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Microbes mediated plastic degradation: A sustainable approach for environmental sustainability

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ABSTRACT

In a little over a century, plastic has gone from being addressed as a scientific marvel to being reviled as an ecological scourge. Development and modernization have brought about a colossal swell in the global plastic fabrication and consumption, due to its immense applications, versatility and relatively paltry cost. The main bottleneck lies in its disposal. They tend to endure in the environment for an implausibly long time and thus traverse from one habitat to another and then get incorporated in food chain, posing ignoramus risks for communities, ecosystems, and the planet. Indiscriminate disposal of plastic waste at startling rates has driven to a search for an all-inclusive, proficient, and sustainable remediation research work looking for a practical alternative to manage, process, and dispose of plastic debris. Albeit, there are several processes such as incineration, landfilling, and recycling available but are unsustainable, costly, and has serious repercussions on the environment, wildlife, marine, and human health. Thus, contemporary focus has been highlighted on the need for substitutes such as biodegradable plastics and surrogate disposal approaches, namely, the potential of microbes to degrade synthetic plastics with no inimical impact. In this regard, bacteria and fungi have been shown to ingurgitate these polymers and metamorphose them into environmental friendly carbon compounds. The present review covers the types of plastics, their applications, plastic degradation with more weight on the multifaceted roles played by microorganisms, their modus operandi, and probable enzymatic mechanisms.

1. INTRODUCTION

Plastic, one of the tenacious and indispensible materials in our lives and backbone of many industries, is ideally suited for a wide variety of applications to the modern generations. Plastics flaunt an unparalled and useful set of properties, namely, durability, strength, light weightedness, water and corrosion-resistance, cheapness, and relative ease in processing making it economical and superior over other materials [1]. Since its approbation, its consumption and production have escalated exponentially leading to beefing up in polymer fabrication and consequently in waste generation [2-4]. Worldwide annual plastic production scaled up from 2 Mt in 1950 to 367m tones in 2020, according to trade association Plastics Europe and is contemplated to further spike in the coming decades outweighing all the fishes in the sea by 2050.

Plastics and their associated compounds exert multitudinous biological impacts on environmental microbiomes. Manufacturing plastic takes heavy toll on fossil fuels extraction, with all the pollution risks that encompasses. Production and incineration of plastic vents greenhouse gases that significantly contribute to global warming [5]. In addition, the accumulation of such polymers which are non-biodegradable due to reprehensible waste management and disposal in the soil leads to low fertility.

Globally, out of total plastics produced, it has been estimated that only one-tenth of plastics undergo recycling, 14% incinerated and the remaining 76% finds their way to landfills or sneak into the natural environment [6]. This anthropogenic detritus have inimically affected

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life on the planet, as well as probity and sustainability [7]. Under the impact of solar UV radiation along with other natural factors, plastic disintegrates into smaller fragments called microplastics or nanoplastics. There are spectra of pernicious impacts that microplastics impinges on the environment [8]. Over the past decade, there have been series of efforts made to keep an eye on impacts of microplastics on the marine environment. According to an investigation, every year, 100,000 tons of plastic products have been jettisoned into the aquatic environment, affecting marine flora and fauna [9]. The accruing of waste spawns problems on all scales right from the ingestion of microscopic particles and the entanglement and throttling of unsuspected animals, benefacting the transport of invasive species across habitats on floating rubble posing significant hazards to marine life [10]. Choking of digestive tracts, deterioration of stomach mucosal lining, or diminishing appetite due to ingestion of plastics and injuries inflicted, starvation due to occlusion of esophagus, and suffocation because of respiratory tract strangulation, all may result due to entanglement of marine animals by plastic debris. Some microplastics have been shown to contain compounds that are known to be carcinogenic and mutagens that intermeddle with the body's organ systems, causing various disorders in both humans and wild animals [11,12]. These chemicals may enter the food chain and results in bioaccumulation at multiple trophic levels [13].

In light of the growing concern about the deleterious repercussions of these non-biodegradable plastics on environmental and human health, microorganisms should be considered extensively for remediation of plastic pollution in the environment. Recently, a handful of microorganisms were reported to eat certain plastics, breaking them down into their constituent molecules. These microorganisms can form biofilms on the periphery of pollutants resulting in a zone called plastisphere where they interact and engender acids or enzymes for the ruin of plastics. These miniature organisms represent a great vision to cope waste plastic materials with no uninvited impacts and could quickly play a key role in building a greener economy. Hence, this review article has been prepared to put in the picture the role of microbes in the biodegradation of plastic waste.

