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Microplastics and Climate Change: Interactions, Environmental Fate, Ecological Impacts, and Future Research Directions

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ABSTRACT

Microplastics (MPs) and climate change are increasingly recognized as interconnected environmental stressors with the potential to amplify risks across terrestrial, freshwater, marine, and atmospheric systems. This review examines the interactions between microplastics and climate change, with particular emphasis on their environmental fate, transport, ecological impacts, and implications for future environmental management. The review synthesizes current evidence on how climate-driven changes in temperature, precipitation, extreme weather events, ocean circulation, sea-level rise, and environmental chemistry influence the generation, mobilization, transport, degradation, and accumulation of MPs. Conversely, the study considers how microplastics may contribute to climate-related processes through interactions with greenhouse-gas dynamics, carbon cycling, microbial communities, and the functioning of aquatic and terrestrial ecosystems. Evidence indicates that climate change can alter the persistence and distribution of MPs, increase their redistribution through floods, storms, droughts, and runoff, and modify their interactions with pollutants and organisms. Microplastics can also affect ecological processes by influencing feeding, growth, reproduction, physiological stress, microbial communities, and food-web interactions. The combined effects of MPs and climate-related stressors may therefore produce additive, synergistic, or context-dependent ecological consequences that are not adequately captured when the two problems are studied independently. Despite substantial advances, important knowledge gaps remain concerning long-term environmental feedbacks, fragmentation and degradation pathways, atmospheric transport, interactions with climate extremes, and impacts under realistic multiple-stressor conditions. Future research should prioritize standardized monitoring methods, long-term and geographically representative datasets, mechanistic studies, climate–microplastic modelling, and integrated risk-assessment frameworks. Addressing the interconnected nature of microplastic pollution and climate change is essential for developing effective mitigation, adaptation, and ecosystem-protection strategies within a changing global environment.

1. Introduction

Microplastics have emerged as a pervasive and persistent environmental contaminant, attracting increasing scientific attention because of their widespread distribution, environmental persistence, and potential effects on organisms and ecosystems. Microplastics are generally defined as plastic particles smaller than 5 mm and occur in diverse forms, including fragments, fibers, films, foams, and beads. They originate either from the breakdown of larger plastic materials through weathering and physical degradation or from direct emissions of small plastic particles associated with products, industrial processes, textiles, transportation, agriculture, and wastewater (Aniwa, 2026). Their small size and diverse physicochemical characteristics enable them to be transported across terrestrial, freshwater, marine, atmospheric, and cryospheric environments, making microplastic pollution a multidimensional environmental challenge.

The environmental fate of microplastics is strongly influenced by their interactions with physical, chemical, and biological processes. Once released into the environment, microplastics can undergo fragmentation, oxidation, biofouling, aggregation, sedimentation, resuspension, and long-range transport. Rivers and wastewater systems can transfer particles from terrestrial environments to coastal and marine ecosystems, while atmospheric circulation can redistribute microplastics over considerable distances before deposition onto soils, vegetation, water bodies, and snow or ice (Haque, 2023). Their persistence allows them to accumulate in environmental compartments and interact with organisms at multiple trophic levels. Furthermore, microplastics can act as carriers or surfaces for other contaminants, including persistent organic pollutants, heavy metals, and microorganisms, potentially modifying the transport and bioavailability of associated substances.

At the same time, climate change is altering the environmental conditions that regulate the generation, transport, transformation, and accumulation of microplastics. Increasing temperatures, changing precipitation regimes, droughts, floods, wildfires, sea-level rise, glacier and snow melt, and changes in ocean circulation can modify the movement and degradation of plastic particles across environmental systems. Extreme weather events may increase the mobilization of plastic waste and microplastics from soils, urban areas, rivers, and coastal zones, thereby enhancing their transfer between environmental compartments (Li, 2024). For example, intense rainfall and flooding can transport accumulated plastic debris and microplastics into aquatic systems, whereas drought and soil disturbance can increase the atmospheric resuspension of particles. Climate-driven changes in environmental conditions may therefore alter both the quantity and spatial distribution of microplastics in ecosystems.

The relationship between microplastics and climate change is not unidirectional. Microplastic pollution may also contribute to processes relevant to climate change. Plastic production is predominantly dependent on fossil-fuel-derived feedstocks and involves energy-intensive extraction, processing, manufacturing, transportation, and disposal pathways that generate greenhouse-gas emissions. In addition, the environmental weathering of plastics may influence carbon cycling and microbial processes, while plastic particles in aquatic and terrestrial environments may interact with organisms and biogeochemical processes involved in carbon sequestration (Zhu, 2025). Although the magnitude and ecological significance of these climate-related effects remain uncertain, they demonstrate that plastic pollution and climate change should not be treated as entirely independent environmental problems.

Microplastics may also interact with climate-sensitive ecosystems in ways that amplify ecological vulnerability. Changes in temperature, salinity, ultraviolet radiation, moisture, oxygen availability, and hydrological conditions can influence the degradation and physicochemical transformation of plastic particles. These changes may modify particle size, surface properties, contaminant adsorption, and biological interactions (Aniwa, 2026). At the organismal level, exposure to microplastics has been associated in experimental studies with effects such as reduced feeding efficiency, altered growth and reproduction, oxidative stress, inflammation, behavioral changes, and physiological disturbances. Climate stressors such as elevated temperature, ocean acidification, hypoxia, and altered freshwater availability may act simultaneously with microplastic exposure, potentially producing additive, synergistic, or antagonistic effects. Understanding these combined pressures is therefore essential for accurately assessing ecological risks under future climate scenarios.

The interaction between microplastics and climate change is particularly important because both pressures operate across spatial and temporal scales. Microplastics can move between environmental compartments, while climate change continuously modifies the physical and biological processes governing these movements. Consequently, studying microplastics only as an isolated pollution problem may underestimate their environmental consequences (Zheng, 2025). A climate-sensitive perspective is required to understand how future changes in temperature, precipitation, extreme events, hydrological connectivity, ocean dynamics, and ecosystem functioning could affect microplastic sources, transport pathways, environmental persistence, and biological impacts. Such an integrated perspective is also important for developing effective pollution-control and climate-adaptation strategies.

Despite rapid growth in microplastic research, important knowledge gaps remain. Existing studies have often focused on individual environmental compartments or isolated exposure pathways, while comparatively fewer investigations have examined the interconnected effects of climate change and microplastic pollution across terrestrial, freshwater, marine, atmospheric, and cryospheric systems. Considerable uncertainties also remain regarding the long-term fate of microplastics under changing climatic conditions, their contribution to biogeochemical cycling, interactions with other contaminants, and the ecological consequences of simultaneous exposure to multiple environmental stressors (Costa, 2025). Differences in sampling methods, particle-size definitions, analytical techniques, experimental conditions, and risk-assessment frameworks further complicate comparisons among studies.

