Sustainable Microbial Approaches for Plastic Biodegradation: Impact on Human Health, Research Advancements, and Challenges

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Abstract

The relentless accumulation of plastic waste poses a significant environmental and public health challenge, necessitating sustainable and innovative management strategies. Microbial biodegradation offers a promising avenue, harnessing the metabolic potential of microorganisms and their enzymes to degrade synthetic polymers into environmentally benign by-products. This review explores recent advancements in microbial approaches to plastic biodegradation, emphasizing mechanisms employed by native and engineered microbial strains to tackle persistent plastics such as polyethylene, polystyrene, and polyethylene terephthalate. Key developments in genetic engineering, synthetic biology, and bioinformatics have significantly improved microbial degradation efficiency, enabling integration into hybrid waste management systems. However, critical challenges remain, including scaling up processes for industrial applications, optimizing degradation rates, and ensuring the environmental safety of biodegradation by-products. This review provides a comprehensive evaluation of these barriers and examines the transformative potential of microbial biodegradation in aligning plastic waste management with circular economy principles. This approach mitigates environmental pollution, promotes human health, and advances global sustainability objectives by converting waste into value-added products.

Keywords: Microbial biodegradation, plastic waste, synthetic polymers, enzyme engineering, circular economy, sustainable solutions

Introduction

Plastic pollution is one of the world’s environmental challenges that have emerged after the middle of the twentieth century. The plastics are mostly made from synthetic polymers extracted from petrochemical sources, and this product are appreciated for its strength, lightweight, and ability to hold a variety of forms. Nevertheless, these attributes have helped them accumulate in terrestrial and marine ecosystems [1]. Identified that global plastic production has been around 8.3 billion metric tons since 1950, out of which 0.74 billion metric tons have been recycled, 0.2 billion tonnes incinerated, and 6.4 billion metric tons dumped in the natural world, including landfills. Plastics have become a scourge of the environment, and their all-weather nature poses several threats to existing ecosystems. In marine ecosystems, plastics comprise about 80% of the beach litter and marine waste, and 8 million metric tons per year are put in the oceans [2]. The atmosphere is covered with these materials, which, when they reach the size of less than 5mm, break down and get ingested by marine organisms, which in turn might be consumed perish the imagination into human food chains with all the ramifications that entails. Additionally, cleanup costs, degraded fisheries, and tourism that are affected, among other impacts, financially cost billions of dollars yearly. Measures that have been taken in the fight against plastic pollution are recycling, the complete ban on the use of plastics, and the development of biodegradable plastics. However, these approaches have their drawbacks. Recycling rates are still low because of problems with sorting and contamination, while biodegradable plastics often have to be disposed of in industrial composting conditions, which are difficult to find [3]. As a result, researchers have sought other approaches, microbial biodegradation being one of them.

Microbial biodegradation utilizes the natural propensity of microorganisms to decompose synthetic polymers into substances that are simpler in structure. Here, microbial enzymes target the chemical connection in the polymers of plastic materials to oligomers, dimers, and monomers that can quickly be metabolized. The bacterium Ideonella sakaiensis, discovered by Yoshida et al., can degrade polyethylene terephthalate (PET), a standard plastic in bottles, by secreting PETase and MHETase [4]. PETase decomposes PET to MHET, an intermediate that can cleave by MHETase into terephthalic acid and ethylene glycol, both biodegradables. Other microorganisms like Pseudomonas putida can degrade polyurethane (PU), the plastic used to make furniture and insulations [5]. Microbum supports organic waste management because these microorganisms decompose plastic waste into valuable energy and biomass instead of using traditional management practices to deal with trash. In addition, microbial consortia have provided the ability to use a single microbial species to degrade simple and multiple forms of plastics because of the integration of the different species [6]. Bioengineered enzymes have also enhanced microbial degradation, and their development has gone a long way. For example, bioethicists have optimized PETase for higher activity and thermal stability to render it capable of large-scale use [7]. These innovative steps have been taken for microbial plastic degradation, but the solution is not yet in practice at such a significant level.

Recent developments in molecular biology, bioinformatics, and synthetic biology have further enhanced the recognition rate in microbial degradation of plastic. Amplicon sequencing has availed new possibilities for detecting microbial groups thriving on plastic-hindered ecosystems containing species with specific degradation profiles [8]. For instance, some recent meta-genomic studies have identified new plastic-degrading enzymes in marine and terrestrial microorganisms. Proteomics and metabolomics have been used to determine the enzymes involved in the degradation of plastics, emphasizing the regulation of the processes and how they can be optimized [9]. To address the complex nature of plastic waste, enzymatic cocktails have been synthesized to target the main components found in the waste; computational modeling helped to design improved enzyme variants delivering higher substrate selectivity and degradation kinetics [10]. Machine learning algorithms have been further integrated to improve the plastic-degrading enzyme discovery process. Screening has been done previously to show that candidate enzymes are structurally compatible with plastic polymers; thus, computational methods can be used predictively and more efficiently [11]. Similarly, recent developments in synthetic biology have made it possible to design synthetic microorganisms suitable for cloning bacterium to degrade different kinds of plastics means inventing solutions for recycling mixed plastic waste [12].

Still, microbial biodegradation undergoes several challenges, which brought about the following: Many commercial synthetic plastics are hydrophobic polymers, including polyethylene and polypropylene. They also have high crystallinity, which prevents them from being attacked by enzymes. Additionally, degradation rates are generally slow to provide with the ever-increasing production rate of plastic waste [13]. Further challenges arise when scaling microbial systems for the sophistication of industrial use. Regular adjustment of the conditions allows for optimal microbial performance and activity but is generally challenging to control in real-world settings. Another issue related to bioengineering concerns is the creation of bioengineered enzymes and genetically modified organisms (GMOs) that are released into the environment, which may pose ethical and ecological issues for ecosystems [14]. However, the economic aspect of degrading microorganisms is still questionable. The expenses required for enzyme synthesis and production, fermentation procedures, and bioreactor costs are high, negatively affecting protease application for diverse purposes. Solving such issues requires synthesizing joint strategies that are more effective and feasible in terms of costs and scalability.

Herein, we comprehensively review microbial routes in plastic biodegradation and emphasize the pioneering work, existing hurdles, and future directions toward environment-friendly solutions. This paper aims at synthesizing existing information on microbial species and enzymes that are known to be involved in the degradation of synthetic polymers and the pathways through which the biodegradation process occurs. Looking at the aspects of microbial solutions to deal with plastics, the review also discusses how higher levels of genetic engineering, bioinformatics, and synthetic biology have consequently enhanced microbes' efficiency and adaptation. Furthermore, this review also assesses some of the drawbacks of the existing microbial degradation systems based on the polymers' chemical properties, i.e., crystalline structure and hydrophobicity, and other limitations of the systems, including the economic and technological barriers in upscaling the applications. A fundamental objective is to evaluate the existing and potential incorporation of microbial biodegradation into complex waste management systems and its conformity to the principles of a circular economy. This paper fills the holes in the existing knowledge. It identifies possible applications of SWM techniques in the hope that this study will assist future research and industrial pursuits in establishing environmentally conscious and fiscally efficient methods for the disposal of plastics in support of the global trend towards sustainability and preservation of the environment.

