Biotechnological Journal of Environmental Microorganisms
"BJEM"

Biotechnological Journal of Environmental Microorganisms(BJEM) 3(12) 2025 670-677

Marine Microbial Biotechnology in the Fight Against the Microplastic Crisis: The Role of Biofilms and the Complexities of Microbial Contamination

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Received : 05 January 2025 / Revised: 19 January 2025 / Accepted : 25 January 2025

Abstract

In recent years, researchers have paid increasing attention to newly emerging contaminants (CECs) in order to identify and eliminate them. Microplastics are known as one of the most important of these contaminants, which are widely present in aquatic environments and sediments with a size of less than 5 mm. These diverse particles arise from the decomposition of large plastic waste or primary sources such as pellets, fishing gear, synthetic textiles, cosmetic-hygiene products, and electronic equipment. The presence of microplastics in the bodies of aquatic animals has caused health concerns and the transfer of dangerous chemical pollutants. Microplastic biofilms also provide a platform for the accumulation of microorganisms, the horizontal transfer of antibiotic resistance genes, and the increase in their rate. Studies have shown that these biofilms can increase cell density and increase the rate of gene transfer by more than 19 times. The effects of biofilms depend on the type of polymer, size, concentration, and environmental conditions, and can limit the spread of resistance in some situations. Thus, emerging pollutants, especially microplastics, pose significant risks to human health and ecosystems by changing the environment and aquatic microbiomes. This review article analyzes the position of microplastics in emerging pollutants, emphasizing the need for further research and the development of effective management policies.

Key words: Emerging pollutants, microplastics, biofilms, horizontal gene transfer, antibiotic resistance, aquatic ecosystem

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doi:10.71886/bioem.2025.1219977

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Introduction

The widespread introduction of newly emerging contaminants (CECs) into aquatic environments is one of the challenging consequences of industrial development and changing consumption patterns in the contemporary world. Many of these synthetic compounds pose a serious threat to the health of aquatic ecosystems and ultimately human health due to their high chemical stability, environmental mobility, and long-term and often unknown ecological effects(Khoshnood, 2025). Among them, microplastics—solid polymer particles smaller than five millimeters in size—have become the focus of environmental research due to their mass production, exceptional persistence in the environment, and high potential for physical and biological interaction (Azizollahi Aliabadi et al., 2024). These particles enter aquatic environments through two main pathways: first, the gradual and physical degradation of larger plastic waste in nature under factors such as sunlight, wind, and waves; and second, the direct release of primary particles from sources such as microbeads in cosmetics, synthetic fibers separated from textiles during the washing process, industrial granules, and even car tires(Khoshnood, 2025).

From Physical Carriers to Biologically Active Platforms

In the early stages of research, the risks associated with microplastics focused mainly on their direct physical effects; such as ingestion by aquatic organisms at different levels of the food chain, causing gastrointestinal obstructions, false satiety, and mechanical transmission along the food chain. However, recent findings in the fields of environmental biology and aquatic microbiology have revealed that these particles do not play a passive and purely physical role, but also act as biologically active platforms or carriers(Jia et al., 2024). The surface of these particles, which is usually hydrophobic, durable, and has a high surface-to-volume ratio, provides ideal conditions for the rapid settlement and aggregation of diverse microorganisms, resulting in the formation of structured and complex communities called biofilms(Kenchegowda et al., 2021). This specialized microscopic ecosystem, known as the plastisphere, is significantly different in species composition, genetic diversity, metabolism, and ecological dynamics from the microbial community of the surrounding water or natural particles such as organic and inorganic materials(Zhou et al., 2024).

Biofilm-Mediated Horizontal Gene Transfer: A Conduit for Antibiotic Resistance

The formation of these specialized biofilms on microplastics has profound bioecological consequences that, in many cases, go beyond the inherent risks of the plastic itself. One of the most concerning and important of these consequences, which has recently attracted much attention, is the role of microplastic biofilms as effective and accelerating channels for the horizontal transfer of antibiotic resistance genes in aquatic environments(Wang et al., 2023; Wang et al., 2024). The extracellular matrix rich in biopolymers that forms the structure of biofilms creates unique and optimal conditions for the efficient exchange of genetic material, especially through important mechanisms such as conjugation and natural transformation, by allowing very high bacterial densities, ensuring physical proximity and direct contact between different cells, and providing a protective shelter from environmental stressors (such as ultraviolet radiation, salinity fluctuations, temperature, and the presence of antimicrobial agents)(Wang et al., 2024).