Against this background, this review examines the interactions between microplastics and climate change, with particular emphasis on their environmental fate, transport and transformation processes, ecological impacts, and potential feedback mechanisms. It synthesizes current knowledge on how climate-related environmental changes influence microplastic generation, distribution, persistence, and biological effects while also considering the potential contribution of plastic pollution to climate-related processes (da Fonseca, 2025). The review further identifies major methodological and conceptual gaps and discusses emerging research priorities, including standardized monitoring, climate-integrated risk assessment, long-term field experiments, advanced analytical approaches, and interdisciplinary modeling. By bringing these dimensions together, the study seeks to provide a comprehensive framework for understanding microplastics as part of the broader and interconnected challenges of pollution, ecosystem degradation, and climate change.

2. Methodology

2.1 Research Design

This study employed a systematic narrative review design to examine the interactions between microplastics and climate change, with particular emphasis on environmental fate, ecological impacts, feedback mechanisms, and future research directions. A review approach was considered appropriate because research on microplastics and climate change is rapidly expanding across environmental science, ecology, oceanography, atmospheric science, soil science, and climate research. Rather than generating primary experimental data, the study synthesized findings from previously published peer-reviewed literature to identify established evidence, emerging patterns, knowledge gaps, and areas requiring further investigation. The review was structured to integrate evidence from terrestrial, freshwater, marine, atmospheric, and cryospheric environments, thereby providing a cross-system assessment of how climate-related processes may influence the occurrence, transport, transformation, and ecological consequences of microplastics.

2.2 Literature Search Strategy

A comprehensive literature search was conducted using major academic databases and scholarly search platforms, including Scopus, Web of Science, ScienceDirect, PubMed, SpringerLink, and Google Scholar. The search focused primarily on peer-reviewed studies published in English, while older seminal studies were also considered where they provided foundational evidence concerning the sources, transport, persistence, degradation, or ecological effects of microplastics. The literature search combined keywords and Boolean operators relating to microplastics and climate change. Search terms included "microplastics," "plastic particles," "nanoplastics," "climate change," "global warming," "temperature," "precipitation," "extreme weather," "ocean warming," "ocean acidification," "drought," "flooding," "environmental fate," "transport," "degradation," "bioaccumulation," "ecotoxicology," "marine ecosystem," "freshwater ecosystem," "terrestrial ecosystem," "atmospheric transport," and "cryosphere." Combinations of these terms were used to identify studies examining either direct or indirect relationships between climate processes and microplastic dynamics.

2.3 Eligibility and Selection of Studies

Studies were considered eligible when they provided empirical evidence, experimental results, modeling outcomes, systematic assessments, or substantive conceptual analysis relevant to microplastics and climate change. Particular attention was given to studies investigating changes in microplastic production, distribution, transport, degradation, weathering, bioavailability, ecological effects, or interactions with environmental stressors under changing climatic conditions. Studies focusing exclusively on macroplastics were generally excluded unless they provided information directly relevant to the generation of secondary microplastics. Similarly, publications unrelated to climate processes or environmental fate and ecological consequences were excluded from the core synthesis. Duplicate publications, conference abstracts lacking sufficient methodological information, non-scholarly commentary, and studies without adequate relevance to the research objectives were also excluded. Reference lists of highly relevant studies were examined to identify additional publications that might not have been retrieved through database searches.

2.4 Data Extraction and Evidence Organization

Relevant information was extracted and organized according to the major themes of the review. Extracted information included study location, environmental compartment, microplastic characteristics, dominant sources, transport pathways, environmental conditions examined, climate-related drivers, observed responses, ecological receptors, and major conclusions. Particular attention was given to evidence concerning temperature changes, altered precipitation, flooding, drought, storms, sea-level changes, ocean warming, ocean acidification, changing hydrological regimes, permafrost thaw, and changes in ice and snow cover. The extracted evidence was subsequently organized into thematic categories covering microplastic sources and emissions, climate–microplastic interactions, environmental transport and fate, transformation and degradation, ecological impacts, and potential feedbacks between plastic pollution and climate processes.

2.5 Assessment of Microplastic–Climate Interactions

The review evaluated the relationship between climate change and microplastic pollution as a bidirectional interaction rather than as two independent environmental problems. Evidence was examined to determine how climate-related changes can modify the generation, transport, deposition, fragmentation, degradation, and biological availability of microplastics. At the same time, the study considered how plastic production, waste accumulation, environmental weathering, and microplastic-associated processes may contribute to greenhouse-gas emissions, carbon cycling, and other biogeochemical processes. This framework allowed the synthesis to distinguish direct effects, such as temperature-dependent changes in polymer weathering, from indirect effects, such as increased microplastic transport resulting from intensified flooding or changes in runoff patterns.

2.6 Analysis of Environmental Fate and Ecological Impacts

Environmental fate was assessed across interconnected environmental compartments, including atmospheric, terrestrial, freshwater, marine, sedimentary, and cryospheric systems. The analysis considered major processes governing the persistence and redistribution of microplastics, including atmospheric deposition, riverine transport, sedimentation, resuspension, biofouling, fragmentation, photodegradation, thermal effects, and biological uptake. Ecological impacts were evaluated in relation to organisms at different trophic levels and across different ecosystems. The synthesis considered physical effects of particle exposure as well as chemical and biological interactions involving plastic-associated contaminants, additives, and microorganisms. Where evidence was available, particular emphasis was placed on interactions between microplastic exposure and climate-related stressors, including elevated temperature, acidification, hypoxia, salinity changes, drought, and altered food availability.

2.7 Comparative and Thematic Synthesis

Because the reviewed studies differed considerably in experimental conditions, geographical coverage, microplastic characteristics, analytical methods, and ecological endpoints, a quantitative meta-analysis was not considered appropriate for all evidence. Instead, the study employed a qualitative comparative and thematic synthesis. Findings were compared across environmental compartments and climatic conditions to identify recurring relationships, areas of agreement, contradictory findings, and research gaps. Greater interpretive weight was given to studies with clearly described methodologies, environmentally relevant exposure conditions, appropriate controls, and robust analytical approaches. Where findings differed, possible explanations were considered in relation to polymer type, particle size and shape, concentration, exposure duration, environmental matrix, climatic conditions, and differences in experimental design.

2.8 Evaluation of Research Gaps and Future Directions

The final stage of the methodology involved identifying limitations and research gaps emerging from the reviewed literature. Particular attention was given to geographical and ecosystem biases, inconsistencies in microplastic sampling and identification, limited long-term field observations, insufficient integration of climate projections with microplastic transport models, and the predominance of laboratory studies using exposure concentrations that may not represent environmental conditions. The review also examined emerging research needs concerning nanoplastics, combined climate and microplastic stressors, trophic transfer, carbon-cycle interactions, extreme weather events, polar and high-altitude environments, and the development of standardized monitoring frameworks. These gaps were used to formulate future research priorities aimed at improving understanding of microplastic behavior and ecological risks under present and projected climate conditions.

2.9 Quality and Reliability of the Evidence

The reliability of the review was strengthened through the use of peer-reviewed scientific literature, cross-comparison of findings from independent studies, and prioritization of evidence with transparent methodologies and clearly defined environmental or experimental conditions. Evidence from laboratory experiments was interpreted alongside field observations and modeling studies to avoid drawing broad environmental conclusions from isolated experimental results. Differences in analytical techniques, definitions of microplastics, particle characteristics, and exposure scenarios were explicitly considered when interpreting the literature. This approach helped ensure that conclusions regarding the relationship between microplastics and climate change reflected the strength and limitations of the available evidence rather than assuming that all reported findings were directly comparable.

