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Bio-Rescue: Bacteria's Role in Tackling Microplastic Menace

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Abstract

Plastic is now considered an essential part of our day-to-day life, as in clothing, toys, household goods, packaging material, equipment, aerospace, agriculture, electrical appliances, pharmaceutical, and cosmetic industries. Low-cost production, strength, low weight, flexibility, durability, insulating capacity, easy handling, and transportation are associated with increased plastic production and use. Global plastic production has been growing over the years and is expected to triple by 2050. Asia played a significant role in producing and consuming plastic goods. China is a major contributor to the global production of plastic, and its share is around 32% of this "white pollution. " Other Asian countries collectively produced nearly 19% of the world's total plastic production. Improper waste management, inadequate recycling infrastructure, and the persistent nature of plastics contribute to their widespread presence in the environment. Plastic can fragment into smaller pieces, resulting in microplastics (MPs) and nanoplastics when exposed to other environmental factors such as wave action and ultraviolet irradiation. Microplastics in the environment are recognized as a threat to human health and ecosystems because it exists in nature for hundreds of years without degrading. The wide application of face masks throughout the COVID-19 period has led to environmental issues, such as solid waste and microplastic pollution in marine and freshwater ecosystems. Microplastics have been identified in digestive systems, blood, and human brains because of their tiny size. Various methods and strategies have been implemented to address plastic pollution and mitigate its environmental impact.

Keyword: Biodegradation, Biofilm, Microplastics, Plastic pollution

Introduction

Over the span of the last 70 years, a marked rise in the worldwide production of plastic was observed, reaching 359 million tonnes in 2018. Microplastics (MPs) are generally considered plastics smaller than 5 millimeters (mm) in size. The existence of microplastics in the environment has sparked worries because of their possible detrimental effects on both human health and ecological systems. MPs can be formed through two main processes, i.e., manufutured for intended use such as in cosmetics or by weathering of primary plastics. There are eight major types of MPs that exist in the world based on the polymer used for production. These are polyamide (PA), polyethylene terephthalate (PET), polyvinylchloride (PVC), polypropylene (PP), polyesters (PES), polystyrene (PS), polyethylene (PE) and polyurethane (PU). Moreover, MPs can be categorized based on their morphology, including fragments, fibers, granules, and films. Among these, fibers and fragments are the most common types and are of significant concern due to their widespread distribution and potential environmental impact.

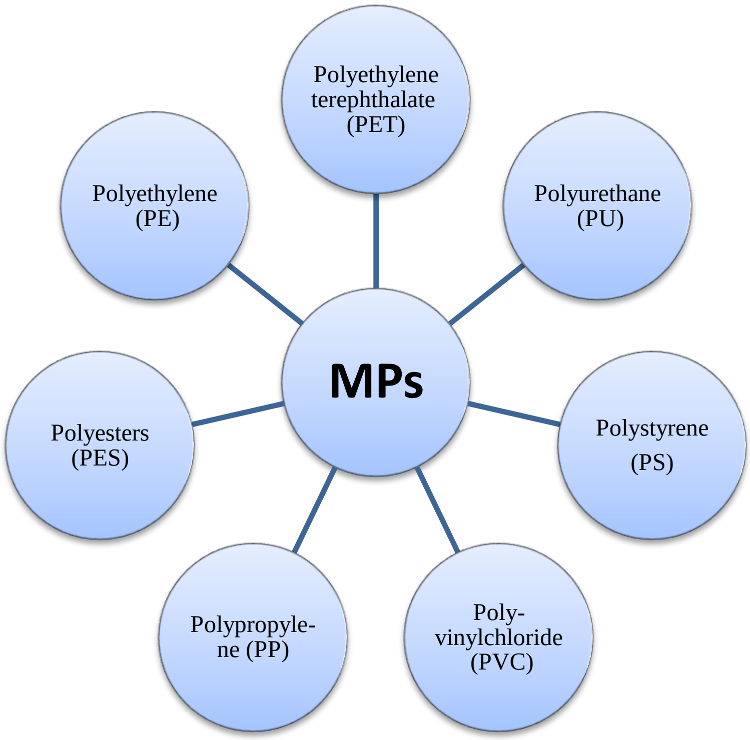

Fig 1. Major types of plastic polymers

Microplastic sources and occurrence

Once plastic is released into the ocean, the large particles break down into smaller particles over time to form microplastics or nanoplastics. The behavior of microplastics is influenced by various factors, and polymer density is a key determinant that affects their buoyancy, interactions with biota, and vertical positioning in the water column. Polymers with a density greater than water will sink, e.g., polyvinyl chloride (PVC), while those with lower density tend to float, e.g., polyethylene (PE) and polypropylene (PP), and have a high chance to travel by the wave action. Biofouling, colonization by organisms, degradation, fragmentation, and the leaching of additives all significantly alter the weight, buoyancy, and distribution of microplastic particles in the water column. The classification of microplastics in marine matrices typically includes two main types: primary and secondary microplastics.

