Environmental Research
and Planetary Health

Review
Volume 2(2), 2026, 106−122
https://doi.org/10.53623/erph.v2i2.1177

The Impact of Microplastic Footprints in Developing Countries: Threats to Ecosystems, Human Health, and Catalysts for Climate Change

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SUBMITTED: 29 April 2026; REVISED: 30 August 2026; ACCEPTED: 1 September 2026

ABSTRACT: Microplastics, defined as plastic particles smaller than 5 mm, are emerging environmental pollutants with increasingly significant global impacts, particularly in developing countries where waste management and pollution control remain challenging. This systematic review examines the occurrence and distribution of microplastics in aquatic ecosystems and evaluates their potential implications for ecological systems, human health, and climate change. Microplastics have been detected in major rivers across Asia and Africa at concentrations ranging from 0.5 to more than 3,000 particles/m^3. Their ecological impacts include adverse effects on plankton, shellfish, and fish, as well as potential alterations in sediment dynamics, food webs, and biogeochemical carbon cycling. Human exposure may occur through multiple pathways, including seafood consumption, fish-derived products, sea salt, and drinking water, raising concerns regarding potential long-term health risks. Moreover, microplastics in aquatic environments may influence greenhouse gas dynamics, including the release of methane (CH_4) and ethylene (C_2H_4), while potentially reducing plankton-mediated carbon sequestration. These interconnected effects highlight the need for integrated mitigation strategies addressing plastic pollution, ecosystem degradation, human exposure, and climate-related impacts.

KEYWORDS: Carbon footprint; climate change; human health; microplastics in developing countries

1. Introduction

Synthetic and semi-synthetic polymeric materials, commonly known as plastics, are composed primarily of long-chain molecules produced through the polymerization of compounds such as ethylene, propylene, and styrene. Their lightweight, durable, water-resistant, and easily moldable properties have resulted in their widespread application across numerous sectors of modern society [1]. However, the same durability that makes plastics commercially valuable also makes them resistant to natural degradation, allowing plastic waste to persist in the environment for decades to centuries. Over time, larger plastic materials can fragment into smaller particles, including microplastics, which subsequently contaminate terrestrial and aquatic environments and may enter food webs [2–4].

Microplastics are generally defined as plastic particles smaller than 5 mm. Environmental contamination by microplastics originates from both primary and secondary sources. Primary microplastics include particles intentionally manufactured at small sizes or released from products and industrial activities, including certain cosmetic products, synthetic textiles, and industrial plastic pellets. Secondary microplastics are generated through the fragmentation and degradation of larger plastic materials under ultraviolet radiation, oxidation, weathering, and mechanical abrasion [5–8]. Microplastic contamination has become widespread and is of particular concern in developing countries, where rapid urbanization, increasing plastic consumption, and inadequate waste-management infrastructure can intensify environmental releases. Consequently, microplastics represent an emerging threat to aquatic ecosystems and may ultimately affect human health through environmental and food-chain exposure while also interacting with processes relevant to climate change [9].

Global research has documented increasing microplastic contamination in aquatic environments, including rivers, estuaries, and coastal waters across Southeast Asia, Africa, and Latin America [10–12]. Recent studies conducted during 2023–2024 further indicate that developing countries may simultaneously act as major generators of plastic waste and recipients of transboundary pollution associated with the international plastic-waste trade [13–15]. These pressures are compounded by limited capacities for solid-waste collection, recycling, wastewater management, and wastewater treatment. Wastewater treatment plants (WWTPs), although capable of retaining a proportion of microplastic particles, may also represent pathways through which residual microplastics are discharged into receiving environments when treatment and containment systems are inadequate [16]. These conditions create disproportionate environmental pressures in countries where monitoring, treatment technologies, and regulatory enforcement remain limited.

The occurrence of microplastics in aquatic environments has important ecological and human-health implications. Microplastic particles can be ingested by organisms at different trophic levels, including plankton, shellfish, and fish, creating opportunities for their transfer through aquatic food webs. Such interactions may affect feeding behavior, physiological processes, organism health, and broader ecosystem functioning [17]. In developing countries, potential human exposure may occur through contaminated drinking water, sea salt, fishery products, and other food-related pathways. Microplastics can also interact with persistent organic pollutants (POPs), heavy metals, and chemical additives, potentially modifying the transport and exposure of organisms to hazardous substances [18]. These multiple exposure pathways raise concerns regarding the long-term consequences of chronic microplastic contamination for both environmental and human health.

