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PLASTIC DEGRADATION BY SOIL MICROORGANISMS

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Abstract: Plastic pollution is a significant environmental concern, but soil microorganisms can degrade plastics through various mechanisms, including photo-oxidative and thermal degradation. Microorganisms like Pseudomonas, Bacillus, and Streptomyces break down plastics using enzymes, offering a promising solution for plastic waste management. However, plastic biodegradation faces challenges like recalcitrant plastics, environmental factors, and limited microbial capabilities. Recent biotechnology advances have improved plastic degradation efficiency, and future research prospects include exploring new enzymes, optimizing conditions, and scaling up processes for sustainable circular economy.

IndexTerms - Plastic, microorganisms, degradation, challenges, advances in biotechnology, future prospects.

1. INTRODUCTION

Plastics are made from fossil fuels, which are non-renewable resources and are strong, long-lasting, moisture-resistant, lightweight, and composed of carbon, hydrogen, nitrogen, sulfur, and other organic and inorganic elements (k. Asmita *et al* 2015). Plastics are widely used due to their strength, light weight, and durability. However, they resist biodegradation, harming the environment and causing pollution. This has led to research on biosynthetic and biodegradable materials to address plastic waste issues, particularly polyethylene plastics (Mahdiyah *et al* 2013). Plastics are used in various industries, but their non-biodegradability harms the environment. Despite introducing biodegradable plastics, none efficiently break down in landfills (Seenivasagan *et al* 2022). The environment is heavily burdened by waste plastics because of their resistance to disintegration, which speeds up their buildup in the environment. When waste plastics are buried in the ground, they destroy the soil for agricultural production and cause water blockage problems (Yoon *et al* 2012). Since it takes thousands of years for it to degrade effectively, environmental concerns about its slow disintegration began in the early 20th century. It should be disposed of correctly to avoid plastic buildup. One major source of contamination in the environment is improperly disposed of plastics. Soil sterility results from plastic sheets or bags that prevent air and water from penetrating the soil. Polyethylene can occasionally clog fish, bird, and marine mammal intestines in the ocean. Numerous plastic waste materials have frequently been discovered while conducting deep-sea research with research submersibles. In recent years, microbial breakdown of polythene and plastic has drawn a lot of attention. Microorganisms found in the environment, such as bacteria, fungus, algae, and others, may naturally break down biodegradable polymers (Divyalakshmi *et al* 2016).

Polymer 5 first breaks down due to a variety of physical, chemical, and biological factors. Polymers in plastics undergo microbial breakdown to produce oligomers and International Science Congress Association monomers. This microbial breakdown might be attributed to both anaerobic and aerobic metabolisms. In this work, microorganisms from a variety of natural sources were isolated, and their potential capacity to degrade polyethylene was screened. Characterizing and identifying the high potential LDPE degraders was the aim of the study that was done. Sequential dilution of sewage sample was used to do the isolation (Botre *et al* 2015).

2.TYPES OF PLASTICS

Plastics like polyethylene (PE), polypropylene (PP), and polyethylene terephthalate (PET), polyvinyl chloride (PVC) degrade through photo-, thermal-, and biodegradation reactions when exposed to the environment. Degradation rates and modes vary among polymers. Photo-degradation causes changes in surface characteristics, forming new functional groups. Microorganisms interact differently with each polymer, forming biofilms. Environmental factors, such as UV exposure, influence degradation. Lab studies support these findings, but plastic degradation is highly dependent on local environmental variables (Fotopoulou *et al* 2019).

Plastics can degrade through chemical, thermal, photo, or biological means. Biological degradation by microorganisms is indicated by physical or chemical changes, such as weight loss or carbon dioxide production. Various factors, including temperature, moisture, oxygen, sunlight, stress, and living organisms, influence polymer degradation. Bioplastics, like Polyhydroxybutyrate (PHB) and Polyhydroxy valerate (P(HB-co-HV)), offer an alternative to traditional plastics (Muthukumar *et al* 2015).

Plastics are generally divided into two categories: thermoplastics and thermoset plastics. They are created by polymerizing tiny molecules by polyaddition or polycondensation. The atoms and molecules that make up thermoplastics are bonded end to end to form a sequence of lengthy, single-carbon chains. To create a linear macromolecule from vinyl monomers, the double bond must be opened, and the reaction will continue through a free (Singh *et al* 2008).