2. Overview of Plastics and Their Environmental Impact

Plastics, derived primarily from petrochemical sources, are indispensable in modern society due to their versatility, durability, and cost-effectiveness. These materials are categorized into thermoplastics, which can be repeatedly melted and reshaped, and thermosetting plastics, which harden permanently after melding. Commonly used polymers include polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), and polyvinyl chloride (PVC). These polymers are widely applied in packaging, textiles, construction, and consumer goods. However, the same characteristics that make plastics useful—durability and resistance to degradation—contribute significantly to environmental challenges. Plastics resist natural biodegradation due to their long polymer chains, often taking 200 to 400 years to break down [15]. Improper disposal leads to their accumulation on land and in aquatic ecosystems. Over time, plastics fragment into microplastics, which pose significant risks to marine and terrestrial species and cause cancer-related diseases [16, 17]. These particles are ingested by wildlife, causing harm that cascades through the food chain [6]. Current waste management practices, such as recycling, incineration, and landfilling, are inadequate to address the scale of the problem. Recycling systems cannot often handle global plastic waste, incineration releases harmful pollutants, and landfilling risks environmental contamination [18].

Plastics enter the environment through various primary and secondary sources, contributing significantly to global pollution. One of the primary sources is industrial and commercial activities, where plastics are manufactured for use in packaging, construction, and consumer products. Industrial waste mismanagement, spillage during transportation, and improper disposal of defective items often lead to plastic pollution. Additionally, microplastics are intentionally added to certain industrial products, such as exfoliants and abrasives, which escape into waterways through wastewater systems. Consumer products and packaging represent another significant source of plastic pollution. Single-use plastics like bags, bottles, and food wrappers are pervasive due to their convenience and affordability. However, improper disposal, littering, and the limited capacity of recycling systems result in widespread environmental accumulation. Agricultural activities also contribute to plastic pollution by using materials such as mulch films, irrigation pipes, and plastic packaging for fertilizers and pesticides [19]. Over time, these materials degrade into microplastics that can infiltrate soil and water systems, posing risks to ecosystems and entering the food chain.

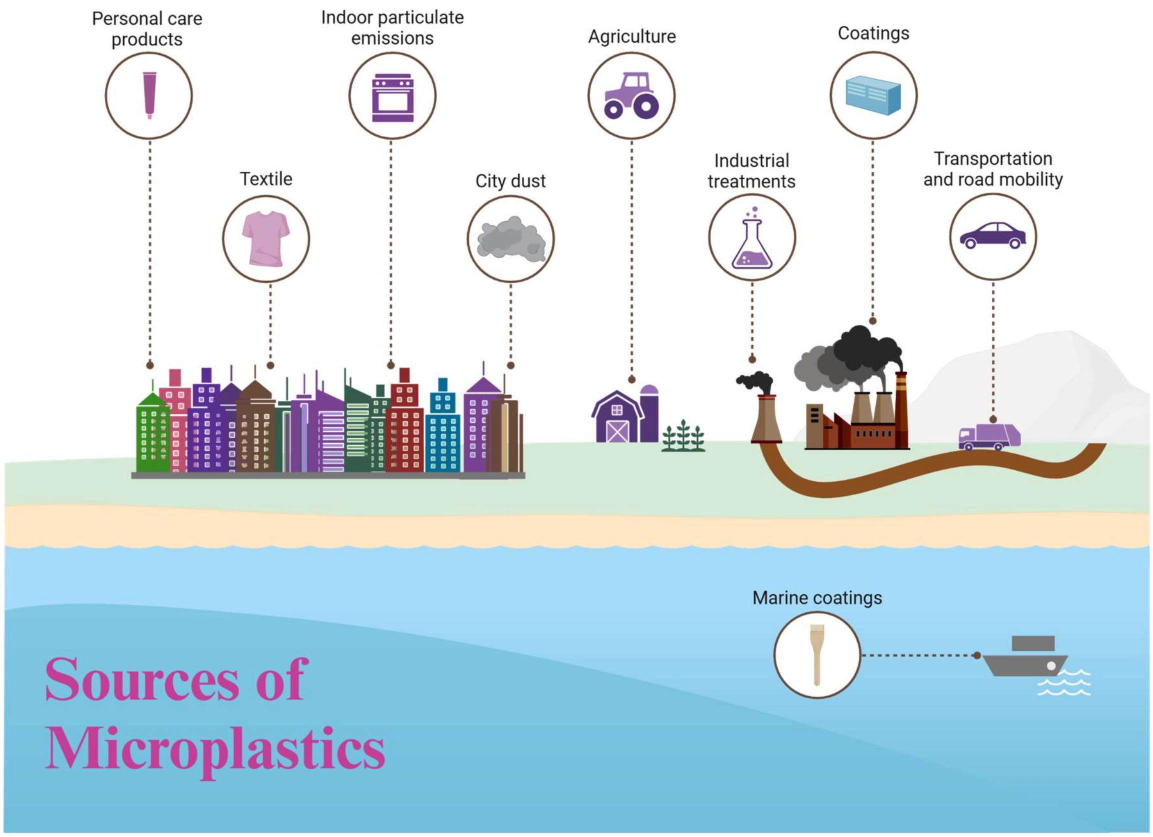

Figure 1: Sources of Plastics in the Environment: Industrial, consumer, agricultural, maritime, and urban contributions to plastic and microplastic pollution.

Fishing and maritime industries are key contributors to marine plastic pollution. Discarded or lost fishing gear, such as nets and lines, becomes "ghost gear" that endangers marine life through entanglement. Additionally, plastic waste from ships, including spills and improperly disposed materials, further exacerbates ocean pollution. Urban runoff during rainfall or storms carries plastic waste from streets and drains into rivers and oceans. Items like plastic bags, bottles, and cigarette butts are everyday in this runoff, alongside microplastics from tire wear and plastic infrastructure. Wastewater treatment plants also play a role in microplastic pollution. Despite their filtration systems, many smaller plastic fragments, including microfibers shed from synthetic textiles during washing, pass through treatment processes and enter aquatic ecosystems. Moreover, larger plastic items in the environment, such as discarded bottles and packaging, undergo fragmentation over time due to sunlight, wind, and mechanical forces, creating secondary microplastics. As illustrated in Figure 1, the sources of plastics in the environment are diverse, encompassing industrial, agricultural, consumer, maritime, and urban activities, and provide details of which plastics and microplastics infiltrate ecosystems, underscoring the pressing need for strategies to mitigate their environmental impact [20].2.1 Types of Plastics

Plastics can be classified into two main categories: thermoplastic and thermosetting plastics, which differ in their properties when exposed to heat. Thermoplastic plastics are processable at high temperatures; they are pliable and can be recycled repeatedly. This property makes thermoplastics like PET, HDPE, LDPE, PP, PS, and PVC prevalent in most application areas, packaging, and containers, as seen in Figure 2. PET is commonly used in bottles for beverages, whereas HDPE is used in milk jugs and toys, among others. These thermoplastics can, in principle, be recycled; however, issues of the efficiency of the recycling process and contamination issues generally impede this process [21]. Meanwhile, in thermoset plastics, the material changes chemically at elevated temperatures, causing the formation of an irreversible network structure of the polymer molecules. This makes it complex and difficult to undergo the process of remelting. Thermosets are very popular: epoxy resins, polyurethanes, and Bakelite. Thermosets are highly durable and heat-resistant plastics with several performance applications in electrical insulation and automotive industries. However, since they cannot be reprocessed or recycled, they pose much concern in the environmental section because they take longer to degrade in landfill sites [22]. The dissimilarities between the families of thermoplastics and thermosets are significant to the environmental performance since thermoplastics can be recycled more readily than thermosets, complicating the waste disposal problem.

