published by

EQA - International Journal of Environmental Quality
ISSN 2281-4485 - Vol. 75 (2026): 1 – 24
Journal homepage: https://eqa.unibo.it/

Marine plastic pollution: ecological risks, environmental distribution, and sustainable mitigation perspectives

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Article info
Received 21/5/2026; received in revised form 17/8/2026; accepted 2/9/2026
DOI: 10.60923/issn.2281-4485/25086

Abstract
Marine plastic pollution has become a major environmental challenge affecting marine biodiversity, ecosystem stability, environmental quality, and human well-being across coastal and oceanic ecosystems. Increasing plastic production, ineffective waste management, urbanization, and transboundary transport processes have accelerated the accumulation of macroplastics, microplastics, and nanoplastics in aquatic environments. This review critically evaluates the major sources, transport pathways, environmental distribution, ecological impacts, socio-economic implications, and mitigation strategies associated with marine plastic contamination. Plastic pollutants primarily originate from municipal waste discharge, riverine transport, fisheries, aquaculture, industrial activities, wastewater effluents, and maritime operations, followed by widespread redistribution through hydrodynamic and atmospheric processes. Major ecological consequences include entanglement, ghost fishing, ingestion, trophic transfer, oxidative stress, endocrine disruption, habitat degradation, pathogen dispersal, and biodiversity decline. Plastic contamination additionally threatens fisheries productivity, seafood safety, tourism economies, public health, and ecosystem-service sustainability. Current mitigation approaches increasingly emphasize circular-economy transition, extended producer responsibility, international governance frameworks, ecosystem-based management, and advanced environmental monitoring technologies. However, substantial challenges remain regarding policy implementation, recycling efficiency, technological inequality, and transboundary waste leakage. Integrated environmental governance, sustainable production systems, scientific monitoring, and evidence-based mitigation strategies are therefore essential for improving long-term marine environmental quality and reducing global plastic contamination.

Keywords: *Anthropogenic pollution; Coastal ecosystems; Ecotoxicology; Environmental management; Marine debris; Marine pollution; Microplastics; Nanoplastics; Plastic waste; Sustainable mitigation.*

Introduction

Plastic pollution has emerged as one of the most persistent and complex environmental challenges affecting marine and coastal ecosystems worldwide (Shih, 2026). The continuous growth of plastic production, unsustainable consumption patterns, ineffective waste management systems, and uncontrolled discharge of plastic residues into aquatic environments have intensified the global burden of marine contamination (Adom, 2026; Ghobish et al., 2025). Plastics possess several advantageous properties, including durability, flexibility, lightweight structure, low production cost, and chemical resistance, which have promoted their extensive utilization across industrial, agricultural, medical, packaging, transportation, construction, and domestic sectors (De Deus et al., 2024). However, these same characteristics contribute to the long-term persistence and environmental accumulation of plastic contaminants in natural ecosystems (Shih, 2026). Recent global estimates indicate that more than 400 million tonnes of plastic are produced annually, while approximately 19-23 million tonnes of plastic waste enter aquatic ecosystems every year through rivers, drainage systems, coastal activeties, fisheries, maritime transportation, urban runoff,

DOI: 10.60923/issn.2281-4485/25086

and industrial discharge (UNEP, 2026). Plastic pollution has consequently evolved into a transboundary environmental issue with ecological, economic, toxicological, and public health implications (Snehamayee et al., 2026). Marine ecosystems are particularly vulnerable because oceans act as the final sink for a substantial proportion of mismanaged terrestrial plastic waste (Marcharla et al., 2024). Plastics currently constitute nearly 85% of total marine litter globally, demonstrating the dominance of synthetic polymer contamination within aquatic environments (UNEP, 2021).

Marine and coastal ecosystems provide indispensable ecological services and socio-economic benefits, including food production, biodiversity conservation, nutrient cycling, climate regulation, carbon sequestration, tourism, transportation, recreation, and fisheries support (Koundouri et al., 2026; Nawab et al., 2025). However, the increasing accumulation of plastic debris threatens ecosystem integrity and environmental quality across pelagic, benthic, estuarine, intertidal, and deep-sea habitats (Villarrubia-Gómez et al., 2017). Plastic contaminants are now widely distributed from coastal shorelines to remote oceanic gyres, polar regions, abyssal sediments, coral reef systems, mangroves, estuaries, and marine organisms representing multiple trophic levels. Previous investigations confirmed the occurrence of plastic debris and microplastics in seawater, sediments, plankton, bivalves, crustaceans, fish, marine mammals, seabirds, and commercially important seafood species (Browne et al., 2011; Cole et al., 2013; Wang et al., 2018). Plastic pollutants are generally categorized into macroplastics, mesoplastics, microplastics, and nanoplastics according to particle size (Adom, 2026; Marcharla et al., 2024). Among these categories, microplastics and nanoplastics have received substantial scientific attention because of their high environmental mobility, persistence, bioavailability, and toxicological significance. Microplastics originate either as primary particles intentionally manufactured in microscopic sizes for industrial and commercial applications or as secondary particles generated through fragmentation of larger plastic debris under physical, chemical, mechanical, and biological degradation processes. Environmental weathering mechanisms including ultraviolet radiation, hydrolysis, oxidation, wave abrasion, salinity fluctuations, and thermal stress progressively degrade larger plastic materials into smaller particles that can persist within aquatic systems for prolonged periods (Thushari and Senevirathna, 2020; Andrady, 2011; Barnes et al., 2009). The ecological implycations of marine plastic pollution are multidimensional and increasingly severe (Nguyen et al., 2023). Entanglement, ingestion, suffocation, starvation, habitat modification, invasive species dispersal, trophic transfer, physiological stress, reproductive disruption, and toxicological contamination represent major ecological consequences associated with plastic accumulation (Adom, 2026). Plastic ingestion has been documented in hundreds of marine species including fish, sea turtles, seabirds, crustaceans, mollusks, and marine mammals. The resemblance of microplastic particles to natural prey items facilitates unintentional ingestion by suspension feeders, deposit feeders, zooplankton, benthic organisms, and pelagic species (Cole et al., 2014; Wright et al., 2013). Moreover, plastics can adsorb and transport persistent organic pollutants, antibiotics, pathogenic microorganisms, and heavy metals, thereby enhancing environmental toxicity and ecological risk within marine food webs (Li et al., 2025). Recent studies further demonstrate that plastic contaminants are capable of transferring across trophic levels and potentially entering the human food chain through seafood consumption. Microplastics have already been detected in fish muscles, shellfish tissues, sea salt, drinking water, and other food products, raising serious concerns regarding food safety and human health (Fulke et al., 2025). Additionally, plastic-associated chemicals such as bisphenol-A, phthalates, flame retardants, and persistent organic pollutants may induce endocrine disruption, oxidative stress, inflammatory responses, and cellular toxicity in exposed organisms (Teuten et al., 2009; Oehlmann et al., 2009). Emerging evidence also suggests that nanoplastics possess enhanced biological reactivity and translocation potential due to their extremely small particle size and large surface area. Apart from ecological deterioration, marine plastic pollution imposes substantial socio-economic consequences on fisheries, aquaculture, tourism, navigation, coastal management, and public health sectors. Ghost fishing by abandoned, lost, or discarded fishing gear causes economic losses and biodiversity depletion in commercial fisheries, while coastal litter accumulation reduces the aesthetic and recreational value of beaches and marine tourism destinations (Walton et al., 2025). The economic burden associated with marine plastic pollution includes cleanup expenditures, fisheries damage, ecosystem degradation, healthcare impacts, and productivity losses. Global environmental and social costs associated with plastic pollution are estimated to range between US$300 billion and US$600 billion annually (United Nations, n.d.). The growing severity of marine plastic

DOI: 10.60923/issn.2281-4485/25086

contamination has intensified international concern regarding the need for integrated mitigation strategies and sustainable waste management frameworks (Stoett et al., 2024). Several global initiatives, including the United Nations Environment Assembly resolutions, the ongoing international plastics treaty negotiations, the MARPOL Convention, and regional marine litter action plans, have emphasized urgent intervention to reduce plastic leakage into aquatic ecosystems (UNEP, n.d.). Nevertheless, the rapid increase in plastic production, limited recycling efficiency, inadequate waste infrastructure, and inconsistent policy implementation continue to hinder effective pollution control. Current projections indicate that plastic waste generation may nearly triple by 2060 under business-as-usual conditions if substantial interventions are not implemented (Thushari and Senevirathna, 2020; UNEP, n.d.). Although numerous studies have investigated individual aspects of marine plastic contamination, a concise and synthesis-oriented environmental review integrating contamination sources, environmental distribution, ecological consequences, toxicological implications, and mitigation perspectives remains necessary for environmental quality management. Therefore, the present review critically evaluates the major sources and transport pathways of marine plastic pollution, global occurrence and distribution patterns, ecological and socio-economic impacts, and current mitigation approaches associated with plastic contamination in marine and coastal ecosystems. The study further highlights emerging environmental concerns, recent scientific developments, and future management priorities for improving marine environmental quality and promoting sustainable aquatic ecosystem protecttion.