2. IMPACT OF PLASTICS ON ENVIRONMENT

From the Arctic to the Antarctic, plastic garbage can be found all over the planet. It clogs municipal sewers, pollutes campgrounds and national parks, and even builds up on Mount Everest. However, due to runoff and our habit of throwing rubbish into the nearby river or lake, plastic is becoming more prevalent in the world's oceans. The amount of plastic debris in the oceans is so large that it is referred to as the "seventh continent." If present trends persist, the oceans will have more plastic than fish by 2050. Floating plastic even generates vast "trash patches" in the Pacific Ocean middle, thousands of kilometers from land, as that flotilla of freed rubber duckies proved [14]. Mountains of plastic debris have been found all across the world's oceans, from Henderson Island, a small deserted coral island in the Pacific Ocean's middle, to the Mariana Trench, which reaches a depth of 36,070 ft [15,16].

The most visible and painful consequences of marine plastics include suffocation, tangling, and ingestion of thousands of marine animals. Plastic trash is mistaken for food by whales, turtles, seabirds, and fish and the majority of them starve to death as their tummies fill with trash. Infections, lacerations, internal injuries, and reduced swimming abilities are also present. Invasive marine species and bacteria are also propagated by floating trash, damaging ecosystems. Invasive species are transported by plastics. Plastics serve as a way for long-distance dispersal; bring species to deserted places where they compete with local species. For example, insect eggs were found on 24% of the plastic pellets analyzed in a research in the Western Atlantic [17].

Microplastic has been discovered in beer, tap water, and salt, as well as in all ocean specimens examined across the world, including the Arctic. Numerous chemicals used in the production of plastic items are classified as carcinogenic and alter the endocrine system, causing reproductive, developmental, immunological, and neurological problems in humans and wildlife. Toxic contaminants grow up on the surface of plastic products after prolonged contact with seawater. Plastic waste consumed by marine animals enters their digestive tracts, where it builds in the food chain over time. Although it is yet to be completely researched, the transmission of contaminants from marine organisms to humans through seafood consumption has been highlighted as a health risk [18]. Plastic pollution can impair not only the waterways and land, but also human health, by harming wildlife and habitats. Plastic, a petroleum-based product, contributes to global warming as well. When plastic garbage is burned, carbon dioxide is released into the air, raising carbon emissions [17]. Plastic waste reduces the visual appeal of tourist destinations, leading to the lower tourism-related income and hefty cleaning and maintenance costs.

3. BIODEGRADATION OF PLASTICS

Plastic waste can be degraded through biotic and abiotic means which are referred to as biodegradation and physicochemical processes, respectively. The first step in any degradation process is usually considered the breakdown of the polymeric material by mechanical forces [19,20]. Microorganisms convert biochemical into compounds and this process is called biodegradation [21]. Depending on the degree of biodegradability and microbial assimilation, fossil-based and bio-based polymers can be included in biodegradable plastics. Plastics degrade due to a variety of factors, including mobility, crystalline structure, functional groups, molecular weight, and chemical additions to the polymers. During the biodegradation of plastics, microorganisms on the surface firstly decrease the molecular weight of the plastics, followed by the transformation of the polymer to its monomers, which are then broken down in a process of mineralization with the release carbon dioxide, water, and methane [21,22]. In case of big polymers, the depolymerization of into smaller monomers is important before being taken by microbes as big polymers pose difficulty in entering through the cellular membrane. Plastics can be degraded in a variety of ways, one of which is enzymatic degradation, in which enzymes attack the polymer substrate after hydrolytic breakage. Bacteria and fungi aid in the degradation of both natural and manmade polymers. Another type of degradation is clear zone development, which occurs when a polymer enters the synthetic medium agar as small particles. Agar plates containing emulsified polymers are often used procedures for the degradation of plastics, which result in the creation of halo zones around the plastics when treated with the microbe.

4. BIODIVERSITY OF PLASTIC DEGRADING MICROBES

The production of the synthetic plastic is one of the fastest growing fields of global industry. It has been estimated that approximately 80% of the total global plastic usage constitutes petrochemical plastic, which includes polyvinyl chloride (PVC), polyethylene (PE), polypropylene (PP), polystyrene (PS), and polyethylene terephthalate (PET). No doubt, plastic materials form an important part of global economy still the challenges and issues in association with their wide ranging applications and utilization cannot be ignored [23]. The major challenge associated with the plastics is the environmental pollution. Microbial communities are the most versatile organisms which play a major role in biodegradation in which microbes either break down the polymers into or utilize these compounds and convert them into simpler waste compounds while others are still able to utilize the excreted wastes [24]. Biodegradation involves four major steps [25]. The first step is biodeterioration in which the metabolic activities of microbes provoke plastic cracks. In the process, the physical properties of the plastics worsen or the microstructure of the matrix is changed. This step is followed by biofragmentation and release of the oligomers. Biofragmentation is followed by degradation and conversion of the oligomers to monomeric units in which oligomers enter inside the cells and secondary degraders assimilate them as a source of carbon. Assimilation of oligomers occurs in the last step in which excretion of completely oxidized metabolites to H_2O, CO_2, N_2, and CH_4. This section will discuss plastic degradation by different groups of microbes [Figure 1].

