Microplastics as Potential Vehicles of Pollutants and Pathogen in Climate Change Settings: A Critical Review of Impacts, Interactions, and Research Gaps

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Abstract. This critical review synthesizes current knowledge on the emerging role of microplastics as vehicles for pollutants and pathogens, particularly within the context of a changing climate. Climate change exacerbates the environmental impacts of microplastics by intensifying their interactions with biological systems. Biofilms colonizing microplastic surfaces facilitate the co-adsorption of pathogens and pollutants, creating localized hotspots of contamination with significant implications for aquatic organisms and potentially human health. The presence of heavy metals and organic pollutants, such as polycyclic aromatic hydrocarbons (PAHs), can exert selective pressures on microbial communities within these biofilms, leading to the enrichment of virulent or metal-resistant strains. Moreover, pollutants can provide a protective environment for pathogens, enhancing their survival and persistence in ecosystems already stressed by climate change. This review highlights critical research gaps, including the long-term effects of microplastic-associated pollutants on biota and the mechanisms by which climate change influences these complex interactions. Addressing these knowledge gaps is crucial for developing effective management strategies to mitigate the risks posed by microplastics and safeguard both environmental and human health in a changing climate.

Keywords: microplastic, climate change, impact, interactions, vehicle, gap

1 Introduction

Microplastics, tiny plastic particles less than 5 millimeters in size, have become a major environmental concern due to their ubiquitous presence and potential to act as carriers of pollutants and pathogens. [1,1–3]. These particles originate from various sources, including the breakdown of larger plastic debris, synthetic fibers shed from textiles, and microbeads used in personal care products. [3–6]. Their widespread distribution in marine and freshwater environments raises critical questions about their ecological impacts, particularly in the context of climate change. As climate alters environmental conditions, it may exacerbate the risks associated with microplastic pollution.[1,3,7].

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Climate change adds complexity to the interaction of microplastics, pollutants, and pathogens, as fluctuating temperatures, altered salinity, increased UV radiation, and changing nutrient availability influence microplastic behavior and effects. These environmental gradients shape the plastisphere (microbial communities on microplastic surfaces), affecting microbial composition and virulence.[7–10].

Pollutants co-occurring with microplastics (MPs) can modify microbial communities, potentially selecting for pathogenic or resistant strains, while MP aging alters surface properties, enhancing contaminant adsorption and synergistic pollutant-pathogen interactions[11]. This dynamic interplay necessitates ongoing research, particularly regarding climate change impacts. The ecotoxicological implications of MPs as pollutant and pathogen vehicles include increased bioavailability, ingestion risks for aquatic organisms, amplified trophic transfer within food webs, and potential human health risks via seafood consumption.[12–15].

2 Methodology

This critical review will synthesize existing literature to analyze the relationship between microplastics and climate change. The review process will adhere to the following steps:

2.1 Defining the Scope and Research Questions

This review focuses on secondary microplastics (MPs), formed from the breakdown of larger plastics (e.g., bags, bottles, fishing gear), composed of polymers such as polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC). Climate change, encompassing global warming, ocean acidification, and altered precipitation, is examined in relation to MPs acting as pollutant and pathogen vehicles. The research questions address the mechanisms of MP-mediated transfer, how climate change exacerbates this transfer, and the existing research gaps in understanding these processes.

2.2 Literature Search Strategy

This review utilized ScienceDirect and Scopus databases, employing keyword combinations related to microplastics, climate change, and pollutants/pathogens. Inclusion criteria were empirical studies published in English, in peer-reviewed journals, between January 2020 and October 2024, focusing on the relationship between microplastics and climate change in marine and coastal ecosystems. Review articles, meta-analyses, opinion pieces, case studies, and solely terrestrial studies were excluded. The PRISMA diagram (Figure 1) visualizes the methodology.

