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Review

Plastic Pollution as a Driver of Aquatic Biodiversity Decline: Mechanisms, Ecological Consequences, and Mitigation Imperatives

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Abstract

Plastic pollution has emerged as one of the most pervasive and ecologically disruptive anthropogenic stressors confronting aquatic ecosystems in the twenty-first century. The present review synthesizes evidence from peer-reviewed literature on the sources, transport pathways, and biological impacts of macro- and microplastic contamination across marine, freshwater, and coastal environments. Physical interactions including ingestion and entanglement inflict direct physiological harm on taxonomically diverse organisms such as fish, sea turtles, seabirds, and marine mammals, manifesting as internal injuries, impaired feeding, compromised reproduction, and mortality. Microplastics (< 5 mm) present additional sublethal hazards by functioning as vectors for persistent organic pollutants and heavy metals, facilitating bioaccumulation and trophic transfer through food webs. Soil-dwelling fauna, including earthworms and nematodes, are similarly affected, with cascading consequences for nutrient cycling and edaphic biodiversity. At the ecosystem level, plastic pollution reduces species richness, degrades critical habitats such as coral reefs and mangroves, and undermines the provisioning of essential ecosystem services. The contamination of aquatic food chains further raises concern for human health via dietary exposure. Effective mitigation requires concerted international policy action, enhancement of waste management infrastructure, reduction of single-use plastic consumption, and sustained investment in biodegradable material alternatives.

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Statement of Sustainability: Plastic pollution threatens ecological sustainability by disrupting aquatic and terrestrial ecosystems, reducing biodiversity, and contaminating food webs. Persistent plastics accumulate in marine, freshwater, and soil environments, impairing organism health, altering nutrient cycling, and degrading habitats such as coral reefs and mangroves. Sustainable management requires minimizing plastic generation, promoting circular material use, and strengthening waste management systems. Transitioning to biodegradable alternatives, improving recycling efficiency, and reducing single-use plastics can limit environmental accumulation. Coordinated policy frameworks, technological innovation, and responsible consumption patterns are necessary to protect ecosystem services, maintain ecological balance, and reduce human exposure to plastic-associated contaminants in food and water resources.

1. Introduction

Plastics are increasingly recognized as a geological marker of the Anthropocene, attributable to their resistance to biological degradation and their long-term persistence in natural environments (De-la-Torre et al., 2020). Since their mass commercialization in the mid-twentieth century, synthetic polymers have underpinned advances in food packaging, drug delivery, construction, automotive engineering, and medical technologies including polymer scaffolds and nano-drug carriers (Qasim et al., 2025). Global plastic production reached approximately 368 million metric tons in 2019, with Asia accounting for the largest share, followed by North America and Europe (Li et al., 2021). Despite these functional utilities, the systemic failure of waste management infrastructures has precipitated widespread environmental contamination. It is estimated that 79% of all plastic ever produced has accumulated in landfills or natural environments, 12% has been incinerated, and only 9% has been recycled (Geyer et al., 2017).

Under a business-as-usual trajectory, cumulative plastic waste entering natural environments may reach 12 billion metric tons by 2050 (Geyer et al., 2017). Approximately 11 million metric tons of plastic enter the world's oceans annually, with projections indicating a potential tripling of this figure by 2060 if current practices remain unaltered (UNEP, 2023). Terrestrial sources contribute substantially to this burden; major river systems, including the Yangtze, Indus, Yellow, Ganga–Brahmaputra, and Nile, function as principal conduits of plastic flux into marine environments (Lebreton et al., 2017). Mismanaged plastic waste traverses vast distances owing to its low density and durability, eventually accumulating in ocean gyres, shorelines, deep-sea trenches, and high-altitude ecosystems (Wright & Kelly, 2017; Abel et al., 2023).

Once introduced into aquatic environments, plastic debris undergoes physical, chemical, and photochemical degradation including UV-induced photodegradation, mechanical abrasion, and thermal action yielding microplastics (< 5 mm) and nanoplastics (< 0.1 μm) (Andrady, 2011). These particles originate additionally from primary anthropogenic sources such as cosmetic microbeads and pre-production plastic pellets (Cole et al., 2011). Their ubiquity across freshwater, marine, soil, atmospheric, and even cryospheric compartments underscores the truly global scale of contamination (Wright & Kelly, 2017). The present review critically examines the ecological mechanisms through which plastic pollution degrades aquatic biodiversity, synthesizes documented impacts across taxonomic groups and ecosystem types, and evaluates the strategic imperatives for mitigation (Azad et al., 2023).