Methodology

Review scope and conceptual framework

The present review was designed to critically synthesize current scientific knowledge regarding the sources, environmental distribution, ecological risks, socio-economic implications, governance frameworks, and mitigation strategies associated with marine plastic pollution across coastal and oceanic ecosystems. The review primarily focused on macroplastics, microplastics, and nanoplastics within marine environments, with particular emphasis on contamination pathways, ecotoxicological mechanisms, ecosystem degradation, biodiversity impacts, marine environmental quality, and sustainable pollution-control approaches. The conceptual structure of the review was developed using an integrated environmental-quality perspective linking pollution sources, transport dynamics, ecological disruption, socio-economic vulnerability, environmental governance, and circular-economy transition frameworks.

Literature search strategy

Relevant scientific literature was collected through comprehensive database searches conducted using Scopus, Web of Science, ScienceDirect, SpringerLink, Google Scholar, and institutional repositories. International environmental reports, marine governance frameworks, and technical documents published by organizations including the United Nations Environment Programme (UNEP), Food and Agriculture Organization (FAO), Organisation for Economic Cooperation and Development (OECD), International Maritime Organization (IMO), World Health Organization (WHO), and GESAMP were additionally evaluated to strengthen the environmental-governance and sustainability dimensions of the review. Searches were conducted using combinations of keywords including “marine plastic pollution”, “microplastics”, “nanoplastics”, “marine litter”, “plastic contamination”, “ecotoxicology”, “marine biodiversity”, “plastic governance”, “circular economy”, “marine environmental quality”, “plastic waste management”, “trophic transfer”, and “marine ecosystem degradation”. Greater emphasis was placed on recent investigations published between 2020 and 2026 to incorporate updated scientific evidence regarding microplastic occurrence, toxicological mechanisms, environmental monitoring technologies, circular economy strategies, and international governance responses.

Literature swelection and data evaluation

The literature selection process prioritized peer-reviewed articles, high-impact environmental studies, internationally recognized technical reports, and globally relevant environmental-policy documents directly associated with marine plastic contamination and environmental quality management. Foundational investigations published before 2020 were additionally incurporated to establish conceptual understanding of plastic fragmentation processes, trophic-transfer mechanisms, contaminant adsorption behavior, marine ecological disruption, and plastic-associated toxicological pathways. Studies were selected based on their scientific relevance, environmental significance, methodological clarity, ecosystem applicability, and contribution

DOI: 10.60923/issn.2281-4485/25086

to understanding marine plastic distribution, ecological effects, socio-economic impacts, and mitigation strategies. Preference was given to studies addressing coastal ecosystems, oceanic pollution transport, biodiversity risks, waste-management systems, marine governance frameworks, and sustainable environmental interventions. Duplicate, weakly relevant, or scientifically unsupported references were excluded during the review synthesis process to improve analytical consistency and thematic coherence.

Thematic synthesis and analytical approach

The collected literature was critically synthesized using a thematic environmental-review approach emphasizing integrated interpretation rather than descriptive summarization. The analysis focused on five major thematic dimensions: (i) sources and environmental transport pathways of marine plastics; (ii) ecological and ecotoxicological consequences; (iii) socio-economic and public-health implications; (iv) governance frameworks and mitigation strategies; and (v) scientific monitoring, technological innovation, and sustainability-oriented management approaches.

Comparative synthesis tables were developed to consolidate complex scientific information regarding contamination sources, ecological risks, governance interventions, socio-economic impacts, and mitigation pathways. Particular emphasis was placed on integrating recent evidence concerning microplastic toxicity, environmental monitoring technologies, extended producer responsibility (EPR), circular-economy transition, and international marine-plastic governance mechanisms relevant to long-term marine environmental-quality improvement.

Sources, transport pathways, and environmental fate of marine plastic contaminants

Marine plastic contamination originates from interconnected terrestrial, coastal, industrial, and ocean-based anthropogenic activities that collectively regulate the generation, transport, fragmentation, redistribution, and long-term persistence of plastic debris within aquatic ecosystems (Andrady, 2011; Barnes et al., 2009). Land-derived inputs constitute the dominant source of marine plastic leakage, contributing approximately 75-80% of total marine debris through municipal waste discharge, urban runoff, riverine transport, industrial effluents, wastewater emissions, tourism activities, and coastal settlement expansion (UNEP, 2026). Rapid urbanization, population growth, excessive consumption of single-use plastics, and inadequate waste management infrastructure have substantially intensified plastic transfer into marine environments (Muñiz and Rahman, 2025), particularly across densely populated coastal regions and developing economies (Law, 2017; OECD, 2022). River systems function as major environmental conveyors linking terrestrial plastic waste to estuarine and marine ecosystems (Lebreton et al., 2017; Meijer et al., 2021). Mismanaged macroplastics deposited within urban landscapes undergo progressive fragmentation during environmental exposure and are subsequently transported into coastal waters through hydrological networks, stormwater drainage, and freshwater discharge systems (Barnes et al., 2009; Andrady, 2011). Recent modelling studies estimated that a limited number of highly polluted rivers contribute disproportionately to global oceanic plastic discharge, particularly within Asia and Africa where waste management capacity remains insufficient (Meijer et al., 2021). Extreme climatic events including flooding, cyclones, monsoonal runoff, hurricanes, and storm surges further accelerate plastic mobilization and offshore redistribution, thereby enhancing transboundary contamination risks across pelagic and benthic marine environments (Thompson et al., 2005; UNEP, 2026). Ocean-based activities also represent substantial contributors to marine plastic accumulation (Gall and Thompson, 2015). Commercial fisheries, aquaculture operations, maritime transportation, offshore industries, and shipping activities release abandoned, lost, or discarded fishing gear (ALDFG), synthetic ropes, fishing lines, nets, buoys, packaging materials, and operational plastic waste directly into marine ecosystems (FAO, 2023; IMO, 2024). Fishing-related plastics are particularly hazardous because of their durability, buoyancy, persistence, entanglement capacity, and long-range transport potential across oceanic circulation systems (Gall and Thompson, 2015; Revel et al., 2019). Recent evidence indicates that fisheries and aquaculture sectors significantly contribute to macroplastic accumulation within subtropical gyres, coastal biodiversity hotspots, and deep-sea benthic habitats (FAO, 2023). Plastic contaminants occur across multiple particle-size classes including macroplastics, mesoplastics, microplastics, and nanoplastics, each exhibiting distinct environmental behaviors and ecological implications (Barnes et al., 2009; Bergui et al., 2026). Among these categories, microplastics and nanoplastics represent the most environmentally pervasive and biologically reactive forms because of their small particle size, high surface-area-to-volume ratio, mobility, persistence, and bioavailability (Wright

DOI: 10.60923/issn.2281-4485/25086

et al., 2013; Guo and Wang, 2019). Primary microplastics originate from intentionally manufactured microscopic polymers used in industrial abrasives, cosmetics, pharmaceuticals, paints, and textile products (Browne et al., 2008). In contrast, secondary microplastics are generated through progressive fragmentation of larger plastic debris under ultraviolet radiation, thermo-oxidative degradation, hydrolysis, mechanical abrasion, and biological weathering processes (Andrady, 2011; Barnes et al., 2009). Continuous environmental fragmentation therefore increases microscopic plastic abundance within marine ecosystems and intensifies ecological exposure pathways throughout aquatic food webs (Cole et al., 2011; Bergui et al., 2026). Polymer physicochemical properties strongly regulate the environmental fate, vertical distribution, and transport behavior of marine plastic contaminants (Guo and Wang, 2019; Cole et al., 2014). Low-density polymers such as polyethylene (PE) and polypropylene (PP) predominantly remain suspended within surface waters and oceanic gyres because of their buoyant characteristics (Guo and Wang, 2019; G. Thushari and Senevirathna, 2020). Conversely, denser polymers including polyethylene terephthalate (PET), polyvinyl chloride (PVC), and polyamide (PA) exhibit greater sedimentation potential and accumulate preferentially within benthic sediments and deep-sea environments, (Cole etal., 2014; Guo and Wang, 2019). Consequently plastic contaminants are now ubiquitously distributed across estuaries, mangroves, beaches, coral reefs, open-ocean gyres, polar waters, abyssal sediments, and marine biota representing multiple trophic levels (Budihardjo et al., 2024; Martin et al., 2017). Recent investigations additionally identify wastewater treatment plants, atmospheric deposition, synthetic textile fibers, tire wear particles, and urban dust as emerging pathways intensifying marine microplastic contamination (Guo and Wang, 2019; Liu and Zheng, 2025). Synthetic microfibers released during domestic laundering and textile degradation represent one of the most abundant forms of secondary microplastics detected within aquatic environments worldwide (Browne et al., 2011; Liu and Zheng, 2025). Atmospheric transport mechanisms further facilitate long-range dispersal of microscopic plastic particles into remote marine ecosystems, including polar and deep-ocean regions previously considered relatively isolated from anthropogenic pollution (Guo and Wang, 2019; Xu et al., 2025). As summarized in Table 1, marine plastic contamination is governed by complex interactions among anthropogenic activities, environmental transport pathways, polymer properties, climatic processes, and hydrodynamic conditions, thereby necessitating integrated mitigation strategies and ecosystem scale environmental management approaches.