An emerging dimension of microplastic research concerns its potential relationship with climate change. Plastics and microplastics may interact with climate-related processes throughout their life cycle, from fossil-fuel-based production to environmental degradation. Once dispersed in aquatic environments, microplastics may influence biogeochemical processes, interfere with phytoplankton productivity and biological carbon sequestration, and contribute to greenhouse gas dynamics during degradation [19]. These interactions indicate that microplastic pollution should not be considered solely as a localized waste-management or ecotoxicological problem, but also as a potential component of broader carbon-cycle and climate-related processes.

Despite growing research interest, an important knowledge gap remains in understanding the integrated relationship among microplastic pollution, ecosystem disruption, human exposure, and climate change, particularly in developing countries. Existing studies have predominantly focused on microplastic abundance, particle characteristics, spatial distribution, and ecological toxicity, while evidence concerning greenhouse gas emissions, disruption of biological carbon sequestration, and the overall carbon footprint associated with microplastic pollution remains fragmented. Furthermore, comparatively limited attention has been given to how inadequate waste-management infrastructure and transboundary plastic flows may amplify these interconnected risks in developing regions. This systematic review aims to critically evaluate microplastic pollution in developing countries by integrating evidence on its occurrence and distribution, ecological and human-health impacts, and potential interactions with greenhouse gas emissions, carbon cycling, and climate change

2. Materials and Methods

2.1. Systematic Review Design.

This study employed a Systematic Literature Review (SLR) approach to identify, evaluate, and synthesize available scientific evidence concerning microplastic pollution in developing countries, with particular emphasis on its occurrence, environmental distribution, ecological impacts, human exposure and health implications, and potential relationships with climate change. The review process was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines to ensure a transparent and systematic procedure for literature identification, screening, eligibility assessment, and final study selection. The systematic approach was selected because existing evidence on microplastics is distributed across environmental science, ecotoxicology, public health, waste management, and climate-related research, requiring an integrated synthesis to identify consistent findings and remaining knowledge gaps.

2.2. Literature Search Strategy.

A comprehensive literature search was conducted using three major scientific databases: PubMed, ScienceDirect, and SpringerLink. The search was restricted to peer-reviewed English-language articles published between 2019 and 2026 to capture recent developments in microplastic research. Search terms were developed to represent four major components: microplastic pollution, environmental occurrence, biological exposure and effects, and climate-related processes. The principal search string was: ("microplastic" OR "micro-plastic" OR "plastic particle" OR "plastic pollution") AND ("concentration" OR "abundance" OR "occurrence" OR "distribution" OR "contamination") AND ("exposure" OR "ingestion" OR "inhalation" OR "human health" OR "ecotoxicity" OR "ecosystem" OR "aquatic ecosystem" OR "climate change" OR "carbon cycle" OR "greenhouse gas"). Search results from the three databases were compiled, and duplicate records were removed before the screening process. The titles and abstracts of the remaining records were subsequently evaluated for relevance to the objectives of the review.

2.3. Eligibility Criteria and Study Selection.

Studies were selected using predefined inclusion and exclusion criteria to maintain consistency throughout the screening process. Articles were considered eligible when they were peer-reviewed original research or review articles published in English between 2019 and 2026 and provided information relevant to microplastic pollution in developing countries. Eligible studies were required to report at least one relevant aspect, including microplastic concentration or abundance, polymer characteristics, environmental distribution, pollution sources, ecological effects, human exposure pathways, potential health implications, or relationships with greenhouse gas emissions, carbon cycling, and climate change. Studies focusing exclusively on macroplastics without relevant microplastic data were excluded. Editorials, conference proceedings, book chapters, preprints, commentaries, and other non-peer-reviewed publications were also excluded. Following removal of duplicates, studies were screened initially by title and abstract. Potentially relevant articles were subsequently subjected to full-text assessment against the eligibility criteria. Reasons for exclusion at the full-text stage were documented to maintain transparency in the study-selection process. The overall identification, screening, eligibility, and inclusion procedures were summarized using a PRISMA flow diagram.