2. Aquatic Biodiversity: Scope and Ecological Significance

Biodiversity is formally defined as the variability among living organisms from all sources including terrestrial, marine, and other aquatic ecosystems and encompasses diversity within species (genetic diversity), between species (species diversity), and of ecosystems (ecosystem diversity) (Convention on Biological Diversity [CBD], 1992). Approximately 1.7–1.8 million species have been formally described, with total global biodiversity estimated at between 8 and 10 million species (Mora et al., 2011). Aquatic ecosystems encompassing rivers, lakes, wetlands, estuaries, and oceans harbour disproportionate species richness relative to their aerial extent. Freshwater ecosystems, despite occupying less than 3% of the Earth's surface, support nearly 10% of all known species (Dudgeon et al., 2006). Marine ecosystems similarly contribute immensely to global biodiversity and ecological stability (Worm et al., 2006).

Species richness within aquatic systems is governed by habitat complexity, climatic regime, latitude, and ecosystem productivity, and generally increases toward the tropics (Gaston, 2000). Estuarine and mangrove systems function as ecotonal edge habitats, sustaining high biodiversity through nutrient trapping and structural heterogeneity (Barbier et al., 2011). Aquatic biodiversity underpins critical ecosystem services including nutrient cycling, water purification, carbon sequestration, and food provision (MEA, 2005). Aquatic microorganisms bacteria and fungi maintain water quality through organic matter decomposition and pollutant detoxification (Dudgeon et al., 2006). Each species contributes unique genetic material that enhances ecosystem resilience under environmental perturbations; biodiversity loss accordingly impairs ecosystem functioning and diminishes adaptive capacity in the face of climate change (Cardinale et al., 2012).

3. Primary Drivers of Aquatic Biodiversity Decline

3.1. Climate Change

Climate change constitutes a systemic threat to aquatic ecosystems through rising water temperatures, altered precipitation regimes, sea-level rise, and ocean acidification (IPCC, 2021). Thermal elevation reduces dissolved oxygen concentrations in water bodies, adversely affecting the physiology and distribution of fish and other aerobic aquatic organisms (Doney et al., 2012). Elevated atmospheric CO_2 concentrations further drive ocean acidification, impairing the calcification of corals, molluscs, and echinoderms taxa that serve foundational roles in reef and benthic community structure (Doney et al., 2012).

3.2. Biological Invasions

Invasive species alter the structure and functional dynamics of aquatic ecosystems by displacing native taxa through resource competition, predation, and habitat modification (Simberloff et al., 2013). Aquatic invasions predominantly occur via ballast water discharge and shipping activities, with plastic debris additionally facilitating the translocation of fouling organisms across oceanic barriers (Molnar et al., 2008). Such biotic homogenization diminishes native biodiversity and can precipitate local extinctions.

3.3. Water Pollution and Chemical Contamination

Industrial effluents, agricultural runoff, sewage discharge, and chemical contaminants collectively impose severe physiological stress on aquatic biota (Carpenter et al., 1998). Toxic pollutants including heavy metals and phenolic compounds accumulate within aquatic organisms, disrupting reproductive physiology and survival (Rochman et al., 2013). Suspended particulate matter impairs gill function in fish and invertebrates and attenuates light penetration, reducing primary productivity through inhibition of photosynthesis (Carpenter et al., 1998).

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3.4. Overexploitation

Commercial overexploitation of marine and freshwater species for food, trade, and recreation has driven significant population declines globally (Coleman & Williams, 2002). More than 400 marine species are subject to direct exploitation by humans, with unsustainable harvesting rates contributing to ecological imbalance and the progressive impoverishment of fish community diversity (Worm et al., 2006).

4. Sources, Composition, and Environmental Transport of Plastic Pollutants

4.1. Production and Waste Generation Trends

The proliferation of single-use plastics is the primary driver of environmental plastic accumulation. The ease and low cost of polymer synthesis, combined with high functional versatility, has sustained demand across packaging, textile, electronics, and consumer goods industries. Insufficient waste management infrastructure particularly across low- and middle-income nations results in substantial proportions of plastic waste entering rivers, coastal zones, and oceans through open dumping, littering, and storm drain overflow (Jambeck et al., 2015; Munno et al., 2021). The packaging industry, which relies heavily on multilayer non-recyclable plastics, represents a disproportionate contributor to this waste stream (Singh & Walker, 2024).