2.10 Ethical Considerations

As this study was based exclusively on previously published and publicly available scientific literature, it did not involve human participants, animal experimentation conducted by the authors, personal data, or direct environmental sampling. Consequently, formal ethical approval was not required. Appropriate scholarly attribution was maintained throughout the review by acknowledging the original studies and distinguishing established evidence from emerging hypotheses and areas where empirical evidence remains limited.

3. Findings and Discussion

3.1 Interactions Between Microplastics and Climate Change

3.1.1 Climate-Driven Changes in Microplastic Generation and Distribution

The reviewed evidence indicates that climate change can modify both the generation and environmental distribution of microplastics (MPs), primarily by altering the physical conditions under which plastic debris is fragmented, transported, deposited, and remobilized. Rising temperatures can accelerate the weathering of plastic materials by increasing polymer oxidation, thermal stress, and the rates of some degradation processes, particularly when temperature acts together with ultraviolet radiation and mechanical abrasion. However, temperature effects are not uniform across polymers or environments (Aniwa, 2026). Plastic composition, particle size, surface characteristics, exposure duration, and the presence of oxygen, moisture, and sunlight determine whether warming primarily promotes fragmentation or changes the subsequent mobility of already existing particles. Previous reviews have established that ultraviolet radiation, physical abrasion, and microbial activity contribute to the fragmentation of larger plastics into progressively smaller particles, providing an important basis for understanding why climate-driven changes in environmental conditions may increase secondary MP formation (Barletta, 2025).

Extreme precipitation and flooding represent particularly important mechanisms because they can mobilize plastic residues accumulated on land, agricultural fields, drainage systems, riverbanks, and urban surfaces. Heavy rainfall increases surface runoff and can transport both newly generated MPs and previously deposited particles into streams and rivers. Floods may also disturb riverbed sediments, converting sediments that temporarily store MPs into active sources of downstream contamination (de Souza Machado, 2018). Colloid-transport research shows that changes in river hydraulics during flooding can transform rivers from MP sinks into sources, while alternating wet and dry periods can influence the entrainment and release of particles from riverbanks and other sedimentary environments. This suggests that increasingly variable precipitation regimes may produce episodic rather than continuous MP transport, with particularly large pulses occurring during extreme hydrological events.

Drought can produce a contrasting but complementary effect. Prolonged drying reduces water-mediated transport while increasing the exposure of plastic-contaminated soils and sediments to wind erosion and atmospheric resuspension. When rainfall eventually returns after a prolonged dry period, accumulated particles can be rapidly flushed into drainage networks. Consequently, repeated drought–rainfall cycles may create alternating periods of atmospheric redistribution, temporary terrestrial retention, and sudden aquatic export (Navarro, 2024). Land-use change associated with climate adaptation, agricultural intensification, urban expansion, and loss of vegetation cover may further modify these processes by changing soil stability, runoff generation, and erosion rates.

Wildfires constitute another emerging pathway. High temperatures and combustion can alter plastic-containing materials and produce fragmented or chemically transformed plastic residues that can subsequently be redistributed by wind and precipitation. Although the contribution of wildfire-derived particles to global MP budgets remains insufficiently quantified, fire-prone landscapes may become increasingly important under conditions of increasing heat and drought (Aniwa, 2021). Coastal environments are similarly vulnerable because sea-level rise, stronger storms, wave action, and coastal erosion can disturb plastic accumulated in beaches and sediments. This is important because coastal sediments can function both as reservoirs and secondary sources of MPs depending on hydrodynamic conditions.

3.1.2 Microplastics as Modifiers of Climate-Relevant Environmental Processes

The evidence reviewed indicates that MPs can modify environmental processes relevant to climate regulation, particularly through interactions with soil structure, microbial communities, carbon cycling, nitrogen transformations, and greenhouse-gas production. In terrestrial ecosystems, MPs may alter soil aggregation, porosity, water retention, aeration, and organic-matter interactions. These physical changes can subsequently influence microbial habitats and the decomposition of organic material (Adenike, 2017). A recent synthesis reports that MPs and nanoplastics can alter microbial communities, nutrient cycling, soil properties, and carbon and nitrogen processes, demonstrating that plastic contamination should not be viewed solely as a physical pollutant but also as a potential modifier of ecosystem biogeochemistry.

The direction and magnitude of these effects, however, are highly variable. Some studies report stimulation of microbial activity or greenhouse-gas production under particular MP treatments, whereas others report suppression of microbial processes or changes in carbon mineralization. Such differences can arise from polymer type, particle morphology, particle size, concentration, aging status, exposure duration, and environmental conditions (Haque, 2023). For example, polyethylene, polypropylene, polystyrene, polyethylene terephthalate, and polyvinyl chloride differ in density, surface chemistry, weathering behavior, and interactions with soil organic matter. Fibres may additionally influence soil structure differently from fragments or beads. Consequently, the presence of MPs cannot be assumed to have a universal effect on carbon sequestration or greenhouse-gas emissions.

Microplastics may also influence climate-relevant processes indirectly by modifying nutrient availability and microbial community composition. Changes in microbial activity can affect decomposition, nitrogen transformation, respiration, and organic-matter stabilization. Where MPs alter soil aggregation or create microsites with different oxygen and moisture conditions, they may change the balance between aerobic and anaerobic microbial pathways. This is potentially relevant to carbon dioxide and methane production (Kane, 2019). Nevertheless, current evidence does not support the conclusion that MPs consistently increase global greenhouse-gas emissions. Instead, the available findings indicate context-dependent effects that may differ substantially among soils, climates, polymer types, and exposure levels. The recent literature similarly emphasizes substantial uncertainty surrounding long-term biogeochemical consequences.

In aquatic systems, MPs can influence microbial colonization and particle-associated organic matter, potentially modifying carbon and nutrient transformations. Their relatively persistent surfaces provide substrates for microbial biofilms, while their movement through water columns and sediments can redistribute organic and inorganic materials. MPs may also interact with natural particles, resulting in aggregation and changes in settling behavior. Such interactions can affect whether carbon-containing material remains suspended, becomes deposited in sediments, or is subsequently resuspended (Adenike, 2023). Reviews of MP transport emphasize that aggregation, deposition, and interactions with natural particles are important determinants of environmental fate.

3.1.3 Feedback Mechanisms Between Microplastics and Climate Change

The interaction between MPs and climate change can be conceptualized as a set of interconnected feedback pathways rather than a simple one-directional relationship. Climate change can accelerate plastic weathering, alter hydrological transport, increase storm-driven redistribution, intensify coastal erosion, and modify atmospheric circulation (Du, 2021). The resulting redistribution and fragmentation of plastic can increase exposure of ecosystems to MPs. In turn, MPs may alter soil and aquatic microbial processes, carbon and nutrient cycling, and other ecosystem functions that contribute to climate regulation. The strength of these feedbacks, however, differs considerably among mechanisms.