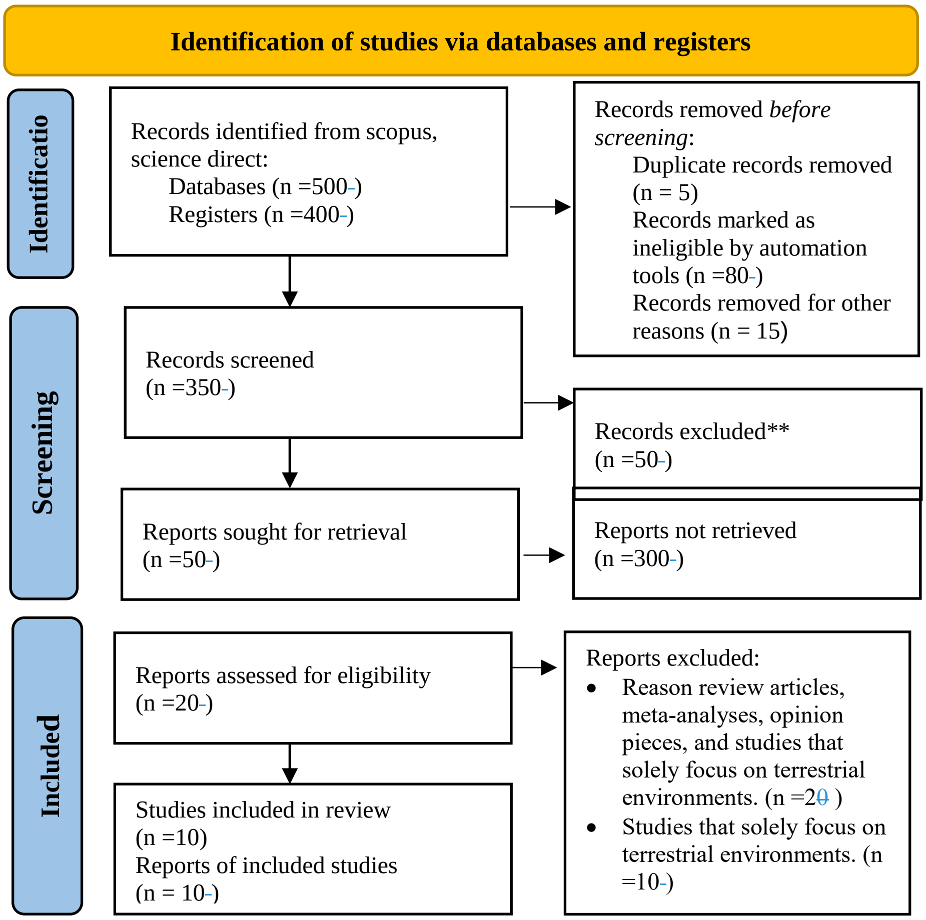

Figure 1. PRISMA flow diagram

2.3 Data Extraction and Analysis

Develop a data extraction form. Systematically collect information from selected articles (study objectives, methodologies, key findings, limitations). Article information author(s), title, journal, year of publication, DOI, and study objectives. Climate change data sources such as meteorological data and climate models. Interactions between Microplastics and Climate Change such as synergistic effects and Feedback loops. Research gaps namely unanswered questions and future research directions. Study limitations, sample size, geographic scope, data quality, and methodological constraints. Qualitative analysis employs thematic analysis to identify key themes, patterns, and contradictions in the literature regarding the interactions between microplastics and climate change. Critical evaluation, assesses the methodological rigor, validity, and potential biases of included studies.

3 Results and Discussion

3.1 Research Related to Impacts, Interactions, and Research Gaps

This critical review examines the multifaceted impacts of microplastics within the context of climate change, focusing on their role as potential vehicles for the transport and accumulation of pollutants and pathogens[3,16–18]. The review delves into the intricate interactions between microplastics, pollutants, and pathogens, analyzing how these interactions are influenced and exacerbated by climate change. Furthermore, it identifies and critically assesses crucial research gaps that hinder a comprehensive understanding of these complex relationships, highlighting the need for further investigation to inform effective mitigation and adaptation strategies for the challenges posed by microplastic pollution in a changing climate. [19–21]. Table 1 shows about impacts, interactions, and research gaps.