3. TYPES OF DEGRADATION

3.1 Photo-oxidative degradation

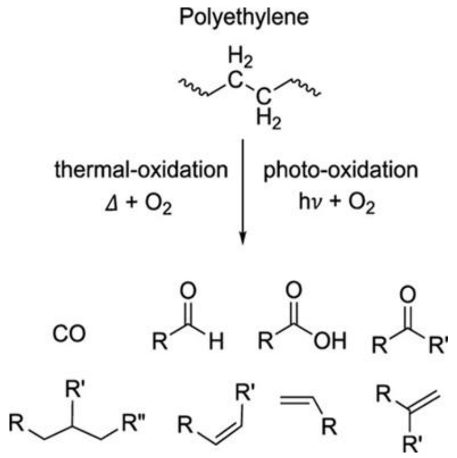
Light is the main factor that damages polymers. Photodegradation and photo-oxidation are two instances of this degradation process, which is initiated by light absorption (Rånby, 1989). The degradation of synthetic polymers is often triggered by ultraviolet (UV) light. Sunlight is the source of UV radiation, which ranges from 290 to 400 nm and determines the lifetime of polymeric materials used in a variety of applications (Jensen and Kops, 1980). At the soft regions of polymers where degradation takes place, photoirradiation generates ester, aldehyde, propyl, and format groups. UV light readily cleaves the C–C bonds (Chamas *et al* 2020).

3.2 Thermal degradation

Thermal and photochemical degradation are oxidative processes, but they differ in their initial steps and reaction sites. Thermal degradation occurs throughout the polymer, initiated by temperature and UV light, and starts at weak bonds, leading to depolymerization. In contrast, photochemical degradation occurs only on the polymer surface. At high temperatures, polymers like polyethylene (PE) and polymethylmethacrylate (PMMA) can decompose into small monomers, illustrating the distinct effects of thermal degradation (Faravelli *et al* 2001).

4. Abiotic degradation pathways

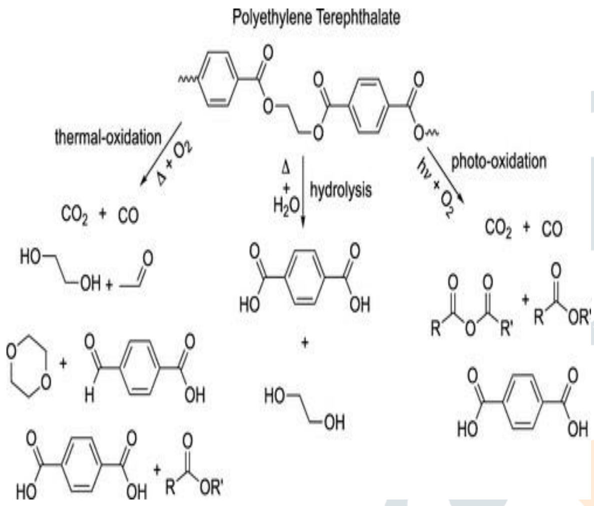
Plastics degrade through physical (cracking, embrittlement) and chemical (bond cleavage, oxidation) mechanisms. Chemical degradation, involving hydrolysis or oxidation, is accelerated by microbial action, heat, light, or combinations thereof. Abiotic processes (light, heat, acids) initiate degradation, breaking down plastics like polyethylene (PE), polyethylene terephthalate (PET), and polylactic acid (PLA) into smaller molecules that are then mineralized by microbes (Chamas *et al* 2020).



POLYETHYLENE (PE)

1. The thermal- and photo-oxidative degradation pathways for polyethylene result in common products, including hydroperoxides (R-OOH), alcohols (R-OH), ketones (R-CO-R'), aldehydes (R-CHO), and carboxylic acids (R-COOH), as well as shorter polymer chains (R', R").

POLYETHYLENE TEREPHTHALATE (PET)



2. The environmental degradation of polyethylene terephthalate (PET) occurs through three common routes, resulting in small molecule products, including terephthalic acid (TPA), mono(2-hydroxyethyl) terephthalate (MHET), and bis(2-hydroxyethyl) terephthalate (BHET), as well as ethylene glycol and vinyl esters.

