



Plastic Pollution and Ecosystem Health: Sources, Pathways, Impacts, and Mitigation Strategies

¹Juliet Akudo Mbabie, ²Blessing J Ifeanyichukwu, ³Flourish Nnedimma Ikechukwu and ⁴Francis Olawale Abulude

^{1,3}Chemistry Advance Research Center, Sheda Science and Technology Complex, FCT, Abuja, Nigeria

²Physics Advance Research Center, Sheda Science and Technology Complex, FCT, Abuja, Nigeria

⁴Environmental and Sustainable Research Group, Science and Education Development Institute, FCT, Abuja, Nigeria

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Corresponding Author: Francis Olawale Abulude

Abstract

Plastic pollution is a major global environmental challenge driven by the large-scale production and persistence of plastic materials. This review examines the sources, pathways, distribution, and ecological impacts of plastics across terrestrial, freshwater, and marine ecosystems. Plastics originate from industrial, domestic, agricultural, and transport-related activities and enter the environment through runoff, river systems, wastewater, and atmospheric processes. Over time, they fragment into microplastics and nanoplastics, increasing their mobility and bioavailability. These particles are widely distributed in soil, water, and air, posing serious risks to biodiversity. Key impacts include ingestion, entanglement, habitat disruption, and chemical toxicity, along with trophic transfer within food webs. The study highlights existing research gaps and emphasizes the need for integrated strategies involving policy, technology, and public awareness to mitigate plastic pollution and protect ecosystem health.

Keywords: Plastic pollution, Microplastics, Ecosystem health, Biodiversity, Environmental pathways, Trophic transfer, Sustainability

Introduction

Plastic materials have become integral to modern society due to their durability, versatility, and low production cost (Thompson *et al.*, 2009; Stanley *et al.*, 2025) ^[2, 15]. Since large-scale production began in the mid-20th century, global plastic output has increased exponentially, exceeding 390 million tonnes annually in recent years (PlasticsEurope, 2023) ^[11]. However, the same properties that make plastics useful—particularly their resistance to degradation—have led to their accumulation in the environment, resulting in a growing global concern over plastic pollution.

Plastic pollution is now recognized as one of the most pervasive environmental challenges, affecting terrestrial, freshwater, and marine ecosystems worldwide. It is estimated that millions of tonnes of plastic waste enter the oceans each year, primarily from land-based sources such as mismanaged municipal waste, industrial activities, and urban runoff (United Nations Environment Programme, 2021) ^[17]. Once released into the environment, plastics can persist for decades to centuries, gradually fragmenting into

smaller particles known as microplastics (<5 mm) and nanoplastics, which are increasingly detected across environmental compartments, including air, soil, and water (Geyer *et al.*, 2017) ^[6]. The environmental distribution of plastics is facilitated by complex pathways involving hydrological processes, atmospheric transport, and biological interactions. Rivers have been identified as major conduits for transporting plastic waste from inland areas to the oceans, while atmospheric deposition contributes to the spread of microplastics to remote and previously pristine environments (Allen *et al.*, 2019) ^[11]. This widespread dispersion has resulted in the ubiquitous presence of plastics, from deep-sea sediments to polar ice, raising concerns about their long-term ecological consequences.

The impacts of plastic pollution on ecosystems are multifaceted. Marine and freshwater organisms frequently ingest plastic debris, mistaking it for food, which can lead to physical injury, reduced feeding efficiency, and mortality. Entanglement in plastic waste further threatens wildlife, particularly larger organisms such as marine mammals,

birds, and turtles (Gall & Thompson, 2015) ^[5]. In addition to these physical effects, plastics can act as vectors for hazardous chemicals, including persistent organic pollutants and heavy metals, which may leach into organisms and bioaccumulate within food webs (Rochman *et al.*, 2013) ^[14]. Emerging research also highlights the role of plastics in altering ecosystem processes. Microplastics can influence soil structure, water retention, and microbial activity in terrestrial environments, while in aquatic systems they provide novel substrates for microbial colonization, forming what is termed the “plastisphere” (Zettler *et al.*, 2013) ^[19]. These changes may disrupt nutrient cycling and ecosystem functioning, with potential implications for biodiversity and ecosystem resilience.