Table 1. Research Related to Impacts, Interactions, and Research Gaps

No	Research (Reference)	Impact	Interaction	Research Gaps
1	The whole life journey and destination of microplastics: A review [22].	MPs pose health risks, potentially altering gut microbiota, metabolism, and intestinal barrier function.	MPs and pollutants interact, altering toxicity and behavior, and impacting gut microbiota and pathogen response.	Understanding of MP transfer to humans and biological toxicities; integrated research on gut health needed.
2	The triple exposure nexus of microplastic particles, plastic-associated chemicals, and environmental	MPs increase exposure to plastic-associated chemicals, exacerbating health risks as plastics fragment.	MPs act as vehicles for pollutants, heavy metals, and pathogens, enhancing pathogenicity	Research on the triple exposure nexus of MPs, plastic chemicals, and pollutants and their health

No	Research (Reference)	Impact	Interaction	Research Gaps
	pollutants from a human health perspective [17].		and immune compromise.	effects is insufficient.
3	Microplastics as an emerging menace to the environment: Insights into their uptake, prevalence, fate, and sustainable solutions [17].	MPs enter the food chain, affecting plants, animals, and humans, with health implications exacerbated by environmental persistence.	MPs facilitate pathogen and pollutant transfer through the food chain.	Gaps in eco-toxicology and MP prevalence hinder risk assessment and sustainable solutions.
4	Micro- and nanoplastics (MNPs) and their potential toxicological outcomes: State of science, knowledge gaps and research needs [23].	MNPs are significant environmental contaminants, driven by oxidative stress, with health risks in biological samples.	MPs act as vehicles for persistent organic pollutants, interacting with pathogens	Knowledge gaps in toxicity of environmentally relevant MNPs;
5	Toxic Chemicals and Persistent Organic Pollutants Associated with Micro-and Nanoplastics Pollution [24]	MPs exacerbate climate change impacts by affecting biodiversity, leaching additives, and adsorbing pollutants.	MPs adsorb pollutants, facilitating pathogen interactions and virulence, impacting organism	Limited understanding of additive degradation in MPs, complicating ecosystem and health risk assessments.
6	Microplastics accumulate fungal pathogens in terrestrial ecosystems [25]	MPs serve as artificial microhabitats for fungal communities, including pathogens, raising public health	MPs accumulate fungal pathogens, acting as reservoirs and vehicles .	Lack of studies on fungal pathogens associated with MPs in terrestrial environments .
7	New Link in the Food Chain? Marine Plastic Pollution and	Plastics in the marine food chain raise concerns about toxic exposures for	Plastics in marine environments facilitate pollutant	Poor understanding of marine plastic consumption's

No	Research (Reference)	Impact	Interaction	Research Gaps
	Seafood Safety [26].	seafood consumers.	sorption, increasing pathogen exposure	toxic impacts on human seafood consumption.
8	Editorial: Plastic pollution in a changing marine environment: effects and risk [27].	MPs interact with marine contaminants, complicating impacts on marine biota and ecosystems	MPs sorb contaminants, creating co-exposure scenarios	Data gaps on litter densities and MP formation mechanisms hinder risk assessment
9	A review of the occurrence, analytical methods, and impact of microplastics in the environment [28].	MPs disrupt soil health, affecting plant growth, agricultural productivity, and microbial activities, exacerbating climate change.	MPs in soil transport toxic chemicals and antibiotics, altering pathogen dynamics	Inconsistent methods for studying MPs impede understanding of their health and environmental impacts.
10	Microplastics in the soil environment: A critical review [28].	MPs change soil physicochemical characteristics, affecting plant growth	MPs alter soil flora and fauna, impacting microbial communities	Insufficient research on MP impacts on soil health.

3.2 Pathogen-Microplastic Interactions

Microplastics (MPs) provide novel niches for pathogens, promoting biofilm formation that enhances pathogen survival and virulence. The hydrophobicity of polymers like polyethylene and polystyrene facilitates pathogen adhesion (e.g., Vibrio spp., E. coli, A. fumigatus), with biofilms providing protection and promoting nutrient exchange, especially with co-occurring pollutants[10]. Biofilm formation and pathogen colonization are influenced by polymer type, MP surface characteristics (size, shape, roughness), and the existing microbial community, impacting infectious disease dissemination in aquatic and terrestrial environments and necessitating further research and mitigation.[10,29,30].