2.2 Plastic Persistence in the EnvironmentPlastics are exceptionally long-lasting in the environment because their chemical composition does not break down easily. Most synthetically produced polymers like polyethylene and polypropylene are stably made and may take many years to degrade in the natural environment [1]. Although biodegradation begins through microbial action, many plastics degrade naturally for a very long time because the materials do not feed the microbes. Also, plastics biodegrade differently from organic materials, where instead of biodegrading to simple compounds, plastics dissolve into micro nanoparticles [20]. These are described as plastic fragments less than 5mm and are also a significant threat to the environment because they are bioavailable and can be consumed by marine organisms, affecting an entire chain. With plastics degrading into microplastics, the prevalent issue of plastic waste cannot go away. In the long run, massive plastic items deteriorate into smaller components, resulting in pellets called microplastics in the water bodies and on land. These particles are generally below the micron size range and cannot adequately deal with by customary waste disposal mechanisms such as recycling products and burning. Numerous studies have identified microplastics in marine and freshwater environments, soils, and the atmosphere [23]. Given their size, microplastics may be consumed by organisms as small as zooplankton and as large as marine mammals. This has led to questions about the bioaccumulation of lousy stuff like – pesticides, heavy metals, and POPs in organisms from the base through the food chain to humans [24].

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Figure 2: Detail exploration of some of the most common types of plastics

2.3 Global Efforts to Combat Plastic PollutionDifferent measures have been undertaken globally due to the increasing environmental challenge posed by plastics in the environment. Such initiatives include enhancing a recycling system and disposal methods and lobbying to restrict plastic manufacture and usage. However, recycling recycles items and is theoretically an ideal solution, posing some challenges as seen in Figure 3. Even where PET and HDPE can be recycled or repurposed, the contents of plastic waste streams and the recycling system's deficiencies can result in lower recycling percentages [3]. In addition, many plastics are non-recyclable, comprising thermoset plastics and contaminants whereby the plastic waste ends up in landfills or is incinerated. One added technique for tackling plastic waste is incineration, in which plastics are burned at high temperatures to minimize their size. While this process produces energy, it emits nasty substances such as dioxins and furans, which are lethal to humans and animals [20]. Third, incineration also emits greenhouse gases, leading to a worse world, best known as climate change. The most popular way of dealing with plastic waste globally is through landfilling; the process comes with problems. They can last hundreds to thousands of years in landfills, releasing toxic soluble materials into the environment, water, and soil [25]. To overcome these problems, governments, organizations, and industries have implemented measures to eliminate plastics and encourage the use of environmentally friendly materials. For instance, over the past few years, many nations have implemented outright bans on some plastics to reduce plastic demand; these include plastic straws, bags, and cutlery.

The EPR programs have been adopted across the European Union in some countries to ensure manufacturers are responsible for disposing and recycling the plastics they manufacture. Also, actions by global organizations like the United Nations Environment Programme (UNEP) have created awareness of the call for collective action at policy, business, and consumer levels, hence initiatives like Clean Seas (UNEP, 2018). However, other technological approaches to fight plastic pollution are being examined apart from these regulatory measures. There is hope in the current research that biodegradable plastics will be created, and these plastics will degrade more efficiently and safely. Biodegradable plastics are relatively new in the market, and if adopted, they could be a better option than conventional plastics that harm the environment in the future. Other advancements refer to enhancing plastic recycling technologies' effectiveness and methods of efficient waste-to-energy conversion [26].

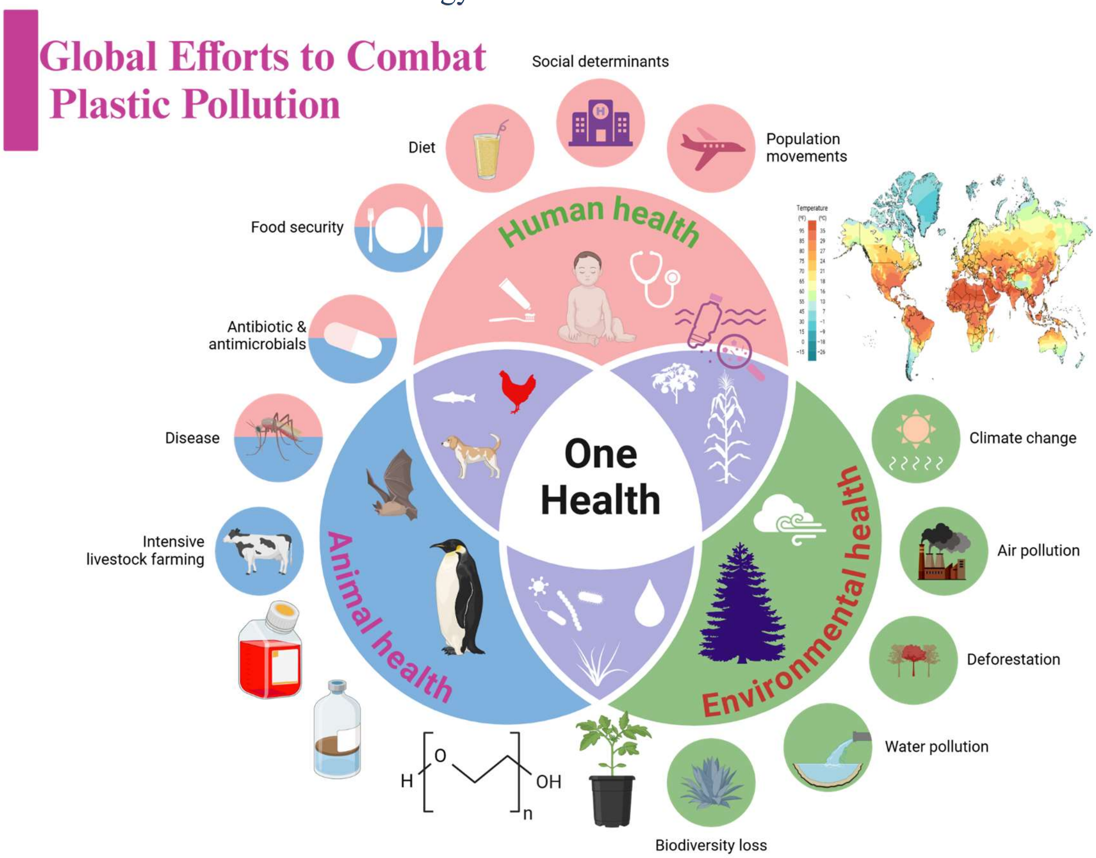

Figure 3: Global Efforts to Combat Plastic Pollution: Strategies and challenges in recycling, incineration, landfilling, regulatory measures, and advancements in biodegradable plastics and recycling technologie

3. Microbial Mechanisms of Plastic Degradation

Microbial degradation of plastics also changes microorganisms such as bacteria, fungi, algae, and other microorganisms that have enzymes to break down the polymers from the plastics into simpler compounds that are biodegradable. These microorganisms use enzymatic mechanisms to break down plastics, including PETase for PET, cutinase for polyethylene, and laccase for lignin-related plastics. The effects of these enzymes are to break the ester linkages within polymer chains so that microorganisms can utilize the degraded products as carbon and energy. However, biofilms, microbial structures attached to a surface, contribute significantly to the ability to maintain microbial activity required for the continued breakdown of the plastic substrate. Still, there are gaps regarding the general scale and efficiency of such biotransformation, as many such microbes only exist to degrade specific kinds of plastics. What has been discussed above shows the necessity of further study to identify new microbial strains, enhance the effectiveness of enzymes, and design microbial communities that can affect more polymers[27, 28].