1. Primary microplastics are intentionally produced with dimensions smaller than 1 nm to 5 mm and used in various products like toothpaste, shower gel, scrubs, cosmetics, etc.
2. Secondary microplastics are initially produced with dimensions greater than 5 mm, which undergo a process of fragmentation due to biological, physical, and chemical weathering, causing the larger plastics to break down into smaller particles, often less than 5.0 mm in size.

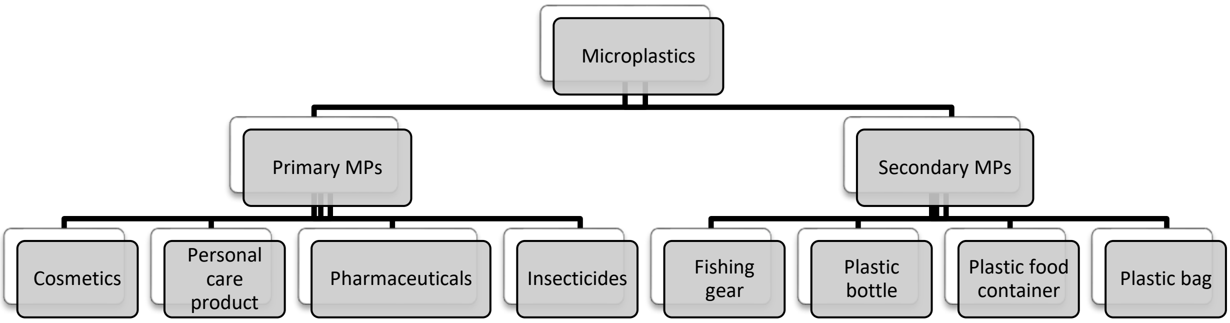

Fig 2. Classification of Microplastic

MPs have been found in terrestrial ecosystems, and improper waste management practices significantly contribute to their presence in soil. Additionally, wastewater treatment facilities (WWTPs) are recognized as major contributors to the discharge of microplastics into water-based ecosystems. While these treatment plants effectively remove larger solid materials, macroplastics and microplastics can often bypass the treatment process and enter water bodies. Microplastics can be found worldwide in coastal regions and aquatic ecosystems, and various transport mechanisms, including wind and ocean currents, influence their distribution. Subsequently, they accumulate in ice sheets, virgin polar areas, and the deep sea. Due to the increased availability of plastic waste, a wider range of organisms at the base of the food chain can consume it by mistaking it as food due to its smaller size and move up to higher trophic levels. MPs have the potential to adversely affect a variety of physiological processes in organisms, including growth and reproduction. Marine organisms, such as fish and shellfish, can directly ingest microplastics from the seawater as they feed or indirectly by ingesting organisms contaminated with microplastics, resulting in the transfer of microplastics up the food chain. As a result, seafood intended for human consumption, including fish and shellfish, may contain varying levels of microplastics. Microplastics have also been found in drinking water sources in addition to food and are among the most common intake pathways into the human body, causing negative impacts on health.

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Management Strategies to Reduce Microplastics

There are various measures at local, regional, national, and international levels to tackle the problem.

1. Legislation

The 1978 Protocol to the International Convention for the Prevention of Pollution from Ships (MARPOL) is an important legal instrument that addresses marine pollution, including regulations related to plastic waste, which prohibits the disposal of plastics and other garbage from ships into the sea.

2. Efficient waste disposal systems

Providing sufficient recycling bins in coastal areas and implementing regular waste collection from various sources is crucial to managing and preventing marine pollution.

3. 3-R Approach

The 3-R approach deals with reducing, reusing, and recycling plastic materials. It means we must reduce the waste volumes, recycle maximum scrap, and reuse it. This approach is crucial for minimizing the harmful effects of open landfills, which are commonly practiced to manage domestic waste.

