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Impact of Biofilm Formation on Microplastic Behaviour in Aquatic Environments: An Comprehensive Review.

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A B S T R A C T

Urban growth, global climate change, and dependence on traditional infrastructure have progressively interfered with natural hydrological processes, causing increased flood hazards, water pollution, urban heat islands, and environmental degradation in cities across the globe. Conventional drainage systems that favor fast conveyance of stormwater out of urban space have proved ineffective in addressing the expanding area of impervious surfaces, unpredictable rainfall patterns, and outdated infrastructure. To respond, SuDS have developed as a holistic, environmentally friendly method of stormwater management. SuDS focus on the application of natural processes, such as infiltration, filtration, storage, and controlled release, to reduce flooding, improve water quality, and promote urban biodiversity. This review critically assesses the principles, design methods, and multifunctional advantages of SuDS, as well as implementation issues including requirements for maintenance, cost, and site-specific limitations. The research includes a comprehensive case study from Saitama City, Japan, presenting real-world results and lessons, and comparing with effective SuDS implementations in Europe, Asia, and North America. Additionally, the potential for implementing SuDS with smart solutions, climate-resilient urban planning, and Sustainable Development Goals (SDGs) is examined, pin pointing opportunities for innovative, sustainable water management in cities that meet environmental, social, and economic goals.

Keywords: Microplastics, Biofilms, Plastisphere, Aquatic Pollution, Antibiotic Resistance, Ecotoxicology, Marine Ecology.

1. Introduction

Plastics have become an essential part of our lives because they are durable, versatile, and affordable. However, these same qualities also make them long-lasting pollutants once they enter the environment. Global plastic production has surpassed 390 million tonnes each year. It is estimated that 11 million tonnes of plastic waste find their way into aquatic ecosystems annually. As time goes on, larger plastic pieces break down into microplastics (MPs), which are defined as plastic particles smaller than 5 mm. These microplastics are now seen as common contaminants in oceans, rivers, lakes, and even drinking water. They vary widely in terms of polymer type (like polyethylene, polypropylene, polystyrene, PVC, and PET), shape (such as fibres, fragments, films, and beads), and surface chemistry, all of which affect how they behave in the environment. Microplastics are not inactive. Once they enter water bodies, they can undergo physical, chemical, and biological changes due to factors like UV radiation, mechanical wear, and microbial colonization. Among these factors, the formation of biofilms has become one of the key influences on microplastic behaviour. Biofilms are communities of microorganisms, including bacteria, algae, fungi, and protozoa, that grow within a self-produced matrix of polymer. When biofilms attach to microplastics, they create what researchers refer to as the "plastisphere." This plastisphere significantly changes the physical and chemical properties, movement, and ecological risks of microplastics.

Understanding how biofilm formation affects microplastic behaviour is crucial. It adds a biological aspect to the already complicated issue of plastic pollution. While we know a lot about the physical and chemical processes affecting microplastics, the ecological interactions at the microbe-plastic interface are still being studied. Long-term monitoring, better detection methods, and interdisciplinary research are also necessary to fully understand the ecological and health risks associated with this issue.

2. Biofilms and the Plastisphere

Microplastics, once introduced into aquatic environments, rarely remain as clean surfaces. Instead, they are rapidly colonized by microorganisms that attach, proliferate, and secrete extracellular polymeric substances (EPS), forming a biofilm. This microbial coating provides physical protection, nutrient retention, and structural stability to microbial communities. Within hours to days, microplastics become embedded in a complex biological matrix, giving rise to what is now termed the plastisphere. The plastisphere is a unique ecological niche, distinct from surrounding water and sediments. It typically consists of diverse microbial assemblages, including bacteria, cyanobacteria, algae, fungi, and protozoa. The composition of these communities is strongly influenced by the polymer type, surface roughness, and environmental conditions. For example, hydrophobic polymers such as polyethylene (PE) and polypropylene (PP) tend to favour colonization by bacteria with hydrophobic cell surfaces, while rough or aged particles provide more attachment sites for microbial growth.

