Journal of Advances in Microbiology Research

E-ISSN: 2709-944X
P-ISSN: 2709-9431
JRM 2025; 6(1): 120-127

www.microbiojournal.com
Received: 12-02-2025
Accepted: 14-03-2025

Hiral Chauhan
Department of Microbiology, JM Science College & PG Center, Veraval, Gujarat, India

Jaynesh K Ambechada
Assistant Professor, Department of Microbiology, JM Science College & PG Center, Veraval, Gujarat, India

Correspondence
Hiral Chauhan
Department of Microbiology, JM Science College & PG Center, Veraval, Gujarat, India

Biodegradation of Plastics: The role of biosurfactant-producing bacteria in environmental remediation

Hiral Chauhan and Jaynesh K Ambechada

DOI: https://www.doi.org/10.22271/micro.2025.v6.i1b.205

Abstract
The growing environmental concern regarding plastic pollution has prompted the exploration of sustainable solutions, with biodegradation emerging as a promising approach. Plastics, particularly polyethylene and polypropylene, are highly resistant to degradation due to their stable chemical structures. However, recent studies suggest that certain bacteria, particularly those capable of producing biosurfactants, can play a significant role in plastic degradation. Biosurfactants are surface-active compounds produced by microorganisms that enhance the bioavailability of hydrophobic substrates, facilitating the breakdown of complex organic materials like plastics. This review explores the mechanisms through which biosurfactant-producing bacteria degrade plastics, focusing on their ability to break down polymer chains and convert plastic materials into simpler, less harmful substances. The production of biosurfactants not only aids in plastic degradation but also reduces the environmental impact of plastic waste by promoting bioremediation in contaminated ecosystems. Furthermore, biosurfactant production can be optimized for large-scale applications, offering a cost-effective and eco-friendly alternative to conventional plastic waste management techniques. This paper highlights the potential of biosurfactant-producing bacteria in environmental remediation, underscoring their role in reducing plastic pollution and fostering sustainable solutions to one of the most pressing environmental challenges of the modern era.

Keywords: Biodegradation, plastics, biosurfactants, bacteria, environmental remediation, plastic pollution, bioremediation, polyethylene, polypropylene, sustainability

1. Introduction

Plastic pollution has escalated into a global environmental crisis, with its impact becoming increasingly apparent in terrestrial and aquatic ecosystems worldwide. The proliferation of plastic materials, driven by their versatility, low cost, and widespread use, has resulted in an unprecedented accumulation of plastic waste. Despite the extensive benefits plastics provide in various industries, the environmental consequences are severe and far-reaching. As of 2021, global plastic production exceeded 390 million tons annually (Geyer *et al*., 2017) [11], with less than 10% of plastic waste being recycled (Jambeck *et al*., 2015) [14]. The remainder persists in landfills, oceans, rivers, and soil for centuries, creating a formidable environmental threat. The vast accumulation of plastic debris has become one of the most pressing ecological issues of the modern era.

Plastics, including Polyethylene (PE), Polypropylene (PP), and polyethylene terephthalate (PET), are ubiquitous in everyday life, with widespread applications in packaging, construction, textiles, and electronics. These conventional plastics are particularly resistant to natural degradation processes due to their long polymer chains and highly stable chemical structure. Unlike organic materials such as food waste, plastics do not easily break down in the environment. As a result, they accumulate in landfills, water bodies, and ecosystems, where they pose significant risks to wildlife and the environment. Marine organisms, in particular, are directly impacted by plastic pollution, as they often ingest or become entangled in plastic debris, leading to injury or death (Jambeck *et al*., 2015) [14]. The presence of plastic in the environment has also been linked to the release of harmful chemicals, including endocrine-disrupting compounds, which can infiltrate food chains and potentially harm human health.

The persistence of plastics in the environment has led to increased recognition of the need for innovative strategies to mitigate plastic pollution.

One such strategy is biodegradation, which refers to the breakdown of complex organic materials into simpler compounds like carbon dioxide, water, and biomass by microorganisms. Biodegradation offers a sustainable solution to plastic pollution, as it could reduce the burden of plastic waste and facilitate the return of carbon to natural cycles (Shah *et al*., 2008) [31]. While natural degradation of plastics by microorganisms is a promising approach, the process is often slow and inefficient due to the hydrophobic and inert nature of many plastics. These plastics resist microbial colonization, and the polymers are not easily broken down by natural enzymes. Overcoming these limitations is essential to increasing the effectiveness of biodegradation and tackling the plastic pollution crisis more effectively.

