.

2.1.2 Industrial Abrasives

Plastic abrasive media typically PE, PP, or polystyrene particles are deployed across the automotive, aerospace, construction, and electronics sectors for sandblasting, surface cleaning, and polishing. During these processes, particles are released via air emissions, wastewater discharge, and waste mismanagement. Their resistance to degradation and small size allow them to bypass industrial filtration systems and infiltrate aquatic ecosystems. Once ingested by aquatic organisms, these particles cause physical harm, digestive obstruction, and serve as vectors for toxic chemical contaminants that bioaccumulate through food webs. Growing regulatory pressure and industry awareness are driving adoption of biodegradable abrasive alternatives and stricter containment practices.

2.1.3 Plastic Resin Pellets (Nurdles)

Plastic resin pellets commonly termed “nurdles” are the raw feedstock from which virtually all plastic consumer goods are manufactured. Typically lentil-sized (< 5 mm), these buoyant, lightweight pellets are composed of PE, PP, and polystyrene and are prone to environmental spillage during production, transport, and processing. Millions of nurdles are released annually into waterways, coastal zones, and beach

environments through inadequate containment (Lillo *et al.*, 2025).

Once dispersed, nurdles are transported by wind and ocean currents, accumulating in marine gyres and shoreline habitats. Their physical resemblance to fish eggs makes them highly attractive to seabirds, fish, and turtles, inducing ingestion and subsequent digestive obstruction, malnutrition, and chemical toxicity. Nurdles effectively concentrate POPs and heavy metals on their hydrophobic surfaces, magnifying toxicity as they move through food webs. Mitigation efforts such as Operation Clean Sweep and legislative proposals including the Plastic Pellet Free Waters Act represent important policy responses to this underappreciated pollution source.

2.1.4 Medical and Agricultural Applications

In medicine, polymer-based microspheres and microparticles are employed in controlled drug delivery, surgical implants, and diagnostic imaging. The improper disposal of single-use medical plastics syringes, tubing, packaging generates microplastic fragments that enter wastewater systems and ultimately reach aquatic environments.

In agriculture, MPs are introduced through polymer-coated slow-release fertilizers, pesticide encapsulants, plastic mulch films, and greenhouse covers. These materials undergo progressive weathering and fragmentation, releasing MPs into soils that are subsequently transported to freshwater systems via runoff and drainage. Agricultural MPs have been shown to impair soil microbial diversity, disrupt nutrient cycling, and may be absorbed by plant tissues, raising concerns for food safety and human exposure (Wang *et al.*, 2018).

2.2 Secondary Sources

Secondary MPs arise from the environmental fragmentation of larger plastic items through the combined effects of abiotic weathering and biological degradation. They represent the dominant MP source in most natural ecosystems (Wright *et al.*, 2013).

2.2.1 Photodegradation: UV Radiation Fragmentation

Photodegradation occurs when ultraviolet (UV-B; 290–315 nm) radiation initiates photo-oxidation in exposed polymer chains, triggering chain scission,

cross-linking, and free radical formation. The resulting embrittlement causes plastic surfaces to develop microcracks that propagate into macroscopic fractures, eventually generating MP fragments. Degradation rates vary by polymer type and environmental exposure; polyethylene and polystyrene undergo more rapid UV-induced fragmentation than polypropylene. Beyond MP formation, photodegradation releases dissolved organic matter and greenhouse gases (CO₂, CH₄), extending its environmental significance beyond plastic pollution per se (Yang, 2022).

2.2.2 Mechanical Degradation: Abrasion from Waves, Wind, and Physical Wear

Mechanical fragmentation occurs when repeated physical forces wave action, sand abrasion, wind erosion, and anthropogenic wear erode plastic surfaces progressively until micro-scale fragments are released. In coastal and fluvial environments, wave energy and sediment abrasion are primary drivers; in urban settings, tire wear, synthetic turf degradation, and construction activities are major contributors (Arya, 2018). Unlike photodegradation, mechanical abrasion is not sunlight-dependent and therefore acts continuously across benthic and deep-water environments where UV penetration is negligible, making it a pervasive and often underestimated pathway for secondary MP generation.