Ecological disruption and environmental risks associated with marine plastic pollution

Ecotoxicological and ecosystem-level impacts of plastic contamination

Plastic contamination exerts multidimensional ecological pressures on marine ecosystems through physical, chemical, biological, and toxicological pathways that collectively alter ecosystem structure, trophic functioning, biodiversity stability, and environmental quality (Shih, 2026; Gall and Thompson, 2015; Wright et al., 2013). The ecological severity of plastic pollution is strongly regulated by contaminant size, polymer composition, environmental persistence, particle abundance, adsorption capacity, and biological accessibility across different trophic levels (Cole et al., 2014; Guo and Wang, 2019). Macroplastics primarily induce physical impacts including entanglement, smothering, habitat alteration, and ghost fishing, whereas microplastics and nanoplastics generate complex ecotoxicological consequences through ingestion, cellular translocation, oxidative stress, inflammatory responses, and contaminant transfer within marine food webs (Wright et al., 2013; Bergui et al., 2026). Entanglement and ingestion represent the most extensively documented ecological consequences associated with macroplastic contamination (Gall and Thompson, 2015). Abandoned, lost, or discarded fishing gear (ALDFG), synthetic ropes, nets, and plastic packaging materials frequently entangle marine megafauna including sea turtles, seabirds, marine mammals, sharks, and commercially important fish species (Revel et al., 2019). Entanglement can induce drowning, suffocation, impaired locomotion, reproductive failure, tissue laceration, and increased predation vulnerability, thereby reducing survival probability and population fitness (Gall and Thompson, 2015). Ghost fishing caused by discarded fishing gear additionally contributes to prolonged biodiversity depletion and mortality within benthic and pelagic ecosystems (FAO, 2023). Microplastic ingestion has been documented across numerous marine taxa including zooplankton, bivalves, crustaceans, polychaetes, fish, seabirds, marine mammals, and coral-associated organisms (Cole et al., 2013; Lusher et al., 2013). The

DOI: 10.60923/issn.2281-4485/25086

Table 1. *Major pathways controlling the environmental distribution and persistence of marine plastic pollutants*

Source sector	Dominant plastic contaminants	Primary transport mechanism	Major environmental sink	Principal ecological implication	Representative references
Municipal and urban waste	Single-use plastics, multilayer packaging, plastic bags	Urban runoff, drainage discharge, riverine transport	Coastal waters, beaches, estuaries	Macroplastic accumulation and secondary fragmentation	UNEP (2026)
Riverine discharge	Fragmented plastics, microplastics, urban debris	Freshwater–marine connectivity	Nearshore and estuarine systems	Continuous oceanic plastic loading	Lebreton et al. (2017); Meijer et al. (2021)
Wastewater treatment effluents	Synthetic microfibers, cosmetic microbeads	Wastewater discharge pathways	Coastal waters and sediments	Persistent microplastic contamination	Browne et al. (2011)
Fisheries and aquaculture	Nets, ropes, fishing lines, buoys, traps	Gear abandonment and offshore loss	Pelagic and benthic habitats	Ghost fishing and faunal entanglement	Gall and Thompson (2015); FAO (2023)
Maritime transportation	Operational plastic waste, cargo residues	Shipping discharge and accidental release	Open-ocean circulation zones	Long-range transboundary pollution	IMO (2024)
Industrial activities	Resin pellets, polymer granules	Industrial leakage and effluent release	Riverine and coastal sediments	Primary microplastic contamination	Cole et al. (2011); UNEP (2026)
Tourism and recreation	Bottles, disposable plastics, food wrappers	Beach littering and shoreline deposition	Intertidal ecosystems	Habitat degradation and aesthetic loss	Thushari et al. (2017)
Atmospheric deposition	Synthetic fibers, tire wear particles, urban dust	Wet and dry atmospheric fallout	Remote marine regions and ocean surface	Diffuse microplastic dispersal	Bergui et al. (2026); Zhang et al. (2025)
Extreme climatic events	Mixed plastic debris	Flooding, cyclonic runoff, storm surges	Offshore and deep-sea environments	Rapid redistribution of contaminants	Thompson et al. (2005); UNEP (2026)
Environmental weathering	Secondary microplastics and nanoplastics	UV degradation, hydrolysis, abrasion	Entire marine water column	Enhanced trophic bioavailability	Andrady (2011); Bergui et al. (2026)

small particle size and prey-like appearance of microplastics facilitate unintentional ingestion by suspension feeders, filter feeders, deposit feeders, and pelagic predators (Auta et al., 2017; Wright et al., 2013). Following ingestion, microplastics may accumulate within gastrointestinal tissues, digestive glands, circulatory systems, and cellular compartments, causing mechanical blockage, feeding suppression, reduced nutrient assimilation, inflamematory responses, and metabolic stress (Browne et al., 2008; Von Moos et al., 2012). Experimental studies further demonstrate that nanoplastics possess elevated cellular penetration capacity because of their nanoscale dimensions and enhanced surface reactivity (Bergui et al., 2026). Beyond physical toxicity, plastic particles function as environmental vectors for hazardous chemical contaminants including persistent organic pollutants (POPs), heavy metals, antibiotics, endocrine-disrupting compounds, and pathogenic microorganisms (Cole et al., 2014; Guo et al., 2019). Hydrophobic contaminants including polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons (PAHs), organochlorine pesticides, and flame retardants exhibit strong adsorption affinity toward plastic polymers, thereby increasing toxicological exposure risks following biological ingestion (Teuten et al., 2009; Cole et al., 2014). Plastic-associated additives such as bisphenol-A (BPA), phthalates, and brominated flame retardants may additionally induce endocrine disruption, reproductive toxicity, oxidative damage, developmental abnormalities, and immunological stress within expo-

DOI: 10.60923/issn.2281-4485/25086

sed organisms (Oehlmann et al., 2009; Lithner et al., 2011). Recent evidence further indicates that microplastics act as ecological substrates for microbial colonization and pathogen dispersal within marine ecosystems (Yu and Singh, 2023; Zettler et al., 2013). The "plastisphere" formed on plastic surfaces facilitates the attachment and transport of bacteria, algae, fungi, and invasive species across geographically distant marine habitats (Macan et al., 2025). Pathogenic genera including Vibrio spp. have been identified on floating plastic debris, raising concerns regarding disease transmission, ecosystem destabilization, and biodiversity disruption within sensitive marine environments (Zettler et al., 2013). Floating plastics additionally enhance biological rafting mechanisms that facilitate transboundary dispersal of invasive species into ecologically vulnerable ecosystems (Corinaldesi et al., 2021). At the ecosystem scale, plastic contamination contributes to habitat degradation, biodiversity decline, physicochemical alteration, and trophic instability across marine environments (Thevenon et al., 2014). Plastic deposition over coral reefs, man-groves, seagrass beds, and benthic habitats reduces light penetration, modifies sediment characteristics, alters oxygen dynamics, and disrupts primary productivity processes (Carson et al., 2011; Theve-non et al., 2014). Microplastic accumulation within sediments may additionally alter porosity, thermal conductivity, and biogeochemical cycling, thereby affecting benthic invertebrate survival and ecosy-stem functioning (Carson et al., 2011). Coral-associated plastic contamination has also been linked with elevated disease prevalence, tissue necrosis, and reduced reef resilience under multiple environmental stressors (Lamb et al., 2018). The ecological impacts of marine plastics therefore extend far beyond visible debris accumulation and increasingly represent a systemic environmental threat affecting ecosystem resilience, trophic interactions, biodiversity conservation, and long-term marine environmental quality (Mejjad et al., 2025). As summarized in Tables 2 and 3, plastic contaminants exert interconnected organism-level, community-level, and ecosystem-scale consequences through complex physical, toxicological, and ecological pathways.