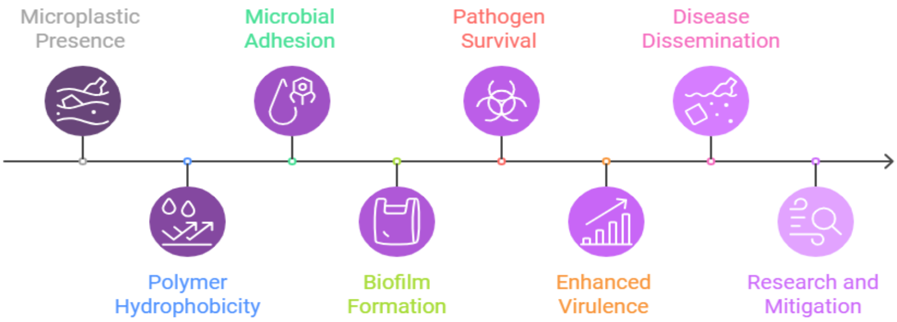

Figure 2. Pathogen Biofilm Formation on Microplastics

The interaction of microplastics (MPs), biofilms, and pathogens significantly impacts infectious disease dissemination in aquatic and terrestrial environments. Pathogen-colonized MPs act as vehicles, transporting microorganisms to new ecosystems and potentially causing disease outbreaks. This presence of pathogens within the plastisphere can also disrupt microbial community balance. Therefore, comprehensive research is urgently needed to elucidate the mechanisms of pathogen attachment, biofilm formation, and virulence enhancement on MPs, as well as to develop mitigation strategies, including plastic pollution reduction, MP removal technologies, and public health measures.[10,10,31].

3.3 Pollutant-Microplastic Interactions

Microplastics act as significant vehicles for various contaminants in the environment, profoundly influencing their fate and ecological impact. This phenomenon, known as pollutant-microplastic interaction, involves the sorption and transport of pollutants by microplastic particles. Several factors contribute to this complex interplay. [11,32–35].

Biofouling, the colonization of microplastic surfaces by microbial communities, plays a crucial role in enhancing pollutant sorption. Biofilms, composed of diverse microbial assemblages, create a matrix that facilitates the attachment of hydrophilic and polar pollutants, such as heavy metals and poly-fluoroalkyl substances (PFAS). This enhancement is attributed to mechanisms like the formation of hydrophilic bridges between pollutants and biofilm components, as well as an increase in surface roughness, providing more sites for pollutant adsorption. [18,36]. Figure 3, shows complex interactions on microplastic surfaces.

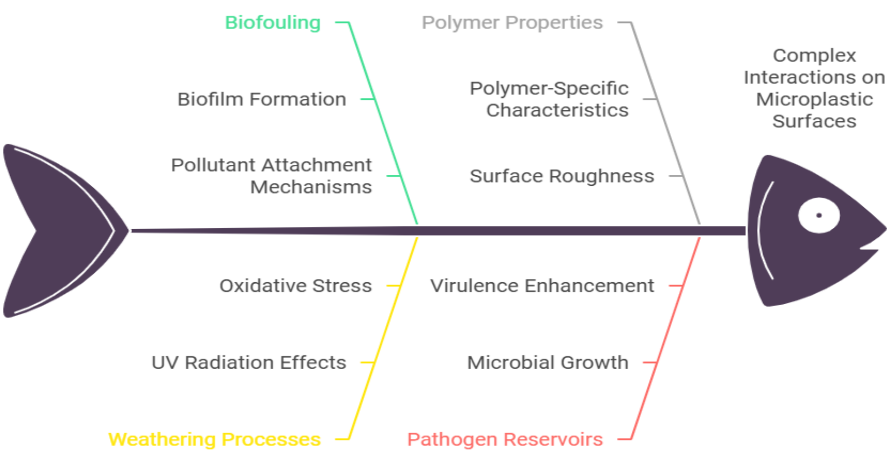

Figure 3. Complex Interaction on MPs

Based on Figure 3, the Ishikawa (fishbone) diagram elucidates the multifaceted interactions occurring on microplastic surfaces, with the "head" designating the core issue: "Complex Interactions on Microplastic Surfaces." Contributing factors, emanating from the central "spine," are categorized into microplastic-intrinsic properties and external biological and environmental influences. The former encompasses "Polymer Properties," further delineated into "Polymer-Specific Characteristics" and "Surface Roughness," while the latter includes "Biofouling" (comprising "Biofilm Formation" and "Pollutant Attachment Mechanisms"), "Weathering Processes" (leading to "UV Radiation Effects" and "Oxidative Stress"), and the role of microplastics as "Pathogen Reservoirs," influencing "Microbial Growth" and potentially inducing "Virulence Enhancement." Consequently, the diagram systematically interrelates the physicochemical attributes of microplastics with biological and environmental processes, collectively contributing to the complex surface interactions observed [37–40].