2.2.3 Biological Degradation: Microbial and Enzymatic Processes

Biological degradation involves the colonization of plastic surfaces by microorganisms bacteria, fungi, and algae that secrete specific enzymes capable of cleaving polymer bonds. Notable examples include the bacterium *Ideonella sakaiensis*, which produces PETase and MHETase enzymes capable of degrading polyethylene terephthalate (PET), and various fungal species that produce cutinases acting on polyurethane and PLA. Biodegradation proceeds through biofilm formation, enzymatic hydrolysis, and eventual mineralization to CO₂ and water. However, this pathway also generates nanoplastics and dissolved organic intermediates with their own ecological consequences. Biotechnological research is actively pursuing engineered microbial consortia and optimized enzyme cocktails to accelerate plastic biodegradation at scale.

2.3 Transport Mechanisms

2.3.1 Ocean Currents and Riverine Flow

Rivers function as the primary conduits transferring land-generated MPs to marine environments, carrying an estimated 0.8–2.7 million metric tons of plastic waste to oceans annually. Urban stormwater runoff, wastewater effluents, and industrial discharges are dominant riverine MP sources. In marine environments, surface and subsurface ocean currents redistribute MPs across vast distances, concentrating them in convergence zones such as the subtropical gyres. The Great Pacific Garbage Patch, spanning an estimated 1.6 million km², exemplifies extreme MP accumulation driven by gyre circulation dynamics (Aytan *et al.*, 2020). Particle density, size, and shape govern vertical distribution, with low-density particles remaining at the surface and denser particles settling into sediments.

MPs are also increasingly recognized as significant atmospheric pollutants capable of long-range transport via wind and precipitation. Studies have detected MPs in the French Pyrenees, Arctic snow, and Antarctic ice, with deposition rates reaching 90–355 particles/m²/day in remote locations. Sea spray alone is estimated to eject ~136,000 tons of MPs into the atmosphere annually, extending contamination far beyond pollution source regions.

2.3.2 Biological Vectors

Aquatic organisms function as active MP vectors through ingestion and subsequent excretion. Zooplankton, bivalves, and fish ingest MPs mistaking them for prey, facilitating trophic transfer to higher predators. MPs have been detected in gut contents, tissues, and feces of over 114 marine species, including deep-sea taxa (Emilyn *et al.*, 2019). Biofouling the colonization of MP surfaces by microorganisms alters particle density and buoyancy, further modulating their transport dynamics. This biological cycling enables MPs to traverse habitat boundaries and be redistributed across ecosystems through animal movement and excretion.

III. OCCURRENCE AND DISTRIBUTION IN AQUATIC ECOSYSTEMS

3.1 Marine Environments

MPs are distributed across the full vertical extent of the marine water column, from surface waters to hadal trenches. Surface MPs are transported laterally by wind-driven currents; midwater MPs reflect turbulence, biofouling, and vertical mixing dynamics; deep-sea sediment MPs accumulate through aggregation with organic matter, fecal pellet transport, and biological sinking. Hadal MP concentrations in the Mariana Trench can reach thousands of particles per kilogram of sediment.

One year after the catastrophic *X-Press Pearl* nurdle spill, Lillo *et al.* (2025) documented continued widespread nurdle contamination in Sri Lankan coastal sediments, with average densities of 588 pellets/m² at the surface and pellet presence to sediment depths of 30 cm, reflecting the exceptional persistence of these particles in the environment.

Microplastic contamination of commercially harvested bivalves presents direct implications for human health. Bolaños and Hizon-Fradejas (2025) characterized MPs extracted from *Perna viridis* (Asian green mussel), *Venerupis philippinarum* (Manila clam), and *Corbicula manilensis* (freshwater clam) sourced from Philippine markets. MP concentrations ranged from 0.52 ± 0.13 to 2.94 ± 0.65 MP/g fresh weight, with fibers and fragments dominating. ATR-FTIR analysis identified polymers including LDPE/EVA, PP, and PU, with direct implications for consumer dietary MP exposure.