2.4. Data Extraction and Evidence Synthesis.

Data from all eligible studies were extracted using a standardized data-extraction framework to ensure comparability among studies. The extracted information included publication year, study location, environmental medium, sampling strategy, analytical and identification methods, microplastic size and morphology, polymer type, reported concentration or abundance, pollution sources, ecological effects, human exposure pathways, potential health implications, and climate-related findings. Particular attention was given to evidence concerning greenhouse gas generation, effects on phytoplankton and aquatic productivity, disruption of carbon cycling, and potential changes in biological carbon sequestration. Because substantial methodological heterogeneity was expected among studies, particularly in sampling procedures, particle-size thresholds, identification techniques, and units used to report microplastic abundance, the evidence was primarily synthesized using a descriptive and narrative approach rather than direct statistical pooling. Quantitative findings were compiled and compared where sufficiently consistent data were available, while summary tables were used to identify geographical patterns, dominant polymer types, environmental concentrations, exposure pathways, and reported ecological and climate-related effects. Finally, the synthesized evidence was evaluated across the ecosystem–human health–climate nexus to identify major research trends, inconsistencies, knowledge gaps, and priorities for future microplastic pollution mitigation in developing countries.

3. Results and Discussion

3.1. Microplastic Occurrence and Threats to Aquatic Ecosystems.

In developing countries, microplastics originate from diverse primary and secondary sources, including domestic waste, industrial activities, synthetic textiles, packaging materials, agricultural plastics, and the fragmentation of larger plastic debris. Microplastics have been reported in several major river systems, including the Mekong, Ganges, Brantas, and Niger Rivers, highlighting the widespread transport of plastic particles through freshwater systems toward coastal and marine environments [20–24]. Surveys conducted between 2022 and 2024 reported microplastic concentrations ranging from approximately 0.5 to more than 3,000 particles/m³ in aquatic environments of developing countries, including Bangladesh and Vietnam. Higher concentrations were generally associated with densely populated urban areas, industrial zones, and river basins receiving substantial anthropogenic inputs. Polyethylene (PE), polypropylene (PP), and polystyrene (PS) were among the most frequently identified polymers, reflecting their extensive use in food packaging, synthetic textiles, and single-use plastic products [25, 26].

The occurrence and characteristics of microplastics in water and sediment across selected developing regions are summarized in Table 1. Considerable geographical variation can be observed in reported abundance, dominant particle morphology, and polymer composition. For example, concentrations in Indonesian freshwater systems ranged from relatively low levels in the Ciwalengke and Cisadane Rivers to substantially higher concentrations in downstream sections of the Brantas River. Similarly, high microplastic abundances have been reported in several African freshwater and sediment environments. Fibers and fragments were the dominant morphological forms across many studies, whereas PE, PP, and PS were among the most commonly detected polymers [33–43]. These findings indicate that microplastic contamination is widespread, although direct comparisons among countries should be interpreted cautiously because studies differ considerably in sampling procedures, particle-size thresholds, extraction methods, analytical techniques, and reporting units.

Table 1. Identification of Microplastics in Water and Sediment in Several Developing Countries.

Environmental Medium	Country/Region	Microplastic Abundance	Dominant Characteristics	Ref.
Water	Bangladesh	Surface water: 0.57–6.63 particles/L	Fiber, fragment; PE, PP, PET	[33]
Water	Indonesia	Brantas River: 133–5,467 particles/m³, with higher levels downstream; Ciwalengke River: 5.85 ± 3.28 particles/L; Cisadane River: 13.33–113.33 particles/m³	Fragment, fiber; PE, PS, PP	[34–36]
Water	Africa	High abundance reported in areas characterized by limited waste-management capacity	Fiber, fragment; PP, PE	[37]
Water	China	Urban waters: 2.3 ± 1.2–104.6 ± 5.6 particles/L; Wei River: 3.67–10.7 particles/L; lakes/reservoirs: mean 3,441 particles/m³; Chishui River: 1.77–14.33 particles/L	Fiber, fragment; PP, PE, PS, silicone, rubber, PTFE	[38]
Water	Thailand	U-Taphao River: 0.24–0.41 particles/L; Phumduang River: 0.68–2.81 particles/5 L	Fiber, fragment; diverse polymers	[39]
Water	Nigeria	Nwangele region rivers: 440–1,556 particles/L	Fragment; diverse polymers	[40]
Water	India	Ganges River: 143–684 particles/1,000 m³	Film; diverse polymers	[41]
Sediment	China	Microplastics detected; quantitative abundance not reported in the summarized data	Fiber, fragment; PP, PE, PS, silicone, rubber, PTFE	[42]
Sediment	Indonesia	552.5–972.5 particles/kg	Fiber, fragment; diverse polymers	[43]
Sediment	Africa	Olifants River: 2,022–9,971 particles/kg; Sabie River: 2,237–27,259 particles/kg	Diverse forms and polymers	[37]

