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Exploring the Aquatic Plastisphere: Interactions of Plastic with Biofilm

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Abstract

Microplastics have emerged as pollutants of concern in recent years due to their persistent nature and their adverse effects on living beings and the ecosystem. The ecosystem is significantly impacted by microplastics because of their tiny size, which makes it easy for them to enter food webs and biogeochemical cycles. In marine ecosystems, microorganisms primarily colonize plastic surfaces, where they can create biofilms, new biological niches for microbial communities, and form plastispheres. Plastic biofilm interactions affect the polymer's physical and chemical properties, thereby leading to its degradation. In order to mitigate the annoyance of microplastic contamination, biofilms are being considered potential candidates for the remediation of marine environments. However, ongoing research in this field offers promising opportunities for developing innovative solutions to address plastic pollution.

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1. Introduction

Plastic products are being produced on a global scale due to their essential role in everyday life. They have become ubiquitous in modern society due to their versatility, durability, and cost-effectiveness. They are used in a wide range of applications, including packaging, construction, transportation, electronics, healthcare, and consumer goods. The global estimate for plastic waste generation was around 350 million metric tons per year. The plastic pollution problem has garnered significant attention due to several factors, including its high production rate, low recycling rate, and inadequate solid waste management practices. The properties, such as high molecular weight, hydrophobicity, and cross-linked chemical structure, contribute to the resilience of most plastics against biodegradation. This resistance to biodegradation is a significant factor contributing to the environmental challenges posed by plastic pollution. In contrast, some plastics may undergo degradation over extended periods through processes like photodegradation or mechanical weathering. Some plastics can undergo degradation through natural processes involving microbial activity. During this process, some of the carbon from the polymer may be mineralized and released as carbon dioxide (CO_2), which can then enter the

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marine biogeochemical cycle. The rate of degradation varies depending on factors such as the type of plastic, environmental conditions, and the presence of specific microorganisms. Microbial communities colonize the surface of plastic debris, forming biofilms and creating a microenvironment that promotes its degradation.

2. Types of Plastic Debris

Larger plastic debris, under the influence of environmental factors such as sunlight, wave action, and physical abrasion, can break down into smaller fragments, ranging from meters to micrometers in size (Debroy et al., 2021). Among all plastic categories, micro- and nanoplastics are of greater concern since these minute particles cannot be trapped by filtration systems, allowing them to enter the oceans and endangering marine ecosystems. Figure 1 shows the major types of plastic debris based on size.

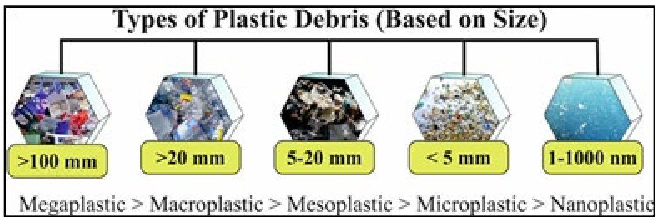

Figure 1: Major types of plastic debris

3. Microplastic

Microplastics (MPs) are defined as synthetic polymeric materials or solid particles, displaying either regular or irregular shapes, with sizes ranging from 1 μm to 5 mm. They originate from either primary or secondary manufacturing processes and are insoluble in water. The MPs are originated from the decomposition and weathering of larger plastic waste in the aquatic environment. Over time, floating plastics become less hydrophobic. Additionally, biofouling on the surface can further alter the buoyancy characteristics of the plastic. These changes in surface properties can cause floating plastics to lose buoyancy and eventually settle on the seafloor. Their stability and endurance allow them to last for hundreds or thousands of years. Plastic debris provides a surface area for microbial colonization. These microbial colonizers attach to the surface of plastic debris and form biofilms, known as plastisphere, which are transported by ocean currents and waves to a new habitat.

4. Plastisphere

The plastisphere is a complex ecosystem consisting of various microorganisms composed of autotrophic organisms, heterotrophic organisms, predators, and symbionts attached to the surface of plastic fragments in the environment, providing a unique niche for microorganisms and forming biofilms. The process of development begins with the aggregation and attachment of bacteria, single-celled eukaryotic organisms, larvae and spores, and dissolved organic matter. During the aggregation and attachment stages, extracellular polymeric substance (EPS) and biofilm matrix components are produced, which promote the formation of a micro-niche and further embedment of cell clusters during the maturation stage. Eventually, microorganisms are dispersed, and the matrix components are degraded. Overall, the development of the plastisphere involves a dynamic interplay between microorganisms, microplastic surfaces, and environmental factors (Figure 2).