3.2 Oceanic Gyres: The Great Pacific Garbage Patch

Subtropical oceanic gyres, driven by Coriolis-deflected surface currents, trap and concentrate floating debris including MPs. The Great Pacific Garbage Patch alone contains an estimated 1.8 trillion plastic pieces, with 92% of its mass composed of particles exceeding 5 mm (Aytan *et al.*, 2020). These gyres represent persistent hotspots for MP pollution, with seasonal and meteorological variation modulating local concentrations (Boyle *et al.*, 2020).

3.3 Freshwater Systems

Freshwater rivers and lakes serve as intermediate reservoirs and transport corridors connecting terrestrial MP sources to marine sinks. Urban runoff, agricultural drainage, and industrial effluents continuously deliver MPs to freshwater networks. Static lake systems accumulate MPs in sediments over extended periods. Fu and Wang (2019) documented that MPs bypass conventional drinking water treatment filters, entering tap water supplies and raising significant public health concerns. Benthic MP accumulation impairs sediment-dwelling organisms and disrupts nutrient cycling; aquatic organisms including fish and mollusks ingest MPs, experiencing physiological harm and toxic exposure.

Freshwater systems in India, including the Ganga River, face compound pressures from organic pollution and emerging contaminants including MPs. Seasonal physicochemical monitoring of the Ganga and associated water bodies near Kanpur demonstrates how degraded water quality amplifies MP-mediated biological impacts on freshwater fauna (Arya and Dubey, 2017; Hemaprabha and Arya, 2025).

3.4 Polar Regions

MPs have been confirmed in Arctic and Antarctic ice cores, snow, and sea ice, demonstrating long-range atmospheric and oceanic transport to Earth's most remote regions (Pal *et al.*, 2024). A pan-Antarctic assessment recorded mean concentrations of 44.8 ± 50.9 particles/L in sea ice, while Arctic snow concentrations reached up to 14,000 particles/L, reflecting the global scale of MP contamination.

3.5 Urban and Industrial Zones

Wastewater treatment plants, stormwater systems, and industrial discharges are major point sources of aquatic MP contamination. MPs enter aquatic systems through sewage effluents, road dust, construction site runoff, and atmospheric deposition (Chen *et al.*, 2025). Urban rivers often exhibit MP concentrations orders of magnitude higher than rural counterparts, reflecting the intensity of anthropogenic MP generation.

IV. PHYSIOLOGICAL EFFECTS ON AQUATIC ORGANISMS

4.1 Digestive Obstruction and Malnutrition

Physical ingestion of MPs is among the most extensively documented ecological impacts. MPs accumulate in the gastrointestinal tracts of fish, bivalves, zooplankton, and other organisms, causing mechanical obstruction that impairs digestion, reduces nutrient absorption, and diminishes feeding drive (Desforges *et al.*, 2014). False satiation where MP-filled organisms reduce food intake leads to energy deficits, stunted growth, and compromised reproductive output. Chronic ingestion induces mucosal inflammation, epithelial abrasion, and weakened immune defenses. Population-level consequences include reduced fecundity, elevated mortality, and food web disruptions (Arya and Dubey, 2017).

4.2 Oxidative Stress and Cellular Damage

MP ingestion and tissue interaction generate reactive oxygen species (ROS), inducing oxidative stress across organ systems. Elevated ROS levels drive lipid peroxidation, protein denaturation, and DNA strand breaks, compromising cellular integrity and metabolic function. Histopathological examination of exposed fish and crustaceans reveals hepatic lesions, gill tissue degeneration, and inflammatory infiltration. These cellular-level injuries impair detoxification capacity, reduce growth efficiency, and heighten susceptibility to secondary infections. The severity and nature of oxidative injury depend on MP particle size, polymer composition, surface chemistry, and duration of exposure (Greeves *et al.*, 2025).