Table 2. *Major ecotoxicological mechanisms associated with marine plastic contamination.*

Impact mechanism	Dominant plastic category	Biological target	Primary ecological consequence	Representative references
Entanglement	Macroplastics, fishing gear	Sea turtles, marine mammals, seabirds, fish	Drowning, tissue injury, impaired mobility	Gall and Thompson (2015)
Ghost fishing	Abandoned fishing gear	Commercial fish and benthic fauna	Long-term biodiversity depletion	FAO (2023); Revel et al. (2019)
Gastrointestinal blockage	Microplastics, fragments, fibers	Fish, mollusks, crustaceans	Feeding suppression and starvation	Wright et al. (2013); Lusher et al. (2013)
Cellular translocation	Nanoplastics	Cellular and circulatory systems	Oxidative stress and inflammatory damage	Bergui et al. (2026); Browne et al. (2008)
Toxic chemical transfer	Plastic-associated POPs and additives	Multiple trophic levels	Endocrine disruption and reproductive toxicity	G. Thushari & Senevirathna. (2020); Oehlmann et al. (2009)
Heavy metal adsorption	Microplastics and nanoplastics	Aquatic organisms	Bioaccumulation and toxicological stress	Guo and Wang (2019); G. Thushari & Senevirathna. (2020)
Antibiotic transport	Polymer-associated pharmaceuticals	Marine microbial communities	Antibiotic resistance proliferation	Guo et al. (2019)
Pathogen dispersal	Floating plastic debris	Coral reefs and coastal ecosystems	Disease transmission and ecosystem destabilization	Zettler et al. (2013)
Invasive species rafting	Floating macroplastics	Coastal biodiversity hotspots	Biogeographical species redistribution	Goldstein et al. (2014)
Sediment modification	Sediment-associated microplastics	Benthic ecosystems	Altered porosity and habitat degradation	Carson et al. (2011); Thevenon et al. (2014)

DOI: 10.60923/issn.2281-4485/25086

Table 3. *Ecosystem-level consequences of marine plastic contamination across coastal and oceanic environments.*

Ecosystem component	Plastic-driven alteration	Major ecological implication	Environmental significance	Representative references
Coral reef systems	Plastic deposition and pathogen transport	Coral disease and reef degradation	Reduced reef resilience and biodiversity	Lamb et al. (2018); Thevenon et al. (2014)
Mangrove ecosystems	Sediment-associated plastic accumulation	Root smothering and habitat stress	Nursery habitat deterioration	Deakin et al. (2025); UNEP (2026)
Seagrass habitats	Surface shading and sediment contamination	Reduced photosynthetic efficiency	Decline in primary productivity	Carson et al. (2011); UNEP (2026)
Pelagic ecosystems	Floating plastic accumulation	Trophic transfer and ingestion	Food-web destabilization	Cole et al. (2013); Wright et al. (2013)
Deep-sea benthic systems	Dense polymer sedimentation	Long-term contaminant persistence	Chronic ecological exposure	Woodall et al. (2014); Martin et al. (2017)
Estuarine environments	Riverine microplastic loading	Elevated contamination gradients	Ecological vulnerability hotspots	Lima et al. (2014); Peters and Bratton (2016)
Polar marine systems	Atmospheric and oceanic plastic transport	Remote ecosystem contamination	Global-scale pollutant dispersal	Bergui et al. (2026); Bergmann et al. (2017)
Intertidal zones	Macroplastic deposition	Habitat modification and faunal stress	Coastal ecosystem degradation	Thushari et al. (2017); Gall and Thompson (2015)
Marine food webs	Microplastic ingestion and bioaccumulation	Trophic contaminant transfer	Seafood safety and ecological risk	G. Thushari & Senevirathna. (2020); Wright et al. (2013)
Biodiversity structure	Chronic ecological disturbance	Species decline and ecological imbalance	Reduced ecosystem resilience	Gall and Thompson (2015); Thevenon et al. (2014)

Socio-economic vulnerability and human-system implications of marine plastic pollution

Marine plastic pollution generates substantial socio-economic disruption by impairing fisheries productivity, aquaculture sustainability, tourism revenue, maritime operations, coastal infrastructure, public health security, and ecosystem-service delivery across marine and coastal regions (Beaumont et al., 2019; UNEP, 2026). The socio-economic burden of plastic contamination extends beyond visible environmental degradation and increasingly represents a multidimensional sustainability challenge affecting economic stability, food security, employment systems, and human well-being at local, regional, and global scales (Macan et al., 2025; OECD, 2022). Recent global assessments estimate that the annual environmental and social costs associated with marine plastic pollution range between US$300-600 billion through ecosystem degradation, fisheries loss, tourism decline, waste management expenditure, and public-health impacts (UNEP, 2023). Commercial fisheries and aquaculture sectors are among the most economically vulnerable systems affected by marine plastic contamination (Revel et al., 2019). Abandoned, lost, or discarded fishing gear (ALDFG) contributes to ghost fishing, gear entanglement, stock depletion, habitat destruction, and mortality of commercially important species, thereby reducing fishery productivity and long-term resource sustainability (Gall and Thompson, 2015; Revel et al., 2019). Plastic accumulation additionally damages fishing vessels, propellers, nets, engines, and operatio-

DOI: 10.60923/issn.2281-4485/25086

nal infrastructure, generating increased maintenance costs, reduced fishing efficiency, and economic losses within artisanal and industrial fisheries (Beaumont et al., 2019). Contamination of seafood organisms by microplastics, persistent organic pollutants (POPs), and plastic-associated toxicants further threatens seafood safety and consumer confidence, thereby affecting international seafood markets and coastal livelihoods dependent on marine resources (Li et al., 2025; Cole et al., 2014). Marine tourism and coastal recreation are similarly affected by plastic contamination through deterioration of environmental aesthetics, ecological quality, and recreational safety (Macan et al., 2025; Beaumont et al., 2019). Plastic debris accumulation on beaches, coral reefs, mangroves, and coastal waters reduces the visual attractiveness and ecological integrity of tourism destinations, leading to declining tourist visitation and reduced tourism-generated revenue (UNEP, 2026). Tourism-oriented coastal economies, particularly small island developing states and biodiversity-dependent regions, are highly vulnerable because tourism activities are strongly linked with ecosystem health, recreational quality, and environmental cleanliness (Thevenon et al., 2014). Coral reef degradation associated with plastic contamination additionnally threatens diving, snorkeling, whale watching, and other marine ecotourism industries that contribute substantially to coastal economic systems (Lamb et al., 2018). Marine plastic pollution also imposes increasing economic pressure on coastal governance and waste-management systems (OECD, 2022). Coastal municipalities and environmental authorities allocate substantial financial resources toward beach cleaning, marine litter removal, waste transportation, and environmental remediation programs (Macan et al., 2025). The persistence and transboundary movement of marine plastics further complicate mitigation efforts and increase long-term management expenditure across coastal nations. Developing countries with limited waste-management infrastructure experience disproportionately higher environmental and economic burdens because of inadequate collection systems, uncontrolled dumping, and insufficient recycling capacity (UNEP, 2023). Public-health implications associated with marine plastic contamination are emerging as a major global concern (Leslie et al., 2022; WHO, 2022). Microplastics and nanoplastics have already been detected in seafood organisms (Li et al., 2025), sea salt, bottled water, drinking water, and atmospheric aerosols, indicating widespread human exposure pathways through ingestion and inhalation processes (Leslie et al., 2022). Plastic-associated chemicals including bisphenol-A (BPA), phthalates, brominated flame retardants, and heavy metals may induce endocrine disruption, oxidative stress, inflammatory responses, reproductive toxicity, metabolic dysfunction, and carcinogenic effects within exposed organisms and potentially humans (Oehlmann et al., 2009; Cole et al., 2014). Although uncertainties remain regarding long-term human toxicological thresholds, increasing evidence suggests that chronic exposure to microscopic plastic particles may represent a significant environmental-health challenge requiring urgent interdisciplinary investigation (WHO, 2022). Plastic contamination additionally undermines ecosystem-service provision and climate resilience across marine environments (Barletta, 2026; Beaumont et al., 2019). Coastal ecosystems including mangroves, coral reefs, seagrass meadows, and estuarine habitats provide essential provisioning, regulating, supporting, and cultural ecosystem services that sustain fisheries productivity, shoreline protection, biodiversity conservation, nutrient cycling, tourism development, and carbon sequestration (Song et al., 2026). Plastic-induced habitat degradation therefore weakens ecosystem functionality, reduces ecological resilience, and compromises long-term socio-economic sustainability under increasing anthropogenic and climatic stressors. The socio-economic impacts of marine plastic pollution are consequently interconnected with ecological degradation, environmental injustice, food-system vulnerability, and sustainable development challenges. As summarized in Table 4, marine plastic contamination exerts multidimensional economic, environmental, and public-health consequences across human and ecological systems, thereby emphasizing the urgent necessity for integrated governance frameworks, sustainable waste-management strategies, and ecosystem-based mitigation approaches.