3.1 Microbial Diversity Involved in Plastic Biodegradation

Many isolates achieve the biodegradation of plastics, including bacterial, fungal, and algal isolates. These organisms have been lucky to have an opportunity to evolve special enzymes capable of breaking down plastic polymers. While several microorganisms have been known to play the role of degrading plastics, the bacteria, in particular, have been studied intensively. At least five are recognized as capable of degrading plastics, including PE, PS, and PET. Ideonella sakaiensis is probably one of the most well-known bacteria that has been identified to break down PET using the enzymes PETase and MHETase , as well as Pseudomonas species that are capable of degrading polymers of hydrocarbon plastics such as styrene. Fungi also influence the degradation of plastics, especially in conditions that involve moisture, such as soil or spoilt organic matter. Aspergillus, Penicillium, Trametes, and other species have been proven to cause biodeterioration caused by polyurethane and polyvinyl chloride (PVC). According to Bae and Singleton, 2007, these fungi attacked and disintegrated the plastics through the secretion of laccases and peroxidases that disintegrated the polymer. Some fungi, bacteria, and, to a smaller extent, algae are being attributed to their capability to break down plastics. However, the role of these last organisms in this process is still not fully understood. Ju and his team noted in their 2019 publication that algae species with enzymes degrade the plastics within the water bodies when exposed to plastic wastes. Specific biodegradation mechanisms of the plastics by the identified microorganisms were demonstrated. For example, Ideonella sakaiensis is PET degrading, and it has two enzymes of PETase, which cleaves PET into a small molecule of methyl ester, which is then catabolized by MHETase [4]. Similarly, fungi utilize oxidative enzymes to break down the polymers of the plastic by cutting the single bonds to produce smaller molecules that can be metabolized at other places. The diversity of microbial communities and the ability of diverse microorganisms to utilize several biodegradation mechanisms have established them as the leading agents in eradicating plastics.

3.1.1 Plastic degradation by fungi

Researchers are doing many studies to demonstrate the role of microorganisms in breaking down plastic waste in terrestrial and marine realms. Marine fungi are under study, but the ability of terrestrial fungi gives directions that marine fungi could also degrade the complex organic matter in the marine ecosystem [29]. The fungi can penetrate the polymers using enzymes that can detoxify pollutants. Surface-active proteins are produced by fungi, i.e., hydrophobins, to coat hyphae to hydrophobic substrates. Certain environmental factors, such as moisture, pH, temperature, etc., affect the degrading activity of fungi [30]. The different fungal strains devour plastic polymers as their only source of carbon and, in return, convert them into eco-friendly carbon compounds [31]. Numerous fungal strains isolated from different sites that can degrade plastic polymers are potentially listed in **Table 1**.

Table 1. Biodegradation ability of fungal species against different plastic types.

Sr. No.	Fungal species	Plastic type	condition	Degradation %	Reference
1	*Aspergillus niger*	LDPE	30 days	22.9 %	[32]
2	*Aspergillus flavus*	LDPE	30 days	16.1 %	[32, 33]
3	*Brown rot*	LDPE	30 days	18.4 %	[32]
4	*white rot*	LDPE	30 days	22.7 %	[32]
5	*Penecillium*	LDPE		0 %	[32]
6	*Penicillium simplicissimum*	LDPE	150 days	58.0%	[34]
7	*Aspergillus nomius*	LDPE	40 days	6.63%	[35]
8	*Aspergillus oryzae (MG779508)*	LDPE	30 ºC	36.4 %	[20, 36]
9	*Trichoderma viride*	LDPE	40 days	5.13 %	[35]
10	*Cladosporium sp.*	LDPE, PUR	--	--	[37, 38]
11	*Fusarium solani*	PUR	Shaking liquid culture technique	100%	[37, 39]
12	*Curvularia senegalensis*	PUR	--	--	[37, 40]
13	*Aureobasidium pullulans*	PUR	--	--	[37]
14	*Aspergillus tamarii*	PET	Temp. 80ºC pH 8.5,	--	[41]
15	*Penicillium crustosum*	PET	Temp. 80ºC pH 8.5,	--	[41]
16	*Zalerion maritimum*	PE	Temp. 25 ºC, pH 8.08 - 8.33	>95 %	[42]
17	*Aspergillus versicolor strain JASS1*	PE	90 days	40.6%	[43]
18	*A. fumigatus S45*	PU	28 days	20%	[44, 45]
19	*Fusarium* species	PU	--	24.5 %	[46]
20	*Aspergillus terreus strain MANGF1*	polythene	pH 9.5	>50 %	[47]
21	*Aspergillus sydowii strain PNPF15*	polythene	pH 3.5	94.44 %	[47]
22	*Pseudozyma japonica*-Y7-09	PCL	15 days,	93.33%	[48]
23	*Pseudozyma japonica*-Y7-09	foam plastic	30 days,	43..2%	[48]
24	*Amycolatopsis mediteranei*	PBS	--	--	[49]

3.1.2 Plastic degradation by bacteria

The bacteria are potent players in plastic degradation [50]. Plastic degradation is possible due to bacteria's inherent ability to break down long-chain fatty acids. In research studies, most bacteria that can biodegrade plastics were isolated from contaminated sites, such as landfills [6]. Moreover, microbes are also present in the gut of different insect larvae, making them plastic-degrading species [51]. Marine bacteria have a tremendous metabolic capacity to degrade hydrocarbons in harsh conditions. Marine environments are an important source of new bacterial plastic-degrading enzymes [52]. Microorganisms' biodegradation ability of bacterial strains as mentioned in Table 2, possess several enzymes including cutinases, esterases, lipases, laccases, peroxidases, proteases, Hydroquinone peroxidase, β-Galactosidase, acid phosphatase, β-glucuronidase, naphthol-AS-BI-phosphohydrolase, leucine arylamidase, alkaline phosphatase, and ureases, etc. that are capable of degrading various types of plastic polymers[6, 53].

Table 2. Biodegradation ability of bacterial strains

Sr. no.	**Bacterial species**	**Plastic-type**	**condition**	**Weight loss percentage %**	**References**
1	*Serratia sp.*	LDPE	Incubated for 150 days	40 %	[3]
2	*Stenotrophomonas sp*	LDPE	Incubated for 150 days	32 %	[3]
3	*Pseudomonas sp.*	LDPE	Incubated for 150 days	21 %	[3]
4	*Clostridium thermocellum*	PET	14 days, 60 º C	60 %	[54]
5	*Vibrio*	PET	Incubated for 60 days	36 %	[4]
6	*Bacillus cereus*	PET	Incubated for 40 days	1.6 %	[4]
7	*Bacillus gottheilii*	PET	Incubated for 30 days	3.0 %	[4]
8	*Pseudomonas sps*	PET	--	5 %	[4]
9	*Ideonella sakaiensis*	PET	21 days, 55 ºC	97 %	[4]
10	*Thermobifida fusca*	PET	Incubated for 21 days, 55 º C	50-55 %	[4, 55]
11	*Mircrobispora rosea*	PBS	8 days	50 %	[37, 56]
12	*Pseudomonas chlororaphis*	PBS	--	--	[37, 57]
13	*Excellospora japonica*	PBS	--	--	[37, 58]
14	*viridilutea*	PBS	--	--	[37, 58]
15	*Caenibacterium thermophilum*	PBS, PHB	--	--	[37, 59]

16	*Alcanivorax borkumensis*	PE	80 days	3.5 %	[60]
17	*A. guillouiae*	PE	28 days incubation	3.35%	[61]
18	*Bacillus* sp. BCBT21	PE	30 days, 55 ºC	44%	[62]
19	*Brevibacillus borstelensis*	PE	Incubation 30 days,	30 %	[37, 63]
20	*Rhodococuus sp.*	PE	--	--	[37, 40, 57, 64]
21	*Gordonia* sp.	PS	30 days	7.73 %	[65]
22	*Novosphingobium* sp.	PS	30 days	2.66%	[65]
23	*Massilia sp. FS1903*	PS	30 days, 30ºC	12.97%	[51]
24	*Micromonospora sp. GMKU 358.*	PLA	14 days	6.16 ng/mm2 /min)	[66]
25	*Streptomyces thermoviolaceus*subsp.	PCL	6 hr, 45 ºC	100%	[55, 67]
26	*Schlegelella thermodepolymerans*	PHA	50ºC	--	[37, 68]
27	Staphylococcus sp.	polythene	40 days	20 %	[69]
28	*Comamonas acidovorans*	PUR	--	--	[37]
29	*Geobacillus thermocatenulatus*	Nylon 6, Nylon 12	20 days, 60 ºC	--	[55]

3.1.3 Plastic degradation by photosynthetic microorganisms

Photosynthetic microbes are elementary parts of phytoplankton at the base of the trophic chain in freshwaters. They may have a role in plastic degradation. Green algae, cyanobacteria, and diatoms are reported on PE bags found in urban water bodies [70]. The blue-green alga holds quantitatively the highest percentage of degradation of LD polyethylene sheets [71]. Microalgae biomass has another advantage in biotechnology: it can be used as a potential filler and booster towards the enhancement of bioplastic, either blending with conventional bioplastic or synthetic polymer [72]. A list of photosynthetic microbes that have the potential to degrade plastic debris, especially in marine environments, is given in **Table 3**.