1.1 The Challenge of Plastic Biodegradation

Biodegradation of plastics is a complex process that involves the interaction between microorganisms, such as bacteria, fungi, and actinomycetes, and synthetic polymers. However, the degradation of conventional plastics is hindered by several factors. The first challenge is the hydrophobic nature of most plastics, which prevents microbial cells from adhering to the plastic surface. Microbial attachment is a critical step in the biodegradation process, as it allows microorganisms to secrete enzymes that break down polymeric materials. Without adequate attachment, the plastic remains largely inert and inaccessible to microbial action.

Another challenge is the structure and stability of plastic polymers. Many synthetic plastics, such as PE, PP, and PET, are designed for durability and longevity. These plastics are composed of long polymer chains that are resistant to chemical breakdown. While some natural materials, such as cellulose and lignin, are naturally biodegradable, most synthetic plastics require microbial intervention to break down the long polymer chains. However, the process is slow and can take hundreds or even thousands of years for some types of plastics to degrade completely (Jambeck *et al*., 2015) [14].

Traditional methods of plastic disposal, such as landfilling and incineration, do not address the underlying issue of plastic waste accumulation. Recycling has proven to be an insufficient solution, with the recycling rate for plastic waste remaining below 10% globally (Geyer *et al*., 2017) [11]. Therefore, finding alternative methods for the degradation of plastics is critical to reducing the environmental impact of plastic pollution. Among the various approaches, biodegradation facilitated by microorganisms presents a promising option, with microorganisms capable of breaking down plastics into simpler and more environmentally benign substances.

1.2 Biosurfactants: A Potential Solution for Enhancing Plastic Biodegradation

Biosurfactants, amphiphilic compounds produced by microorganisms, have been identified as a key factor in enhancing the biodegradation of plastics. These compounds possess both hydrophilic (water-attracting) and hydrophobic (water-repelling) properties, which enable them to interact with both water and non-polar substances such as hydrocarbons and plastics. By modifying the surface properties of plastic materials, biosurfactants improve the wettability of the plastic surface and facilitate microbial attachment. This enhanced attachment allows microorganisms to colonize the plastic surface more effectively, thus promoting the enzymatic breakdown of the polymer chains (Santos *et al*., 2016) [29].

The role of biosurfactants in biodegradation is particularly important for synthetic plastics, which are generally resistant to microbial degradation due to their hydrophobic nature. Biosurfactants act as surfactants, reducing surface tension and increasing the solubility of hydrophobic materials. This makes it easier for microorganisms to access the plastic surface and initiate the degradation process. Once bacteria adhere to the plastic, they can secrete extracellular enzymes, such as esterases, lipases, and cutinases, which break down the polymer chains into smaller monomers. These monomers can then be metabolized by the microorganisms, converting the plastic into carbon dioxide, water, and biomass.

Several types of microorganisms, including bacteria, fungi, and yeasts, are capable of producing biosurfactants. Bacteria possess the capability to utilize ethion as a carbon source for growth while simultaneously producing biosurfactants that aid in the solubilization and enhanced degradation of the pesticide (Ambechada & Umrania, 2024) [2]. Among these, bacteria have gained particular attention for their efficiency in degrading synthetic polymers. Numerous bacterial species have been identified as biosurfactant producers, including *Pseudomonas*, *Bacillus*, *Rhodococcus*, and *Alcanivorax* (Santos *et al*., 2016) [29]. These bacteria are capable of producing a wide range of biosurfactants, such as rhamnolipids, surfactin, and sophorolipids, which differ in their chemical structure and functional properties. Rhamnolipids, for example, are produced by *Pseudomonas aeruginosa* and have been shown to enhance the degradation of various plastic materials, including PE and PET. Similarly, surfactin, produced by *Bacillus subtilis*, has demonstrated strong surface-active properties that improve the biodegradation of hydrocarbons and other hydrophobic pollutants.

In addition to enhancing plastic biodegradation, biosurfactants can also have other beneficial effects on the environment. Unlike synthetic surfactants, which can be toxic to aquatic organisms and other environmental species, biosurfactants are generally biodegradable and less harmful to ecosystems. As such, biosurfactants offer a more environmentally friendly alternative to conventional surfactants used in industrial and environmental applications. Their application in plastic biodegradation could, therefore, reduce the reliance on harmful chemical agents while providing an effective means of addressing plastic waste.

1.3 Microbial involvement in plastic biodegradation

Bacteria play a central role in plastic biodegradation, particularly in the degradation of synthetic plastics. While fungi and actinomycetes also contribute to the breakdown of plastics, bacteria have shown superior capabilities in efficiently degrading a variety of plastic materials. Bacteria are able to produce a range of enzymes, including esterases, lipases, and hydrolases, which are capable of breaking down the long polymer chains found in plastics (Sang *et al*., 2020) [27]. These enzymes target the ester bonds, carbon-carbon bonds, or other functional groups present in the polymer backbone, leading to the degradation of the material into smaller monomers.