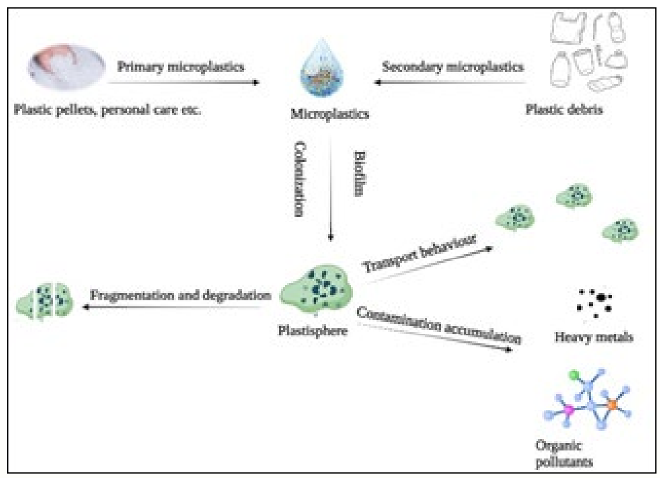

Figure 2: Environment behavior of the plastisphere in the aquatic environment

4.1. Structure of plastisphere

Plastisphere consists of primary producers, produce organic compounds from inorganic substances (e.g., cyanobacteria, diatoms, and microalgae), predators that consume other microorganisms as a source of energy (e.g., choanoflagellates and hydroid colony), symbionts, organisms that live in close association with other organisms, (e.g., sulfide-oxidizing ectobionts on suctorian ciliates) and decomposers (e. g., fungi). It also includes pathogenic, invasive, or plastics-degrading species (Yu et al., 2023).

4.2. The factors affecting the development of aquatic plastisphere

4.2.1. Plastic substrate

The common substratum characteristics of a substratum are its type, type, size, density, shape, color, and surface characteristics. The surface characteristics have been further clarified in terms of specific surface area, hydrophobic and hydrophilic performance, surface roughness, hardness, and surface charge.

4.2.2. Environmental conditions

Diverse environmental factors, including pH, salinity, temperature, dissolved oxygen, illumination, nutrient concentrations, and hydrodynamics, can affect the plastisphere's functional properties and composition.

4.3. Colonization time

The life cycle of the aquatic plastisphere comprises three stages, namely, early colonization, community succession, and dynamic balance (Figure 3). The colonization time of the plastisphere ranges from short-term (1–2 weeks), medium-term (1–2 months), and long-term (7–12 months).

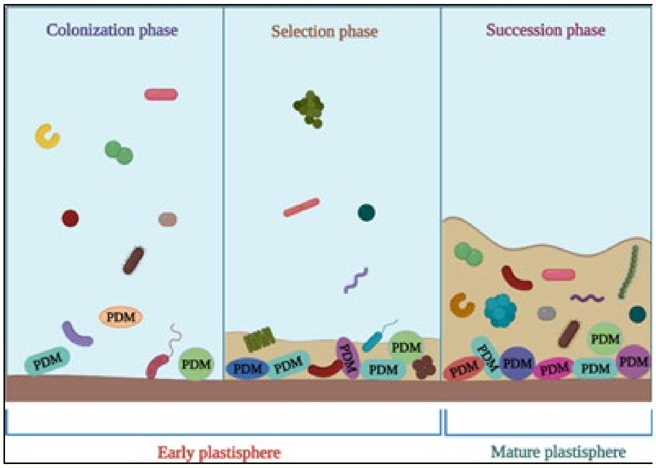

Figure 3: Main stages in Plastisphere colonization (Source: Dey et al., 2022)

5. Plastisphere Succession Stages

5. 1. Colonization or initial surface attachment

A pioneering microbial community begins to colonize and attach to the surface of the plastic, initiating the process of biofilm formation. According to reports, Gammaproteobacteria and Alphaproteobacteria dominated in the early stages of biofilms. The formation of secondary biofilm requires many months. Table 1 displays the days exhibiting bacterial dominance in biofilm formation.

Table 1: Days exhibiting bacterial dominance in biofilm formation (Du et al., 2022)

Days	Dominance of bacteria
30	Rhodobacteraceae (Alphaproteobacteria), Microtrichaceae (Acidimicrobiia), Flavobacteriaceae (Bacteroidia)
75	Moraxellaceae (Gammaproteobacteria), Bacillaceae (Bacilli)
135	Flavobacteriaceae (Bacteroidia), Microtrichaceae (Acidimicrobiia), Pirellulaceae (Planctomycetes), Rhodobacteraceae (Alphaproteobacteria)

5.2. Selection phase

Here, polymer-degrading organisms proliferate and adapt to utilize plastic as a carbon and energy source. This phase is characterized by the enrichment of microbial populations capable of breaking down the polymer molecules, often through the secretion of enzymes that catalyze degradation reactions.

5.3. Succession phase

In this phase, the plastic-degrading organisms may be outcompeted or supplanted by cross-feeders, grazers, and other microbes that utilize the degradation by-products as nutrients.