Biofilm formation on microplastics has several consequences for their environmental behaviour:

1. Altered Physicochemical Properties – Biofilms increase surface roughness, change surface charge, and often enhance hydrophilicity, which can promote aggregation with organic matter and minerals.
2. Density Modification – The accumulation of biomass and entrapped inorganic particles within biofilms can increase the density of microplastics, causing formerly buoyant plastics to sink and altering their vertical distribution.
3. Pollutant Interaction – Biofilms enhance the adsorption of trace metals, antibiotics, pesticides, and persistent organic pollutants (POPs), effectively transforming microplastics into mobile pollutant carriers.

3. Biofilm Formation on Microplastics

- **Surface Preparation:**The Prior to the microorganisms, dissolved organic matter, proteins, and inorganic ions swiftly sorb on the surface of the microplastic. This conditioning film also alters the physicochemical properties of the plastic by enhancing the hydrophilicity and reactivity and consequently the adhesion of the microbes.
- **Preliminary Attachment**: Pioneering microorganisms demonstrate reversible attachment to the pre-conditioned substrate through hydrophobic interactions, van der Waals attraction, and electrostatic attraction. The choice and roughness of the surface polymer both play major roles in what microorganisms colonize the surface first. EPS Secretion When early attachments become organized, the microbes begin to synthesize extracellular polymeric substances (EPS)—a slime-like substance consisting of polysaccharides, proteins, and nucleic acids. This holds cells in place better and creates a protective microenvironment that traps and shields the microbes from environmental stress factors.
- **Maturation:** The biofilm transforms to a three-dimensional structure, characterized by cell aggregates, water flow channels, and increased microbial diversity. This step amplifies the strength of the biofilm, activates interspecific interactions among the cells, and enables the plastisphere to become a micro-ecosystem.
- **Biofouling and Success**: Over time, bigger organisms such as algae, protozoa, and invertebrate larvae can reside in the biofilm, leading to biofouling. This growth significantly amplifies the population density of microplastics, often causing floating plastics to sink, and consequently altering their movement and dispersion in water ecosystems.