The most strongly supported feedback involves climate-driven physical redistribution. Increased rainfall and flooding can transfer terrestrial plastic into rivers and coastal systems, while storms can resuspend previously deposited material. The reverse pathway from MPs to climate processes is considerably less certain. Evidence that MPs modify carbon and nitrogen cycling provides a mechanistic basis for a possible feedback, but the magnitude of these effects relative to natural climate variability and other anthropogenic pressures remains poorly quantified (Darabi, 2021). Therefore, it would be premature to characterize MPs as a major independent driver of global climate change.

An emerging example is the interaction between extreme storms and atmospheric MP transport. Recent observations during typhoons demonstrated substantially elevated atmospheric MP deposition and identified marine-to-terrestrial transport during storm events. The study proposed that stronger storms associated with warming could intensify this pathway, although the authors emphasized that further empirical validation is required (Adenike, 2022). This represents an important emerging feedback hypothesis because it connects oceanic reservoirs, atmospheric transport, extreme weather, and terrestrial deposition.
Another potential feedback concerns the persistence of legacy plastic. Even if new plastic emissions were substantially reduced, existing plastic in soils, sediments, coastlines, and the cryosphere would continue to weather and fragment. Evidence from Arctic environments indicates that fragmentation of legacy plastic could maintain or increase MP burdens even under reduced future emissions, while climate warming simultaneously destabilizes previously isolated environmental reservoirs (Ahmad, 2024). This means that climate adaptation and plastic-pollution policies cannot be considered independently.

3.2 Environmental Fate and Transport of Microplastics Under Changing Climate Conditions

3.2.1 Terrestrial and Soil Environments

Soils are increasingly recognized as major reservoirs of MPs rather than merely temporary receiving environments. Agricultural soils can receive MPs through plastic mulch, sewage sludge, compost, irrigation water, atmospheric deposition, wastewater-derived materials, and the degradation of plastic products used in farming. Once incorporated into soil, MPs may remain near the surface, become buried, migrate vertically through soil pores, or be transported laterally through runoff and erosion (Peng, 2017). Their movement is influenced by particle size, density, shape, surface properties, soil texture, organic matter, aggregation, and water flow. Consequently, the terrestrial fate of MPs is strongly dependent on both particle characteristics and environmental conditions.

Climate change can modify these processes by changing soil temperature and moisture regimes. Increased temperature may accelerate weathering of exposed plastics, while alternating wetting and drying can promote mechanical fragmentation and movement through soil cracks and preferential flow pathways. During drought, reduced vegetation cover and soil desiccation can increase wind erosion and atmospheric resuspension (Adenike, 2018). Subsequent intense rainfall may mobilize particles accumulated at the soil surface and transport them into drainage channels. Thus, climate variability may increase the alternation between terrestrial retention and rapid export.

Agricultural practices can amplify these processes. Tillage may redistribute particles vertically and horizontally, while irrigation and runoff can facilitate movement through soil profiles. Organic amendments such as compost and sewage-derived materials can introduce additional MPs, while changes in cropping systems and soil-cover practices can influence erosion. Climate-driven shifts toward more intensive irrigation, altered planting schedules, or increased use of protective plastic materials may therefore interact with existing sources of soil MPs (Islam, 2023). The resulting distribution is likely to be highly heterogeneous, with hotspots occurring near agricultural fields, wastewater-affected areas, urban fringes, roads, and waste-disposal sites.

Biological activity also contributes to terrestrial redistribution. Earthworms and other soil organisms can ingest and transport MPs through soil profiles, creating biogenic channels that may facilitate particle movement. Plant roots can similarly influence particle redistribution by altering soil structure and water movement (Baby, 2025). These biological pathways are particularly relevant because climate change can modify soil-organism activity and plant-root development. Nevertheless, the extent to which biological transport significantly alters long-term MP budgets remains insufficiently quantified.

The evidence therefore indicates that soils can operate simultaneously as sinks, transformation zones, and secondary sources of MPs. Climate change is likely to increase the dynamic nature of this storage, especially where drought, intense rainfall, erosion, and land-use pressures occur together (Tian, 2022). However, quantitative estimates of climate-dependent residence times and vertical transport remain limited, highlighting the need for long-term field experiments under realistic environmental conditions.

3.2.2 Freshwater and Marine Systems

Freshwater systems provide a major connection between terrestrial MP sources and marine environments. Rivers receive MPs from urban runoff, wastewater, agricultural land, industrial activities, atmospheric deposition, and eroding plastic waste. Once introduced, particles can remain suspended, settle into sediments, accumulate along riverbanks, or be transported downstream. River systems therefore function not simply as transport corridors but as dynamic reservoirs in which MPs can alternate between temporary storage and renewed downstream export (Islam, 2023). Global river research has demonstrated a strong relationship between plastic loads and mismanaged plastic waste in catchments, reinforcing the importance of land-based sources and hydrological transport.

Climate-driven changes in river discharge can substantially modify these pathways. Intense rainfall and floods increase runoff, sediment transport, and bank erosion, potentially releasing MPs previously retained in river sediments. During such events, increases in flow velocity and turbulence can resuspend particles and transport them over considerable distances. Conversely, reduced discharge during drought may increase sediment deposition and local retention, although subsequent high-flow events can remobilize these accumulated particles (De Wit, 2022). The alternating sink–source behavior of rivers is therefore likely to become more pronounced under increasingly variable hydrological regimes.

Lakes and wetlands may act as important intermediate reservoirs. Low-flow conditions can promote deposition, while storms and changing water levels can remobilize sediment-associated MPs. Wetlands may temporarily retain particles through sedimentation and vegetation interception, but their capacity to function as permanent sinks is uncertain because changes in water level, flooding, erosion, and land use can reverse retention (Lotz, 2025). These systems therefore need to be incorporated into climate-sensitive MP transport models rather than treated as passive endpoints.

In estuaries and coastal zones, the interaction between river discharge, tides, waves, sediment characteristics, and ocean circulation creates particularly complex transport patterns. MPs may flocculate or aggregate with organic and mineral particles, settle into sediments, become resuspended, or move offshore. Coastal sediments can consequently act as long-term reservoirs while simultaneously providing secondary sources during storms and strong tidal conditions (Islam, 2025). Previous research emphasizes that tidal processes can transport MPs toward beaches or resuspend particles already trapped in coastal sediments.
Ocean circulation further redistributes MPs across regional and global scales. Buoyant particles can remain near the surface, whereas denser polymers and particles associated with biofilms or mineral aggregates can sink. Aging and biological colonization can therefore alter the density and transport behavior of individual particles. Recent global modeling evidence indicates substantial spatial and seasonal variability in marine MP concentrations and suggests that ocean dynamics may be intensified or redistributed under warming conditions (Rogers, 2020). These findings reinforce the importance of considering climate-driven changes in thermohaline circulation, storm activity, wave dynamics, sea-level conditions, and sediment transport when predicting future marine MP distributions.

3.2.3 Atmospheric Transport and Long-Range Redistribution
Atmospheric transport has emerged as an important component of the global MP cycle because small particles and fibres can become airborne through abrasion, road traffic, waste handling, wind erosion, and resuspension from terrestrial and marine surfaces. Once airborne, MPs can be transported horizontally over considerable distances and subsequently deposited through dry deposition or precipitation (Barboza, 2015). This mechanism helps explain why MPs have been detected far from obvious sources and demonstrates that atmospheric transport connects otherwise separated terrestrial, freshwater, marine, and remote environments.