Table 3: Plastic Degradation Potential of Photosynthetic Microorganisms in Marine Environments: A Comparative Analysis of Algae, Cyanobacteria, and Diatoms

Sr no.	Photosynthetic microbes	Plastic-type	conditions	Degradation %	reference
1	Spirulina sp.	PP	112 days	TS 0.1977 MPa/day.	[73]
2	Spirulina sp.	PET	112 days	TS 0.9939 MPa/day	[73]
3	Chlorella vulgaris	PET	30 days	5.57 %	[74]

4	Chlamydomonas reinhardtii	PET	--	--	[75]
5	Scenedesmus dimorphus (green alga)	LDPE	--	3.74 %	[71]
6	Anabaena spiroides (Cyanobacterium)	LDPE	--	8.18 %	[76]
7	Navicula sp. (diatoms)	PS	--	16 %	[77]

3.2 Enzymatic Degradation of Plastics

Microorganisms degrade plastic by many processes; however, enzymatic degradation is perhaps the most efficient process. As depicted in **Figure 4** found that several enzymes are involved in the biodegradation of certain specific types of plastics. Of these enzymes, PETase, cutinase, and laccase are the most explored from the standpoint of plastic degradation. Ideonella sakaiensis, the bacterium that debuted in May 2016, can degrade PET, one of the most widely used polymers in packaging. PETase breaks the ester linkages within PET to change it into a water-soluble hydrolysis product that other enzymes can efficiently utilize. A similar enzyme, MHETase, acts in harmony with the PETase to break up the PET degradation products into simpler constituent molecules, such as TPA and EG, which the microorganism can incorporate [78]. Some enzymes reported to depolymerize these polymers effectively include esterases and cutinase, which depolymerizes PBS polyester and PET. The specific enzyme of cutinase helps break down the ester bonds within the polymer structure to help the microorganism within the process. This enzyme is present in many bacteria and fungi, such as Candida antarctica, *Thermobifida fusca*, and *Aspergillus species* [15]. Cutinase enzymes are prime suited for the biodegradation of hydrophobic polymers because they enable microbial degradation of plastics in polymeric materials that are usually immune to biodegradation. Another important enzyme involved in the breakdown of plastics is laccase, which has a special role in degrading plastics with aromatic moieties like polystyrene. Laccase is an oxidase enzyme that degrades the plastic polymers by losing electrons and oxidizing the molecular oxygen, thus breaking the polymer chain. This enzyme is most efficiently produced from fungi, namely Trametes versicolor and Pleurotus ostreatus [79]. Laccases are helpful for the degradation of synthetic polymers containing aromatic rings, and efforts are being made to examine their capacity to degrade polystyrene and polyether polyurethane. Because these enzymes depolymerize large plastic polymers into metabolizable molecules, they are also helpful in bioremediation efforts. The discoveries and further optimization of these enzymes are of particular interest, which may be significant for innovating environmentally friendly approaches to combating plastic pollution.

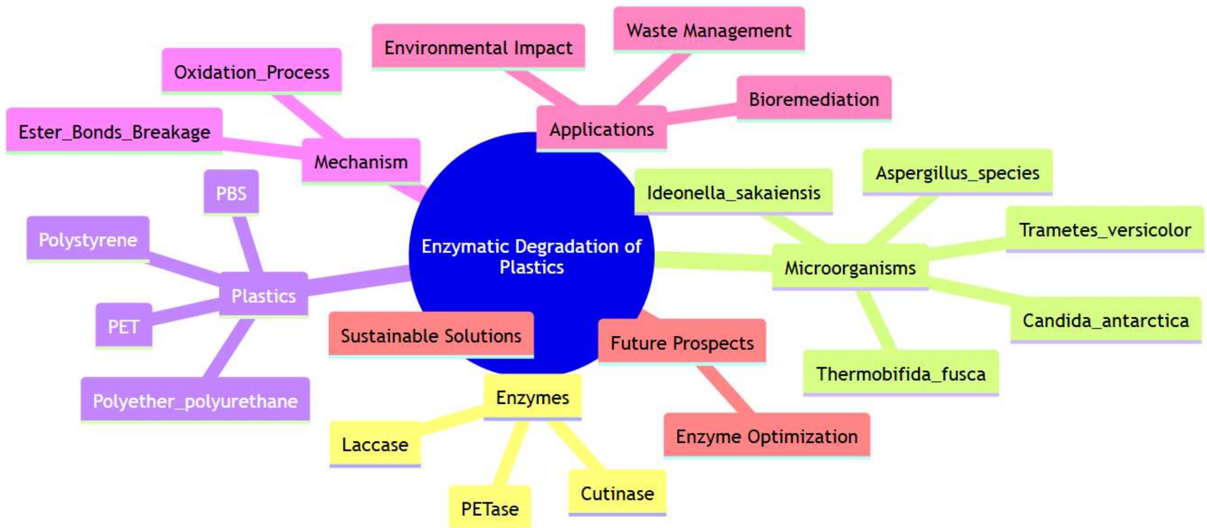

Figure 4: Enzymatic Degradation of Plastics: Enzymes, Microorganisms, Mechanisms, Applications, and Future Prospects"

3.3 Biofilm Formation in Plastic Biodegradation

Microbial adhesion is a significant factor in microbial plastic biodegradation since biofilm formation on plastic surfaces reduces the efficiency of interaction between microbes and plastics. Biofilms are microorganisms embedded in a complex matrix and part of a surface like plastics. The structure of the biofilm benefits the plastic-degrading microorganisms in the following ways: the organisms receive better protection against various stress factors, they have better access to nutrients, and last but not least, it protects the organisms against antimicrobial agents. Biofilms also enhance the ability of microorganisms to break down plastics because the construction of complex organometallic films results in a focused release of enzymes. Table 2 Some bacterial species isolated from plastics and their contribution to the degradation of plastics in natural environments biofilm-forming bacteria like Pseudomonas and Bacillus biofilm-forming bacteria like Pseudomonas and Bacillus species. These bacteria form extracellular polymeric substances or EPS that enable them to stick to plastic surfaces to form a micro niche where plastic degradation occurs [80]. In this biofilm structure, please, cutinase, and laccase are produced that degrade the plastic polymers and convert them into smaller molecules. The microorganisms later consume these fragments as carbon that supports the growth of the organisms. It is important to understand the structure of biofilms under treatment for degradation, as it forms an important parameter. For this reason, the density of biofilm, microbial population, and the concentration of EPS always play a role in the rate and effectiveness of biodegradation of plastics. Multi-species biofilms can have a more significant number of enzymes and chemical pathways in the filming community, which can degrade different polymers in plastic [81]. Furthermore, there is always the ability of cross-talks between bacteria and fungi that form the biofilms to act synergistically to accelerate plastic degradation since fungi may produce different enzymes that break plastics, unlike bacteria (Singh et al., 2008). The present study considers biofilm formation as a pivotal process in the degradation of plastics. The increased thickness and density of the bacterial layers and the localized synthesis of depolymerase enzymes within biofilms contribute to microbial plastic degradation and biofilms' importance in the biodegradation process. Thus, one might consider that the biofilm-based bioremediation strategies for treating natural environments contaminated with plastics could open new vistas.