Despite growing awareness and research efforts, significant gaps remain in understanding the full extent of plastic pollution and its long-term impacts (Stanley *et al.*, 2025) ^[15]. In particular, the effects of nanoplastics, the interactions between plastics and other environmental stressors, and the effectiveness of mitigation strategies require further investigation. Against this backdrop, this study aims to provide a comprehensive review of plastic pollution and its implications for ecosystem health, with a focus on sources, pathways, ecological impacts, and mitigation strategies. By synthesizing current knowledge, the study seeks to contribute to a better understanding of this global issue and to inform evidence-based policy and management interventions.

Literature review

The conceptual diagram provides a comprehensive framework for understanding the lifecycle and environmental dynamics of plastic pollution across interconnected ecosystems. It begins by identifying the primary origins of plastics, which include industrial manufacturing, domestic consumption, agricultural activities, and transport-related sources. These activities generate a wide spectrum of plastic materials, ranging from large debris to microscopic particles, all of which contribute to environmental contamination.

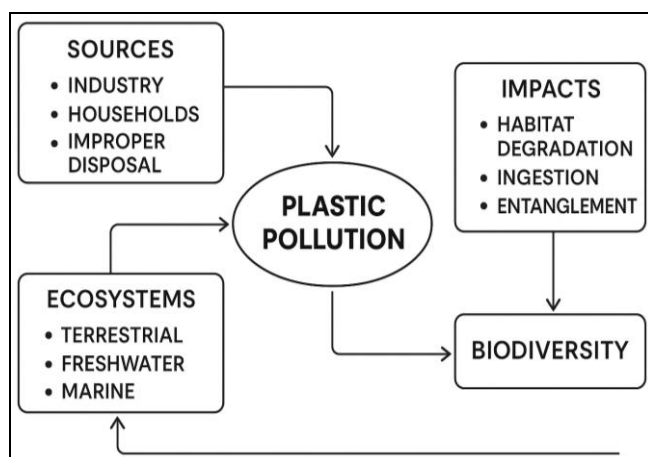


Fig 1: The conceptual diagram showing sources of plastic pollution, ecosystem Health, impacts, and biodiversity

The framework further illustrates the various environmental pathways through which plastics are transported (Liu and Zheng, 2025) ^[10]. Surface runoff, river systems, wastewater

discharge, and atmospheric circulation collectively facilitate the movement of plastics from land-based sources into aquatic environments. These pathways are not isolated; rather, they interact continuously, enabling plastics to circulate between terrestrial, freshwater, and marine systems. A key feature of the diagram is the transformation of plastics once they enter the environment. Through exposure to sunlight, physical abrasion, and biological processes, larger plastic items gradually fragment into smaller particles such as microplastics and nanoplastics. This transformation significantly increases their environmental persistence and enhances their potential for interaction with living organisms. The diagram also highlights the distribution and accumulation patterns of plastics within different ecological compartments. In soils, plastics can alter physical properties and influence microbial activity, while in aquatic systems they may remain suspended, float on the surface, or settle in sediments. Such variability in distribution determines the extent and nature of ecological exposure. Another critical component of the framework is the depiction of biological interactions. Organisms across multiple trophic levels encounter plastics through ingestion or physical contact, leading to adverse effects such as reduced feeding efficiency, physiological stress, and in severe cases, mortality. Additionally, plastics can act as carriers of chemical contaminants, thereby introducing toxic substances into biological systems (Liu and Zheng, 2025) ^[10].