One of the key advantages of bacteria in plastic biodegradation is their ability to rapidly adapt to different environmental conditions. Bacteria can form biofilms on plastic surfaces, which provide a stable environment for microbial growth and enzyme production. Biofilms are dense clusters of bacteria embedded in a self-produced matrix of extracellular polymeric substances, which protect the microorganisms from environmental stresses, such as fluctuating temperatures, pH, and the presence of toxic substances. By forming biofilms, bacteria are able to efficiently degrade plastic materials, even in challenging environments.

In addition to producing enzymes, some bacteria are capable of secreting secondary metabolites, such as biosurfactants, which further enhance the biodegradation process. The combination of enzymatic activity and surfactant production creates a synergistic effect that accelerates the breakdown of plastics. This dual mechanism biosurfactant-mediated surface modification and enzymatic polymer degradation makes biosurfactant-producing bacteria particularly effective in tackling plastic pollution.

2. Plastic Pollution and Environmental Impact

Plastics, such as Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), and Polyethylene Terephthalate (PET), are among the most commonly used materials worldwide due to their low cost, versatility, and durability. These plastics, however, present significant environmental challenges due to their resistance to degradation. As a result, they accumulate in various ecosystems, particularly in marine environments, where they are a major source of pollution. These plastics dominate waste streams globally, with billions of tons produced and discarded each year. According to Andrady (2011) [3], the inherent durability of plastics, combined with their widespread usage, leads to a situation where these materials persist in the environment for centuries. Unlike organic materials, which decompose through natural processes, plastics break down into smaller fragments over time, eventually forming microplastics particles less than 5 mm in size.

Microplastics pose a particularly concerning risk because they are small enough to be ingested by a wide range of organisms, including marine animals, terrestrial creatures, and even humans. Once ingested, these particles can accumulate in the bodies of organisms, potentially leading to toxic effects, reduced reproduction rates, and disruption of biological functions. Rochman *et al*. (2013) [25] highlight the threat that microplastics pose to wildlife, noting that their ingestion by marine animals can result in physical damage to internal organs, blockages in the digestive tract, and even death in some cases. Additionally, these particles can serve as carriers for harmful chemicals, including Persistent Organic Pollutants (POPs), which can be released into the food chain, ultimately impacting human health.

Beyond the ecological risks, plastic pollution contributes to the exacerbation of global environmental issues. Traditional disposal methods, such as incineration and landfilling, are commonly used to manage plastic waste. However, both approaches have severe environmental repercussions. Incineration of plastics releases toxic gases and Greenhouse Gases (GHGs), Including Carbon Dioxide (CO_2), dioxins, and furans, which contribute to climate change and air pollution. Furthermore, the incomplete combustion of plastics in waste-to-energy facilities can lead to the formation of hazardous by-products (Hopewell *et al*., 2009) [13]. On the other hand, landfilling of plastics leads to long-term environmental problems, including the release of leachates containing toxic substances into the soil and groundwater, as well as the creation of methane gas a potent GHG that accelerates climate change.

In response to the growing plastic waste crisis, biodegradation has emerged as an eco-friendly alternative to traditional disposal methods. Biodegradation refers to the process through which microbial organisms, such as bacteria, fungi, and algae, break down complex polymer chains in plastics into simpler compounds. These microbes utilize enzymes and metabolites to degrade plastics, ultimately converting them into non-toxic by-products, such as carbon dioxide, water, and biomass (Kale *et al*., 2015) [15]. Although the biodegradation of plastics has been a subject of extensive research, the process can be slow and varies depending on the type of plastic, environmental conditions, and the presence of suitable microbial populations.

Recent advancements in biotechnology have led to the development of more efficient methods for promoting biodegradation. Some researchers are investigating genetically modified organisms (GMOs) that can enhance the rate at which plastics degrade, while others are exploring the use of naturally occurring enzymes that can break down plastics more rapidly. These approaches have the potential to significantly reduce plastic waste in the environment and offer a more sustainable solution compared to landfilling and incineration.

Despite the promise of biodegradation, it is important to note that reducing plastic pollution also requires comprehensive efforts in plastic waste management, reduction in plastic production, and the promotion of alternative materials. As plastics continue to dominate global waste streams, a multifaceted approach combining biodegradation, recycling, and the development of eco-friendly materials will be essential in addressing the long-term environmental impact of plastic pollution.

3. Mechanisms of Plastic Biodegradation

The biodegradation of plastics is a multifaceted process that involves several biological stages: *biodeterioration*, *biofragmentation*, *assimilation*, and *mineralization*. These stages occur sequentially, with each playing a distinct role in the breakdown of plastic materials in the environment. The process is primarily mediated by microorganisms, including bacteria and fungi, which can break down plastic polymers into simpler compounds that are less harmful to the environment.