Amplified Gene Transfer and the Self-Reinforcing Cycle of Resistance

Recent experimental and field studies have clearly shown that the presence of biofilm communities on microplastics can significantly increase the transfer rate of plasmids and other genetic elements carrying resistance genes (ARGs). Some reports indicate an increase of up to 19-fold compared to controlled conditions without biofilms or in the presence of natural particles(Zhou et al., 2024). This phenomenon makes biofilm-contaminated microplastics mobile and highly efficient agents for the spread and propagation of antibiotic resistance in vast water bodies, from rivers and lakes to coastal waters and the deep ocean. Thus, a dangerous and self-reinforcing cycle is formed in the global antimicrobial resistance crisis(Azizollahi Aliabadi et al., 2024).

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Biofilms as Agents of Plastic Degradation and Transport

The formation of biofilms on microplastics can also yield certain environmental benefits. For instance, biofilms can facilitate the biodegradation of plastic particles, as some of the associated microorganisms produce depolymerizing enzymes capable of breaking down polymer structures. Additionally, biofilms alter the physicochemical properties of microplastics—such as increasing their density and reducing surface hydrophobicity—which promotes vertical transport in water and soil, potentially decreasing their interaction with surface-dwelling organisms(-Paerl et al., 2001). These surface modifications, along with the increased specific area provided by biofilms, can further enhance microbial enzymatic activity and weathering processes. Moreover, understanding and harnessing biofilm-forming microbes with plastic-degrading potential opens avenues for bioremediation strategies aimed at reducing microplastic pollution in natural ecosystems(Ventura et al., 2024).

The Plastisphere: A Hub for Nutrient Cycling and Bioremediation

Biofilm formation on microplastics offers additional ecological benefits that complement those outlined earlier. Beyond facilitating physical transport and enhancing biodegradation, these microbial assemblages – known as the plastisphere – actively participate in key biogeochemical cycles. Metagenomic evidence shows that plastisphere communities harbor functional genes for nitrogen transformation processes, including denitrification(Saranraj, 2025). This enables them to contribute to the removal of excess nitrogen from aquatic environments, effectively supporting natural water purification. Furthermore, biofilms create localized anaerobic microenvironments,allowing oxygen-sensitive processes like denitrification to occur even in oxygenated waters. Importantly, many of the microorganisms within the plastisphere simultaneously carry plastic-degrading genes, suggesting a dual capability: breaking down plastic polymers while participating in nutrient cycling. The degradation of plastics or their additives may also supply additional carbon, fueling microbial nitrogen removal. Thus, the plastisphere represents not only a potential agent for plastic remediation but also a functionally active component in aquatic nutrient dynamics, highlighting its complex yet potentially beneficial role in polluted ecosystems(Fortin et al., 2025).

Knowledge Gaps and the Path Forward in Plastisphere Research

Despite significant advances in understanding microplastic-microorganism interactions, important knowledge gaps remain. The simultaneous and reciprocal influence of particle characteristics (polymer type, size, shape, age), environmental hydrochemical conditions (temperature, salinity, nutrients, presence of other pollutants), and the structure and dynamics of the biofilm microbial community on the quantity and quality of resistance gene transfer is not fully understood (Azizollahi Aliabadi et al., 2024; Wang et al., 2024). Also, how to effectively utilize the potential of marine microbial biotechnology—including identifying degrading microorganisms, developing plastisphere-based biomonitoring methods, and designing biological solutions for risk reduction—requires further systematic exploration and investigation.

Discussion

The present systematic review confirms the crucial role of biofilms formed on microplastic surfaces as a key factor in changing the dynamics of microbial communities and accelerating the spread of antibiotic resistance genes (ARGs) in aquatic environments. This finding highlights the need to reconsider the assessment of environmental risks of microplastics from passive pollutants to active agents in microbial ecological engineering.

Selective selection and formation of specific microbial communities

microplastics do not simply act as a physical substrate, but rather selectively select bacteria with

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the ability to adhere and adapt to their specific surface conditions, leading to the formation of microbial communities distinct from the surrounding aquatic environment or natural particles(Azizollahi Aliabadi et al., 2024; Jia et al., 2024). These communities, which often include pathogenicity-associated bacteria and carriers of resistance factors, establish the concept of the "plastisphere" as an independent and potentially dangerous microbial ecosystem(Jia et al., 2024).

Molecular mechanisms facilitating gene transfer

The dramatic increase in the rate of horizontal gene transfer (HGT) in these biofilms can be attributed to a set of synergistic mechanisms. First, the high cell density resulting from entrapment in the extracellular matrix (EPS) maximizes the likelihood of physical contact necessary for processes such as conjugation. Second, this matrix acts as a biological sponge, trapping significant amounts of naked DNA (containing ARGs), which provides ideal conditions for natural transformation events(Wang et al., 2023; Zhou et al., 2024). Third, local stressful conditions on the microplastic surface (such as the presence of heavy metals or other adsorbed contaminants) can induce physiological responses associated with increased genetic mobility (such as activation of the SOS response) in bacteria. Reports of several-fold increases in gene transfer rates support the power of this environment to facilitate genetic exchange(Zhou et al., 2024).