Multi-scale governance and strategic responses to marine plastic pollution

International governance and global mitigation frameworks

The transboundary mobility of marine plastics has transformed plastic pollution into a global environmental governance challenge requiring coordinated in-

DOI: 10.60923/issn.2281-4485/25086

Table 4. *Major socio-economic consequences and human-system risks associated with marine plastic pollution.*

Impact sector	Plastic-driven stressor	Socio-economic consequence	Long-term sustainability implication	Representative references
Commercial fisheries	Ghost fishing, stock depletion, gear damage	Reduced fishery productivity and economic loss	Declining marine resource sustainability	Revel et al. (2019)
Aquaculture systems	Microplastic contamination and habitat degradation	Reduced seafood quality and market value	Food-security vulnerability	G. Thushari & Senevirathna. (2020)
Tourism and recreation	Beach litter and coastal pollution	Declining tourist visitation and revenue loss	Economic instability in coastal economies	UNEP (2026)
Maritime transportation	Plastic entanglement in propellers and engines	Increased operational and maintenance costs	Reduced maritime efficiency	Beaumont et al. (2019)
Coastal governance	Waste accumulation and remediation requirements	Increased cleanup and waste-management expenditure	Long-term financial burden	OECD (2022); UNEP (2023)
Public health systems	Human exposure to microplastics and additives	Toxicological and health-related risks	Emerging environmental-health challenge	Leslie et al. (2022); WHO (2022)
Seafood safety	Trophic transfer of contaminants	Reduced consumer confidence	Market instability and food-system disruption	G. Thushari & Senevirathna. (2020)
Small island economies	Coastal ecosystem degradation	Reduced tourism and fishery income	Socio-economic vulnerability	Thevenon et al. (2014); UNEP (2026)
Ecosystem services	Habitat degradation and biodiversity decline	Loss of regulating and supporting services	Reduced climate resilience	Beaumont et al. (2019)
Coastal communities	Environmental deterioration and livelihood stress	Employment instability and social inequity	Sustainable development constraints	Lidström et al. (2026); UNEP (2023); OECD (2022)

ternational intervention across production, consumption, waste management, and environmental protection sectors (Koundouri et al., 2026; UNEP, 2023; OECD, 2022). International governance frameworks increasingly prioritize lifecycle-based mitigation strategies integrating plastic reduction, circular-economy transition, sustainable material design, extended producer responsibility (EPR), and transboundary waste regulation (Borrelle et al., 2020; Wu et al., 2025). Among existing instruments, MARPOL Annex V remains one of the principal international legal frameworks regulating ship-generated marine litter by prohibiting plastic disposal from maritime vessels (IMO, 2024). Simultaneously, the UNEA Resolution 5/14 initiated negotiations toward a legally binding global plastics treaty addressing the full lifecycle of plastics, including production control, recycling efficiency, waste leakage prevention, and environmental remediation (UNEP, 2026). Recent policy assessments identify this treaty process as a potentially transformative mechanism for harmonizing global plastic governance and strengthening international accountability (Wu et al., 2025). Additional governance instruments including the Basel Convention, Stockholm Convention, Convention on Biological Diversity (CBD), and Sustainable Development Goal 14 (SDG 14) contribute indirectly to marine plastic mitigation through hazardous-waste regulation, biodiversity conservation, chemical-risk management, and marine sustainability targets (Luo et al., 2025; United Nations, 2023). However, weak enforcement capacity, uneven technological infrastructure, low recycling efficiency, and inconsistent regulatory implementation continue to limit global mitigation effectiveness, particularly within developing

DOI: 10.60923/issn.2281-4485/25086

economies (UNEP, 2023; OECD, 2022).

Regional marine governance and ecosystem-based management strategies

Regional governance systems play a critical operational role in translating global environmental commitments into ecosystem-specific marine management actions (UNEP, 2026). Frameworks established under the UNEP Regional Seas Programme support coordinated monitoring, policy harmonization, scientific-data exchange, and marine-litter reduction across major regional marine systems including the Mediterranean, Baltic, Caribbean, and South Asian Seas (UNEP, 2026). The European Union Marine Strategy Framework Directive (MSFD) represents one of the most comprehensive regional marine-litter governance models through ecosystem-based monitoring and Good Environmental Status (GES) targets for marine ecosystems (Thanigaivel et al., 2025; FAO, 2023). Descriptor 10 specifically addresses marine litter and promotes standardized assessment of plastic abundance, ecolo-gical impacts, and mitigation effectiveness across European waters (Wu et al., 2025; UNEP, 2026). Regional initiatives increasingly target abandoned fishing gear, wastewater-derived microplastics, single-use plastics, and coastal waste leakage through circular-economy development, fisheries management, recycling infrastructure, and source-reduction policies (FAO, 2023; UNEP, 2026). Nevertheless, substantial disparities remain regarding monitoring capacity, financial investment, technological resources, and regulatory enforcement among regional coastal systems, particularly within developing nations and small island economies (OECD, 2022). As summarized in Table 5, contemporary marine plastic governance increasingly emphasizes integrated lifecycle intervention, ecosystem-based management, circular-economy transition, and transboundary environmental coopera-tion as core pillars for long-term marine pollution mitigation.

National policy actions and regulatory interventions for marine plastic mitigation

National governments increasingly implement regulatory, economic, and institutional interventions to reduce plastic leakage into aquatic ecosystems through source reduction, waste-management improvement, recycling expansion, and consumption control strategies (UNEP, 2023; OECD, 2022). National policies targeting single-use plastics, plastic bags, expanded polystyrene products, and non-recyclable packaging materials have expanded rapidly across both developed and developing economies because upstream prevention is considered more effective than downstream remediation approaches (Xanthos and Walker, 2017; UNEP, 2026). Regulatory mechanisms including product bans, levies, taxation systems, mandatory recycling targets, landfill restrictions, and eco-design requirements increasingly form the foundation of national plastic-governance frameworks (OECD, 2022). Several countries including Rwanda, Bangladesh, Kenya, New Zealand, members of the European Union, and selected states within the United States and India have implemented restrictions or bans on lightweight plastic bags and disposable plastic products to reduce environmental leakage and marine litter generation (UNEP, 2023). Simultaneously, national marine-litter action plans increasingly integrate circular-economy transition, extended producer responsibility (EPR), source segregation, and sustainable packaging systems within broader environmental sustainability agendas (OECD, 2022). Nevertheless, regulatory effectiveness remains strongly dependent on enforcement capacity, recycling infrastructure, public compliance, and institutional coordination, particularly across rapidly urbanizing developing economies (Borrelle et al., 2020).

Circular-economy approaches and the 3rs framework

The principles of reduction, reuse, and recycling (3Rs) constitute a central framework for minimizing plastic waste generation and reducing environmental contamination across terrestrial and marine ecosystems (Geyer et al., 2017; UNEP, 2023). Reduction strategies emphasizing sustainable consumption, eco-design, biodegradable alternatives, packaging minimization, and elimination of unnecessary single-use plastics are considered the most effective long-term interventions because they directly decrease virgin plastic production and waste generation (OECD, 2022). Reuse systems including refillable packaging, reusable containers, deposit-return schemes, and sustainable product redesign reduce material throughput and improve resource efficiency within circular economies (Plastics Europe, 2026). Recycling strategies further contribute to plastic mitigation by recovering post-consumer waste, reducing landfill dependence, and decreasing environmental leakage into aquatic ecosystems (Khan et al., 2024; Geyer et al., 2017). However, recent assessments indicate that global recycling efficiency remains critically low because of polymer heterogeneity, contamination, weak collection systems, and inadequa-

DOI: 10.60923/issn.2281-4485/25086

Table 5. *Major global and regional governance frameworks addressing marine plastic pollution and lifecycle mitigation.*