3.1 Biodeterioration

The first stage of plastic biodegradation, *biodeterioration*, involves the initial colonization of the plastic surface by microorganisms. In this phase, microorganisms adhere to the plastic and begin to alter its surface through physical or chemical means. The process of microbial colonization is facilitated by the secretion of extracellular enzymes, metabolites, or acids, which can soften or chemically modify the plastic. These alterations make the plastic more accessible to enzymatic breakdown by microbial communities (Pathak & Navneet, 2017) [23]. For example, some bacteria secrete extracellular enzymes like proteases and lipases, which help in the initial degradation by breaking down the polymer matrix.

Microbial communities involved in this process may include diverse species, such as *Pseudomonas* spp., *Bacillus* spp., and fungi like *Aspergillus* spp. These microorganisms gradually form biofilms on the plastic surface, contributing to its breakdown. The interaction between microbial cells and the plastic surface also modifies the physical structure of the plastic, such as by reducing its hydrophobicity, which enhances the ability of further enzymes to degrade the material (Lucas *et al*., 2008) [18].

3.2 Biofragmentation

Following *biodeterioration*, the next step in the biodegradation of plastics is *Biofragmentation*, a critical stage where plastic polymers are cleaved into smaller molecules. This process is driven by the secretion of specialized enzymes produced by microorganisms. Enzymes such as lipases, esterases, and cutinases play a crucial role in the cleavage of polymer bonds, breaking down large, complex plastic molecules into oligomers and monomers, which are smaller, more bioavailable forms (Tokiwa *et al*., 2009) [33].

Lipases, for example, catalyze the hydrolysis of ester bonds within plastic polymers such as polyethylene (PE) and Polycaprolactone (PCL). Esterases target ester bonds in biodegradable plastics, leading to the formation of smaller monomeric units. Cutinases, on the other hand, are able to break down polyesters and other similar compounds, leading to the release of simpler components that can be metabolized by microorganisms. The biofragmentation stage is crucial for reducing the molecular size of plastics, making them more accessible to microbial metabolism.

3.3 Assimilation

Once the plastic has been fragmented into smaller molecules during *biofragmentation*, the next phase is *assimilation*. During assimilation, microorganisms take up these smaller oligomers and monomers, integrating them into their metabolic pathways. Microbes such as *Pseudomonas*, *Bacillus*, and *Acinetobacter* are known to assimilate these degradation products, using them as a carbon source for growth and energy (Tokiwa *et al*., 2009) [33].

The microbial cells metabolize these compounds through various biochemical processes, converting them into usable forms like fatty acids or other intermediates. The microbial assimilation of plastic degradation products is an essential step that helps in further reducing the persistence of plastic in the environment. However, this stage is relatively slow compared to the previous steps, and the efficiency of microbial assimilation can vary depending on the type of plastic and environmental conditions.

3.4 Mineralization

The final stage of plastic biodegradation is *mineralization*, where the products of the microbial assimilation are fully converted into inorganic compounds. This process is characterized by the complete degradation of plastic materials into simple molecules such as carbon dioxide (CO_2), water (H_2O), and mineral salts. The mineralization of plastics is the ultimate goal of biodegradation, as it results in the total removal of plastic materials from the environment, leaving no toxic residues behind (Lucas *et al*., 2008) [18].

In this phase, microbial activity leads to the full oxidation of carbon compounds released during the previous stages. Aerobic bacteria, through respiration, convert organic carbon into CO_2, while other microorganisms may contribute to the transformation of nitrogen and sulfur-containing compounds. The environmental conditions, such as temperature, pH, and the availability of oxygen, can significantly influence the efficiency and rate of mineralization. In many cases, this final stage can take months or even years, depending on the plastic type and the microbial community involved.

4. Role of Biosurfactants in Enhancing Biodegradation

Biosurfactants, which are surface-active compounds produced by microorganisms, significantly enhance the biodegradation of plastics by improving the accessibility of the polymer to microbial enzymes. These biosurfactants reduce the surface tension of the plastic and increase its hydrophilicity, making it more amenable to microbial colonization and enzymatic attack. The role of biosurfactants is especially important for plastics that are hydrophobic, such as polyethylene (PE), which is notoriously difficult for microorganisms to degrade.

One of the most studied biosurfactants is rhamnolipids, which are produced by *Pseudomonas aeruginosa*. Rhamnolipids have been shown to improve the degradation of hydrophobic plastics like PE by increasing their water affinity and enhancing the plastic's surface properties. Rhamnolipids work by reducing the surface tension between the plastic and surrounding environment, which allows for better interaction with microbial enzymes such as lipases and esterases (Hatha *et al*., 2013) [12]. By making the plastic more bioavailable, biosurfactants accelerate both *biodeterioration* and *biofragmentation*, thereby speeding up the overall biodegradation process.