3.4 Synergistic Pathogen-Pollutant Interactions on MPs

The co-occurrence of pathogens and pollutants on microplastic (MP) surfaces presents a complex and multifaceted challenge in environmental science. Biofilms that colonize MP surfaces act as microcosms, facilitating the co-adsorption of both pathogens and pollutants, thereby creating localized "hotspots" of contamination[10]. The presence of heavy metals, persistent organic pollutants (POPs) such as polycyclic aromatic hydrocarbons (PAHs), and other organic contaminants can significantly influence microbial behavior within these biofilms [8,29]. Table 2, shows synergistic Pathogen-Pollutant Interactions on MPs.

Table 2. Synergistic Pathogen-Pollutant Interactions on MPs [31]

Pathogen	Pollutant	Synergistic Interaction/Effect
General Microbial Communities/Biofilms	Heavy Metals (e.g., Cd, Hg, Pb)	Enrichment of virulent or antibiotic-resistant strains due to selective pressure.
General Microbial Communities/Biofilms	Persistent Organic Pollutants (POPs)	Protection of pathogens from environmental stressors (UV radiation, oxidative stress, predation).
Specific Pathogenic Bacteria (e.g., Vibrio)	Various Organic Contaminants	Potential for increased virulence gene expression; enhanced colonization of MPs
Specific Pathogenic Viruses	Various Pollutants	Potential for increased viral persistence and infectivity.

3.5 Impact to Climate Change

Microplastics (MPs) profoundly influence environmental dynamics, particularly under climate change, which alters environmental conditions (e.g., salinity, UV exposure, nutrients) and shapes the plastisphere (MP-colonizing microbial communities), affecting both MP properties and microbial assemblages/virulence. Pollutants leached from plastics further modify microbial behavior, potentially favoring pathogenic or resistant strains, with biofilm aging enhancing these complex pollutant-pathogen synergies[10]. Consequently, MPs act as vehicles for long-distance transport of contaminants, increasing their bioavailability and trophic transfer risks, threatening aquatic life and human health via seafood consumption. These synergistic interactions disrupt ecological balance, necessitating further research on long-term MP effects in changing climates and their role in exacerbating ecological degradation.. [38,41,42].

3.6 Research Gap

Despite increasing awareness of microplastic (MP) impacts, significant research gaps persist, particularly regarding real-world studies in heterogeneous systems. Mechanistic understanding of pollutant-induced changes in pathogen virulence and resistance within MP-associated microbial communities, the role of emerging pollutants (especially in tropical systems), and human health implications of MP exposure (including transfer mechanisms and toxicities) require further investigation[43]. Research on the combined effects of MPs, plastic-associated chemicals, and environmental pollutants remains insufficient, as does understanding of micro- and nano-plastic toxicity, plastic additive degradation, MP-mediated terrestrial fungal pathogen dispersal, and the impact of marine plastic consumption on seafood safety[10]. These knowledge gaps, coupled with inconsistent MP research methodologies and limited data on MP prevalence and formation, hinder effective risk assessment and mitigation strategies across diverse ecosystems, including soil health and agricultural practices[23].

4 Conclusion

This review synthesizes 2020-2024 research on the interactions of microplastics (MPs), pollutants, and pathogens in marine and coastal ecosystems under climate change. It demonstrates that MPs, especially within the plastisphere (biofilm), act as vehicles for pollutant sorption and pathogen proliferation, with climate change influencing these dynamics. This synergy can enhance pathogen virulence, resistance, and persistence, leading to adverse ecotoxicological effects, including increased bioavailability of harmful substances, trophic transfer, and seafood-related human health risks. Despite these findings, further research is needed to address gaps in real-world data, mechanistic understanding of pathogen behavior, impacts of emerging pollutants and regional variations, and human health implications, highlighting the need for standardized MP research methodologies.

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