The movement of plastics through food webs is also emphasized, demonstrating how contaminants can be transferred from lower to higher trophic levels (Diepens and Koelmans, 2018) ^[4]. This process underscores the broader ecological implications of plastic pollution, including its potential impact on human health through the consumption of contaminated food and water. Plastic pollution is presented as a dynamic and interconnected process, linking sources, transport mechanisms, environmental distribution, and ecological consequences. It underscores the complexity of the issue and reinforces the need for integrated and multidisciplinary approaches to effectively manage and mitigate plastic pollution.

The conceptual diagram depicting the movement of plastic pollution across ecosystems provides an integrated perspective on how plastics originate, are transported, and ultimately affect biodiversity. The framework begins with the identification of major plastic sources, including industrial production, urban waste, agricultural inputs, and consumer activities. These sources generate both macroplastics and microplastics, which enter the environment through improper disposal, wastewater discharge, and diffuse emissions. Studies have shown that land-based sources account for the majority of plastic inputs into natural systems, particularly in regions with inadequate waste management infrastructure (Geyer *et al.*, 2017) ^[6]. The diagram further illustrates the pathways through which plastics move across ecosystems. Surface runoff and river systems serve as primary conduits, transporting plastic debris from terrestrial environments into freshwater and marine systems. Rivers have been identified as significant contributors to marine plastic pollution, acting as links between inland and coastal environments (Lebreton *et al.*, 2017) ^[9]. In addition, atmospheric transport has emerged as

an important mechanism, enabling microplastics to travel long distances and deposit in remote ecosystems (Allen *et al.*, 2019) [1].

Within these environments, plastics undergo physical and chemical transformations, fragmenting into smaller particles through processes such as photodegradation and mechanical abrasion. This fragmentation increases their persistence and bioavailability, allowing them to interact more readily with organisms. Microplastics are now widely distributed across environmental compartments, including soils, sediments, and water columns (Barnes *et al.*, 2009) [2]. The diagram also highlights the accumulation of plastics in different ecological zones. In terrestrial systems, plastics accumulate in soils, affecting soil structure and microbial activity. In aquatic systems, buoyant plastics remain at the surface, while denser particles settle in sediments, creating long-term reservoirs of contamination. Such distribution patterns influence the extent of exposure for different organisms.

A critical component of the framework is the interaction between plastics and biota. Organisms across trophic levels ingest plastic particles, often mistaking them for food, which can lead to physical harm, reduced feeding efficiency, and mortality (Gall & Thompson, 2015) [5]. Entanglement in larger debris further threatens species survival. Moreover, plastics can adsorb toxic chemicals from the surrounding environment, acting as vectors for contaminants that may enter biological systems (Rochman *et al.*, 2013) [14]. The movement of plastics through food webs, as shown in the diagram, underscores their role in trophic transfer and bioaccumulation. This process can result in the transfer of contaminants from lower to higher trophic levels, ultimately affecting predators and potentially humans. Consequently, plastic pollution contributes to biodiversity loss, altered species interactions, and reduced ecosystem resilience. The conceptual diagram emphasizes the interconnected and dynamic nature of plastic pollution, linking sources, pathways, environmental distribution, and ecological impacts. It highlights the need for integrated management approaches that address each stage of the plastic lifecycle to effectively mitigate its effects on biodiversity.

Methodology

This study employed a systematic review approach to analyze existing literature on plastic pollution and its ecological implications. A comprehensive search was conducted across major scientific databases, including Scopus, Web of Science, ScienceDirect, PubMed, and Google Scholar. Relevant grey literature from international organizations was also considered. Search terms included combinations of keywords such as “plastic pollution,” “microplastics,” “ecosystem impact,” and “environmental sustainability.” The review focused on studies published between 2000 and 2025 to ensure the inclusion of both foundational and recent research. Inclusion criteria comprised peer-reviewed articles and reports addressing plastic pollution in terrestrial, freshwater, and marine ecosystems, while exclusion criteria included non-data-driven publications and studies unrelated to ecological impacts. Data extracted from selected studies included information on sources of plastics, types and size classifications, environmental pathways, ecological impacts,

and mitigation strategies. The data were analyzed using qualitative thematic synthesis, allowing for the identification of patterns and relationships across studies. To enhance reliability, the quality of selected studies was assessed using established appraisal criteria, and findings were organized into thematic categories aligned with the study objectives.