4. Pioneering Advances in Plastic Biodegradation

The essential mechanisms of biodegradation of plastics have been developed by discovering effective microorganisms and enzymes for the degradation of persistent plastics in the environment. The discovery of microorganisms capable of degrading plastics has been enhanced through traditional and enhanced screening approaches that follow isolating bacterial/fungal strains from polluted environments, including landfills, marine and freshwater bodies, and municipal solid wastes. *Ideonella sakaiensis*, found in 2016, is the first and only bacterium known to degrade PET, a plastic-type frequently used for bottles and textiles. This microorganism can metabolize PET and uses PETase to degrade the polymer chains of PET to obtain its monomers, which it feeds on as carbon [82]. It is established that other inducible enzymes like cutinase, laccase, and hydrolases have now been discovered, extending the possibility of biodegradation of different types of plastics, including polyethylene (PE), polystyrene (PS), and polyvinyl chloride (PVC). Besides microbial strains, there are appreciable advancements in the genetic and metabolic programs of biodegradation of plastics. In the last few years, genomic analysis has revealed genes that code for the enzymes breaking down plastics and shed light on the biochemical mechanisms of the process. Another area targeted in synthetic biology and genetic engineering is the improvement of the efficiency of microorganisms to degrade plastic by modifying Escherichia coli or Pseudomonas putida to express plastic-degrading enzymes [83]. Another area of advances in biodegradation includes the identification of new strains and enzymes and, better still, the optimization of the used enzyme in bioreactor systems. New strategies include the bioengineering of microbial communities that have enhanced the potential to degrade various plastics at once and work collectively to biodegrade the plastics. In addition, advancements in the field of bioremediation touch issues regarding the possibility of combining microbial degradation of plastics with other treatment processes like composting or wastewater treatment – which may open new horizons for massive environmental restoration and the problem of waste disposal of plastics [84]

4.1 Identification of Plastic-Degrading Microorganisms

Research in plastic biodegradation has focused on the ability to determine microorganisms capable of degrading plastic polymers. Different methods have been adopted to isolate plastic-degrading bacteria from soil, water, and sites containing plastic waste. These approaches primarily work by culturing microorganisms along with plastic matrices and measuring their capability to degrade or physiochemically transform plastics. Therefore, microbial enrichment, DNA sequencing, and PCR have been applied to determine the plastics-degrading microbes, including bacteria, fungi, and algae [85]. *Ideonella sakaiensis* is one of the most promising findings in microbial degradation of plastics whose member has been found to degrade polyethylene terephthalate, also known as PET, which is widely used to make bottles for beer, soft drinks, water, and foods and packages, among others. *I. Sakaiensis* was discovered in 2016 by Yoshida and company, who realized that this bacterium could disintegrate PET through the activity of two enzymes: PETase and MHETase. Before being broken down by MHETase, PETase can synthesize the breakdown of PET into a smaller monomer. The finding was a revolution in plastic degradation because it had a natural solution to plastic that was once considered highly non-biodegradable. Besides *I. sakaiensis*, other microorganisms, for example, Pseudomonas species, have been discovered as having the potential to degrade most plastics like polyethylene (PE) and polystyrene

(PS) [86]. Because of identifying such microorganisms, more knowledge about the macromolecular plastic biodegradation processes and the possibility of scale increase has been revealed. However, there are still problems in enhancing the degradation process and diversifying plastic substrates digestible by these microorganisms.

4.2 Genetic and Metabolic Pathways of Plastic Degradation

Identifying and elucidating the genetic and metabolic networks underpinning plastic biodegradation is important for developing strategies. There is information in several studies that reveal the genes that encode those plastic-degrading enzymes. For example, the genome of *I. sakaiensis* has been sequenced to identify genes encoding PETase and MHETase in this organism. Identifying these genes has created new avenues for considering the mechanisms of plastic biodegradation on the molecular level and manipulating these pathways for practical applications. Plastic degradation is usually associated with metabolic pathways in which the plastic polymers are broken down into monomers that are further degraded in the environment. When degrading PET, *I. sakaiensis* utilizes PETase to oxidatively depolymerize PET into terephthalic acid and ethylene glycol, which is then energetically metabolized by the microorganism [82]. Similarly, other microbes, including Bacillus and Pseudomonas, also use pathways similar to those used to decompose hydrocarbons common in plastics like polystyrene and polyethylene [86]. They have provided the complicated details of the biochemical mechanisms by which microorganisms can use plastics as carbon resources. This has been the key to understanding how microbial bioresources can be exploited for biodegradation plastics.

With the help of recent breakthroughs in graduate genetic engineering and in the domain of synthetic biology, scientists can stimulate a higher potential for the biodegradability of microorganisms. To enhance the rate of plastic decomposition and the variety of polymers that these microbes can decompose, researchers study how to alter the genes related to plastic degradation. Introducing plastic-degrading genes into model organisms has proved useful and is an example of synthetic biology in improving biodegradation mechanisms. Further, new technologies, including the CRISPR-Cas9 system, enhance enzyme production and augment the depth of plastic degradation by microorganism [87]. These advancements in genetic and metabolic engineering are creating a unique foundation for introducing new approaches toward the bioremediation of plastic waste.

4.3 Innovations in Biodegradation Research

In the past years, new extraordinary enzymes and microorganisms that are relatively efficient in breaking down plastics were identified in biodegradation studies. New enzymes, including laccases, cutinases, and polyesterases, have been a focus of isolation owing to their ability to degrade most types of plastics. Scientists use metagenomic methods to receive new plastic-degrading enzymes from composting samples, soil, and marine sources. It is reported that these enzymes might help compost plastic waste, primarily those not susceptible to natural biodegradation, including polyethylene, polystyrene, and polypropylene [28] FIG. 1. Besides, the advancements have not limited itself to the discovering of enzymes but also involve improving the process of biodegradation for industrial uses. There is a new promising idea concerning microbial consortia, the united group of microorganisms collaborating to decompose the polymers of plastics. Microbial consortia are more beneficial than individual strains because microorganisms from the same group can decompose different plastic polymers and degrade complex plastic blends simultaneously. It has been shown that mixed microbial cultures work more effectively on the biodegradation of plastics than individual bacteria and that some consortia take less than half of the time required by individual strains to degrade plastics [86]. Recent works of different authors have also looked at utilizing bioreactors and bioremediation technologies to enhance the biodegradation process of plastic waste in a controlled environment, as presented in **Table 4**. For instance, there are culture vessels, known as bioreactors, in which environmental microorganisms that degrade plastics have been cultured to enhance the constant breakdown of plastic products. This approach is being addressed in plastic recycling plants where plastic wastes can be digested to produce bioplastics and biofuels [88]. Developing and optimizing new enzymes, novel microbial consortia, and advanced bioreactor systems will open new avenues for the future bioremediation of plastic wastes on an industrial scale.

Table 4 lists patents on the microorganisms, methods, and enzymes beneficial to degrade plastic [89].