5.MICRO-ORGANISMS INVOLVED IN PLASTIC DEGRADATION

Microorganisms such as *Pseudomonas, Bacillus, and Streptomyces* play a crucial role in plastic degradation, breaking down polymers into smaller fragments. These microbes utilize enzymes to degrade plastics, offering a promising solution for plastic waste management (Elahi *et al* 2012).

Microbial degradation of plastics occurs biofilm formation on the plastic surface. The composition of microbial biofilms varies depending on the plastic material and environment. Studies have investigated plastic degradation using pure cultures or naturel samples/environment. The process can be divided into four stages, and understanding biofilm formation and microbial interactions is crucial for developing effective plastic biodegradation strategies (Taktarova *et al* 2021).

6.CHALLENGES IN PLASTIC BIODEGRADATION

There is a need for plastics that decompose quickly in natural environments while retaining their properties. Standard methods (e.g., ASTM, EN) evaluate biodegradability in various environments and composting -conditions. Plastics that fully mineralize in industrial composting facilities can be classified as biodegradable or compostable, posing minimal risk of microplastic exposure. However, global data on the composting rate of biodegradable plastics is currently lacking (kubowicz *et al* 2017). Plastic pollution has severely impacted ecosystems, but biodegradation can mitigate this issue. New organisms are emerging that can break down resistant polymers, while biodegradable polymers are being developed that are more susceptible to microbial attack. This explores the fate of these plastics, their molecular structure, and the enzymes involved in their breakdown, as well as biotechnological solutions for converting plastic waste into useful substrates (Wierckx *et al* 2018). Despite numerous reports on microbial degradation of plastics, complete and rapid biodegradation under ambient conditions remains elusive. Plastics' recalcitrant nature, macroscopic structure, and low degradation rates hinder biodegradation. Existing studies have limitations, and conclusive evidence for complete biodegradation by microorganisms is lacking. This chapter reviews the challenges in plastic bioremediation, including experimental conditions, plastic type variations, and the underlying mechanisms of microbial degradation (Cherian *et al* 2022). Chemical recycling of plastics has environmental drawbacks, while enzymatic catalysis faces limitations like poor stability and high cost. Biomimetic catalysis offers a promising solution, combining enzyme-like activity with inorganic material stability. This approach has shown potential in plastic degradation by imitating enzyme active centers and substrate-binding clefts. Drawing inspiration from biomass conversion, biomimetic catalysis may provide a sustainable solution for plastic recycling, but challenges and opportunities need to be addressed (Wu *et al* 2014).

Plastics, largely derived from hydrocarbons and petroleum by-products, have increased in production and consumption globally due to their versatility. However, most plastics are non-biodegradable, posing a significant threat to the environment and human health due to poor waste management, inadequate recycling, and improper disposal. This chapter discusses types of plastics, environmental and health hazards, mechanisms of plastic degradation, biodegradation, and its challenges, as well as future prospects for sustainable plastic waste management (Singh *et al* 2021) Bioplastics, made from natural materials, offer environmental advantages as they are biodegradable and/or biobased. Although they have a low market share (1% of total plastic production), bioplastics are used in packaging, agriculture, and other fields. Biodegradable plastics can help with waste management, but their biodegradability must be considered in specific disposal environments and timelines. They are best suited for applications requiring easy disposal, such as food packaging and medical products (Rujnic *et al* 2017). Plastic pollution has become a significant environmental concern due to the slow degradation properties of plastic waste. Commonly used petroleum-based plastics like HDPE, LDPE, PS, PU, PET, PP, and PVC contribute to this issue. To address this problem, research efforts worldwide focus on developing eco-friendly and economically viable solutions. In India, the government has emphasized the need to tackle plastic pollution, and research publications on plastic degradation have increased significantly since 2019. Currently, scientists explore various methods for plastic degradation, including microbial, enzymatic, chemical, and plant-based approaches (Agnihotri *et al* 2023).