4.3 Endocrine Disruption

MPs serve as vectors for a suite of endocrine-disrupting chemicals (EDCs) including bisphenol A (BPA), phthalate plasticizers, and brominated flame retardants that leach into tissues following ingestion. These EDCs mimic or antagonize natural hormones, binding to estrogen, androgen, and thyroid hormone receptors. In fish and mollusks, MP-associated EDC exposure has been linked to altered sex steroid concentrations, suppressed gonadal development, reduced fertility, and intersex conditions. Developmental life stages are particularly vulnerable,

as hormonal homeostasis is critical for organogenesis and sexual differentiation. At the population level, sustained endocrine disruption threatens reproductive success, genetic diversity, and long-term species viability (Hemaprabha and Arya, 2025).

4.4 Immune Modulation and Pathogen Vectoring

MPs modulate aquatic organism immune responses, compromising disease resistance and increasing vulnerability to secondary infections. The platisphere the microbial biofilm community colonizing MP surfaces can harbor pathogenic bacteria, antibiotic-resistant genes, and invasive taxa, facilitating their transport into new environments. Organisms ingesting MP-associated pathogen vectors face amplified infection risks, with potential cascade effects on ecosystem health and zoonotic disease transmission.

V. BEHAVIORAL AND ECOLOGICAL IMPACTS

5.1 Altered Feeding Behavior

MP contamination disrupts natural foraging behavior in aquatic organisms. Visual similarity between MPs and prey items leads to their preferential ingestion, particularly by visual predators. Conversely, chemical cues from contaminated prey may alter prey selection and foraging patterns. Documented effects include reduced prey capture efficiency in crustaceans and fish, altered prey preference hierarchies, and modified foraging area utilization (Du *et al.*, 2021). These behavioral disruptions reduce energy assimilation efficiency and propagate through food webs via altered predator-prey dynamics.

5.2 Impaired Locomotion and Predator Avoidance

Physical adhesion of MP particles to gill surfaces, appendages, and sensory organs impairs locomotion, respiration, and sensory perception in affected organisms. Documented behavioral consequences include reduced swimming speed, impaired burst-escape performance, and diminished responsiveness to predator stimuli (Sen *et al.*, 2025). These impairments increase predation vulnerability and reduce competitive fitness, with potential demographic consequences at the population level.

5.3 Habitat Modification and Ecosystem Disruption

Sediment MP accumulation substantially alters benthic habitat structure, affecting sediment porosity, oxygen penetration, and substrate quality. Benthic community composition shifts occur in response to these physical modifications, with sensitive taxa being displaced and MP-tolerant assemblages expanding. MP-induced changes in microbial community composition disrupt nutrient cycling, organic matter decomposition, and oxygen dynamics in both sediment and water column environments (Verma and Prakash, 2020). Coral reefs face particular vulnerability, as MPs impair feeding, promote pathogenic colonization, and cause physical abrasion of coral tissues.

VI. BIOACCUMULATION AND TROPHIC TRANSFER

6.1 Tissue Retention and Distribution

MPs and the chemical contaminants they carry accumulate progressively in organism tissues with increasing exposure duration. Distribution studies have detected MPs in gut contents, liver, gill, and gonadal tissues of fish, bivalves, and crustaceans. Nanoplastics ($< 1 \mu\text{m}$) are of particular concern, as their reduced size enables translocation across epithelial barriers and cellular membranes, potentially reaching organ systems including the liver, kidney, and brain distant from the initial ingestion site (Pal *et al.*, 2024). The persistence of MPs within tissues means that even intermittent or episodic exposure can result in cumulative body burdens.

6.2 Trophic Transfer and Biomagnification

MPs ingested by primary consumers are transferred to predators through normal trophic interactions, enabling upward propagation through food webs. This trophic transfer has been documented across multiple levels, from zooplankton to forage fish to piscivorous predators. The associated chemical contaminants particularly lipophilic POPs undergo biomagnification, with concentrations increasing at successive trophic levels. Detection of MPs in commercially important fish and shellfish species poses direct human exposure risks via seafood consumption (Bolaños and Hizon-Fradejas, 2025).