4.2. Microplastic Origins and Physicochemical Properties

Microplastics (< 5 mm) originate from two principal pathways: (i) primary microplastics, manufactured at microscale for applications in cosmetics (e.g., polyethylene microbeads) and industrial abrasives; and (ii) secondary microplastics, generated through the fragmentation of larger plastic items under UV radiation, mechanical abrasion, and thermal stress (Cole et al., 2011; Andrady, 2011). Common morphological forms include fibres, fragments, films, foams, pellets, and microbeads. The environmental fate and transport of these particles are governed by intrinsic properties polymer density, shape, and surface chemistry as well as extrinsic hydrodynamic forces (Rochman et al., 2013). Their omnipresence has been confirmed across diverse compartments: soils, groundwater, rivers, oceans, wetlands, polar snow, and montane ecosystems (Wright & Kelly, 2017).

4.3. Ocean Accumulation Zones

Convergent ocean currents concentrate plastic debris in subtropical gyres. The North Pacific Subtropical Gyre colloquially designated the 'Great Pacific Garbage Patch' has been estimated to cover an area exceeding twice the surface of Texas and contains between 6 and 12 million tons of plastic (Abel et al., 2023). Analogous accumulation zones have been identified in the South Pacific, North and South Atlantic, and Indian Ocean Subtropical Gyres. Plastic pollution has additionally been detected in some of Earth's most remote environments, including the hadal zones of deep-sea trenches (Abel et al., 2023). If all oceanic plastic were gathered, the quantity would fill approximately 5 million shipping containers (UNEP, 2023).

5. Documented Ecological Impacts of Plastic Pollution on Aquatic Biota

The following table synthesizes documented impacts of plastic pollution across major taxonomic and functional groups in aquatic ecosystems, as reported in peer-reviewed literature (Table 1; Figure 1).

Table 1. Documented effects of plastic pollution on representative aquatic and associated terrestrial organisms.

Organism Group	Plastic Interaction	Documented Effects	Key Reference
Marine Fish	Ingestion of microplastics mistaken for plankton	Physical obstruction, reduced feeding, internal injury, mortality	Wright et al. (2013)
Sea Turtles	Ingestion of plastic bags resembling jellyfish; entanglement in nets	Internal injuries, starvation, reproductive failure; leatherback listed as critically endangered	Moon et al. (2023)
Seabirds (Procellariforms)	Ingestion of plastic fragments resembling prey items	Reduced feeding capacity, gut obstruction, mortality	Isangedighi et al. (2018)
Marine Mammals (Cetaceans)	Entanglement and ingestion of macro- and microplastics	Strangulation, drowning, impaired reproduction	Isangedighi et al. (2018)
Zooplankton / Invertebrates	Passive ingestion of microplastics (< 5 mm)	Oxidative stress, reproductive impairment, trophic transfer of contaminants	Cole et al. (2011); Wright et al. (2013)
Freshwater Organisms (Great Lakes)	Exposure to microplastic pellets and fibres in sediment and water column	Bioaccumulation, habitat degradation, altered species composition	Arturo & Corcoran (2022)
Soil Fauna (Earthworms, Nematodes)	Ingestion and mechanical fragmentation of microplastics	Altered soil structure, reduced microbial diversity, disrupted nutrient cycling	Rehman et al. (2025)
Coral Reefs / Mangroves	Smothering by plastic debris; toxic chemical leaching	Habitat degradation, reduced photosynthesis, species loss	Gregory (2009)

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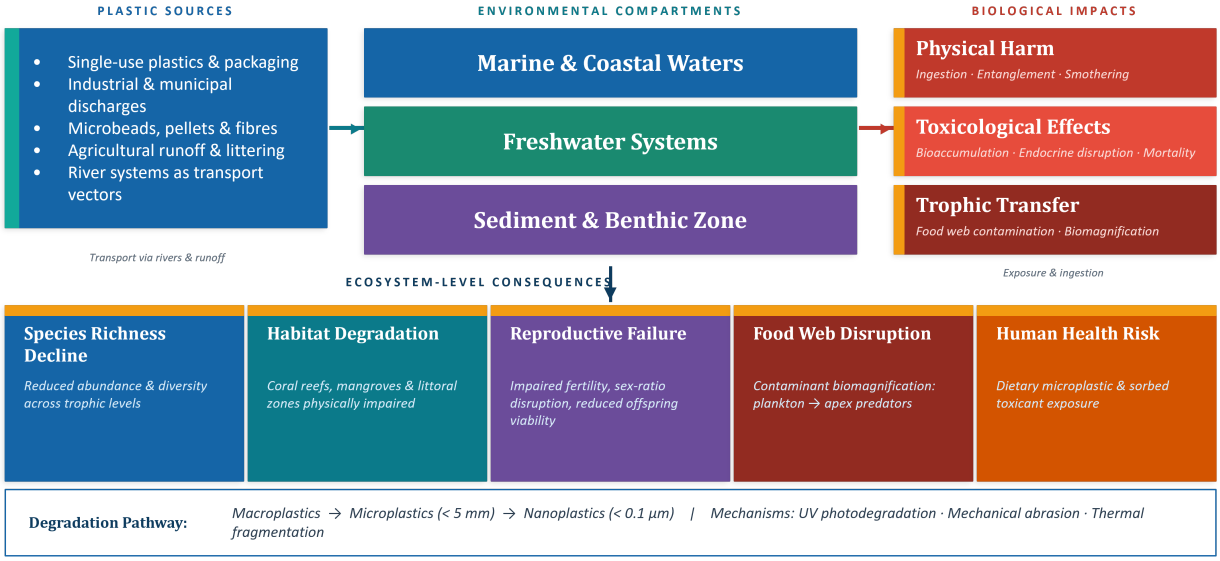