7.BIOTECHNOLOGY ADVANCES IN PLACTIC DEGRADATION

Fossil-based plastics have severe environmental impacts, but some microorganisms can degrade and metabolize them. Microbe-based strategies offer a promising approach for degrading, recycling, and valorizing plastic waste. Recent advances in biotechnology-based biodegradation of traditional and bio-based plastics highlight the mechanisms of biodegradation, while progress in recycling and valorization provides feasible solutions for tackling the plastic waste dilemma (Qin *et al* 2021). Nature has its own slow process of recuperation, but exploring environmental microbes and enhancing their plastic degradation capabilities through biotechnology can provide an eco-friendly solution. Recent research emphasizes understanding the biogeochemistry of microorganisms in the environment and standard evaluation methods to harness their potential for plastic biodegradation (Kumari *et al* 2021). Starting with the microbial or enzymatic biodegradation of plastic waste, four distinct strategies are examined. Alternative methods are discussed, including the creation of bio-composites and the grafting of polymer structures. Additionally described is the area of upgrading or using plastic trash (Bassi *et al* 2017). Chemical and mechanical recycling methods are limited by the complexity of composite plastics. However, recent advancements in biodegradation using enzymes and microorganisms offer a promising alternative, enabling biotechnological plastic degradation and bio-upcycling (Lee *et al* 2023). Biodegradation of plastics by microbes is often slow or ineffective without prior degradation by external agents. Enzymatic degradation has emerged as a promising approach, using enzymes from microbial sources to break down synthetic polymers. This review highlights biotechnological approaches to enhance enzyme efficiency, offering a key solution to the global plastic waste problem and contributing to sustainable plastic waste management (Dhaundiyal *et al* 2023).

8.FUTURE PROSPECTS AND RESEARCHS

Plastic products have become ubiquitous, but their decomposition releases toxic additives into the environment, posing a significant risk to living beings. Photocatalytic technology has emerged as a promising solution for degrading environmental organic contaminants, including plastics and plastic-derived compounds. This chapter reviews the photocatalytic degradation process, underlying mechanisms, and future prospects for removing toxic pollutants, with a focus on developing more efficient photocatalysts and innovative application methodologies (Keshu *et al* 2024). Genetic engineering techniques, such as gene manipulation and recombinant DNA technology, can enhance microorganisms' ability to degrade plastics. Researchers have used tools like CRISPER-Cas9 to modify microorganisms, producing enzymes like manganese-dependent peroxidase and laccase that break down plastics. While promising, developing genetically modified microorganisms to degrade all types of plastics remains a challenge, requiring further research on enzyme specificity and affinity for complex plastic structures (Sharma *et al* 2024). As fossil fuel sources dwindle, converting plastic waste into fuel offers a sustainable solution. Plastic waste can be transformed into fuel through various techniques, including thermal and catalytic pyrolysis, microwave-assisted pyrolysis, and fluid catalytic cracking. Co-pyrolysis of plastic waste with biomass is also a promising approach. By utilizing plastic waste as a fuel source, we can reduce waste disposal issues and promote a more sustainable environment, helping to mitigate the depletion of fossil fuels (Wong *et al* 2015). The increasing use of plastics has led to a significant environmental pollution challenge. To address this, microbial bioremediation has emerged as a promising solution, leveraging microbial communities to break down plastics into simpler, safer products. This review explores the current understanding of microbial plastic degradation, including enzyme-based and non-enzyme-based methods, and discusses the types of plastics, their uses, and factors affecting biodegradability (Mishra *et al* 2020).

9. CONCLUSION

Plastic pollution poses serious ecological and human health concerns. Enzymatic degradation offers a promising solution, but more research is needed to optimize conditions and understand enzyme mechanisms. Recent studies have focused on enzymes from bacteria, such as PETase and cutinases, and selecting suitable microorganisms for specific plastics is crucial. This review highlights the potential of microorganisms and their enzymes in breaking down plastics. Microbial degradation of plastics has gained global attention for its potential to combat plastic pollution. Recent advancements in enzymatic PET recycling have made closed-loop recycling feasible. To tackle other plastics like PE, PVC, PUR, and PS, systematic studies combining conventional strategies with computational techniques, bioinformatics, and modern tools like machine learning and molecular dynamics simulations are necessary to discover and enhance plastic-degrading enzymes.

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