Sr no.	**Patent Number**	**Year**	**description**
1	US7960154B1	2011	Polyester-degrading bacteria, polyester-based-plastic degrading enzymes, and polynucleotides encoding the enzymes
2	EP1849859B1	2014	Novel polyester plastic degrading microorganisms, polyester plastic-degrading enzymes, and polynucleotide encoding the enzyme.
3	JP4625900B2	2011	Thermophilic polyester degrading bacteria
4	CN103980535B	2017	The method of bacillus extracellular laccase degrading polyethylene
5	WO2019053392A1	2019	Enzymatic process for depolymerization of post-consumer poly (ethylene terephthalate) by a glycolysis reaction
6	WO2019168811A1	2019	Enzymes for polymer degradation
7	FR3088070A1	2020	Process for the enzymatic degradation of polyethylene terephthalate
8	WO2018143750A1	2018	Microorganisms isolated from Tenebrio molitor larvae have plastic-degrading activity, and the method for degrading plastic is the same.
9	US20150247018A1	2015	Biodegradation of petroleum-based plastic by microbial flora
10	JP2004166542A	2004	New plastic decomposing bacterium
11	JP2004261102A	2004	Microorganisms for degrading ester bonds containing plastic, plastic degrading enzyme, and polynucleotide encoding the enzyme
12	JP2004166540A	2008	New plastic splitting enzyme and gene encoding the enzyme

5. Persistent Challenges in Microbial Plastic Biodegradation

Despite the current advancements in microbial degradation of plastics, some main barriers slow down the application of such processes for correctly handling plastic waste. Among these challenges are the low rate of biodegradation, toxicity of the plastics, narrow microbial degradation ability, and difficulty duplicating laboratory conditions in real life. Polymer degradation by microorganisms remains one of the biggest hurdles in microbial plastic biodegradation because it is slow. April 2007 Did You Know Organic polymers composed of plastic are usually very resistant to microbial adhesion simply because their structure is explicitly made to be as physically and chemically rugged as possible to last as long as possible. On this basis, many common plastics include polyethylene (PE), polypropylene (PP), and polystyrene (PS), whose carbon chains are long to be broken down and utilized by microorganisms. Consequently, microbial plastic degradation is a relatively slow process, and it can take years or even tens of years to degrade naturally [90]. Several factors can determine the rate of microbial biodegradation of plastics. Of these characteristics, we can cite the positive influence of the particular properties of the used plastic material. For instance, wherein a polymer has more excellent crystallinity and further chemical composition, the material is likely to be more resistant to attack by microbes. Consequently, low crystallinity plastics, characterized as amorphous plastics, are more susceptible to biodegradation by microorganisms [91]. Also, the disposal environment's temperature, humidity, and oxygen concentration affect the microbial biodegradation rate. Humidity and heat have a positive relationship regarding microbial action, where heat accelerates microbial activities, and a decrease in temperature slows them down. In addition, the type of plastic used contributes as well; polyethylene and polypropylene, used in packaging, are less likely to become microbial biodegradable than PET [92].

Another big problem in microbial degradation of plastics is that plastic contains many additives and monomers that are toxic to microbes. Plastics are generally composed of numerous chemical additives, including plasticizers, flame retardants, stabilizers, and colorants. These are all important for making plastics and operating their properties, but they can be lethal to microbes. These additives can also reduce the rate at which plastic-degrading microbes' function and their capability to break down plastics [93]. Moreover, in the case of PET, the monomers generated at the initial stage of the biodegradation process of plastics, such as terephthalic acid, are toxic to the microorganisms. These toxic by-products can affect the functions of microbial cells differently, reduce the degree of microbial richness, and reduce the overall efficiency of biodegradation processes. In the face of these toxicity challenges, researchers are seeking various measures. One approach focuses on primary microorganisms with a natural immunity to pollutants typically found in plastics and can be isolated to be grown in captivity. For instance, certain species of bacteria in the group Pseudomonas have been demonstrated to withstand the toxic components typically included in plastic materials and biodegrade the plastic material [55]. The other approach whereby the difficulties of this field could be overcome involves developing genetically modified microorganisms with better capability of enduring toxins related to plastics. Further development of synthetic biology and genetic engineering techniques, including CRISPR-Cas9, can create more sustainable strains of microorganisms in environments containing toxic additives in plastic products [87]. In addition, biodegradation processes can be enhanced through chemical modifications during plastic manufacture to remove or mask toxic elements to microorganisms.

Although the ability of microorganisms to convert plastics into carbon dioxide has been documented, the list of microorganisms that can assimilate plastics has remained narrow and short.

Most microorganisms have been identified to degrade a single plastic or, at most, a few plastic polymers. For example, Ideonella sakaiensis has been discovered to degrade PET rapidly but does not possess the same capacities as the other most frequently used plastics, such as PE or PP [94]. Likewise, many present-day plastic-degrading microorganisms can only degrade certain plastics, making their efficiency low in addressing all sorts of plastic waste across the globe. Again, the restrictive range of microbial degradation is partly because different plastics have diverse chemical compositions and are ideal for different microbial enzymes. Sometimes, the microorganisms do not have the enzymes required to degrade specific plastic polymers. Lastly, the breaking down mechanism of plastics can be selective; certain bacteria can only respond to a single type of polymer at a time. This effort is further compounded by an increased developmental plastic-type complex that is more fabricated and designed to be much harder to biodegrade [95]. To overcome this limitation, researchers are also working on microbial consortia, which are sets of different microorganisms that can degrade a diversified range of plastics. As previously mentioned, microbial consortia use the advantage that each microbial strain can degrade a particular type of plastic. Furthermore, genetic engineering of microorganisms to secrete enzymes that can degrade various plastics may offer a way to expand the list of plastics known to be biodegradable [96].

Another significant problem in the extensive use of microbial biodegradation of plastics is the problem of scaling up the research findings from laboratory studies into actual life use. This is particularly so given that in laboratory environments, all the environmental variables are predictable and adjustable; hence will always grow the microorganisms that degrade plastics under the best biomechanical conditions. However, real-life presented to microorganisms have occasional changes in temperature, humidity, and available oxygen levels. These factors can significantly influence microbial action and slow down the biodegradation process of the plastics. Ensuring microbial plastic biodegradation is effective at extensive scale application is an entirely different prospect, especially for large-scale environments like landfills or oceans. For instance, plastics are trapped beneath the waste layers in landfilling, and there is little interaction between the microbial matrix and the plastic substrate. Likewise, the marine environment harbors a characteristic feature that gas, such as large spread plastic waste, and unfavourable conditions, including high saline concentration and low temperature, can hinder microbial biodegradation [18]. In addition, the vast amounts of plastic waste generated in such ecosystems may even likely out-compete the indigenous microorganisms in decomposing plastics. To overcome these challenges, the research emphasizes how biodegradation could be enhanced to suit the prevailing environmental conditions. For instance, bioreactors that provide the appropriate conditions to calibrate microbial consortia regarding the degradation of plastics are being designed [97]. Further, field-level research has been conducted to evaluate the success of the microbial biodegradation of the developed technology in the ocean and other landfills. It seeks to explore the way forward in boosting and enhancing the scalability and efficacy of the microbial biodegradation process.

5. Persistent Challenges in Microbial Plastic Biodegradation

Some limitations of microbial-mediated plastic biodegradation are the slow rate of biodegradation because of the unyielding chemical bonds of plastics and the absence of proper microbial enzymes. Polyethylene, polystyrene, and many other types of plastics do not tend to degrade naturally in the environment, and hazardous chemicals that may be present in some plastics hinder biodegradation. Moreover, most microorganisms can solve the biodegradation of different plastics, which does not contribute to standard biodegradation practices. Although laboratory-scale biodegradation processes can be tried in real environments, including landfills and oceans, it is pretty challenging due to environmental interactions. Alleviating these problems demands improved microbial strain improvement, enhanced operant environments, and innovative biotechnology tools and solutions.