Figure 1. Pathways of plastic pollution impacts on aquatic biodiversity.

5.1. Fish

Although large-scale controlled experiments on plastic impacts in wild fish populations remain limited, field-based evidence is accumulating. In the North Pacific Central Gyre, approximately 43% of 580 sampled fish contained plastic fragments in their stomachs, averaging approximately three pieces per individual (Cunningham et al., 2020). Studies of fish in the English Channel reported plastic occurrence in 32.8% of gastrointestinal tracts examined (Cunningham et al., 2020). Many ingested fragments are colourless, white, or blue colours corresponding to plankton, the principal dietary component suggesting visual misidentification as the primary ingestion mechanism. Microplastic ingestion results in physical obstruction of digestive passages, reduced assimilation efficiency, oxidative stress, impaired endocrine function, and increased mortality risk (Wright et al., 2013).

5.2. Sea Turtles

Necropsy studies have consistently documented the presence of plastic debris in the digestive tracts of sea turtles, including fishing lines, cables, netting, polystyrene foam, and plastic bags (Moon et al., 2023). Polyethylene bags floating in the water column resemble medusae a principal food source for leatherback turtles (*Dermochelys coriacea*) rendering accidental ingestion particularly prevalent. Populations of the leatherback sea turtle have undergone pronounced declines over the past three decades attributable to anthropogenic pressures including plastic entanglement and ingestion, resulting in the species' classification as Critically Endangered on the IUCN Red List (Moon et al., 2023).

5.3. Seabirds and Marine Mammals

Procellariform seabirds including albatrosses, shearwaters, and petrels are among the most severely affected taxonomic groups due to surface-feeding behaviour and the visual similarity between plastic fragments and their prey (Isangedighi et al., 2018). Marine mammals, particularly cetaceans, sustain both ingestion-related and entanglement-related injuries; the latter may cause strangulation, reduced feeding capacity, and drowning (Isangedighi et al., 2018). Marine litter is estimated to threaten approximately 600 species globally, with 80% of documented organism–debris interactions attributable to plastic materials (Meem et al., 2021).

5.4. Freshwater Ecosystems and the Laurentian Great Lakes

Research on plastic contamination in freshwater systems has expanded substantially, with the Laurentian Great Lakes comprising Lakes Superior, Michigan, Huron, Erie, and Ontario representing one of the most intensively studied freshwater plastic pollution systems globally (Yoga and Singh, 2020; Wagner, 2021; Arturo & Corcoran, 2022). Surveys of lake shorelines have detected high concentrations of pre-production pellets and fragmented microplastics, with commercial shorelines and urban littoral zones exhibiting the greatest densities. Plastic accumulation in freshwater habitats modifies benthic community structure, introduces persistent contaminants into food webs, and may alter the reproductive ecology of invertebrates and fish species dependent on nearshore habitats (Shah et al., 2021; Sivaraman and Siddhuraju, 2022; Rajabattula et al., 2025).

6. Impacts on Soil and Edaphic Biodiversity

6.1. Physical and Chemical Alteration of Soil Properties

Microplastics that deposit within terrestrial systems modify the physical and chemical properties of soils, alter the structural and functional diversity of microbial communities, and accumulate within plant tissues (Hanif et al., 2024). Through absorption of environmental contaminants, microplastics increase the bioavailability of toxic substances and can alter soil aggregate structure, bulk density, and porosity with cascading effects on water retention and aeration (Farrelly et al., 2021; Elegbeleye et al., 2023; Hanif et al., 2024; Dutta et al., 2025).