Key variables influencing the final outcome

The potential of microplastics to enhance HGT is not constant and is a complex function of several intrinsic and environmental variables. The chemical nature of the polymer (e.g. polyethylene versus polystyrene) influences the initial composition of the biofilm community and thus the potential for transmission(Jia et al., 2024). Particle size is a determining factor, as smaller particles (in the micro and nano range) provide a unique surface-to-volume ratio, allowing for denser biofilm formation and thus more efficient intercellular interactions(Wang et al., 2024). Furthermore, environmental aging processes (weathering, UV radiation) can enhance both biofilm establishment and selective pressure for the survival of resistant bacteria by increasing surface roughness and pollutant adsorption capacity. This stratification of factors emphasizes the need to consider these variables in risk assessment models. However, the ecological narrative of the plastisphere is not exclusively one of risk. Recent research offers a more nuanced perspective by revealing that the same biofilms implicated in ARG dissemination can also host microbial consortia with the capacity to biodegrade the underlying plastic substrate. These biofilm-forming microorganisms can produce depolymerizing enzymes and, through altering microplastic properties such as density and hydrophobicity, may influence the particles' environmental fate and reduce their bioavailability to surface-dwelling organisms. This dualistic nature underscores the complexity of microplastic-biofilm interactions, where the same microbial habitat can simultaneously act as a vector for genetic pollutants and a potential self-mitigating system for plastic degradation(Ventura et al., 2024).

Ecological implications

From microbial resistance to ecosystem disruption: The implications of this phenomenon are multifaceted and widespread(Shade et al., 2012). At the first level, this mechanism directly contributes to the spread of antimicrobial resistance in aquatic environments and expands the gene pools of ARGs that can enter the human health cycle through various pathways, including aquaculture and drinking water(Amarasiri et al., 2020). At the second level, microplastics, as "mobile carriers," transport resistance genes over long distances and blur the boundaries between distinct ecosystems(Khanam et al., 2025). At the third level, the induced changes in the structure and function of the native microbial community can disrupt vital processes in aquatic ecosystems, such as the carbon and nitrogen cycles and the decomposition of organic pollutants. Thus, the risk of microplastics today is a combination of toxicity, physical damage, and disruption of microbial ecosystems.

Importantly, the functional profile of the plastisphere extends beyond plastic degradation and gene transfer. Metagenomic insights indicate that these microbial communities are not merely opportunistic colonizers but can be metabolically integrated into fundamental ecosystem processes(Purohit et al., 2020). They harbor functional genes for key biogeochemical pathways, such as denitrification, and can create localized anaerobic microenvironments that facilitate these processes even in oxygenated waters. This suggests that microplastics, via their biofilms, may inadvertently become novel, albeit synthetic, micro-habitats that contribute to nutrient cycling(Visca et al., 2025). Furthermore, the co-occurrence of plastic-degrading and nitrogen-cycling genes in the same microorganisms hints at a potential metabolic synergy, where the breakdown of polymers or their additives could supply carbon to fuel nitrogen-removal processes. Therefore, the ultimate ecological impact of the plastisphere may represent a complex trade-off between its role in spreading genetic contaminants and its potential, unintended contributions to ecosystem functions, framing it as a dual-force entity in polluted aquatic systems(Fortin et al., 2025).

Future solutions and the role of marine biotechnology

Meeting this multidimensional challenge requires the use of innovative strategies. In this regard, marine microbial biotechnology can play a pivotal role. One axis is the search for the identification and application of indigenous microorganisms or microbial consortia with the ability to selectively biodegrade polymers. Another axis is the development of biomonitoring methods based on plastisphere-specific molecular markers for rapid and accurate assessment of the level of contamination and the risk of resistance in an environment. However, to realize this potential, future research should focus on (1) conducting long-term field studies to assess the real dynamics of HGT under complex natural conditions, (2) conducting a quantitative assessment of the risk of ARGs transmission through the aquatic food chain, and (3) applied research on the feasibility and effectiveness of biotechnological solutions.

In summary, biofilm formation on microplastics presents an emerging risk scenario in which a synthetic pollutant actively rewires the genetic network of the environmental microbiome. Effective management of this crisis requires moving beyond the traditional view of microplastics and incorporating their ecological-microbial implications, particularly in relation to the antimicrobial resistance crisis, at the heart of research, regulatory, and policy agendas.

Results:

A systematic review of selected articles revealed the following key findings regarding the role of microplastic biofilms in aquatic ecosystems:

1. Formation and characteristics of the plastisphere:

Biofilms form on a variety of microplastics (polyethylene, polystyrene, polypropylene) in marine and freshwater environments(Azizollahi Aliabadi et al., 2024; Jia et al., 2024). The composition of the plastisphere microbial community differs from that of free water and natural particulate microbial communities in terms of species richness and abundance(Azizollahi Aliabadi et al., 2024; Jia et al., 2024). In these communities, bacteria associated with pathogenicity (such as Vibrio and Pseudomonas) and bacteria known to carry antibiotic resistance genes (ARGs) are often enriched(Jia et al., 2024).