5.1 Slow Biodegradation Rates

Another problem associated with microbial plastic biodegradation is that the process by which microorganisms degrade plastics takes a very long time. Many plastic polymers are chemically superb because they are stable and usually do not decompose under microbial action because they are made to last. Many plastics, including polyethylene (PE), polypropylene (PP), and polystyrene (PS) polymers, are characterized by a long aliphatic carbon backbone that is not easily biodegraded by microorganisms. Consequently, microbial plastic degradation can be considered relatively slow, so it may take several years or decades for a given type of plastic to disintegrate naturally [90]. The following are some factors that regulate the microbial biodegradation rate of plastics. One fundamental aspect is the properties of the plastic material and its chemical composition. For example, plastics with better crystalline structures and bulky molecular chains possess better resistance against microbial degradation. On the other hand, less crystalline polymers, those with low crystallinity, are more susceptible to biodegradation by microorganisms [55]. Also, the atmospheric conditions of the environment within which these degradative microorganisms are placed, including temperature, humidity, and oxygen availability, can greatly influence the rate of microbial biodegradation. Higher temperature and higher moisture favour microbial processes, while lower temperature or low moisture tends to reduce microbial processes. The type of plastic also affects microbial degradation with polyethylene and polypropylene, the material used in packaging products, being more resistant than polyethylene terephthalate (PET) [98].

5.2 Plastic Toxicity and Microbial Inhibition

Another major problem concerning microbial plastic biodegradation relates to the effect of plastic additives and monomers on microorganisms. Plastics may be composed of numerous other chemical substances, such as plasticizers, flame retardants, stabilizers, and colorants, which are known to be toxic in the degradation of microorganisms. Such substances can reduce the capability of microorganisms to degrade plastic and their metabolic function [99]. Furthermore, while the monomers formed during the degradation of the plastics, including terephthalic acid, those from PET are toxic to microbes. Toxic by-products they produce can inhibit microbial cell functions, reduce microbial richness, and slow biological degradation. To overcome these toxicity challenges, authors are working with several approaches. The first strategy is the selective isolation and synthesis of microorganisms resistant to assorted toxins in plastics. For example, it was established that some forms of Pseudomonas can withstand and break down plastics with toxic components [86]. Another one is using genetically modified microorganisms to increase their resistance to toxic substances connected with plastics. Technological development in synthetic biology and genetic engineering, including the application of CRISPR-Cas9 genetic engineering, allows for the development of engineered, more resistant strains of microorganisms that can survive in contaminated plastic environments with various toxic additives [87]. Secondly, biodegradation processes can also be enhanced before the plastic is fed to microorganisms by removing the toxins that hinder the physical processes.

5.3 Limited Microbial Plastic Degradation Spectrum

Some microorganisms have been known to degrade certain types of plastics, but the variety of plastics activists of such microorganisms can biodegrade is still limited. Most microorganisms are adapted to degrade only one or, at most, a few varieties of plastic polymers. For example, Ideonella sakaiensis is capable of degrading polyethylene terephthalate (PET) but is not capable of doing so for other forms of plastics, such as polyethylene (PE) or polypropylene (PP) [94]. Likewise, the majority of the identified plastic-degrading microorganisms are capable of metabolizing only specific types of plastics. Thus, they are inefficient, especially for the wide range of plastics generated worldwide. The causative of this limited range of microbes is the underlying fact that plastics are polymer and vary chemically; hence, they are only conducive for microbial enzymes that are specific to them. At other times, the microorganisms originate without having the ability to create enzymes that can degrade given plastic polymers. Moreover, biodegradation processes of plastics involve particular forms, and separate bacteria can only decompose one type of polymer at a time. This is compounded by the emergence of many plastic products specially designed to be highly durable and rugged to degrade [94]. To overcome such drawbacks, scholars are finding a way towards the microbial consortia where we impute numerous microorganisms that share a common purpose: to break down a vast range of plastics. The microbial consortia can take advantage of the collective effects of various microbes that have the feasibility of degrading particular types of plastics. Also, promising synthetic biology solutions include engineering microorganisms to secrete enzymes that can break down several plastics, ensuring more plastics can be biodegraded [91].

5.4 Environmental Conditions and Scalability

Probably the single biggest problem with large-scale microbial plastic biodegradation is the failure of real-world results to mirror laboratory results. In laboratory conditions, conditions are favorable, and microorganisms that degrade plastic can be cultured under a favorable environment. However, in the real world, many conditions affect microorganisms, including varying temperatures, humidity, and oxygen levels. They can notably affect microbial action and decrease the outcomes of plastic degradation. In large-scale applications, microbial plastic biodegradation in landfills or oceans may pose further difficulties. For example, in landfills, plastics are covered with waste and shielded from actually contacting the plastic substrate from an array of microbes. Likewise, palustrine and marine habitats might also entail a large amount of plastic pollution and adverse conditions for microbial degradation, including salinity and low temperatures [18]. In addition, the current MBDCs might not contain sufficient microbes to deal with the high concentrations of plastic waste in those environments. Towards this end, research is directed at fine-tuning the aspects of biodegradation to the environment. For instance, innovation in the bioreactor is actively working to provide the right conditions for the microbial population for optimal degradation of plastics [100]. Also, laboratory experiments are being carried out to examine the efficiency of microbial biodegradation in the real world, including seas and dumps, to know ways of enhancing versatility and productivity.

7. Future Prospects and Research Directions

Microbial plastic degradation as a primarily research-based solution has promising prospects in combating the global plastic crisis, especially in its attempts to apply microbial plastic degradation to a circular economy system, implement AI and ML technologies, and combine all fields of study. Microbial degradation could supplement the widely used mechanical and chemical recycling processes since it can transform plastics into reusable resource inputs, making the plastic life cycle less damaging [20]. They can potentially minimize screening time and resources such as artificial intelligence and machine learning, which can be utilized to refine strain selection, estimate microbial degradation efficiency, and incorporate screening automation [101]. In addition, AI can be used to develop genetically modified microorganisms that can break down plastics at a higher rate, improving the process's efficienc [102]. Interdisciplinary cooperation between Microbiologists, chemists, Environmental Engineers, and Policymakers is needed to incorporate microbial bioremediation into an integrated waste management model, develop a Centralized Biodegradation System, and solve the global plastic problem. Such partnerships will help advance new effective types of biodegradation solutions and encourage the progress of the circular plastic economy to minimize the negative influence of plastic waste and enhance global efforts in creating sustainable alternatives. Using microbial degradation of plastics in conjunction with current waste management processes and large-scale bioremediation projects will allow the large-scale salvage of valuable components from plastic waste and prevent further environmental harm.

Conclusion

In conclusion, microbial biodegradation stands at the forefront of addressing the growing global challenge of plastic waste accumulation, offering a promising and sustainable alternative to conventional disposal methods. Through the remarkable metabolic versatility of microorganisms and their specialized enzymes, substantial progress has been made in the degradation of persistent plastics like polyethylene, polystyrene, and polyethylene terephthalate. Advances in genetic engineering, synthetic biology, and bioinformatics have significantly enhanced microbial efficacy, facilitating the scalability of biodegradation processes and their integration into hybrid waste management systems. However, persistent challenges—from economic feasibility to optimizing degradation rates and ensuring environmental safety—remain obstacles to large-scale implementation. To overcome these, interdisciplinary collaborations and continued innovation are essential for refining the efficiency and safety of microbial solutions. As we move toward a circular economy model, the potential for converting plastic waste into valuable by-products holds promise for a sustainable future. By advancing microbial biodegradation technologies, researchers can pave the way for innovative waste management strategies that reduce plastic pollution and contribute to broader environmental sustainability goals. The path forward will require continued research, investment, and collaboration to unlock the full potential of this transformative approach.

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