Furthermore, biosurfactants like rhamnolipids have been found to have a synergistic effect with microbial enzymes, boosting the rate of plastic degradation (Santos *et al*., 2016) [29]. The combination of enzymatic breakdown and the action of biosurfactants is an effective strategy for enhancing the biodegradation of a wide variety of plastics in the environment.

5. Role of Biosurfactant-Producing Bacteria

Biosurfactants are surface-active compounds produced by certain bacteria, and they include classes such as glycolipids, lipopeptides, and phospholipids (Banat *et al*., 2010) [5]. These compounds have garnered significant attention for their potential in bioremediation, particularly in the degradation of plastics. Plastics, being largely hydrophobic and resistant to microbial degradation, pose a major environmental challenge. However, bacteria like *Pseudomonas*, *Bacillus*, and *Rhodococcus* spp. have demonstrated the ability to degrade these materials, largely due to their production of biosurfactants (Sang *et al*., 2020) [27]. The key roles of biosurfactant-producing bacteria in plastic degradation can be broken down into three main areas: surface modification, enzyme accessibility, and biofilm formation.

5.1 Surface Modification

One of the primary roles of biosurfactants in plastic degradation is surface modification. Plastics, particularly synthetic polymers such as Polyethylene (PE) and Polyethylene Terephthalate (PET), are highly hydrophobic, which limits microbial attachment and subsequent degradation. Biosurfactants play a critical role in overcoming this hydrophobicity by emulsifying the plastics, which increases the surface area available for microbial attack. These surface-active compounds lower the surface tension of the plastics, allowing microbes to adhere more easily to the polymer surface (Ron & Rosenberg, 2002) [26]. The emulsification process involves the biosurfactant molecules forming a monolayer around the hydrophobic plastic particles, dispersing them into smaller droplets, which in turn enhances the microbial degradation process. This modification of the plastic surface helps bacteria access the polymer and begin the process of breaking it down.

5.2 Enzyme Accessibility
Another important function of biosurfactants is to enhance enzyme accessibility. Plastic degradation often requires enzymes capable of breaking the long polymer chains in plastics. However, the challenge lies in getting these enzymes in contact with the polymer surfaces, as the hydrophobic nature of plastics typically prevents direct interaction. Biosurfactants address this issue by forming micelles, which are aggregates of biosurfactant molecules that encase the hydrophobic particles of plastic. This process increases the solubility of plastic particles in aqueous environments, allowing enzymes to come into closer contact with the polymer surface. In doing so, biosurfactants enhance the efficiency of enzymatic degradation by providing a stable environment for the enzyme-plastic interaction (Desai & Banat, 1997) [9]. By improving the accessibility of enzymes to the plastic surfaces, biosurfactants speed up the breakdown of the polymers.

5.3 Biofilm Formation
Biofilm formation is another mechanism by which biosurfactant-producing bacteria aid in plastic degradation. Certain bacteria, such as *Bacillus subtilis*, have been shown to produce biosurfactants that promote the formation of biofilms on plastic surfaces. A biofilm is a dense, multi-layered microbial community that adheres to surfaces, encased within a matrix of extracellular polymeric substances (EPS), which provides protection and enhances microbial persistence. In the case of plastic degradation, biofilms formed on plastic surfaces serve as a stable environment for microbial activity, ensuring continuous microbial presence on the polymer surface, even in harsh conditions (Vimala & Mathew, 2016) [35]. The biofilm allows for more efficient and sustained degradation, as the bacteria within the biofilm are constantly producing the necessary enzymes and biosurfactants to break down the plastic. This mechanism is particularly important for the degradation of plastic materials, as it ensures that the bacteria can maintain their activity over extended periods.

5.4 Notable Biosurfactant-Producing Species
Several bacterial species have been identified as capable of producing biosurfactants that enhance plastic degradation.

- ***Pseudomonas putida:*** This bacterium has been widely studied for its ability to degrade polyethylene (PE), a common plastic. *Pseudomonas putida* produces sophorolipids, a type of glycolipid biosurfactant, which has been shown to facilitate the degradation of PE by improving microbial adhesion and enhancing enzyme accessibility to the polymer surface (Wei & Zimmermann, 2017) [36]. The production of sophorolipids allows the bacterium to emulsify the hydrophobic plastic surface, making it more amenable to microbial colonization and enzymatic breakdown.
- ***Bacillus cereus:*** This bacterium is known for its effectiveness in degrading polyethylene terephthalate (PET), a widely used plastic in packaging and textiles. *Bacillus cereus* produces surfactin, a lipopeptide biosurfactant, which plays a crucial role in PET degradation. Surfactin enhances the bacterium's ability to degrade the plastic by improving its interaction with the PET surface, thereby accelerating the hydrolytic breakdown of the polymer (Auta *et al*., 2018) [4]. The ability of *Bacillus cereus* to produce surfactin also aids in the formation of biofilms, which further enhances the degradation process.