2. Horizontal transfer of antibiotic resistance genes (HGT):

Microplastic biofilms significantly increase the rate of horizontal transfer of ARGs through conjugation mechanisms and, in particular, natural transformation(Wang et al., 2023; Zhou et al., 2024).
In vitro studies have reported an increase in gene transfer rates of up to 19-fold in the presence of microplastic biofilms compared to control conditions(Zhou et al., 2024). The potential for gene transfer is influenced by and may be enhanced by the presence of other contaminants (e.g., antibiotics and heavy metals) adsorbed onto microplastics(Jia et al., 2024; Wang et al., 2024).

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3. Factors affecting gene transfer potential

Polymer type

Different polymers (e.g., PE vs. PS) can create distinct microbial communities and thus different potentials for HGT(Jia et al., 2024; Wang et al., 2024).

Particle size and concentration: Smaller particles (micro and nanoplastics) facilitate biofilm formation and bacterial interactions due to their higher surface-to-volume ratio. Increasing concentrations of microplastics can also lead to an increase in the overall abundance of ARGs in the environment(Wang et al., 2024).

Aging of microplastics

Environmental aging processes (UV light, abrasion) that alter surface properties (roughness, oxygenated functional groups) can increase the adsorption of microorganisms and contaminants, thereby altering the potential for gene transfer(Jia et al., 2024; Wang et al., 2024).

4. Primary ecological implications:

Biofilm-covered microplastics act as "mobile carriers" for ARGs and resistant bacteria and can alter the geographical patterns of antibiotic resistance spread in aquatic environments(Wang et al., 2023; Wang et al., 2024; Zhou et al., 2024).This phenomenon can disrupt the structure and function of native microbial communities and their dependent ecosystem processes(Azizollahi Aliabadi et al., 2024). The accumulation of biofilm-bearing microplastics in sediments or coastal areas can make them secondary and concentrated reservoirs for ARGs and potential pathogens(Jia et al., 2024; Zhou et al., 2024).

5. Dual-function potential of the plastisphere: Biodegradation and bioremediation

Beyond serving as vectors for genetic contaminants, biofilms on microplastics exhibit a functional duality. Certain microbial consortia within the plastisphere possess enzymatic machinery for polymer depolymerization, indicating a natural potential for plastic biodegradation. Furthermore, biofilm formation alters key physicochemical properties of microplastics, such as increasing their density and reducing surface hydrophobicity, which can influence their vertical transport and environmental persistence(Ventura et al., 2024).

6. Integration into biogeochemical cycles

Emerging metagenomic evidence reveals that plastisphere communities are not metabolically isolated. They harbor functional genes associated with critical nutrient cycles, most notably nitrogen transformation processes like denitrification. The structured biofilm environment can create localized anaerobic microzones, enabling these processes even in oxygenated waters. Importantly, many of these nutrient-cycling microorganisms simultaneously carry plastic-degrading genes, suggesting a potential metabolic link between polymer breakdown and biogeochemical functions(Fortin et al., 2025).

Conclusion

This review demonstrates that microplastics, through the formation of specialized biofilms (the plastisphere), have evolved from a physical pollutant into an active and complex agent of microbial ecological change in aquatic environments. Compelling evidence confirms that these biofilms act as potent accelerators for the horizontal transfer of antibiotic resistance genes, effectively serving as mobile hotspots that exacerbate the global antimicrobial resistance crisis. However, a complete ecological risk assessment must also acknowledge the functional duality revealed by recent research. The same plastisphere communities implicated in spreading genetic contaminants also harbor microbial consortia capable of degrading plastic polymers and participating in fundamental biogeochemical cycles, such as nitrogen transformation. This paradoxical nature—being both a vector for pollutants and a potential self-mitigating system—frames the plastisphere not merely as a threat, but as a synthetic micro-habitat with complex and competing ecological outcomes. Therefore, managing this multidimensional challenge requires a sophisticated, two-pronged approach. The primary focus must remain on source reduction to limit plastic input into ecosystems. Concurrently, we must advance targeted research and biotechnology development that seriously addresses the microbiological consequences. This includes not only strategies to disrupt harmful processes like gene transfer but also exploring ways to harness the inherent biodegradative and biogeochemical potentials of the plastisphere for environmental remediation. Ultimately, effective policy and mitigation must be grounded in an understanding of microplastics as active ecological engineers, whose full impact lies at the intersection of environmental toxicity, genetic pollution, and altered ecosystem function.

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