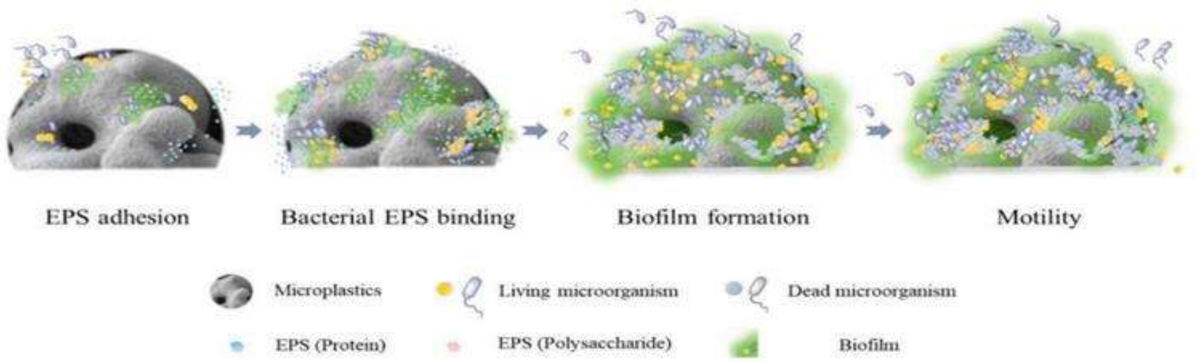

Fig 1. BiofilmformationprocessonMPs

4. Ecotoxicological Implications

The biofilm development on the microplastics (MPs) not only modifies the surface properties of the MPs but also enhances the capacity of the MPs to be carriers of environmental pollutants. The extracellular polymeric substance (EPS) matrix produced by the biofilm-related microorganisms contains many functional groups including carboxyl, hydroxyl, phosphate, and amine groups that undergo highly affinitive interactions with many pollutants. These include: Heavy metals (e.g., Pb, Cd, Hg, Cu, Zn), that are complexed by negatively charged functionalities of the EPS. Persistent organic pollutants (POPs), including polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs), are heavily adsorbed matter because there are hydro. Pesticides and herbicides, which can accumulate on biofilm surfaces and enter aquatic food webs. Drugs and personal care products that sorb to EPS and get carried long distances. The enriching action by pollutants converts MPs into "Trojan Horses"—transportable carriers that can concentrate and release contaminants to the water organisms consuming them.

The ingestion of biofilm-coated MPs by aquatic organisms has been linked to a range of toxicological responses:

- Oxidative stress – increased production of reactive oxygen species (ROS) damages lipids, proteins, and DNA.
- Immune suppression – altered cytokine activity and reduced disease resistance in fish and invertebrates.
- Metabolic disruption – interference with energy allocation, growth, and enzyme activities.
- Reproductive toxicity – reduced egg production, hatching success, and larval survival in exposed species.

5. Antibiotic Resistance and Pathogen Transport

.Biofilm-coated MPs may be hotspots for the accumulation and horizontal gene transfer (HGT) of antibiotic resistance genes (ARGs). Evidence shows ARG and pathogenic bacteria (e.g., Vibrio, Pseudomonas) enrichment in MP biofilms. Such biofilm assemblages may alter nutrient dynamics (e.g., sulfur, nitrogen) and degrade plastics and carry pathogens beyond geographically defined boundaries by ocean currents. The global spread of ARGs constitutes a significant public health threat, particularly to coastal communities whose livelihood relies on seafood.

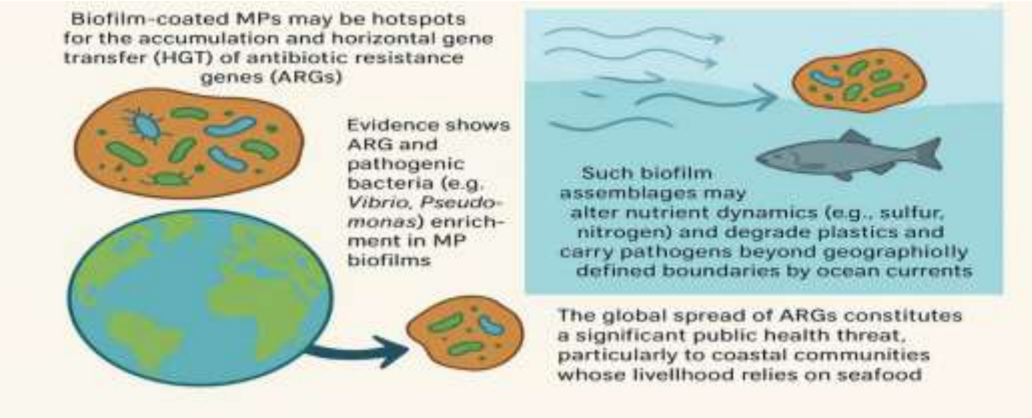

Fig2. antibiotic resistance and pathogen transport

6. Human Health Risks

Human exposure to microplastics (MPs) and the respective biofilms remains a global concern since MPs have pervaded food items, potable water, and respirable air globally. The routes of exposure are ingestion, inhalation, and dermal exposure and each one has distinctive risk attributes that are predictably amplified by the presence of the biofilms and sorbed pollutants.

6.1 Exposure path

Ingest:MPs were identified in different food items such as seafood, shellfish, fish, sea salt, and tap water. Since the majority of the marine animals ingest biofilm-entwined MPs, humans who eat the animals ingest the plastics together with the adsorbed contaminants and the microorganisms. Tap and bottled potable water has also been shown to contain MPs, the majority of which potentially harbour biofilms.