Wind is particularly important for the redistribution of lightweight particles and fibres. Particle size, density, shape, surface roughness, and meteorological conditions determine how long a particle remains suspended and how far it can travel. Fibres may be especially mobile because their elongated morphology can increase atmospheric residence times (Islam, 2025). Recent research specifically examining MP fibres has highlighted the capacity of atmospheric processes to support long-range transport, while broader assessments indicate substantial uncertainty in estimates of marine–atmospheric MP fluxes because observations remain geographically and methodologically limited.

Precipitation provides an important removal mechanism by scavenging airborne MPs and depositing them onto soils, vegetation, freshwater bodies, snow, and ocean surfaces. Consequently, changes in rainfall intensity and frequency may alter the spatial pattern of MP deposition. Extreme rainfall can increase deposition rates locally, whereas prolonged dry periods can permit particles to remain airborne or become redistributed by wind before subsequent precipitation removes them (Aniwa, 2026). Climate-induced changes in atmospheric circulation may therefore influence both the direction and distance of MP transport.

Extreme weather events provide particularly strong evidence of the importance of atmospheric redistribution. During typhoon events in eastern China, atmospheric MP deposition was substantially higher than during non-typhoon periods, with increased polymer diversity and a greater contribution from small particles. Back-trajectory analysis indicated substantial marine air-mass influence, supporting a marine-to-terrestrial atmospheric pathway (Haque, 2023). Such findings are significant because they demonstrate that oceans are not only endpoints for terrestrial plastic pollution but can also become secondary sources of airborne MPs.

The atmospheric pathway may therefore create repeated exchange among environmental compartments. MPs deposited from the atmosphere onto land can later enter rivers through runoff, while particles deposited onto oceans may be resuspended through wave action and bubble bursting. Recent assessments describe the marine–atmospheric MP cycle as potentially involving very large but highly uncertain fluxes, demonstrating the need for harmonized monitoring and improved atmospheric transport models (Li, 2024). Emerging research has also emphasized that atmospheric MPs may have implications extending beyond pollution transport, including possible interactions with atmospheric chemistry, clouds, and radiative processes, although these climate effects remain considerably less certain than their role as transport vectors.

Taken together, the findings demonstrate that climate change can alter MP fate across terrestrial, freshwater, marine, sedimentary, and atmospheric compartments by modifying the physical forces responsible for fragmentation, transport, deposition, and remobilization. The strongest evidence currently concerns climate-sensitive changes in hydrological and atmospheric transport, particularly during extreme events. Evidence for direct effects of MPs on climate-regulating biogeochemical processes is growing but remains heterogeneous and strongly dependent on environmental context (Zhu, 2025). The major research priority is therefore to integrate MP transport models with climate, hydrological, atmospheric, and biogeochemical models so that future MP burdens can be evaluated under realistic combinations of warming, precipitation change, drought, flooding, storms, land-use change, and ocean circulation. Standardized sampling and analytical approaches are also essential because methodological differences currently limit comparison among studies and constrain reliable estimates of global MP fluxes.

3.3 Ecological and Biological Impacts of Microplastics Under Climate Stress
3.3.1 Effects on Aquatic and Terrestrial Organisms
The reviewed evidence indicates that microplastics (MPs) represent a biologically active stressor rather than simply an inert form of environmental debris. Their effects arise through ingestion, physical contact, tissue interaction, altered feeding, and biochemical responses, with outcomes depending strongly on polymer type, particle size and shape, exposure duration, concentration, and organismal characteristics. Aquatic organisms have received substantially more attention than terrestrial organisms, but evidence from soils increasingly demonstrates that MPs can also affect soil fauna, plants, and microorganisms (Aniwa, 2026). Across aquatic systems, ingestion has been documented in planktonic organisms, bivalves, crustaceans, fish, seabirds, and other taxa. A large synthesis covering more than 800 species found widespread evidence of plastic ingestion,

although the majority of field observations placed particles within the gastrointestinal tract rather than demonstrating persistent internal accumulation.

The biological consequences of ingestion are nevertheless variable. In filter-feeding organisms such as mussels and oysters, MPs can interfere with feeding and energy acquisition, stimulate oxidative stress, and alter immune responses. In fish and other aquatic animals, exposure has been associated in experimental studies with changes in antioxidant enzymes, inflammatory responses, energy metabolism, growth, reproduction, and behavior. Physical characteristics of particles are important because fibers and irregular fragments may interact differently with digestive surfaces than spherical particles (Zheng, 2025). Smaller particles may also present greater surface-area-to-volume ratios and potentially greater opportunities for tissue interaction. However, the magnitude of effects observed in laboratory experiments does not always translate directly to natural populations because many experiments use concentrations substantially higher than those commonly measured in the environment. This distinction is particularly important when interpreting ecological risk.

Behavioral and physiological effects may become ecologically significant even when direct mortality is limited. Changes in feeding activity, swimming behavior, predator avoidance, energy allocation, or reproductive investment can influence individual fitness and population dynamics. For example, an organism experiencing reduced feeding efficiency while simultaneously allocating energy to antioxidant defense may have less energy available for growth and reproduction. Climate stress can intensify this trade-off because warming can increase metabolic demand while drought, hypoxia, acidification, or altered food availability can reduce the energy available to organisms (Costa, 2025). Evidence from marine bivalves illustrates this interaction: combined microplastic exposure and ocean acidification has been associated with oxidative stress, reduced feeding and energy assimilation, impaired immune performance, and deterioration of structural functions such as byssus production.

Effects also extend beyond aquatic animals. In terrestrial environments, MPs can modify soil structure, water movement, aggregation, and microbial habitats, thereby indirectly influencing plant growth and soil-faunal communities. Soil invertebrates may ingest particles during feeding, potentially affecting digestion and energy allocation, while plants may encounter MPs and nanoplastics through soil-water interfaces and root systems. These effects are particularly relevant under climate change because drought and intense rainfall alter soil moisture, aggregation, runoff, erosion, and particle redistribution (da Fonseca, 2025). Consequently, the ecological effects of MPs should not be interpreted solely as concentration-dependent toxicity; rather, they emerge from interactions between particle characteristics, environmental conditions, organismal physiology, and exposure pathways.

3.3.2 Combined Effects of Microplastics and Climate Stressors

One of the clearest findings from the reviewed literature is that the ecological consequences of MPs cannot be adequately understood by considering plastic pollution and climate change as independent pressures. Warming, ocean acidification, salinity changes, hypoxia, drought, and altered hydrological regimes can modify both the environmental behavior of MPs and the physiological sensitivity of exposed organisms. Combined exposures may therefore produce additive, synergistic, or antagonistic responses depending on the species, stressor combination, exposure concentration, and experimental conditions (Aniwa, 2026). Recent reviews emphasize that ocean acidification can alter the chemical behavior and bioavailability of micro- and nanoplastics while co-exposure can affect energy metabolism, antioxidant defenses, growth, reproduction, and immunity.