Governance framework	Scale	Core regulatory focus	Strategic intervention mechanism	Primary environmental objective	Key implementation challenge	Representative references
MARPOL Annex V	Global	Ship-generated marine litter	Prohibition of plastic disposal from vessels	Reduction of ocean-based plastic leakage	Weak enforcement and illegal discharge	IMO (2024); UNEP (2023)
UNEA Global Plastics Treaty negotiations	Global	Full plastic lifecycle governance	Legally binding international agreement	Global reduction of plastic pollution	Negotiation complexity and political consensus	UNEP (2026); Wu et al. (2025)
Basel Convention amendments	Global	Transboundary plastic waste movement	Plastic waste trade regulation	Control of hazardous and non-recyclable waste transfer	Limited enforcement capacity	Luo et al. (2025); UNEP (2019)
Stockholm Convention	Global	Persistent organic pollutants (POPs)	Chemical-risk restriction	Reduction of toxic contaminant exposure	Limited direct plastic-production control	Thushari & Senevirathna. (2020); UNEP (2023)
Convention on Biological Diversity (CBD)	Global	Biodiversity conservation	Ecosystem-based protection measures	Marine ecosystem resilience preservation	Weak compliance mechanisms	UNEP (2026)
SDG 14 ("Life Below Water")	Global	Marine sustainability targets	Integrated sustainable development framework	Reduction of marine pollution	Non-binding implementation structure	United Nations (2023)
UNEP Regional Seas Programme	Regional	Regional marine-litter coordination	Collaborative monitoring and policy harmonization	Ecosystem-scale pollution reduction	Uneven regional governance capacity	UNEP (2026)
EU Marine Strategy Framework Directive (MSFD)	Regional	Ecosystem-based marine management	Good Environmental Status (GES) targets	Standardized marine-litter reduction	High operational and monitoring costs	United Nations (2023); UNEP (2026)
Regional fisheries initiatives	Regional	Abandoned fishing gear management	ALDFG monitoring and retrieval programs	Reduction of ghost fishing impacts	Limited offshore monitoring infrastructure	FAO (2023)
Circular economy strategies	Global/Regional	Plastic production and consumption transition	Recycling, eco-design, material recovery	Reduction of virgin plastic dependency	Technological and financial barriers	OECD (2022); Borrelle et al. (2020)
Extended Producer Responsibility (EPR) frameworks	National/Regional	Producer accountability	Post-consumer waste recovery obligations	Improved collection and recycling efficiency	Weak industrial compliance	OECD (2022); UNEP (2023)
National single-use plastic bans	National/Regional	Consumption reduction	Plastic bag and packaging restrictions	Source-level waste minimization	Substitution and enforcement challenges	UNEP (2023); FAO (2023)
Marine litter monitoring networks	Regional/Global	Standardized environmental assessment	Harmonized monitoring methodologies	Improved evidence-based governance	Data inconsistency across regions	GESAMP (2019); UNEP (2026)

DOI: 10.60923/issn.2281-4485/25086

te recycling infrastructure (OECD, 2022). Consequently, integrated circular-economy transition remains essential for achieving sustainable marine plastic mitigation and long-term environmental-quality improvement.

Extended Producer Responsibility and lifecycle accountability mechanisms

Extended Producer Responsibility (EPR) has emerged as a major policy mechanism for shifting post-consumer waste-management responsibility from municipalities toward manufacturers, importers, and commercial distributors (OECD, 2022; UNEP, 2023). EPR frameworks promote lifecycle accountability by requiring producers to finance or manage product collection, recycling, recovery, and environmentally sound disposal systems (Mallick et al., 2024). These frameworks encourage sustainable product design, recyclable material innovation, reduced packaging intensity, and investment in waste-management infrastructure (OECD, 2022). Deposit-return systems, producer-financed recycling programs, mandatory recovery targets, and plastic-credit mechanisms increasingly operate under EPR-oriented policy structures across multiple economies (UNEP, 2023). Recent evidence suggests that EPR implementation can substantially improve collection efficiency, recycling performance, and circular-material recovery while reducing marine plastic leakage from urban systems (Raubenheimer and McIlgorm, 2018). However, weak industrial compliance, limited monitoring capacity, informal waste sectors, and insufficient financial investment continue to constrain EPR effectiveness within many developing countries (OECD, 2022).

Public-private partnerships and industrial engagement for plastic-free coastal systems

Industrial participation and private-sector collaboration are increasingly recognized as critical components of marine plastic governance because corporations, manufacturers, retailers, packaging industries, and supply-chain actors strongly influence plastic production, consumption, and waste generation patterns (UNEP, 2023; Plastics Europe, 2026). Public–private partnerships (PPPs) facilitate collaborative implementation of recycling infrastructure, sustainable packaging systems, waste-collection programs, and circular-economy innovation within coastal and urban environments (OECD, 2022). Several multinational corporations and industrial alliances have adopted voluntary commitments targeting recyclable packaging, recycled-content integration, virgin-plastic reduction, and elimination of unnecessary single-use plastics (Plastics Europe, 2026). Simultaneously, eco-labeling systems, green procurement policies, sustainable certification programs, and corporate environmental reporting increasingly encourage environmentally responsible production and consumption practices (UNEP, 2026). Nevertheless, concerns remain regarding greenwashing, inconsistent reporting standards, weak accountability mechanisms, and insufficient alignment between corporate commitments and measurable environmental outcomes (Dauvergne, 2026). Integrated collaboration among governments, industries, researchers, local communities, and environmental organizations therefore remains essential for advancing sustainable plastic governance and reducing marine contamination risks. As summarized in Table 6, effective marine plastic mitigation increasingly depends on coordinated interaction among regulatory systems, circular-economy frameworks, industrial accountability mechanisms, and multi-stakeholder governance approaches.

Economic, educational, and scientific pathways for long-term marine plastic governance

Economic instruments and market-based mitigation mechanisms

Economic instruments increasingly represent critical policy tools for reducing plastic consumption, improving waste-management efficiency, and accelerating circular-economy transition through market-based environmental governance approaches (OECD, 2022; UNEP, 2023). Plastic taxes, landfill charges, environmental levies, deposit-return systems, subsidy reforms, and polluter-pays mechanisms are widely applied to internalize the environmental costs associated with plastic production, consumption, and disposal (Xanthos and Walker, 2017; OECD, 2022). Such instruments aim to alter producer and consumer behavior by discouraging unnecessary plastic use while incentivizing sustainable alternatives, recycling systems, and material recovery infrastructure (UNEP, 2023). Plastic bag taxation systems implemented across several economies have demonstrated substantial reductions in disposable plastic consumption and coastal litter generation (Xanthos and Walker, 2017). Deposit-return schemes additionally improve collection efficiency and recycling performance through financial incentives for post-consumer material recovery (OECD, 2022). Simultaneously, subsidy mechanisms supporting biodegradable materials, green manufacturing technologies, and recy-

DOI: 10.60923/issn.2281-4485/25086

Table 6. *Integrated policy, circular-economy, and industrial strategies for reducing marine plastic pollution.*

Strategic approach	Core intervention mechanism	Operational scale	Major environmental objective	Key implementation tools	Principal environmental benefit	Major limitation/ challenge	Representative-countries/ organizations	Sources
Single-use plastic bans	Restriction of disposable plastic products	National	Source-level waste reduction	Product bans, import restrictions, regulatory enforcement	Reduced plastic leakage into aquatic ecosystems	Weak enforcement and substitution issues	Rwanda, Kenya, EU member states, Bangladesh	UNEP (2023); Xanthos and Walker (2017)
Plastic taxation and levies	Economic disincentives for plastic consumption	National	Consumption reduction	Plastic bag taxes, environmental levies	Reduced single-use plastic demand	Public resistance and policy inconsistency	Ireland, Denmark, South Korea	OECD (2022); UNEP (2026)
Deposit-return systems	Post-consumer material recovery	National/ Regional	Increased recycling efficiency	Refund-based collection schemes	Improved bottle and packaging recovery	Infrastructure and operational costs	Germany, Norway, Canada	OECD (2022); Plastics Europe (2026)
Recycling infrastructure expansion	Waste collection and processing improvement	National/ Regional	Circular-material recovery	Material recovery facilities, sorting systems	Reduced landfill and marine leakage	Polymer contamination and low recycling efficiency	EU, Japan, South Korea	Geyer et al. (2017); OECD (2022)
Eco-design strategies	Sustainable product redesign	Industrial	Reduced material intensity	Biodegradable materials, recyclable packaging	Reduced lifecycle environmental impact	Technological and economic barriers	EU Circular Economy initiatives	UNEP (2023); OECD (2022)
Reusable packaging systems	Product reuse and refill models	Industrial/ Commercial	Waste minimization	Refillable containers, reusable packaging	Reduced virgin plastic production	Consumer adaptation challenges	Loop Global, Unilever initiatives	Plastics Europe (2026)
Extended Producer Responsibility (EPR)	Producer lifecycle accountability	National/ Industrial	Improved post-consumer waste management	Mandatory recovery and recycling targets	Increased collection and recycling rates	Weak compliance and monitoring gaps	EU, Canada, Japan	Mallick et al. (2024); OECD (2022)
Plastic-credit systems	Market-based waste offset mechanisms	Corporate/ Internationa l	Waste recovery financing	Plastic recovery certification	Increased recycling investment	Credibility and accountability concerns	Verra and corporate sustainability programs	UNEP (2023); Dauvergne (2026)
Public–private partnerships (PPPs)	Collaborative governance and infrastructure development	National/ Regional	Integrated marine-litter mitigation	Joint waste-management projects	Improved operational capacity	Financial sustainability challenges	UNEP partnerships, regional coastal programs	OECD (2022); UNEP (2026)
Corporate sustainability commitments	Voluntary industrial plastic reduction	Corporate	Reduced packaging waste	Recyclable packaging targets	Increased circular-economy transition	Greenwashing risks	Coca-Cola, Unilever, Nestlé	Plastics Europe (2026); Dauvergne (2026)
Eco-labeling and green procurement	Sustainable consumption promotion	National/ Industrial	Environmentally responsible purchasing	Certification and procurement standards	Increased market preference for sustainable products	Limited consumer awareness	EU Ecolabel systems	UNEP (2026); OECD (2022)
Community-based waste management	Localized waste collection and awareness	Local/ Regional	Coastal pollution reduction	Community recycling and cleanup programs	Improved local environmental quality	Limited scalability	Coastal municipalities and NGOs	UNEP (2023); FAO (2023)
Informal-sector waste integration	Inclusion of waste-picking systems	National/ Urban	Improved collection efficiency	Cooperative recycling systems	Enhanced material recovery	Social and regulatory barriers	India, Brazil, Indonesia	OECD (2022); UNEP (2023)
Circular economy transition	System-wide material-flow redesign	Global/ National	Long-term sustainability transformation	Recycling, reuse, sustainable production	Reduced dependency on virgin plastics	Structural economic transition barriers	EU, OECD countries	OECD (2022); Geyer et al. (2017)