As shown in Table 1, densely populated Asian river systems frequently exhibit substantial microplastic contamination, whereas freshwater systems in Africa show considerable spatial variability and generally less comprehensive monitoring coverage. This difference should not be interpreted as evidence of lower contamination in Africa, as it may reflect disparities in sampling intensity, analytical capacity, and environmental monitoring infrastructure. Studies from Southeast Asia commonly identify PE and PP associated with household waste, packaging, and other consumer products, whereas agricultural plastic residues and textile-derived fibers may represent important sources in some African environments [33–43]. Developing countries therefore face a complex pollution burden arising from increasing domestic plastic consumption, inadequate waste management, international plastic-waste flows, and heightened vulnerability to environmental and climate-related pressures [18].

Microplastic contamination of aquatic environments also creates pathways for biological exposure and food-web transfer. Particles smaller than 500 μm have been detected in a substantial proportion of fish samples examined in South and Southeast Asia [27]. Microplastics have also been reported in sea salt, shellfish, and farmed fish, with concentrations varying considerably among products, locations, and analytical methods [28, 29]. In addition, studies have identified microplastics in surface-derived drinking water and bottled water in several Asian and African locations [22]. Collectively, these findings demonstrate that microplastics are not restricted to environmental compartments but can occur in resources and products directly associated with human consumption.

The persistence of microplastics in aquatic ecosystems is closely associated with inadequate plastic-waste management and limitations in wastewater treatment infrastructure. Reported microplastic removal efficiencies in wastewater treatment systems vary widely, ranging from approximately 20% to 98%, depending on treatment configuration, particle characteristics, and analytical methods [30–32]. Conventional primary and secondary treatment processes may remove a substantial proportion of larger particles, whereas smaller microplastics can remain in treated effluent and subsequently enter receiving waters. In addition, microplastics retained in sewage sludge or biosolids can be transferred to terrestrial environments when these materials are applied to agricultural land, creating a secondary pathway for environmental contamination [30–32].

Long-term microplastic exposure may also affect aquatic organisms and ecosystem functioning. Experimental and field studies have reported changes in phytoplankton productivity, zooplankton communities, and the growth, reproduction, and physiological condition of bivalves and fish [44, 45]. Many reported effects are sublethal and include oxidative stress, metabolic disturbance, altered feeding behavior, and impaired reproduction. Although such effects may not immediately cause organism mortality, their cumulative influence could affect population dynamics, biodiversity, food-web stability, and ecosystem functions. Microplastics have also accumulated in sediments at concentrations reaching thousands of particles per kilogram in some investigated environments (Table 1). Such accumulation may alter interactions among sediment particles, microorganisms, nutrients, and dissolved organic matter, with potential consequences for nutrient transformation and carbon cycling [46, 47]. These observations establish an important connection between plastic pollution and the ecological functioning of aquatic and coastal environments.

3.2. Human Exposure and Potential Health Risks.

Microplastic contamination of food and drinking-water sources has raised increasing concern regarding chronic human exposure, particularly in developing countries where seafood constitutes an important component of dietary protein. Microplastics can be ingested by plankton, bivalves, crustaceans, and fish and may subsequently be transferred through aquatic food webs [48]. Human exposure can therefore occur through multiple pathways, including seafood, drinking water, sea salt, and potentially agricultural products. The widespread use of PE, PET, PS, and PP in packaging, bottles, textiles, and household products is consistent with the frequent detection of these polymers in environmental and biological samples.