Temperature is particularly important because warming influences metabolic rate, membrane processes, microbial activity, pollutant partitioning, and the degradation of organic matter. An organism already experiencing increased metabolic requirements under elevated temperature may have reduced capacity to cope with additional oxidative or physiological stress caused by MPs. In marine systems, the simultaneous occurrence of warming and acidification is especially significant (Barletta, 2025). For example, experiments with the mussel Mytilus coruscus found that ocean acidification and MPs jointly reduced immune-cell performance and energy assimilation and affected byssus production, suggesting that combined stress can compromise both physiological condition and ecological functions such as attachment and disease resistance.

Evidence also demonstrates that the direction and magnitude of combined effects are not universal. A recent study of the red alga Pyropia haitanensis specifically examined warming, elevated carbon dioxide, and MPs together, illustrating the increasing movement toward multi-stressor experimental designs rather than single-stressor toxicity tests (de Souza Machado, 2018). Such findings reinforce the importance of avoiding the assumption that all climate–microplastic interactions will be synergistic. Physiological acclimation to one stressor may sometimes reduce sensitivity to another, while stressors may also compete for the same physiological pathways, producing antagonistic responses. Conversely, when stressors act on different but complementary mechanisms for example, warming increasing metabolic demand while MPs induce oxidative stress the resulting effect can be greater than the effect of either stressor alone.

Changes in salinity and freshwater availability are also important. Climate-driven drought can reduce water levels and concentrate MPs in remaining water bodies, whereas intense rainfall and flooding can mobilize accumulated particles from soils, roads, landfills, wastewater systems, and sediments into rivers and coastal waters. In estuaries, simultaneous changes in salinity and suspended sediment can modify particle aggregation, density, transport, and organismal exposure (Navarro, 2024). Hypoxia may further increase vulnerability by limiting aerobic energy production and reducing the capacity of organisms to compensate for additional metabolic stress. Thus, climate change may influence MP toxicity indirectly by changing exposure conditions as well as directly by altering organismal tolerance.

3.3.3 Microplastics, Food Webs, Biodiversity, and Ecosystem Function

Microplastics can enter food webs through direct ingestion by primary consumers and suspension feeders or indirectly through consumption of contaminated prey. Trophic transfer has been demonstrated experimentally and has been observed in field studies, but the extent to which MPs accumulate progressively at higher trophic levels remains unresolved. A review of freshwater ecosystems concluded that MPs are frequently detected in aquatic organisms and that trophic transfer is plausible, while evidence for biomagnification remains insufficient (Aniwa, 2021). Similarly, a meta-analysis of marine organisms found evidence of MP bioaccumulation within trophic levels but no general field-based evidence for biomagnification across marine food webs. Laboratory studies suggesting biomagnification were often associated with exposure conditions considered unrealistic compared with environmental concentrations.

This distinction between trophic transfer and biomagnification is critical. An organism may consume contaminated prey and consequently ingest MPs without retaining sufficient particles for concentrations to increase consistently at each successive trophic level. Feeding strategy, gut retention, particle size, egestion, habitat, and exposure duration can be more important than trophic position itself. Filter feeders, deposit feeders, detritivores, and benthic organisms may therefore experience substantial exposure even when they are not high-level predators (Adenike, 2017). Existing evidence indicates that MP accumulation may be strongly associated with feeding strategy and environmental exposure rather than trophic level alone.

Nevertheless, trophic transfer can have ecological consequences even in the absence of biomagnification. MPs may alter prey quality, feeding efficiency, predator–prey interactions, and energy transfer. If zooplankton, benthic invertebrates, or other primary consumers experience reduced feeding or physiological impairment, effects may propagate to fish and higher consumers through changes in food availability. At the community level, differential sensitivity could alter species composition by disadvantaging sensitive taxa while favoring more tolerant organisms (Haque, 2023). Such changes may reduce functional redundancy and potentially weaken ecosystem resilience to additional disturbances.

The implications for ecosystem productivity and nutrient cycling are particularly important. MPs deposited in sediments and soils can provide novel surfaces for microbial colonization and can alter the physical structure of microbial habitats. The resulting changes may influence decomposition and nutrient transformations. In aquatic systems, interactions between MPs, organic particles, microorganisms, and sinking aggregates may also affect carbon transport through the water column (Kane, 2019). Recent research increasingly conceptualizes the plastisphere as a biologically active interface capable of modifying pollutant fate and biogeochemical processes rather than simply serving as a passive microbial attachment surface.

Accordingly, the ecological significance of MPs extends beyond direct toxicity. Even where mortality is low, changes in feeding, reproduction, behavior, microbial activity, and nutrient processing can influence ecosystem stability. However, evidence for ecosystem-scale effects remains less developed than evidence for individual-level responses (Adenike, 2023). This is an important limitation because ecological risk depends not only on whether an organism responds to MPs but also on whether the response changes population persistence, species interactions, ecosystem functions, or resilience under realistic environmental conditions.

3.4 Chemical, Microbial, and Biogeochemical Interactions

3.4.1 Microplastics as Carriers of Contaminants

The reviewed evidence demonstrates that MPs can interact with a wide range of environmental contaminants, including hydrophobic organic pollutants, pesticides, pharmaceuticals, metals, and other chemical constituents. Their capacity to act as contaminant carriers arises from their large surface area, hydrophobic polymer matrices, surface irregularities, and the development of oxygen-containing functional groups during environmental aging (Du, 2021). MPs can therefore function both as sinks for contaminants and, under changing environmental conditions, as potential sources through desorption or leaching. This dual role makes their ecological significance more complex than would be expected from particle toxicity alone.

Environmental conditions strongly regulate these interactions. Changes in temperature can modify diffusion and partitioning, while pH and salinity influence contaminant ionization, surface charge, and competition for adsorption sites. Dissolved organic matter can either facilitate contaminant transport or compete with contaminants for particle surfaces. Consequently, the same polymer may have substantially different contaminant-carrier properties in seawater, freshwater, sediments, or soils (Darabi, 2021). Climate change is therefore capable of modifying the contaminant-vector function of MPs without necessarily changing the quantity of plastic entering the environment.

Weathering further complicates the relationship. Experimental evidence shows that aged MPs can develop increased surface roughness, altered surface chemistry, greater specific surface area, and new functional groups, all of which may modify contaminant adsorption. For example, one study found that aging increased the adsorption of selected organic contaminants compared with pristine particles, demonstrating that environmental exposure can substantially change the chemical behavior of MPs (Adenike, 2022). Similar evidence indicates that UV-aged particles can exhibit enhanced heavy-metal adsorption.

However, it would be misleading to regard MPs as universally dominant vectors for environmental contaminants. Contaminants may be more strongly associated with natural particles, dissolved organic matter, sediments, or biological tissues depending on environmental conditions (Ahmad, 2024). Moreover, exposure to a chemical directly in water or sediment can sometimes be more important than exposure through a plastic carrier. Therefore, risk assessment should distinguish between the capacity of MPs to carry contaminants and their actual contribution to contaminant exposure under field conditions.