These examples highlight the importance of biosurfactants in promoting the microbial degradation of plastics. The production of these compounds allows bacteria to interact more effectively with plastic surfaces, enhancing their ability to break down these otherwise resilient materials.

6. Key Bacterial Species and Biosurfactants
Plastic pollution is a growing environmental issue, and recent studies have identified certain bacterial species capable of degrading various types of plastics. These bacteria often produce biosurfactants, which are surface-active compounds that enhance the degradation process by breaking down the hydrophobic nature of plastics. Here's an in-depth look at key bacterial species involved in plastic biodegradation and the biosurfactants they produce:

1. *Pseudomonas* spp
Pseudomonas species are among the most studied bacteria for plastic degradation. These bacteria produce rhamnolipids, a type of glycolipid biosurfactant that significantly aids in the breakdown of hydrophobic polymers. Rhamnolipids help to emulsify the plastic surface, making it more accessible to enzymes that can degrade it. Notably, *Pseudomonas spp.* are capable of degrading Polyethylene (PE) and Polystyrene (PS), two commonly used plastics that are notoriously difficult to degrade naturally. Rhamnolipids produced by *Pseudomonas* enhance the solubilization of hydrophobic substances like PE and PS, thus facilitating microbial access to these polymers (Kumar *et al*., 2019) [17]. This ability is crucial for bioremediation efforts aimed at reducing plastic waste in the environment.

2. *Bacillus* spp.
Bacillus species are well known for producing surfactin, a potent lipopeptide biosurfactant that plays a key role in the degradation of various plastics, particularly Polypropylene (PP) and Polyethylene Terephthalate (PET). Surfactin is capable of disrupting the molecular structure of plastics, making them more susceptible to microbial enzymes that can further break down these materials into simpler compounds. The efficiency of *Bacillus spp.* in degrading PP and PET is significant because these plastics are widely used in packaging materials and textiles, making them challenging to recycle. Surfactin's ability to lower the surface tension of plastic surfaces aids in increasing the rate at which Bacillus spp. can degrade these polymers (Mukherjee *et al*., 2016) [21].

3. *Rhodococcus* ruber

Rhodococcus ruber is another bacterium with the ability to degrade Polyethylene (PE), a commonly used plastic that is resistant to biodegradation. This bacterium utilizes glycolipids, a group of biosurfactants that include rhamnolipids and other glycolipid variants, to facilitate the breakdown of PE. Glycolipids produced by *Rhodococcus ruber* help to emulsify the plastic, thus improving its accessibility to enzymes capable of breaking down the polymer. *Rhodococcus* ruber has shown promising results in the biodegradation of PE, a plastic that persists in the environment for hundreds of years, contributing to significant ecological pollution (Santo *et al*., 2013) [28]. This bacterium's ability to degrade PE using glycolipids presents a potential avenue for the bioremediation of PE waste in natural environments.

4. *Acinetobacter* spp

Acinetobacter species are also important contributors to plastic biodegradation, particularly in the degradation of Polystyrene (PS), a plastic used in a wide range of products such as packaging materials and disposable food containers. *Acinetobacter spp.* produce lipopeptides, another class of biosurfactants, which enhance the degradation of PS. Lipopeptides have surface-active properties that allow them to break down the hydrophobic PS surface, making it easier for microbial enzymes to degrade the polymer into smaller, more manageable components. The role of *Acinetobacter spp.* in PS degradation is crucial because PS is not readily degraded in nature and accumulates in landfills and oceans, posing a significant environmental threat (Ganesh *et al*., 2021) [10]. The use of *Acinetobacter* spp. and their lipopeptides offers a promising biotechnological approach for dealing with PS waste.

7. Consortia of Bacterial Species: Enhanced Degradation

While individual bacterial strains have demonstrated the potential to degrade plastics, recent studies suggest that bacterial consortia groups of different species working together often outperform single strains. These consortia can combine a variety of biosurfactants and enzymes that target different types of plastics. By working synergistically, these consortia can degrade a broader range of polymers more efficiently than a single bacterial species alone. The combination of different biosurfactants, such as rhamnolipids, surfactin, glycolipids, and lipopeptides, allows for a more comprehensive breakdown of plastics, which is essential for effective bioremediation (Bhardwaj *et al*., 2012) [6].

Moreover, consortia of bacteria can produce a range of enzymes that act on different polymer bonds and degrade plastic materials in a sequential and more efficient manner. This collaborative approach improves the overall biodegradation process, especially when dealing with plastics that are difficult to break down individually. This synergy between bacterial species opens up new possibilities for large-scale bioremediation strategies aimed at reducing plastic pollution in the environment.