Importantly, recent biomonitoring studies have reported microplastic particles or polymer-related signals in several human biological matrices, including feces, placenta, blood, breast milk, testes, and semen. The principal findings from selected studies are summarized in Table 2. For example, microplastics were detected in all fecal samples examined in one prospective case series, whereas particles were identified in four of six placentas in another investigation. Studies have also reported detectable polymer-associated material in human blood and microplastics in breast milk and reproductive tissues [50–54]. Although these findings provide evidence of human exposure, detection in biological samples should not itself be interpreted as evidence of disease or clinical toxicity.

Table 2. Detection and Characteristics of Microplastics in Human Biological Samples.

Biological Sample	Sample Size and Analytical Method	Detected Polymer(s)	Key Findings	Ref.
Feces	8 participants; fecal samples analyzed using microscopy/spectroscopy	PP, PET, and other polymers	Microplastics were detected in all analyzed fecal samples.	[50]
Placenta	6 human placentas; maternal, fetal, and chorioamniotic tissues analyzed using Raman microspectroscopy	PP	Twelve microplastic fragments (5–10 μm) were detected in 4 of 6 placentas.	[51]
Blood	22 healthy adult donors; venous whole-blood samples analyzed using double-shot Py-GC/MS	PET, PE, styrene polymers, PMMA	Polymer concentrations above the LOQ were detected in 17 of 22 participants (77%), with a mean total concentration of 1.6 μg/mL.	[52]
Breast milk	34 breastfeeding mothers; breast-milk samples analyzed using Raman microspectroscopy	PE, PVC, PP	Microplastics were detected in 26 of 34 samples (76%), with particle sizes ranging from 2 to 12 μm.	[53]
Testes and semen	6 testicular and 30 semen samples; analyzed using Py-GC/MS and LD-IR	Testes: PS (67.7%); semen: predominantly PE and PVC	Mean abundance was 11.60 ± 15.52 particles/g in testicular tissue and 0.23 ± 0.45 particles/mL in semen.	[54]

Abbreviations: MP, microplastic; PE, polyethylene; PP, polypropylene; PET, polyethylene terephthalate; PS, polystyrene; PVC, polyvinyl chloride; PMMA, polymethyl methacrylate; Py-GC/MS, pyrolysis–gas chromatography/mass spectrometry; LD-IR, laser direct infrared spectroscopy; LOQ, limit of quantification.

As summarized in Table 2, substantial methodological differences exist among human biomonitoring studies. Analytical approaches include Raman microspectroscopy, pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS), and laser direct infrared spectroscopy (LD-IR), while sample sizes remain relatively small in many investigations [50–54]. Consequently, comparisons of concentrations among tissues and populations remain challenging. Nevertheless, the detection of microplastics in multiple biological matrices supports the need for further investigation into their absorption, distribution, persistence, and elimination within the human body.

Microplastics may also interact with other environmental contaminants. Their relatively large surface area and hydrophobic properties can facilitate interactions with heavy metals, including Pb, Cd, and Hg, as well as persistent organic pollutants such as polycyclic aromatic hydrocarbons and polychlorinated biphenyls [18]. Plastic particles may additionally contain chemical additives incorporated during manufacturing. These characteristics have raised concerns regarding their potential role as carriers or co-exposure matrices for hazardous chemicals. However, the extent to which microplastic-associated contaminants contribute to actual human toxicological risk depends on particle characteristics, contaminant concentrations, exposure levels, bioavailability, and physiological conditions and therefore requires further investigation.

The issue is particularly relevant to developing countries that depend strongly on fisheries and aquaculture for food security and protein supply. Microplastic contamination has been reported in fish feed, drinking water, sea salt, and other exposure media in countries such as Bangladesh and Indonesia [49]. Agricultural pathways also warrant attention because microplastics introduced through irrigation, plastic mulch, fertilizers, or biosolid application may accumulate in soils and potentially interact with food crops. Consequently, human exposure should be considered within a broader environmental continuum linking plastic production and disposal with water, soil, food systems, and biological uptake.

Experimental evidence suggests that microplastic exposure can induce oxidative stress and inflammatory responses under certain exposure conditions. Animal studies have also reported particle accumulation or associated effects in the liver, kidneys, and gastrointestinal tissues [55–57]. However, these experimental findings should not be directly extrapolated to human disease. Current evidence concerning the health consequences of microplastic exposure is dominated by in vitro experiments, animal studies, biomonitoring investigations, and indirect exposure assessments [59–63]. Robust longitudinal epidemiological evidence demonstrating causal relationships between environmental microplastic exposure and specific chronic diseases in humans remains limited.