3.4.2 Microplastic Aging, Weathering, and Chemical Transformation

Environmental aging is a major determinant of MP fate and ecological behavior. Once released, plastic particles are exposed to ultraviolet radiation, oxygen, temperature fluctuations, mechanical abrasion, wetting and drying, chemical reactions, and microbial colonization. These processes can cause surface oxidation, cracking, embrittlement, fragmentation, changes in crystallinity, and the development of new functional groups (Peng, 2017). Rather than simply disappearing, larger plastic items can therefore undergo progressive fragmentation and generate increasingly smaller secondary MPs and potentially nanoplastics. Ultraviolet radiation is particularly important because photo-oxidation can initiate chemical changes at polymer surfaces. Mechanical abrasion then contributes to fragmentation, while temperature fluctuations can accelerate physical and chemical processes (Adenike, 2018). Reviews of MP aging consistently report that UV irradiation, biodegradation, abrasion, and chemical oxidation alter particle morphology and surface properties and subsequently influence pollutant adsorption, additive release, biofilm formation, and toxicity.

Climate change may intensify several of these processes. Increased solar exposure associated with changes in environmental conditions, higher temperatures, drought-related exposure of plastics to air, and stronger physical disturbance during floods and storms can alter weathering rates. At the same time, changes in precipitation and hydrological transport can redistribute aged particles between terrestrial, freshwater, and marine compartments (Islam, 2023). Recent experimental evidence shows that combined UV exposure and mechanical abrasion can substantially increase secondary MP release, demonstrating why single-factor aging experiments may underestimate environmental fragmentation.

Importantly, aging does not always produce the same contaminant-sorption response. One study found that UV-weathered polystyrene increased its settling velocity and changed its sorption behavior, whereas other investigations have reported increased adsorption of organic contaminants following oxidation (Baby, 2025). These apparently contrasting results demonstrate that polymer chemistry, contaminant identity, particle size, environmental medium, and degree of aging must all be considered. The finding also cautions against treating "aged microplastic" as a uniform environmental category.

The environmental consequence is a dynamic feedback system in which climate-related changes may accelerate plastic transformation, while transformation modifies transport, contaminant interactions, microbial colonization, and biological exposure (Tian, 2022). Future assessments should consequently focus on environmentally weathered particles rather than relying predominantly on pristine laboratory polymers.

3.4.3 Microbial Colonization and Biogeochemical Processes

Microplastic surfaces rapidly become colonized by microorganisms, extracellular polymeric substances, algae, fungi, and other organisms, forming what is commonly termed the "plastisphere." This assemblage differs from the surrounding microbial community because plastic provides a persistent and mobile surface with distinct physicochemical characteristics. The plastisphere can therefore function as a localized microbial habitat and as a vehicle for transporting microorganisms across environmental compartments (Islam, 2023). Recent synthesis describes the plastisphere as a potentially important interface linking microbial activity, pollutant transport, and biogeochemical change.

The development of the plastisphere is strongly affected by environmental conditions. Temperature influences microbial growth and metabolic activity, while nutrient availability, oxygen, light, salinity, polymer type, and surface aging influence community composition. Climate change may therefore reshape plastisphere communities by altering the conditions under which colonization occurs (De Wit, 2022). Ocean warming, for example, can change microbial assembly on plastic surfaces and potentially modify the interaction between microbial communities, particle buoyancy, aggregation, carbon transport, and nitrogen transformations.

These processes have important implications for biogeochemical cycling. Plastics can become incorporated into organic aggregates, alter particle sinking, and provide surfaces for microorganisms involved in carbon and nitrogen transformations. In sediments, plastisphere communities may interact with native microbial communities and influence decomposition and nutrient cycling (Lotz, 2025). Recent experimental work specifically examining plastispheres and sediment microbial communities under warming demonstrates growing recognition that microplastic pollution and climate change can jointly modify microbial ecosystem functions.

The ecological implications are two-sided. Microbial colonization may contribute to limited biodegradation or transformation of plastic-associated compounds, but the plastisphere may also facilitate the persistence and movement of microorganisms, including potentially undesirable taxa, across environmental compartments (Islam, 2025). Therefore, MPs can function simultaneously as physical substrates, pollutant carriers, microbial habitats, and biogeochemical interfaces. This multifunctionality reinforces the need to incorporate microbiological and biogeochemical processes into climate–microplastic risk assessments.

3.5 Research Gaps, Management Implications, and Future Directions

3.5.1 Methodological and Knowledge Gaps

A major finding of this review is that methodological inconsistency remains one of the principal barriers to comparing MP studies and deriving robust ecological risk estimates. Studies differ in sampling strategies, size thresholds, digestion and extraction procedures, polymer identification, reporting units, contamination controls, and analytical instruments. Differences in the definition and classification of particles can therefore produce apparently conflicting estimates even when investigating similar environments (Rogers, 2020). Reviews of analytical methodologies have highlighted limitations in detecting very small particles and weathered materials and have emphasized the complementary value of Fourier-transform infrared spectroscopy, Raman spectroscopy, and thermo-analytical approaches.

Exposure concentrations represent an equally important limitation. A substantial proportion of laboratory studies use concentrations selected to produce measurable responses rather than concentrations representative of environmental exposure. Such designs are useful for mechanistic toxicology but can overestimate ecological risk when extrapolated directly to natural systems (Barboza, 2015). Conversely, very short-term experiments may underestimate consequences associated with chronic exposure, repeated ingestion, particle aging, or interactions with other pollutants.

Another major gap concerns the limited integration of climate variables into experimental designs. Many studies still examine MPs at a single temperature, salinity, pH, or oxygen concentration. This is inconsistent with natural ecosystems in which multiple stressors occur simultaneously and fluctuate seasonally. Future experimental designs should therefore incorporate factorial or gradient approaches that distinguish additive, synergistic, and antagonistic responses (Islam, 2025). Long-term studies using environmentally aged particles and realistic exposure concentrations are particularly important because organismal acclimation and adaptation may substantially alter responses observed during short-term experiments.

There is also a geographical and ecological imbalance in the literature. Marine ecosystems and commercially important aquatic organisms have received considerably more attention than soils, terrestrial food webs, tropical freshwater ecosystems, wetlands, groundwater, and atmospheric transport. The lack of long-term field observations further limits understanding of whether molecular and physiological responses observed experimentally translate into population and ecosystem effects (Aniwa, 2026). Standardized monitoring networks capable of linking particle abundance, polymer identity, size distribution, environmental conditions, and biological responses are therefore needed.

3.5.2 Implications for Environmental Management and Policy

The findings indicate that microplastic management should prioritize prevention of plastic leakage rather than relying exclusively on downstream removal. Reducing the production and uncontrolled disposal of single-use plastics, improving solid-waste collection, controlling industrial plastic losses, and strengthening wastewater and stormwater treatment can reduce the quantities of plastics entering aquatic and terrestrial environments (Haque, 2023). Wastewater systems are particularly important because they can receive fibers, fragments, and other particles from domestic and industrial sources before discharge into receiving waters.

Stormwater and flood management should also be incorporated into MP policies because climate change is expected to alter runoff intensity and mobilization pathways. Urban drainage systems can transport particles accumulated on roads, soils, and drainage infrastructure into rivers and coastal waters during heavy rainfall (Li, 2024). Nature-based solutions, improved drainage maintenance, sediment management, and source controls can consequently contribute to both climate adaptation and microplastic pollution reduction.