6.3 Vector Role for Co-Contaminants

The surface chemistry of plastic polymers confers high affinity for hydrophobic organic contaminants, including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), dichlorodiphenyltrichloroethane (DDT), and other chlorinated pesticides. Heavy metals including lead, cadmium, and mercury also adsorb onto MP surfaces. Upon ingestion, desorption of these contaminants into biological tissues can occur under gut-phase conditions, potentially delivering concentrated toxin loads to internal organs. This vector effect substantially enhances the ecotoxicological significance of MP exposure beyond the physical effects of the particles themselves (Boyle *et al.*, 2020).

VII. REGULATORY AND POLICY CONSIDERATIONS

International and national regulatory frameworks are increasingly targeting MP pollution at source. Bans or restrictions on intentional microplastic additives in cosmetics have been enacted in the United States (Microbead-Free Waters Act, 2015), the United Kingdom, Canada, and the European Union (Regulation EU 2023/2055). Several nations have introduced extended producer responsibility legislation targeting single-use plastics. The United Nations Environment Assembly has advanced negotiations toward a legally binding Global Plastics Treaty to establish minimum standards for MP monitoring, reporting, and management.

Effective policy frameworks must address the full lifecycle of plastic materials, from design and production through use, collection, treatment, and valorization. Circular economy approaches that minimize plastic waste generation and maximize material recovery represent a systemic complement to end-of-pipe regulatory controls. Development and market introduction of genuinely biodegradable substitutes for high-MP-risk applications, synthetic textiles, cosmetics, agricultural films require coordinated policy support and standardized environmental biodegradability certification.

VIII. RESEARCH GAPS AND FUTURE DIRECTIONS

8.1 Methodological Standardization

MP research is hampered by substantial methodological heterogeneity. Variability in sampling designs, extraction procedures, particle size thresholds (typically 1 μm to 5 mm), and analytical tools (FTIR spectroscopy, Raman spectroscopy, scanning electron microscopy, pyrolysis-GC/MS) limits cross-study comparability and meta-analytic synthesis. Reliance on visual identification in many legacy studies risks systematic under-enumeration and polymer misclassification. The development of globally standardized, validated protocols for MP sampling, identification, and quantification in water, sediment, and biota matrices is a critical priority for advancing the field (Chen *et al.*, 2025).

8.2 Chronic and Multigenerational Exposure Studies

The majority of published MP ecotoxicology data derive from short-term, acute-exposure experiments at concentrations exceeding realistic environmental levels. Chronic, environmentally realistic exposure studies spanning multiple life stages and generations are required to capture cumulative physiological damage, including inflammation, immune suppression, endocrine disruption, and reproductive failure. Multigenerational studies are essential for identifying epigenetic and heritable effects of MP exposure. Without longitudinal chronic exposure data, ecological risk assessments will remain incomplete and potentially underprotective.

8.3 Synergistic Toxicities

Environmental MPs rarely occur in isolation; they co-exist with diverse chemical contaminants including heavy metals, POPs, pharmaceuticals, and emerging substances. Experimental evidence demonstrates that co-exposure to MPs and co-contaminants can produce synergistic toxic effects exceeding the sum of individual exposures. For instance, combined MP and cadmium exposure has been shown to amplify oxidative stress and histopathological damage in aquatic organisms. Mechanistic understanding of MP-contaminant interaction chemistry, desorption kinetics under biological conditions, and resultant

toxicological synergies requires focused research investment.