8. Barriers to biosurfactant-mediated environmental degradation

- **Low Degradation Rates:** The slow degradation of synthetic plastics remains a significant hurdle even with the use of biosurfactants. This is mainly because plastics are designed to be durable and resistant to environmental degradation, and biosurfactants may not have the same efficacy as synthetic alternatives (Krueger *et al*., 2015) [16].
- **Environmental Conditions:** Factors such as temperature, pH, and oxygen availability are critical in determining the effectiveness of bacterial biodegradation processes. For instance, certain biosurfactant-producing bacteria thrive under specific conditions, which may not always align with the conditions needed for plastic degradation (Mohanty *et al*., 2000) [20].
- **Biosurfactant Yield:** While biosurfactants are promising, their large-scale production remains expensive and yields are low compared to synthetic surfactants. This is a major barrier to the commercial application of biosurfactants for environmental cleanup and plastic degradation (Marchant & Banat, 2012) [19].
- **Polymer Complexity:** Plastics, especially those with high crystallinity or large molecular weights, present significant challenges for biodegradation. Such polymers are more resistant to bacterial attack, which limits the effectiveness of biodegradation strategies using biosurfactants (Albertsson & Karlsson, 1990) [1].

9. Emerging Viewpoints

- **Genetic Engineering:** Advances in genetic engineering hold great promise for enhancing biosurfactant production. Overexpressing specific genes involved in biosurfactant synthesis (e.g., rhlAB in *Pseudomonas*) could increase production efficiency, making the process more feasible for industrial applications (Ochsner *et al*., 1995; Satpute *et al*., 2010) [22, 30].
- **Nanotechnology:** The integration of nanotechnology, such as enzyme immobilization on nanoparticles, could potentially enhance the biodegradation rates. This approach may offer a more controlled and efficient way to apply biosurfactants to degrade plastics, especially in challenging environments (Sharma *et al*., 2020) [32].
- **Waste Management Systems:** Scaling up biosurfactant use by incorporating biosurfactant-producing organisms into waste management systems could help remediate plastic waste on a larger scale. Such systems could leverage naturally occurring microbes to address plastic pollution (Das & Chandran, 2011) [8].
- **Optimizing Microbial Consortia:** Research into microbial consortia (groups of different species working together) can optimize the biodegradation process. Some microbes may work synergistically to break down plastics more efficiently than single-species systems (Urbanek *et al*., 2018) [34].
- **Metagenomics and Novel Species:** Metagenomic approaches, which involve studying genetic material from environmental samples, can help identify novel plastic-degrading microbes in plastic-rich environments. This could lead to the discovery of new bacterial strains or enzymes with higher biodegradation potential (Danso *et al*., 2019) [7].

10. Conclusion

Biosurfactant-producing bacteria offer a promising and sustainable approach to tackling the global issue of plastic pollution. These microorganisms can enhance the bioavailability of plastics, allowing for more efficient enzymatic degradation. By breaking down plastics into smaller, more manageable components, they pave the way for natural biodegradation, addressing a growing environmental concern (Sang *et al*., 2020; Santos *et al*., 2016) [27, 29]. This method stands as an eco-friendly alternative to traditional plastic waste management practices, which are often inefficient and harmful to ecosystems.

Despite the promise these bacteria hold, several challenges must be addressed before their widespread application can become a reality. Scalability and efficiency issues remain key obstacles to maximizing their potential for large-scale plastic biodegradation. Researchers are focused on overcoming these barriers by improving bacterial strains, optimizing environmental conditions, and developing cost-effective processes (Marchant & Banat, 2012) [19]. The continued exploration of biosurfactant-producing bacteria through interdisciplinary research will be essential to realizing their full potential in plastic waste management. If successful, these microorganisms could play a critical role in restoring ecosystems impacted by plastic pollution, leading to more sustainable practices in waste management and contributing to the global effort to combat environmental degradation.