Inhale:Airborne MPs and fibres, including synthetic clothing and indoor dust fibres, are breathed in daily. The particles can carry surface biofilms and contaminants along and into the respiratory tract. Since the size of the inhaled MPs is small, the MPs can be deposited inside the bronchioles and the alveoli and can stimulate inflammatory responses.

Skin Contact: While dermally absorbed exposure represents a secondary route other than ingestion and inhalation, the MPs are actually found in personal hygiene products and sewage effluents. Recreational water exposure (e.g., swimming) can permit restricted movement of the MPs or pertinent microbial communities to the integument, provided there are open wounds on the body.

6.2 Nano plastics and Cell

Smaller MPs, particularly nano plastics (<200 nm), pose greater risks due to their potential to cross biological barriers. Laboratory studies have demonstrated that nano plastics can be internalized by intestinal epithelial cells, macrophages, and lung cells via endocytosis or diffusion. Once in circulation, they may translocate to secondary organs such as the liver, kidneys, spleen, and even the brain. Accumulation in these organs raises concerns about chronic toxicity and long-term health consequences.

6.3 Potential Health Effects

MPs and the related biofilms may induce inflammatory reactions and excessive production of reactive oxygen species (ROS). Cellular dysfunction occurs following oxidation of lipids and proteins and oxidative stress in the DNA. Inhaled or orally consumed MPs can also impair routine immune functions by interfering with the cytokine signal and starting chronic inflammation. This can decrease host defence functions and increase infectious susceptibility. Experimental research has implicated that the exposure to MPs and the corresponding chemicals may result in decreased fertility, damaged embryonic development and transgenerational consequences. Initial evidence shows that nano plastics can potentially cross the blood–brain barrier and introduce the likelihood of neuroinflammation and different neuronal signaling disruption.

7. Factors Influencing Biofilm Formation

7.1. Surface Characteristics

7.1.1 Surface Roughness

Irregular or roughened surfaces promote increased surface contact and form "niches" where microbes attach easily. Smooth surfaces (such as Teflon or polished glass) are resistant to attaching.

7.1.2 Surface Hydrophobic

Hydrophobic plastics (LDPE, HDPE, PVC, PP) enhance microbial adhesion via hydrophobic interactions. Hydrophilic surfaces (glass, certain metals) can resist adhesion but permissively accommodate biofilms under specific circumstances.

7.1.3 Surface Chemistry & Charge

Typical bacterial cell walls are negative. Surfaces with a positive charge (cationic coatings) attract them strongly. Metals are in a position to release ions (Cu, Zn, Fe) suppressing or stimulating microbial adherence in a concentration-related m2. Microbial Factors

7.2. Microbial Factors

7.2.1 Extracellular Polymeric Substances

EPS is a jelly-like matrix developed in situ from polysaccharides, protein, nucleic acids, and lipid.

Glue that helps initial attachment, Prevents microbes from antibiotics, disinfectants and shear stress, Storing nutrients.

7.2.2 Motility Structures

Flagella: Allow microbes to swim towards surfaces.

Pili/Fimbriae: Hair-like projections assisting in adhesion.

7.2.3 Quorum Sensing (QS)

Microbial "cell-to-cell communication" via chemical messages

QS controls: EPS production, Virulence gene expression, Biofilm maturation and release.

7.2.4 Species Diversity

Mixed species biofilms are stronger than single species ones. They exchange nutrients, trade resistance genes, and develop protective coatings.

Example: Marine biofilms are comprised of algae, fungi, and bacteria mechanism.

7.3. Environmental Conditions

7.3.1 Temperature

Each species also has an optimal range (e.g., Pseudomonas aeruginosa grows best at 30–37 °C). Too high/low temperatures retard biofilm metabolism.

7.3.2 pH

Neutral to slightly alkaline (pH 6.5–8.5) is ideal. Alkaline or acidic conditions inhibit most of the microorganisms.