Accordingly, proposed associations with carcinogenicity, endocrine disruption, cardiometabolic disorders, reproductive toxicity, and other chronic conditions should currently be interpreted as potential risks rather than established clinical outcomes [59–63]. This distinction is important because evidence of exposure, biological response, and disease causation represents different levels of scientific inference. Future studies should therefore prioritize standardized exposure assessment, larger population-based cohorts, longitudinal monitoring, dose-response relationships, and mechanistic investigations that can connect environmental exposure with clinically relevant outcomes.

From a preventive perspective, upstream control remains important for reducing potential human exposure. Strategies such as decreasing unnecessary single-use plastic consumption, improving solid-waste collection, preventing uncontrolled plastic disposal, and enhancing wastewater treatment could reduce microplastic inputs into aquatic and terrestrial environments [16]. These measures are particularly relevant to developing countries characterized by limited waste-management infrastructure, rapidly growing urban populations, and high dependence on aquatic food resources [58].

3.3. Microplastics and Climate Change.

An emerging area of research concerns the relationship between plastics, microplastics, and climate-related processes. This relationship extends across the entire plastic life cycle, beginning with fossil-fuel extraction and polymer production and continuing through product use, waste management, environmental degradation, and disposal [64, 65]. Because most conventional plastics are derived from petroleum and natural gas, their production is associated with greenhouse gas emissions from resource extraction, transportation, energy consumption, and manufacturing [65]. The climate implications of microplastic pollution should therefore be interpreted within this broader life-cycle context rather than attributed exclusively to microplastic particles themselves. Following their release into the environment, plastics can undergo photochemical and oxidative degradation under ultraviolet radiation, heat, and other environmental conditions. Experimental studies have demonstrated that certain polymers, particularly PE, can release hydrocarbon gases, including methane (CH_4) and ethylene (C_2H_4), during photo-oxidative degradation [19, 66]. Waste-management practices such as uncontrolled burning and incineration can additionally generate CO_2 and other atmospheric emissions. These processes demonstrate a connection between plastic pollution and greenhouse gas dynamics, although the magnitude of emissions attributable specifically to environmentally dispersed microplastics remains insufficiently quantified [64–67].

Microplastics may also influence climate-related processes indirectly through their interactions with marine ecosystems. Phytoplankton play an essential role in oceanic carbon cycling by fixing CO_2 through photosynthesis and contributing to the biological carbon pump. Experimental evidence suggests that microplastic exposure can affect plankton through ingestion, physical interactions, changes in nutrient availability, and interactions with particle-associated biofilms [17, 19]. Under certain conditions, these effects may influence phytoplankton growth, productivity, and community structure, with potential implications for biological carbon sequestration [44]. However, the magnitude and direction of these effects at ecosystem and global scales remain uncertain and require further quantitative investigation.

The interconnected pathways linking plastics, environmental contamination, ecosystem processes, and climate-related effects are illustrated in Figure 1. The conceptual framework demonstrates that climate interactions may occur through both direct pathways, such as greenhouse gas emissions associated with plastic production, degradation, and waste management, and indirect pathways involving changes in aquatic productivity and carbon cycling. Importantly, these pathways also interact with ecological degradation and potential human exposure, emphasizing that microplastic pollution should be considered within a broader environment–health–climate nexus. Microplastics have additionally been detected in snow, ice, and glacier environments. Their presence has generated interest in whether deposited plastic particles could modify surface properties, including albedo, and thereby influence melting processes [17]. However, evidence quantifying the contribution of microplastics to large-scale cryospheric albedo changes remains limited. This potential pathway should therefore be regarded as an emerging research question rather than an established driver of global warming. Nevertheless, the detection of microplastics in remote cryospheric environments demonstrates their capacity for long-range transport and reinforces the global nature of plastic pollution. For developing countries, the interaction between plastic pollution and climate vulnerability presents an additional policy challenge. Many of these countries experience rapid growth in plastic consumption while simultaneously facing limitations in waste collection, recycling, wastewater treatment, and environmental monitoring. They may also be disproportionately exposed to climate-related hazards. Integrating plastic-pollution reduction with broader environmental and climate policies could therefore provide complementary benefits, particularly through reductions in fossil-based plastic consumption, uncontrolled burning, environmental leakage, and inefficient waste management [19, 58].