Sources and Types of Plastic Pollutants

Plastic pollutants originate from a wide range of anthropogenic activities and are broadly categorized into primary and secondary plastics (Ziani *et al.*, 2023) [20]. Primary plastics are intentionally manufactured in small sizes, such as microbeads used in cosmetics, industrial abrasives, and plastic pellets (nurdles), while secondary plastics result from the fragmentation of larger plastic debris due to environmental weathering processes. Major sources include industrial production, urban waste, agricultural practices, and household consumption, with mismanaged waste playing a dominant role in environmental contamination (Figure 2).

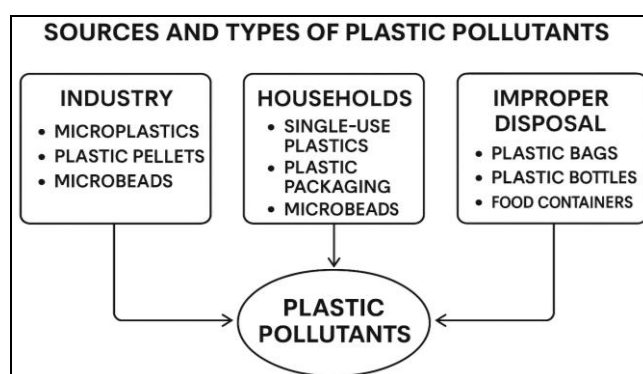


Fig 2: Conceptual diagram of the sources of pollution

In terrestrial systems, plastic inputs arise from landfills, agricultural mulching films, sewage sludge application, and atmospheric deposition. Studies indicate that soil systems act as significant sinks for microplastics, often exceeding concentrations found in aquatic environments (Issac and Kandasubramanian, 2021) [7]. In aquatic ecosystems, plastics enter through riverine transport, wastewater discharge, stormwater runoff, and maritime activities such as fishing and shipping (Table 1). Plastic pollutants are also classified by size into macroplastics (>25 mm), mesoplastics (5–25 mm), and microplastics (<5 mm), with emerging concern over nanoplastics due to their ability to penetrate biological tissues. Microplastics are particularly problematic because of their high surface area, persistence, and capacity to adsorb toxic chemicals. Synthetic textiles represent a significant and often overlooked source, releasing microfibrils during washing, while tyre wear particles contribute substantially to urban microplastic pollution. Additionally, improper waste disposal and inadequate recycling infrastructure in developing regions exacerbate environmental loading. Overall, the diversity of sources and types of plastic pollutants highlights the complexity of the problem and underscores the need for integrated waste management strategies. The continuous input of plastics into ecosystems ensures their persistence and widespread distribution, making them one of the most ubiquitous environmental contaminants globally (Kumar *et al.* 2021) [8].

Table 1: Major Sources and Types of Plastic Pollutants

Source Category	Examples	Type	Pathway
Industrial	Pellets, microbeads	Primary microplastics	Industrial discharge
Household	Bottles, packaging	Secondary plastics	Waste mismanagement
Agriculture	Mulch films	Macro/microplastics	Soil/runoff
Transportation	Tire wear	Microplastics	Road runoff
Textiles	Microfibers	Microplastics	Wastewater

Pathways and Distribution: The movement of plastics through ecosystems is governed by multiple physical,

chemical, and biological processes. Plastics are transported from terrestrial environments into freshwater systems primarily via surface runoff, wind dispersal, and stormwater drainage, eventually reaching rivers and oceans. Rivers serve as critical conduits, carrying large quantities of plastic debris from inland areas to marine environments. In aquatic systems, ocean currents, tides, and wind patterns facilitate the widespread distribution of plastics, leading to their accumulation in gyres, coastal zones, and even remote regions such as polar environments (Figure 3). Recent evidence shows that microplastics are present in virtually all environmental compartments, including air, water, and soil, demonstrating their global dispersal.