7.3.3 Oxygen level

Aerobic microbes form biofilms on air-water surfaces. Anaerobic microorganisms thrive inside tight-packed biofilms that limit oxygen diffusion. Leading to "micro-niches" within a single biofilm.

7.4.Chemical Factors

7.4.1 Organic Pollutants

Carbon sources: hydrocarbons, oils, microplastics

Plastics discharge additives (BPA, phthalates) that can be metabolized by microbes.

7.4.2 Inorganic Substances

Heavy metals (Pb, Cd, Hg, Zn, Cu): Toxic at high doses, but biofilm microbes tend to develop resistance and even use metals as electron acceptors.

7.4.3 Antimicrobials / Disinfectants

Low doses may result in selection of resistant microbes.

Biofilm EPS will neutralize disinfectants like chlorine.

7.5. Host / External Biological Factors (when biofilms form on living tissues or inside organisms)

7.5.1 Immune Response

Host immune cells attack microbes, but biofilms resist phagocytosis due to EPS protection.

7.5.2 Microbiome Interactions

Competition: Some microbes produce bacteriocins to kill competitors.

Cooperation: Cross-feeding (e.g., one species breaks down a compound that another uses).

8. Future Research Priorities

Despite growing awareness of the plastisphere and its ecological implications, significant knowledge gaps remain. Addressing these gaps is essential for predicting long-term risks and designing effective mitigation strategies. Key future research priorities include:

8.1 Standardization of Techniques

Establish standard procedure for sampling, isolation, and characterization of microplastic and the respective biofilms. Standardize analysis methods (e.g., spectroscopy, microscopy, molecular techniques) to allow comparison among studies.

8.2 Human Health Risks

Assess the chances for nano plastics and biofilm-associated microbes to cross biological barriers and be delivered in human tissue. Discuss the function of the plastisphere as a bank of antibiotic resistance genes (ARGs) and pathogenic microorganisms. Estimate human exposure quantities from seafood, potable water consumption, and inhaled atmospheric MPs.

8.3 Biodegradation and Remedy

Develop and design microorganisms and enzymes that can expedite degradation of plastics in the biofilms. Assess nature-engineering technologies including constructed wetlands, bioreactors, and periphytic biofilms as MP cleanup technologies. Create environmentally safe antifouling methods to reduce negative coverage by biofilm on MPs while not impacting aquatic. Cooperation: Cross-feeding (e.g., one species breaks down a compound that another uses).

9. Conclusion

The growing body of evidence highlights that biofilm formation on microplastics (MPs) is not a passive phenomenon but a dynamic ecological process with far-reaching implications for aquatic ecosystems and human health. Once released into the environment, MPs rapidly undergo surface conditioning and microbial colonization, leading to the establishment of complex biofilms—collectively referred to as the plastisphere. These biofilms fundamentally transform the physicochemical properties of MPs, altering their buoyancy, density, transport pathways, and degradation potential.

The association among MPs and biofilms produces ecological hotspots that sustain microbial richness, yet become carriers for the focusing and movement of contaminants, toxic heavy metals, and persistent organic pollutants. Altering surface chemistry and increasing sorption, biofilms efficiently convert MPs into "Trojan Horses" carrying poisonous substances and pathogenic microorganisms across environmental compartments. This conversion promotes the introduction into food webs at a faster rate and enables biomagnification and trophic transference.

For aquatic species, biofilm-coated MPs pose risks of oxidative stress, immune suppression, metabolic disruption, reproductive toxicity, and altered feeding behaviour. At higher trophic levels, these risks cascade upward, culminating in human exposure through seafood consumption, contaminated drinking water, inhalation of airborne particles, and, to a lesser extent, dermal contact.

Overall, biofilm development on MPs amplifies the environmental and health risk of plastic pollution as a threshold effect at the nexus of materials, microbes, and contaminants. This challenge needs a systems approach integrating scientific creativity, rulemaking action, and worldwide cooperation to reduce risk and protect ocean ecosystems and human health for the future.

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