6.2. Effects on Soil Fauna and Nutrient Cycling

Soil macro- and meso-fauna including earthworms, nematodes, springtails, and mites are primary vectors of microplastic redistribution within soil profiles. In earthworms, ingested plastic fragments may be mechanically ground into finer particles, which are subsequently dispersed through egestion, surface attachment, and burrowing activities (Rehman et al., 2025). Microplastics discharge from earthworm bodies into deeper soil horizons via bioturbation, altering microbial habitat conditions and decomposition dynamics. Microplastics have been demonstrated to affect soil material cycling by influencing carbon, nitrogen, and phosphorus availability, with implications for primary and secondary ecosystem productivity (Rillig et al., 2021). Arthropods, which reach peak densities in the uppermost 10 cm of soil, further contribute to vertical microplastic transport (Singh et al., 2019).

7. Bioaccumulation, Trophic Transfer, and Human Health Implications

Plastic particles particularly microplastics function as reservoirs for hydrophobic persistent organic pollutants (POPs), polycyclic aromatic hydrocarbons, polychlorinated biphenyls, and heavy metals, concentrating these toxicants at surface concentrations orders of magnitude above ambient seawater levels (Rochman et al., 2013). Upon ingestion by aquatic organisms, sorbed contaminants may desorb into gastrointestinal tissues, entering circulation and accumulating in lipid-rich tissues. Through trophic transfer, contaminant loads are amplified across successive trophic levels a process of biomagnification that imposes greatest toxicological risk on apex predators and the humans that consume marine food products (Rochman et al., 2013).

Plastics also contain additive chemicals introduced during manufacture including plasticizers such as phthalates, flame retardants such as polybrominated diphenyl ethers, and stabilizers many of which exhibit endocrine-disrupting properties (Wright & Kelly, 2017). Disruption of endocrine function in aquatic organisms can impair reproductive success, alter sex ratios, and reduce offspring viability. Microplastic particles have been detected in human blood, lung tissue, and placentae, though the clinical significance of such exposures remains an active area of investigation. Additionally, plastic degradation under environmental conditions releases greenhouse gases including methane and ethylene, contributing incrementally to atmospheric warming and potentially interfering with marine carbon fixation by phytoplankton (UNEP, 2018).

Addressing plastic pollution in aquatic environments necessitates a systemic, multi-scalar approach integrating regulatory, technological, economic, and behavioural interventions. At the policy level, transition toward a circular plastic economy emphasizing material reduction, reuse, and end-of-life recyclability has been identified as the most effective strategy, with modelling indicating a potential 80% reduction in plastic pollution within two decades under ambitious but feasible scenarios (UNEP, 2023). International binding agreements, extended producer responsibility frameworks, and bans on single-use plastics represent foundational regulatory instruments (Derraik, 2002; Syberg et al., 2021).

Improved waste management infrastructure particularly in rapidly urbanizing regions of South and Southeast Asia is a prerequisite for reducing plastic leakage into waterways (Deudero and Alomar, 2015; Jambeck et al., 2015). Technological innovation in biodegradable polymer substitutes, advanced mechanical and chemical recycling, and wastewater microplastic filtration systems represents a complementary suite of solutions. Demand-side interventions including public education, corporate sustainability commitments, and economic instruments such as plastic levies can reduce consumption at the source. Community-led shoreline and riverine cleanup programmes, while insufficient as standalone interventions, contribute to monitoring data and localized pollution reduction (Mugobo et al., 2022; Chauhan et al., 2022).

9. Conclusion

Plastic pollution constitutes a multifaceted and escalating environmental stressor with demonstrably severe consequences for aquatic biodiversity at organismal, population, community, and ecosystem levels. The evidence reviewed herein demonstrates that plastic debris in both macro and microscopic forms harms taxonomically diverse organisms through direct physical mechanisms and indirect chemical pathways, disrupts food web dynamics through bioaccumulation and trophic transfer, degrades critical habitats including coral reefs and freshwater littoral zones, and compromises the delivery of essential ecosystem services. The contamination of aquatic food chains poses a documented risk to human health that remains incompletely characterized. Mitigation of this crisis demands immediate, coordinated action encompassing global policy reform, circular economic models, enhanced waste infrastructure, and societal transformation in the production and consumption of plastic materials. Without substantive intervention, the trajectory of plastic accumulation in aquatic ecosystems will continue to erode biodiversity and undermine the ecological foundations upon which both aquatic life and human well-being depend.

Author Contributions

Anshul: Conceptualization; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing – original draft; Archit Kapil: Data curation; Visualization; Vansh Gupta: Data curation; Methodology; Resources; Software; Validation; Visualization; Writing – original draft; Writing – review & editing; Gayatri Saini: Data curation; Writing – original draft; Sandeep Kumar Barwal: Supervision; Writing – original draft; Writing – review & editing; Harsh Singh: Writing – original draft; Writing – review & editing.

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