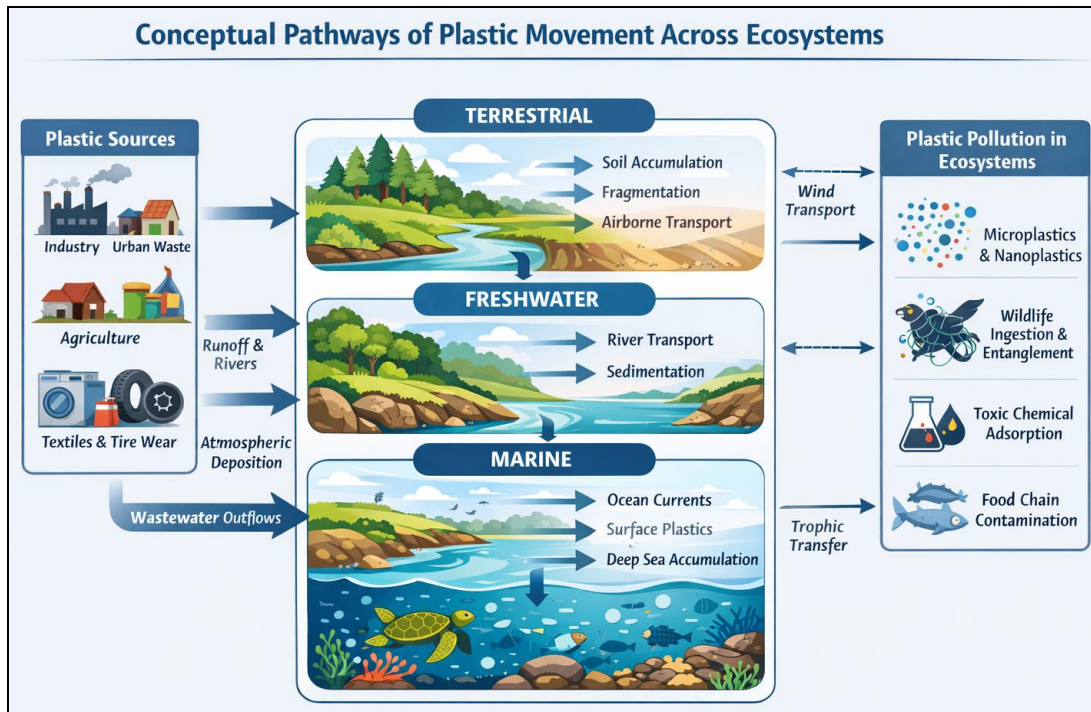


Fig 3: Conceptual Pathways of Plastic Movement Across Ecosystems (Illustrates sources (industrial, household), transport pathways (runoff, rivers, atmosphere), and distribution across terrestrial, freshwater, and marine ecosystems).

Atmospheric transport has emerged as a significant pathway, with microplastics being carried over long distances and deposited through precipitation. This process contributes to contamination in remote and previously pristine ecosystems. Furthermore, plastics undergo fragmentation into smaller particles through photodegradation, mechanical abrasion, and biological activity, increasing their mobility and bioavailability. Sedimentation processes lead to the accumulation of plastics in riverbeds, lake sediments, and ocean floors, where they may persist for extended periods. In contrast, buoyant plastics remain in surface waters, increasing the likelihood of interaction with marine organisms. Biological vectors also play a role in plastic distribution. Organisms ingest plastics and transport them across trophic levels, facilitating their movement within and between ecosystems. This trophic transfer contributes to the widespread presence of microplastics in food webs. The complex interplay of these pathways results in the ubiquitous presence of plastics across all ecosystems, highlighting the need for a systems-based understanding of plastic transport and fate to inform mitigation strategies.