8.4 Ecosystem Services Impacts

MP contamination threatens a spectrum of critical ecosystem services including water purification, nutrient cycling, primary production, and biodiversity maintenance yet quantitative field-based assessments of these service impacts remain scarce. Disruption of microbial community composition in sediments may impair nutrient turnover and oxygen exchange; inhibition of filter-feeding organisms reduces natural water purification capacity; habitat degradation from sediment MP accumulation diminishes habitat quality and biodiversity. Comprehensive ecosystem-scale studies integrating ecological modeling and empirical measurement are needed to quantify service losses attributable to MP contamination.

8.5 Ecological Modeling and Risk Assessment

Predictive ecological models capable of simulating MP transport, fate, biological uptake, and food web dynamics across spatial and temporal scales are essential for proactive environmental management. Risk assessment frameworks must incorporate particle size distributions, polymer type, surface chemistry, co-contaminant loads, and species-specific sensitivity to yield ecologically meaningful hazard assessments. Current models are constrained by insufficient field validation data and inadequate parameterization for diverse ecosystem types. Investment in interdisciplinary model development and validation, integrating hydrodynamics, ecotoxicology, and food web ecology, is urgently needed to support evidence-based regulatory decision-making.

IX. ECO-FRIENDLY SUBSTITUTES AND MITIGATION TECHNOLOGIES

9.1 Biodegradable Material Alternatives

Replacement of MP-generating materials with genuinely biodegradable alternatives represents the most effective long-term mitigation strategy. Promising substitutes include cellulose microbeads derived from plant fibers (cosmetics), starch-based polymers (packaging and films), polylactic acid (PLA) from fermented corn starch (textiles and containers), and chitosan from crustacean shells (water filtration and cosmetics). Critical evaluation of environmental

biodegradability under realistic conditions not only laboratory composting conditions is essential to ensure that alternatives deliver genuine environmental benefits.

9.2 Natural Coagulants for MP Removal

Natural coagulants offer promising, low-toxicity approaches for MP removal from water treatment streams:

Coagulant Source	MP Removal Efficiency	Mechanism
<i>Moringa oleifera</i> seeds	Up to 89%	Charge neutralization and flocculation
Chitosan (from shrimp)	Up to 94%	Polymer bridging
Cactus mucilage	~85%	Hydrophobic association
Microbial EPS (biofilm)	~90%	Bio-adhesion and aggregation

9.3 Nature-Based Solutions

Constructed and restored wetland systems using macrophytes such as reeds, cattails, and bulrushes trap and filter suspended MPs from water flows. Biochar filters produced from agricultural waste biomass exhibit strong MP adsorption capacity and offer a low-cost water treatment option applicable at community scales. Mycoremediation, exploiting the plastic-degrading enzymatic capabilities of certain fungal species, represents an emerging biological treatment approach with potential for scalable application.

X. CONCLUSION

Microplastics represent a multifaceted, pervasive, and rapidly intensifying threat to global aquatic ecosystems. Their ubiquity from polar ice fields to deep-sea sediments, combined with documented impacts on organismal physiology, behavior, food web dynamics, and ecosystem services, establishes MP pollution as one of the most pressing environmental challenges of the twenty-first century. Current evidence demonstrates that MP contamination disrupts digestive function, induces oxidative stress and cellular damage, disrupts endocrine homeostasis, impairs behavioral capacities, and facilitates the

trophic transfer and biomagnification of toxic co-contaminants across diverse aquatic taxa. Freshwater systems, including highly impacted river systems such as the Ganga, face compounded vulnerability to MP contamination given their role as conduits for land-based plastic waste and their critical importance for biodiversity and human water security (Arya and Dubey, 2017; Naqash et al., 2020; Hemaprabha and Arya, 2025).

Addressing the microplastics crisis requires urgent, collaborative action spanning ecological science, environmental policy, industrial innovation, and public engagement. Priority areas include methodological standardization for environmental monitoring, long-term chronic exposure research, development of biodegradable material alternatives, implementation of enforceable global policy frameworks, and investment in scalable remediation technologies. Ultimately, protecting aquatic biodiversity, ecosystem services, and human health from the long-term consequences of microplastic pollution demands a fundamental rethinking of society's relationship with plastic materials across their entire lifecycle.

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