6. Plastic-Microbe Interactions In Aquatic Environments

As soon as plastic particles are released into the marine ecosystem, they float on the surface due to their low density compared to water and are transported further. The degradation of microplastics in aquatic environments is accomplished by abiotic and biotic mechanisms. Abiotic degradation involves physical and chemical degradation, whereas biotic degradation is comprised of microbial degradation. A combination of these processes regulates the transport and fate of microplastics. Light and oxygen are the main abiotic factors causing the degradation of microplastics through hydrolysis, thermal degradation, photodegradation, and oxidative damage (Miao et al., 2023). The mechanism of microplastic degrading enzymes can be categorized into surface modification mechanisms and degradation mechanisms. The surface modification mechanism involves the alteration of the surface properties of the plastic, which can make it more accessible to degradation processes and is followed by a group of hydrolases (lipases, carboxylesterases, cutinases, and proteases), whereas the degradation mechanism is adopted by enzymes (viz., oxidases, amidases, laccases, hydrolases, and peroxidases) that are involved in the actual degradation of polymer, breaking them down into smaller fragments by the secretion of relevant enzymes; the microbes then ingest these subunits. Once inside the cells, these degradation products are incorporated into metabolic pathways to gain the energy required for cell growth.

7. Biofilm Formation and Degradation of Microplastics

Plastics are rapidly coated with a thin film of inorganic and organic matter that serves as a substratum for microbial colonization and biofilm formation (Figure 4).

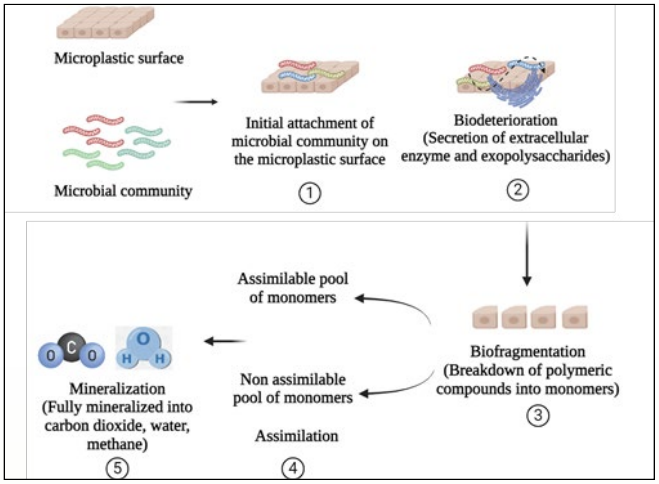

Figure 4: Steps involved in biofilm formation and in the degradation of microplastics

7.1. Microbial biofilm formation

Biodegradation of microplastics starts with the initial attachment of pioneering microbes and the development of biofilm on the plastisphere. The hydrophobic plastic surface promotes microbial colonization and biofilm formation, leading to a reduction in polymer buoyancy and hydrophobicity. Environmental factors significantly influence the colonization of microbes and the formation of biofilms.

7.2. Biodeterioration

The formation of a biofilm on a microplastic surface is followed by the biodeterioration step, which leads to a loss of physical integrity of the polymer. This is carried out primarily by exoenzymes secreted by microbes. At this stage, the EPS secreted by the microbes provides strong adhesion to the polymer surface, and the enzymes' catalytic activity initiates the disintegration of the polymeric structure.

7.3. Bio-fragmentation

Bio-fragmentation is a depolymerization process that converts the deteriorated polymer into oligomers, dimers, and monomers that can be assimilated by microbes, leading to an increase in their biomass. This is a critical step in the biodegradation of MPs mediated by biofilm and is regulated by the catalytic activity of microbial enzymes that weaken the carbon skeleton of polymers and promote fragmentation.

7.4. Assimilation

Assimilation is a crucial step in the biodegradation of MPs; in it, the atoms from the fragmented polymer are integrated within the microbial cells. To enter the microbial cell, the assimilable monomers must cross biological membranes (carried through active or passive transportation) and integrate with catabolic pathways for energy production.

7.5. Mineralization

In the last step, the polymers are completely degraded, resulting in the release of final products like CO_2, N_2, H_2O, and CH_4. Alternately, the metabolic intermediary products can be integrated with other biochemical pathways.

8. Conclusion

As global plastic use rises, microplastic pollution will worsen, necessitating urgent mitigation strategies. At sea, plastics quickly form biofilms through microbial colonization. Hence, to mitigate the foreseen nuisance of microplastic contamination, biofilms are being explored as potential candidates for the remediation of marine environments. Bioengineered microbes and modified enzyme systems are highly promising in this regard. Extensive investigations on plastisphere communities and the use of such advanced molecular techniques will pave the path for remediating our marine ecosystem.

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