Ecological Impacts

Plastic pollution exerts profound effects on biodiversity and ecosystem processes. One of the most immediate impacts is ingestion, where organisms mistake plastic particles for food, leading to physical blockages, reduced feeding efficiency, and starvation (Table 2). This has been documented across a wide range of species, including fish, seabirds, and invertebrates. Entanglement is another critical impact, particularly for larger marine species such as turtles and mammals, resulting in injury, restricted movement, and mortality. Beyond physical harm, plastics act as carriers of toxic substances, including heavy metals and persistent organic pollutants, which can leach into organisms upon ingestion. At the ecosystem level, plastic pollution alters habitat structure and function. For example, plastic debris can smother coral reefs and benthic habitats, reducing biodiversity and disrupting ecological interactions. Microplastics also influence microbial communities, forming what is known as the “plastisphere,” which can alter nutrient cycling and ecosystem dynamics. In terrestrial ecosystems, microplastics affect soil properties, including porosity, water retention, and microbial activity

(de Souza Machado *et al.*, 2018) [3]. These changes can impair plant growth and reduce agricultural productivity. Recent findings indicate that microplastics may interfere with photosynthesis and nutrient uptake, posing risks to food security. Furthermore, plastics contribute to the alteration of food webs through trophic transfer and bioaccumulation. Predators consuming contaminated prey may experience increased exposure to toxins, leading to physiological stress and reduced reproductive success. Overall, plastic pollution represents a significant driver of biodiversity loss and ecosystem degradation, with impacts that are both direct and indirect, and often cumulative over time.

Table 2: Ecological Impacts of Plastic Pollution

Impact Type	Description	Ecosystem
Ingestion	Plastic consumption by organisms	Aquatic
Entanglement	Physical trapping	Marine
Toxicity	Chemical contamination	All
Habitat alteration	Structural disruption	Marine/Soil
Trophic transfer	Movement through food chains	All

Mitigation Measures and Policy Responses

Efforts to address plastic pollution involve a combination of policy interventions, technological innovations, and behavioral changes. At the global level, initiatives such as the proposed United Nations treaty on plastic pollution aim to establish legally binding measures to reduce plastic production and improve waste management. National policies, including bans on single-use plastics and extended producer responsibility (EPR) schemes, have shown effectiveness in reducing plastic waste generation. However, implementation remains uneven, particularly in developing countries where infrastructure challenges persist. Technological solutions focus on improving waste collection, recycling efficiency, and the development of biodegradable alternatives. Advances in microplastic removal technologies, such as filtration systems and novel materials, show promise in reducing contamination in water systems.

sustainable solutions. While still in early stages, these methods offer potential for reducing plastic persistence in the environment. Community-based interventions, including public awareness campaigns and behavioral change initiatives, play a crucial role in reducing plastic consumption and improving waste disposal practices (Figure 4). Despite these efforts, significant challenges remain, including the scale of plastic production, economic dependencies, and limited enforcement of regulations. Addressing plastic pollution requires a holistic approach that integrates policy, technology, and societal engagement (Prata *et al.*, 2019) [12].

Research Gaps and Future Directions

Although significant progress has been made in understanding plastic pollution, several knowledge gaps remain. One major limitation is the lack of standardized methodologies for sampling, detection, and quantification of microplastics, which hinders comparability across studies. There is also a limited understanding of the long-term ecological and health effects of microplastics, particularly at the cellular and molecular levels. Emerging evidence suggests that microplastics can penetrate biological tissues and potentially cause toxicity, but further research is needed to establish causal relationships. Data on plastic pollution in terrestrial ecosystems are relatively scarce compared to marine environments, despite growing evidence of significant contamination. Similarly, the impacts of nano plastics remain poorly understood due to analytical challenges.

Future research should focus on developing standardized protocols, improving detection technologies, and conducting long-term monitoring studies. Interdisciplinary approaches that integrate environmental science, toxicology, and socio-economic analysis are essential for a comprehensive understanding of the issue. Additionally, more studies are needed in developing regions, where plastic pollution is often most severe but least studied. Addressing these gaps will enhance the effectiveness of mitigation strategies and support evidence-based policymaking aimed at reducing the global burden of plastic pollution.