4. Education and public enlightenment

Education and public awareness play a critical role in addressing environmental issues, including the problem of plastic pollution and marine litter. Incorporating environmental topics into educational curricula and engaging the public in volunteer projects and awareness campaigns can have a significant impact.

5. Integration and harmonization of trans-disciplinary

Involving various stakeholders, including industries, NGOs, communities, and government entities at different levels, is essential for developing comprehensive and effective solutions in addressing environmental problems associated with plastic pollution and decision-making.

Biodegradation of Microplastic by Bacteria

Biodegradation is a natural process where microorganisms, such as bacteria, fungi, and other microbes, break down and transform or alter organic or inorganic substances into simpler compounds through metabolic or enzymatic action. A multitude of research efforts have focused on the breakdown of microplastics through microbial action.

Bacteria that can degrade microplastics have been isolated from various habitats, including wastewater, sludge, contaminated sediments, municipal landfills, compost, mangroves, frozen soils, and ocean sediments. Both pure cultures of bacteria and bacterial consortia (mixed cultures of different bacterial strains) can be used for microplastic degradation. In particular, the bacterial consortium exhibits increased community stability and efficiency. Physico-chemical parameters, like temperature, oxygen level, salinity, pH, and substrate properties, play an improtant role in influencing breakdown process of microplastics by bacteria. Addition to that, surface and structural characteristics of microplastics, including polymer composition, can significantly influence their degradation. The attachment of microorganisms, formation of biofilms, and subsequent biodegradation of microplastics are impacted not just by microbial abilities but also by material properties and surface features of microplastics. These include surface free energy, electrostatic interactions, roughness, topography, and hydrophobicity.

Bacteria responsible for polypropylene degradation included *Bacillus*, *Pseudomonas, Chelatococcus, Rhodococcus, Microbacterium Vibrio sp,* and *Lysinibacillus fusiformis.* These bacteria are obtained from a wide range of habitats, including compost, cow dung, mangrove habitat, and land contaminated with plastic waste. These microbial isolates are found to form a biofilm on microplastics. Bacterial strain *Exiguobacterium sp.* from the guts of mealworms is able to form biofilm and degrade polystyrene. Several marine bacteria, such as *Alcanivorax borkumensis*, could degrade alkyl cycloalkanes, isoprenoid hydrocarbons, alkanes, and branched aliphatic compounds. Other bacteria associated with microplastic biodegradation included *Bacillus cereus* and *Bacillus gottheilii*, *Enterobacter asburiae*, *Nocardia asteroids*, *Rhodococcus rhodochrous*, *Streptomyces badius*, *Rhodococcus ruber*, *Comamonas acidovorans* and *Clostridium thermocellum*, *Exiguobacterium sp.*, *Ideonella sakaiensis*, *Pseudomonas chlororaphis*, *Pseudomonas putida*, and *Thermomonospora fusca*. Moreover, MPs degrading bacteria belonging to the *Shewanella*, *Moritella*, *Psychrobacter*, *Pseudomonas*, *Alcanivorax*, and *Tenacibaculum* genera from deep-sea sediment samples were obtained from a depth of 5000–7000 m.

Mechanism of Bacterial Degradation of Plastic

Physicochemical degradation involves environmental factors and processes that alter plastics' physical and chemical properties. These changes can make microplastics more susceptible to microbial enzyme activity by altering functional groups and reducing polymer length. The combined effect of abiotic factors and extracellular enzymes produced by microorganisms leads to bio-deterioration and bio-fragmentation of plastics. This degradation process results in the breakdown of larger polymer chains into smaller particles, followed by further degradation into oligomers, dimers, and monomers. These particles further degrade into microplastics or nanoparticle size. Generally, four phases are involved in the attachment or biodegradation process of the microbes, namely biodeterioration, bio-fragmentation, assimilation, and mineralization.

1. The initiation of biodeterioration involves the attachment of microorganisms to the material's surface, followed by the formation of a biofilm around the plastic polymer.
2. The bio-fragmentation microbes produce the extracellular enzyme, which acts on the polymer, converts it into oligomer, dimer, or monomer, and prepares it for easy ingestion. This process involves the cleavage of chemical bonds, reducing the material to simpler compounds.
3. Assimilation involves microbial cells taking up the simpler molecules produced in the previous steps and using them as a source of energy and nutrients for their growth and metabolism via simple or facilitated diffusion.
4. Mineralization involves the production of daughter metabolites such as CO_2, H_2O, and CH_4.