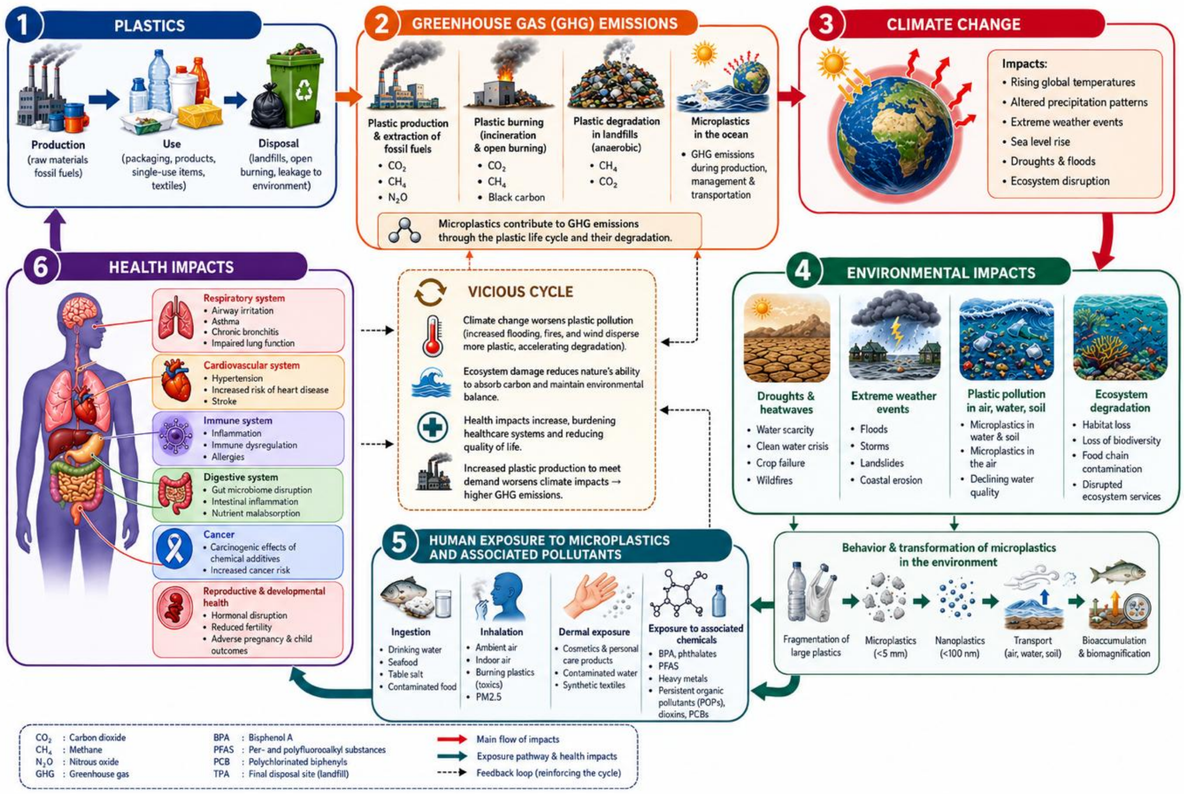

Figure 1. Interconnected Pathways Linking Plastic and Microplastic Pollution with Ecosystem Health, Human Exposure, Carbon Cycling, and Climate-Related Processes.

Nevertheless, proposals to incorporate a specific "microplastic carbon footprint" into national greenhouse gas inventories require stronger quantitative evidence. Current studies demonstrate plausible direct and indirect interactions between plastics and climate processes, but substantial uncertainty remains regarding the magnitude of emissions or carbon-sequestration changes attributable specifically to environmental microplastics. Future research should therefore develop standardized life-cycle and environmental accounting approaches capable of distinguishing emissions from plastic production and waste management from those directly associated with microplastic degradation and ecological interactions.