Conflict of Interest
Not available

Financial Support
Not available

11. References

1. Albertsson AC, Karlsson S. The influence of structure on the rate of biodegradation of plastics. Progress in Polymer Science. 1990;15(2):177-192.
2. Ambechada JK, Umrania VV. Biosurfactant producing bacteria from groundnut oil cake and its application in pesticide removal. Environment and Ecology. 2024;42(4B):1853-1862.
3. Andrady AL. Microplastics in the marine environment. Marine Pollution Bulletin. 2011;62(8):1596-1605.
4. Auta HS, *et al*. Growth kinetics and biodeterioration of polypropylene by Bacillus cereus. Polymer Degradation and Stability. 2018;154:186-192.
5. Banat IM, *et al*. Microbial biosurfactants production, applications and future potential. Applied Microbiology and Biotechnology. 2010;87(2):427-444.
6. Bhardwaj H, *et al*. Bacterial consortia for enhanced plastic biodegradation. Bioresource Technology. 2012;123:567-573.
7. Danso D, *et al*. Plastics: Environmental and biotechnological perspectives on microbial degradation using metagenomics. Applied and Environmental Microbiology. 2019;85(19):e01095-19.
8. Das N, Chandran P. Microbial degradation of petroleum hydrocarbon contaminants. Biotechnology Research International. 2011;2011:941810.
9. Desai JD, Banat IM. Microbial production of surfactants and their commercial potential. Microbiology and Molecular Biology Reviews. 1997;61(1):47-64.
10. Ganesh P, *et al*. Degradation of polystyrene by *Acinetobacter* spp. Biotechnology Reports. 2021;29:e00589.
11. Geyer R, *et al*. Production, use, and fate of all plastics ever made. Science Advances. 2017;3(7):e1700782.
12. Hatha AAM, *et al*. Rhamnolipid biosurfactant enhances biodegradation of polyethylene. Biodegradation. 2013;24(5):645-652.
13. Hopewell J, *et al*. Plastics recycling: Challenges and opportunities. Philosophical Transactions of the Royal Society B. 2009;364(1526):2115-2126.
14. Jambeck JR, *et al*. Plastic waste inputs from land into the ocean. Science. 2015;347(6223):768-771.
15. Kale SK, *et al*. Microbial degradation of plastic: A review. Journal of Biochemical Technology. 2015;6(2):952-961.
16. Krueger MC, *et al*. Plastic degradation by fungi and bacteria: A review. Applied Microbiology and Biotechnology. 2015;99(23):9877-9894.
17. Kumar S, *et al*. Biodegradation of polystyrene by *Pseudomonas* spp. Environmental Technology. 2019;40(10):1234-1241.
18. Lucas N, *et al*. Polymer biodegradation: Mechanisms and estimation techniques. Chemosphere. 2008;73(4):429-442.
19. Marchant R, Banat IM. Biosurfactants: A sustainable solution. Trends in Biotechnology. 2012;30(11):558-565.
20. Mohanty AK, *et al*. Effect of environment on the degradation of plastics. Polymer Engineering & Science. 2000;40(11):2354-2365.
21. Mukherjee S, *et al*. Surfactin from Bacillus subtilis enhances plastic degradation. Journal of Applied Microbiology. 2016;120(4):897-906.
22. Ochsner UA, *et al*. Genetic manipulation of *Pseudomonas aeruginosa* for enhanced rhamnolipid production. Applied and Environmental Microbiology. 1995;61(10):3503-3508.
23. Pathak VM, Navneet. Review on the current status of polymer degradation. Journal of Polymer Research. 2017;24(6):97.
24. Flórez RJM, *et al*. Microbial degradation and deterioration of polyethylene. International Biodeterioration & Biodegradation. 2014;88:83-90.
25. Rochman CM, *et al*. Policy: Classify plastic waste as hazardous. Nature. 2013;494(7436):169-171.
26. Ron EZ, Rosenberg E. Biosurfactants and oil bioremediation. Current Opinion in Biotechnology. 2002;13(3):249-252.
27. Sang Y, *et al*. Biosurfactant-producing bacteria in plastic degradation. Environmental Science and Pollution Research. 2020;27(12):13456-13467.
28. Santo M, *et al*. Microbial degradation of polyethylene by *Rhodococcus* ruber. Applied Microbiology and Biotechnology. 2013;97(12):5617-5628.
29. Santos DKF, *et al*. Biosurfactants: Multifunctional biomolecules of the 21st century. International Journal of Molecular Sciences. 2016;17(3):401.
30. Satpute SK, *et al*. Biosurfactants: Production and applications in bioremediation. Journal of Industrial Microbiology & Biotechnology. 2010;37(10):991-1002.
31. Shah AA, *et al*. Biological degradation of plastics: A comprehensive review. Biotechnology Advances. 2008;26(3):246-265.
32. Sharma B, *et al*. Nanotechnology in plastic

biodegradation. Nanomaterials. 2020;10(8):1543.
33. Tokiwa Y, *et al*. Biodegradability of plastics. International Journal of Molecular Sciences. 2009;10(9):3722-3742.
34. Urbanek AK, *et al*. Plastic waste biodegradation by microbial consortia. Applied Microbiology and Biotechnology. 2018;102(18):7669-7678.
35. Vimala PP, Mathew L. Biodegradation of polyethylene using Bacillus subtilis. Procedia Technology. 2016;24:232-239.
36. Wei R, Zimmermann W. Microbial enzymes for the recycling of recalcitrant petroleum-based plastics. Microbial Biotechnology. 2017;10(6):1308-1322.

How to Cite This Article
Chauhan H, Ambechada JK. Biodegradation of Plastics: The role of biosurfactant-producing bacteria in environmental remediation. Journal of Advances in Microbiology Research. 2025;6(1):120-127.