Microorganisms have the ability to break down microplastics using the mechanisms mentioned above and can release a unique enzyme that breaks down microplastics; that enzyme differs according to the environment of the microbes.

Enzymes such as rubredoxin, alkaline hydroxylase, alkaline monooxygenase, and rubredoxin reductase are secreted by bacteria during the degradation of PE materials. Several extracellular enzymes that play a crucial role in microplastic degradation include amidases, hydrolases, carboxylesterases, lignins peroxides, esterases, lipases, laccases, cutinase, PETase, MHETase, hydrolytic enzymes, and manganese peroxides are secreted by bacteria at the time of plastic degradation which increases the hydrophilicity of microplastics and converts them to carbonyl or alcohol residues. Hydrolase enzymes, such as esterase, lipases, and cutinase, catalyze hydrolysis reactions, which act on plastic surfaces and degrade microplastics by speeding the cleavage of chemical bonds. These enzymes work on the surface, forming cracks, but are unable to diffuse into the polymer. After the hydrolysis of polymer chains, monomers are released. These monomers, which are the smaller building blocks of the original polymer, are then assimilated into the cytoplasm of microbial cells and enter various metabolic pathways for further utilization. Here's a breakdown of the process. This step is followed by mineralization steps, done with the help of microbes. During this process, metabolic intermediates with carbonyl and hydroxyl groups are metabolized within the cell using pathways such as the tricarboxylic acid (TCA) cycle and the β-oxidation pathway. Upon complete mineralization, carbon dioxide evolves and forms several intermediate compounds (H_2O, N_2, and CH_4), which serve as a source of energy for microbial development.

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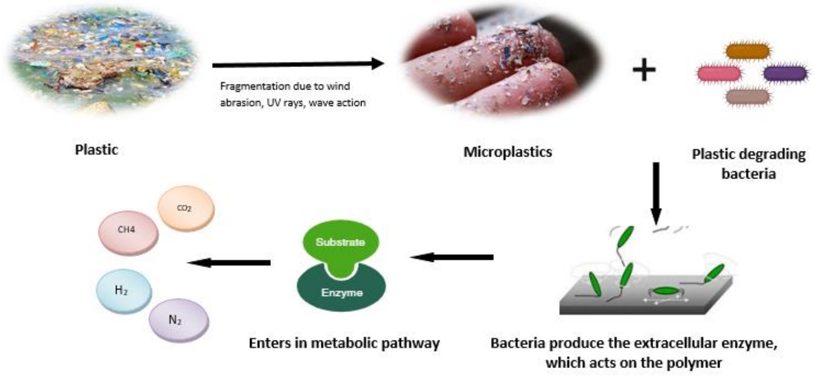

Fig 3. Mechanisms of biodegradation by bacteria

For example, *Ideonella sakaiensis* is a notable bacterium that has been identified for its ability to degrade polyethylene terephthalate (PET), a common plastic used to produce bottles and other packaging materials. This bacterium was isolated from PET-polluted environments, specifically in the sediment of the Sakai River in Sakai City, Japan. These bacteria adapt over time to efficiently utilize the degradation products of PET as a nutrient source. Bacteria produce specialized degrading enzymes, like PETase and MHETase, to break down the synthetic polymer (PET) into smaller, more accessible compounds. This instance provides environmental proof that bacteria may modify their genomes to suit their environment and produce the necessary enzymes to aid PET breakdown.

Some bacteria have evolved the capability to utilize plastic as a carbon source for their growth and development. The process involves the formation of biofilms on the solid surface of plastic materials, where bacteria secrete specialized enzymes to cleave synthetic polymers into monomers.

Conclusion

Plastics and its products have become an integral part of human life. A world without plastics seems unimaginable in today's world. Though plastic has modified our daily lives and reduced our workload, it has degraded the environment in several ways. Furthermore, macroplastics can form micro and nanosize plastics, and these smaller plastics are very hard to detect in the environmental matrix, and their removal from the environment is very difficult. In this regard, various bacterial degradation studies have been conducted by several researchers, and they have identified numerous bacterial strains that can degrade microplastics. Bacterial degradation is considered a relatively eco-friendly approach compared to some other methods. Certain bacteria possess the ability to break down plastics through enzymatic processes. However, the rate of natural bacterial degradation of plastics is often slow, and there's room for improvement in terms of efficiency. Hence, more research should focus on improving bacterial strains' efficiency.

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