3.4. Research Challenges, Knowledge Gaps, and Future Priorities.

Despite increasing scientific attention, several major challenges continue to limit understanding of microplastic pollution and its environmental and health consequences. One of the most important limitations is the absence of universally standardized methods for microplastic sampling, extraction, identification, and quantification. Studies employ different particle-size thresholds, filtration procedures, density-separation techniques, and analytical methods, including microscopy, Fourier-transform infrared spectroscopy (FTIR), Raman spectroscopy, and Py-GC/MS [68–70]. These methodological differences substantially reduce comparability among studies and complicate attempts to establish spatial and temporal trends.

Internationally harmonized protocols and quality-control procedures are therefore required to improve data comparability and support the development of scientifically defensible monitoring standards.

A second major research gap concerns human health. Most available evidence is derived from cross-sectional biomonitoring, laboratory experiments, and animal studies, whereas longitudinal epidemiological and prospective cohort studies remain limited. Consequently, the long-term implications of chronic microplastic exposure, potential bioaccumulation, dose-response relationships, and interactions with chemical contaminants remain poorly characterized. Future research should integrate environmental exposure measurements with human biomonitoring and clinical outcomes to determine whether observed biological responses translate into measurable health effects.

A third gap concerns the microplastic–climate nexus. Although evidence indicates that the plastic life cycle contributes to greenhouse gas emissions and that certain plastics can release gases during environmental degradation, the specific contribution of microplastics to regional or global greenhouse gas budgets remains poorly quantified [64–67]. Similarly, evidence that microplastics may affect phytoplankton productivity and carbon cycling is biologically plausible but has not yet been sufficiently scaled from laboratory observations to ecosystem-level carbon budgets. Addressing this gap will require interdisciplinary studies combining polymer science, marine ecology, biogeochemistry, climate science, and life-cycle assessment.

Developing countries face additional implementation challenges because many have inadequate waste-collection systems, limited wastewater treatment infrastructure, insufficient environmental monitoring capacity, and uneven regulatory enforcement [71–73]. Economic dependence on inexpensive single-use plastics can further complicate policy interventions, particularly in rapidly urbanizing regions where affordable alternatives may be limited. In addition, informal waste collectors and recyclers play important economic and environmental roles in many developing countries. Policy reforms should therefore recognize these socioeconomic conditions rather than relying solely on regulatory restrictions developed for higher-income settings.

Finally, fragmented governance remains an important barrier to effective microplastic management. Responsibilities for solid waste, wastewater, environmental protection, public health, industrial regulation, and climate mitigation are frequently distributed among different institutions with limited coordination. A coordinated and interdisciplinary approach involving researchers, governments, industry, communities, and the waste-management sector is therefore required. Priority actions include harmonizing microplastic detection methods, improving waste and wastewater treatment technologies, expanding environmental monitoring, developing long-term human epidemiological studies, reducing unnecessary plastic consumption, and integrating plastic pollution into broader sustainable-development and climate strategies [71–75]. Addressing these research and governance gaps will be essential for developing affordable, scalable, and context-specific strategies capable of reducing microplastic pollution while protecting ecosystem integrity and human health.

4. Conclusions

Microplastic pollution in developing countries represents not only a local environmental concern but also part of a broader global challenge affecting biodiversity, human health, and climate-related processes. Current research provides growing scientific evidence of the multifaceted risks associated with the occurrence, persistence, and accumulation of microplastics in aquatic and terrestrial environments. However, several major challenges remain: (i) circular and low-emission plastic waste management systems remain inadequately developed and implemented; (ii) wastewater treatment technologies are not yet sufficiently effective in capturing smaller microplastic particles; (iii) the potential carbon footprint and climate-related implications of microplastics have not been adequately incorporated into climate mitigation strategies; and (iv) cross-sectoral and international collaboration to reduce plastic consumption, environmental leakage, and transboundary plastic waste remains insufficient. Addressing these challenges requires an integrated approach combining scientific research, technological innovation, effective waste management, regulatory frameworks, and coordinated policy interventions. Such an approach is essential for reducing microplastic pollution and associated environmental and health risks while supporting sustainable development and broader climate mitigation objectives in developing countries.

Competing Interests

The authors declare that they have no competing interests.

Author Contributions

All authors contributed to the conceptualization, methodology, literature review, data analysis, interpretation of findings, and preparation and revision of the manuscript. All authors read and approved the final manuscript.

Data Availability

All data supporting the findings of this systematic review are available within the published studies cited in this article.

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