DOI: 10.60923/issn.2281-4485/25086

cling innovation increasingly contribute to sustainable plastic-management transition (UNEP, 2026). Nevertheless, economic instruments remain constrained by institutional weakness, enforcement limitations, market instability, and unequal financial capacity across developing economies (Borrelle et al., 2020).

Public awareness, environmental education, and capacity-building strategies

Behavioral transformation and public participation are essential components of long-term marine plastic mitigation because consumption patterns, waste-disposal practices, and community engagement strongly influence environmental leakage pathways (UNEP, 2023; Vince and Hardesty, 2017). Public-awareness campaigns increasingly promote sustainable consumption, waste segregation, recycling participation, and reduction of single-use plastics through educational programs, media outreach, citizen-science initiatives, and community-based environmental activities (Hauser-Davis et al., 2026; Bettencourt et al., 2023). Environmental education programs integrated within schools, universities, coastal communities, and industrial sectors improve ecological literacy and strengthen public understanding regarding the environmental, ecological, and human-health consequences of plastic pollution (UNESCO, 2021). Coastal cleanup campaigns, marine conservation movements, and citizen-monitoring networks further enhance social participation and local stewardship toward marine ecosystem protection (Lidström et al., 2026; Vince and Hardesty, 2017). However, awareness alone remains insufficient without supportive policy infrastructure, accessible waste-management systems, and sustained institutional commitment (UNEP, 2023). Capacity-building initiatives targeting local governments, waste-management authorities, researchers, industries, and coastal communities are increasingly prioritized within marine-litter governance frameworks (UNEP, 2026). Technical training, institutional strengthening, financial support, and technological-transfer programs improve monitoring capacity, waste-management performance, and evidence-based environmental governance, particularly within developing coastal economies characterized by limited infrastructure and high plastic leakage rates (OECD, 2022).

Scientific monitoring, technological innovation, and evidence-based environmental assessment

Scientific investigation and long-term environmental monitoring are fundamental for understanding plastic distribution dynamics, ecological risks, contamination pathways, and mitigation effectiveness across marine ecosystems (GESAMP, 2019; UNEP, 2026). Standardized monitoring methodologies for assessing macroplastics, microplastics, polymer composition, sediment contamination, ecological exposure, and trophic transfer are increasingly necessary for generating comparable datasets and supporting evidence-based environmental management (GESAMP, 2019). Recent technological advancements including remote sensing, drone surveillance, hyperspectral imaging, machine learning, artificial intelligence (AI), automated spectroscopy, and geospatial modelling substantially improve marine plastic detection, source tracking, and contamination assessment across coastal and oceanic systems (Gayathrri et al., 2025; Cernian and Iliuta, 2025; Olawade et al., 2026). AI-assisted monitoring systems additionally facilitate predictive modelling of plastic transport pathways, accumulation hotspots, and environmental-risk distribution under varying hydrodynamic and climatic conditions (UNEP, 2026). Analytical techniques including Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, pyrolysis–gas chromatography–mass spectrometry (Py-GC/MS), and scanning electron microscopy (SEM) increasingly enhance polymer identification, particle characterization, and contaminant analysis within marine matrices (Huang et al., 2022). Simultaneously, interdisciplinary research integrating ecotoxicology, environmental chemistry, oceanography, microbiology, and sustainability science remains essential for understanding long-term ecosystem-level implications of marine plastic contamination (Hartmann et al., 2019). Despite recent scientific progress, major knowledge gaps persist regarding nanoplastic toxicity, chronic exposure thresholds, trophic transfer mechanisms, atmospheric transport dynamics, and long-term ecosystem resilience under combined anthropogenic stressors (WHO, 2022; UNEP, 2026). Strengthening global scientific collaboration, harmonized monitoring frameworks, open-access environmental databases, and transdisciplinary research networks therefore remains critical for advancing marine plastic governance and sustainable environmental-quality management. As summarized in Table 7, long-term mitigation of marine plastic pollution increasingly depends on integrated interaction among economic instruments, behavioral transformation, institutional capacity-building, scientific innovation, and evidence-based environmental governance.

DOI: 10.60923/issn.2281-4485/25086

Table 7. *Economic, educational, and scientific mechanisms supporting long-term marine plastic mitigation and environmental governance.*

Strategic domain	Core intervention mechanism	Operational objective	Key implementation approaches	Primary environmental benefit	Major governance challenge	Representative institutions/ countries	Sources
Plastic taxation	Economic disincentive for plastic use	Reduction of disposable plastic consumption	Plastic bag levies, environmental taxes	Reduced plastic demand and litter generation	Political esistance and weak enforcement	Ireland, Denmark, South Korea	Xanthos and Walker (2017); OECD (2022)
Deposit-return systems	Incentivized material recovery	Increased recycling efficiency	Refund-based collection systems	Improved packaging recovery rates	Operational and infrastructure costs	Germany, Norway, Canada	OECD (2022); UNEP (2023)
Landfill and disposal charges	Waste-disposal cost internalization	Reduced uncontrolled dumping	Landfill taxation and waste fees	Improved waste-management performance	Illegal dumping risks	EU member states	OECD (2022)
Subsidies for sustainable alternatives	Promotion of eco-friendly materials	Circular-economy transition	Green manufacturing incentives	Reduced virgin plastic dependency	Financial sustainability limitations	EU Circular Economy initiatives	UNEP (2026); OECD (2022)
Polluter-pays mechanisms	Environmental liability assignment	Producer accountability	Environmental compensation frameworks	Reduced environmental externalities	Monitoring and compliance gaps	OECD countries	OECD (2022); UNEP (2023)
Environmental education	Ecological literacy enhancement	Behavioral transformation	School curricula and awareness programs	Improved sustainable consumption practices	Limited long-term behavioral retention	UNESCO programs	UNESCO (2021); Bettencourt et al. (2023); Hauser-Davis et al. (2026)
Public awareness campaigns	Community engagement	Reduction of littering behavior	Media outreach and social campaigns	Increased public participation	Campaign sustainability limitations	UNEP campaigns and NGOs	Vince and Hardesty (2017); UNEP (2023)
Coastal cleanup programs	Community-based marine conservation	Removal of accumulated debris	Volunteer cleanup campaigns	Improved coastal environmental quality	Short-term impact without source control	Ocean Conservancy initiatives	UNEP (2026); Vince and Hardesty (2017)
Citizen-science initiatives	Participatory environmental monitoring	Data generation and stewardship	Volunteer-based monitoring networks	Improved local environmental engagement	Data standardization challenges	Marine Debris Tracker and NGOs	Bettencourt et al. (2023); Hauser-Davis et al. (2026)
Institutional capacity building	Technical and governance strengthening	Improved waste-management performance	Training and technological transfer	Enhanced environmental governance	Financial and institutional limitations	UNEP and regional coastal programs	UNEP (2026); OECD (2022)
Scientific monitoring frameworks	Standardized contamination assessment	Evidence-based management	Harmonized monitoring protocols	Improved dataset comparability	Regional methodologica l inconsistency	GESAMP and UNEP	GESAMP (2019); UNEP (2026)
Remote sensing and drones	Spatial plastic detection	Monitoring of accumulation hotspots	UAVs and satellite-based observation	Large-scale marine-litter assessment	High technological costs	EU marine monitoring programs	Gayathrri et al. (2025)
Artificial intelligence (AI) systems	Predictive environmental modelling	Plastic transport forecasting	Machine learning and geospatial modelling	Improved pollution prediction accuracy	Data integration complexity	UNEP-supported monitoring systems	Olawade et al. (2026); Cernian and Iliuta (2025); UNEP (2026)
FTIR and Raman spectroscopy	Polymer identification	Microplastic characterization	Spectroscopic analysis	Improved contaminant identification	Laboratory cost and expertise requirements	Research laboratories worldwide	Huang et al. (2022); Dey et al. (2024)
Py-GC/MS analysis	Chemical composition assessment	Advanced polymer quantification	Thermochemical analytical methods	High-resolution polymer detection	Expensive instrumentatio n	Advanced analytical laboratories	Huang et al. (2022); Dey et al. (2024)
Interdisciplinary ecotoxicological research	Integrated environmental-risk assessment	Understanding ecosystem-level impacts	Multi-sector scientific collaboration	Improved ecological-risk interpretation	Knowledge gaps on nanoplastics	Global marine research institutions	Hartmann et al. (2019); WHO (2022)
Open-access environmental databases	Data accessibility and collaboration	Global scientific coordination	Shared monitoring platforms	Improved transboundary governance	Data harmonization limitations	UNEP and GESAMP databases	UNEP (2026); GESAMP (2019)