Fig 4: Framework for Plastic Pollution Mitigation Strategies (Shows the interaction between policy, technology, and community actions in reducing plastic pollution and improving ecosystem health).

Conclusion

Plastic pollution remains a critical and escalating environmental challenge with far-reaching implications for ecosystem health and biodiversity. This review has demonstrated that plastics originate from diverse sources, including industrial activities, household consumption, agriculture, and transportation, and are transported through complex pathways such as runoff, river systems, and atmospheric processes. These pathways facilitate the widespread distribution of plastics across terrestrial, freshwater, and marine ecosystems. The findings further highlight that plastic pollution exerts significant ecological impacts, including ingestion, entanglement, habitat degradation, and chemical toxicity. Microplastics, in particular, pose a unique threat due to their persistence, mobility, and ability to interact with biological systems and food webs. In addition, plastics contribute to alterations in ecosystem processes, including soil structure, nutrient cycling, and microbial dynamics. Despite increasing global attention and mitigation efforts, the scale of plastic pollution

Bioremediation approaches, involving microorganisms capable of degrading plastics, are also being explored as

continues to grow, largely due to inadequate waste management systems and rising plastic production. Addressing this issue requires integrated and multidisciplinary approaches that combine scientific research, policy interventions, technological innovations, and public engagement.

Limitations of the study

This study is limited by its reliance on secondary data obtained through a systematic review of existing literature. As such, the findings depend on the quality, scope, and methodologies of the reviewed studies, which may vary significantly across regions and disciplines. Another limitation is the lack of standardized methods for sampling and analyzing microplastics, which affects the comparability of results across different studies. Additionally, there is a disproportionate focus on marine ecosystems in the literature, with relatively limited data available for terrestrial and freshwater systems, particularly in developing regions. Furthermore, emerging areas such as nanoplastics and their long-term ecological and human health effects remain under-researched, limiting the ability to draw comprehensive conclusions in these areas.

Contribution to Knowledge

This study contributes to the existing body of knowledge by providing a comprehensive and integrated synthesis of plastic pollution across multiple ecosystems. It brings together fragmented research on sources, pathways, ecological impacts, and mitigation strategies into a unified framework, enhancing understanding of the interconnected nature of plastic pollution. The study also highlights the role of emerging pollution sources, such as synthetic textiles and tire wear particles, which are often underrepresented in traditional assessments. By incorporating these sources, the research broadens the scope of plastic pollution studies. In addition, the development of conceptual frameworks and structured analyses in this review provides a useful reference for future research and policy development. The identification of critical research gaps further contributes to guiding future scientific investigations and environmental management strategies.

Recommendations

Based on the findings of this study, the following recommendations are proposed:

1. Strengthen Waste Management Systems: Governments should invest in efficient waste collection, recycling infrastructure, and proper disposal systems to reduce plastic leakage into the environment.
2. Promote Policy and Regulatory Measures: Implementation of policies such as bans on single-use plastics, extended producer responsibility (EPR), and stricter environmental regulations should be enhanced and enforced.
3. Encourage Technological Innovation: Research into biodegradable materials, advanced recycling technologies, and microplastic removal systems should be prioritized to reduce environmental contamination.
4. Enhance Public Awareness and Education: Community-based programs and awareness campaigns should be promoted to encourage responsible

consumption and waste disposal practices.

5. Support Interdisciplinary Research: Future studies should integrate environmental science, toxicology, and socio-economic perspectives to better understand the impacts of plastic pollution.
6. Focus on Understudied Areas: Greater research attention should be directed toward terrestrial ecosystems, freshwater systems, and developing regions where data are currently limited.
7. Develop Standardized Methodologies: Establishing uniform protocols for sampling and analysis of plastics, particularly micro- and nanoplastics, will improve data comparability and reliability.

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