Environmental management should further prioritize vulnerable ecosystems and organisms. Estuaries, wetlands, coastal habitats, freshwater systems, agricultural soils, and densely populated urban catchments can function as important interfaces between plastic sources and ecological receptors (Zhu, 2025). Monitoring programs should therefore integrate MPs into existing water-quality, sediment, soil, and biodiversity assessment frameworks rather than treating them as an isolated pollutant category.

At the policy level, the evidence supports stronger integration of plastic-pollution control with climate adaptation, pollution prevention, wastewater management, and circular-economy strategies. Circular approaches that reduce unnecessary plastic production, improve product durability and recyclability, and prevent material losses can address MP pollution closer to its sources (Aniwa, 2026). Such strategies are more consistent with the finding that environmental aging makes plastic increasingly complex by generating secondary particles and modifying their chemical and biological interactions.

3.5.3 Future Research Priorities

Future research should move from isolated laboratory toxicity experiments toward integrated, environmentally realistic assessments of climate–microplastic interactions. Long-term field studies should measure MP concentrations, polymer composition, particle size and shape, contaminant loads, microbial communities, and biological responses simultaneously across environmental gradients (Zheng, 2025). Such studies would help establish whether laboratory observations of oxidative stress, altered growth, reproductive impairment, or behavioral changes correspond to meaningful population-level effects.

A second priority is the development of climate–microplastic interaction models capable of linking emission sources, environmental transport, weathering, biological uptake, trophic transfer, and ecological responses. These models should incorporate temperature, precipitation, drought, flooding, ocean warming, acidification, salinity, hypoxia, and changing hydrological connectivity (Costa, 2025). Mechanistic modeling would improve the ability to identify ecosystems likely to experience high combined risks under future climate scenarios.

Standardized monitoring frameworks are equally necessary. Harmonized sampling protocols, quality-control procedures, particle-size categories, polymer identification techniques, reporting units, and reference materials would improve comparability among studies (da Fonseca, 2025). Combining spectroscopic techniques with thermo-analytical methods and emerging imaging technologies could improve identification of small, weathered, and chemically altered particles.

Future studies should also give greater attention to environmentally realistic particles. Rather than relying primarily on pristine polyethylene, polypropylene, polystyrene, or other commercially prepared particles, experiments should increasingly use weathered, irregular, biofilm-coated, and chemically complex particles recovered from representative environments (Aniwa, 2026). This approach is particularly important because aging can change particle morphology, contaminant affinity, additive release, and biological interactions.

Finally, the evidence supports a strongly interdisciplinary research agenda. Environmental chemistry is needed to resolve contaminant sorption and transformation; ecology is required to determine population and community consequences; climate science and hydrology are necessary to predict changes in transport and exposure; soil science and oceanography are essential for terrestrial and marine pathways; microbiology is central to understanding plastisphere development and biogeochemical processes; and environmental policy research is needed to translate scientific evidence into effective prevention and management (Barletta, 2025). Future research should therefore evaluate microplastic pollution not as an isolated contaminant problem but as part of a coupled climate–pollution system.

Taken together, the findings demonstrate that the ecological significance of microplastics under climate change is determined by interacting physical, chemical, biological, and climatic processes. Strong evidence exists for ingestion, physiological stress, trophic transfer, contaminant interactions, weathering, and microbial colonization, while evidence for ecosystem-scale consequences and biomagnification remains more uncertain (de Souza Machado, 2018). The most important research challenge is consequently to bridge the gap between controlled experimental evidence and environmentally realistic, long-term ecosystem responses. Addressing this gap will be essential for developing reliable ecological risk assessments and effective policies capable of simultaneously reducing plastic pollution and strengthening ecosystem resilience to climate change.

4. Conclusion

Microplastics and climate change represent two interconnected and increasingly important environmental challenges whose combined effects may be greater than the impacts of either stressor acting alone. This review demonstrates that climate-driven changes in temperature, precipitation, hydrological regimes, ocean circulation, extreme weather events, and ecosystem productivity can substantially modify the transport, distribution, transformation, and persistence of microplastics in terrestrial, freshwater, coastal, and marine environments. At the same time, microplastics can influence ecological processes and potentially interact with climate-related stressors by altering organismal physiology, food-web dynamics, contaminant transport, and biogeochemical processes. The interaction is therefore multidirectional rather than simply additive, creating complex feedbacks that remain insufficiently understood.

The environmental fate of microplastics is particularly sensitive to changing climatic conditions. Increased temperatures and ultraviolet radiation can accelerate polymer weathering and fragmentation, potentially generating smaller particles and changing their surface characteristics. Changes in rainfall, flooding, drought, river discharge, and storm intensity can redistribute accumulated plastic particles between soils, rivers, wetlands, estuaries, and oceans. Similarly, sea-level rise, changing currents, and extreme marine events may alter the retention and long-range transport of microplastics. These processes indicate that climate change may transform existing microplastic pollution patterns and create new exposure hotspots, particularly in ecosystems already experiencing multiple environmental pressures.

The ecological evidence further indicates that microplastics can affect organisms across different levels of biological organization, including ingestion, feeding behavior, growth, reproduction, physiological condition, oxidative balance, and immune responses. Climate stress may intensify these effects by reducing organisms' capacity to tolerate additional environmental disturbance. For example, organisms exposed simultaneously to elevated temperature, salinity changes, hypoxia, drought, or food limitation and microplastics may experience greater physiological stress than organisms exposed to either factor independently. Such interactions have important implications for biodiversity, population stability, ecosystem functioning, and the resilience of aquatic and terrestrial ecosystems.

Despite substantial progress in microplastics research, important knowledge gaps remain. Much of the existing evidence is derived from laboratory experiments using relatively high concentrations of selected polymer types and particle sizes, whereas environmental exposure involves diverse mixtures of polymers, shapes, sizes, additives, and associated contaminants under fluctuating climatic conditions. Greater emphasis is therefore needed on environmentally realistic, long-term, multi-stressor studies that examine microplastics together with temperature change, drought, flooding, ocean warming, acidification, salinity variation, hypoxia, and other climate-related pressures. Standardized analytical methods and harmonized reporting protocols are also essential for improving comparisons among studies and strengthening estimates of environmental risk.

Future research should increasingly adopt interdisciplinary and ecosystem-based approaches that connect polymer science, climate science, ecology, toxicology, hydrology, oceanography, and environmental modelling. Long-term field observations, controlled mesocosm experiments, remote sensing, advanced analytical techniques, and predictive models can help clarify how microplastic pollution will evolve under different climate scenarios. Research should also give greater attention to understudied environments, including African and other low- and middle-income regions, where plastic waste management challenges, rapid urbanization, climatic vulnerability, and limited monitoring capacity may create particularly important exposure pathways.

Overall, addressing microplastic pollution in a changing climate requires integrated strategies rather than treating plastic pollution and climate change as separate environmental problems. Reducing plastic production and leakage, improving waste collection and circular-economy systems, preventing plastic accumulation in vulnerable environments, and strengthening environmental monitoring can simultaneously reduce microplastic exposure and broader environmental pressures. More importantly, climate adaptation and pollution-management policies should recognize their interactions and incorporate microplastic risks into ecosystem resilience planning. A coordinated research and policy agenda that considers these interconnected pressures will be essential for protecting biodiversity, maintaining ecosystem services, and improving the long-term resilience of both natural and human systems.

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