DOI: 10.60923/issn.2281-4485/25086

Environmental quality management perspectives and future research priorities

Marine plastic pollution has become a critical environmental-quality issue because persistent plastic accumulation alters ecosystem functionality, physico-chemical stability, biodiversity structure, and ecological resilience across coastal and oceanic environments. Current evidence demonstrates that plastic contaminants are no longer restricted to localized marine litter zones, but are increasingly integrated within aquatic food webs, sediment systems, coastal habitats, and biogeochemical processes through long-term environmental transport and fragmentation mechanisms (Hartmann et al., 2019; UNEP, 2024). Consequently, effective mitigation requires integrated environmental-quality management approaches capable of simultaneously addressing pollution prevention, ecosystem protection, sustainable resource use, and long-term environmental resilience. Future environmental management strategies should prioritize source-oriented interventions emphasizing reduction of single-use plastics, circular-economy transition, sustainable material design, and improved waste-management infrastructure, particularly within rapidly urbanizing coastal regions characterized by high plastic leakage rates (OECD, 2022; Borrelle et al., 2020). Strengthening environmental governance through extended producer responsibility (EPR), ecosystem-based marine management, harmonized monitoring systems, and transboundary regulatory cooperation will remain essential for reducing marine plastic emissions and improving environmental-quality outcomes (UNEP, 2023; IMO, 2024). Scientific monitoring and environmental-risk assessment frameworks additionally require substantial advancement to improve evidence-based marine governance. Standardized methodologies for assessing microplastic abundance, polymer composition, trophic transfer, sediment contamination, and ecological exposure remain necessary for generating comparable environmental datasets across regional and global marine systems (GESAMP, 2019). Emerging technologies including remote sensing, geospatial modelling, artificial intelligence-assisted monitoring, and spectroscopic characterization techniques provide important opportunities for improving marine pollution surveillance and environmental-quality assessment within complex aquatic ecosystems (Topouzelis et al., 2019; Cowger et al., 2021). Several critical research gaps also persist regarding nanoplastic toxicity, chronic exposure thresholds, atmospheric transport pathways, contaminant interactions, and long-term ecosystem-level responses under combined anthropogenic and climatic stressors (WHO, 2022; Allen et al., 2019). Future interdisciplinary investigations integrating environmental science, ecotoxicology, oceanography, sustainability studies, and public-health research are therefore necessary for strengthening understanding of cumulative ecological risks and improving sustainable mitigation strategies. Long-term protection of marine environmental quality will ultimately depend on coordinated interaction among governments, industries, scientific institutions, and local communities aimed at achieving sustainable production systems, resilient coastal ecosystems, and environmentally responsible resource-management frameworks under increasing global environmental pressures.

Conclusions

Marine plastic pollution has evolved into a pervasive and multidimensional environmental crisis that threatens the ecological integrity, biogeochemical stability, biodiversity resilience, and socio-economic sustainability of coastal and oceanic ecosystems worldwide. The continuous expansion of plastic production, unsustainable consumption patterns, ineffective waste-management infrastructure, and transboundary transport pathways have collectively intensified the accumulation of macroplastics, microplastics, and nanoplastics throughout marine environments. Plastic contaminants are now ubiquitously distributed across beaches, estuaries, mangroves, coral reefs, pelagic waters, deep-sea sediments, polar regions, and marine food webs, demonstrating the globalized nature and long-term persistence of plastic-derived pollution. The present review demonstrates that marine plastic contamination exerts interconnected physical, chemical, biological, ecotoxicological, and socio-economic impacts across multiple ecological scales. Entanglement, ghost fishing, ingestion, trophic transfer, oxidative stress, endocrine disruption, pathogen dispersal, invasive-species rafting, habitat degradation, and biodiversity decline collectively undermine ecosystem functionality and environmental quality. Microplastics and nanoplastics represent particularly critical contaminants because of their high mobility, bioavailability, adsorption capacity, and cellular translocation potential. Increasing evidence confirming the occurrence of plastic-associated contaminants within seafood organisms, marine food webs, drinking water, and atmospheric pathways further emphasizes the emerging human-health implications associated

DOI: 10.60923/issn.2281-4485/25086

with chronic plastic exposure. The review further highlights that marine plastic pollution extends beyond ecological deterioration and increasingly represents a systemic sustainability challenge affecting fisheries productivity, aquaculture systems, coastal tourism, maritime infrastructure, public health, climate resilience, and ecosystem-service provision. Developing coastal regions and densely populated economies remain disproportionately vulnerable because of limited waste-management capacity, rapid urbanization, inadequate recycling systems, and weak regulatory enforcement. Consequently, marine plastic pollution is closely associated with environmental injustice, socio-economic instability, food-security vulnerability, and long-term sustainable-development constraints. Current global mitigation efforts demonstrate increasing transition toward lifecycle-based governance frameworks integrating source reduction, circular-economy strategies, extended producer responsibility (EPR), ecosystem-based management, sustainable packaging systems, and international regulatory cooperation. International initiatives including the UNEA global plastics treaty negotiations, MARPOL Annex V, regional marine-litter frameworks, and circular-economy policies represent important advances toward coordinated marine-plastic governance. Nevertheless, major challenges persist regarding policy implementation, technological inequality, weak institutional capacity, inconsistent monitoring systems, limited recycling efficiency, industrial accountability, and transboundary waste leakage. Long-term mitigation therefore requires integrated collaboration among governments, industries, researchers, environmental organizations, and local communities. The review additionally emphasizes the growing importance of scientific innovation, standardized environmental monitoring, artificial intelligence-assisted modelling, remote sensing technologies, spectroscopic characterization methods, and interdisciplinary environmental assessment for improving evidence-based marine governance. However, substantial scientific uncertainties remain regarding nanoplastic toxicity, chronic exposure thresholds, atmospheric transport dynamics, trophic-transfer mechanisms, and cumulative ecosystem-level consequences under combined anthropogenic and climatic stressors. Strengthening harmonized global monitoring frameworks, open-access environmental databases, and transdisciplinary research networks therefore remains essential for advancing marine environmental-quality management and sustainable aquatic ecosystem protection. Overall, effective mitigation of marine plastic pollution will require a transformative transition from linear plastic-dependent economic systems toward sustainable circular-economy models emphasizing prevention, reduction, reuse, recovery, accountability, and environmental stewardship. Without urgent and coordinated intervention, continued plastic accumulation may irreversibly compromise marine biodiversity, ecosystem resilience, environmental quality, and human well-being across future generations. The protection of marine and coastal ecosystems therefore represents not only an environmental necessity, but also a critical global sustainability priority for ensuring long-term ecological security, socio-economic stability, and planetary health.

Funding
This work received no external funding.

Conflicts of interest
No conflicts of interest have been disclosed by the paper's author.

Declaration of generative ai and ai-assisted technologies in the writing process
The author used generative artificial intelligence (AI) and AI-assisted technologies during the language refinement, structural organization, and editorial improvement of the manuscript. These technologies were applied exclusively to support grammatical correction, sentence optimization, formatting consistency, and academic language enhancement. All scientific interpretation, literature synthesis, conceptual deve-lopment, data evaluation, critical analysis, and final intellectual content were independently conducted, verified, and approved by the author. The author accepts full responsibility for the accuracy, originality, integrity, and scientific validity of the manuscript.

Data availability statement
The author confirms that all data supporting the findings of this study are available within the article.

Author contributions
F. A. Samiul Islam solely conceptualized the study, conducted the literature investigation, developed the review framework, performed the scientific analysis and interpretation, prepared the tables, wrote the original manuscript draft, revised and edited the manuscript, and approved the final version for submission.

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DOI: 10.60923/issn.2281-4485/25086

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