4.1. Archaea

Archaea are one of the most versatile groups of the microbes thriving in the extreme environmental conditions which even define physical barrier or too severe for existence of life including deep-sea hydrothermal vents, hypersaline ponds, or strictly anoxic ecosystems [26]. They may be extreme halophiles, hyperthermophiles, methanogens, and sulfur-metabolizing thermophiles. These extremophilic microbial communities possess unusual characteristics which make them a valuable bioresource for the development of

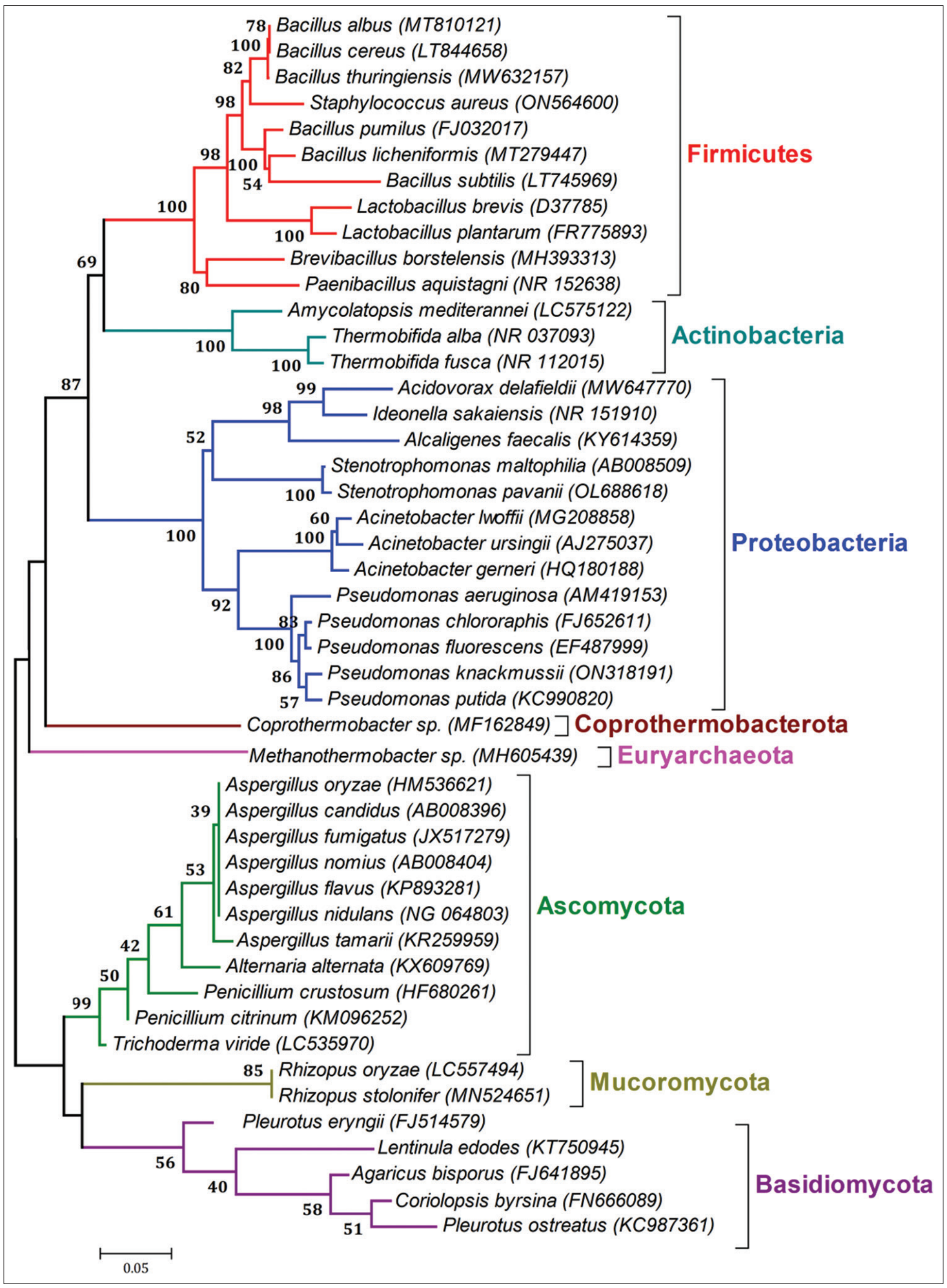

Figure 1: Phylogenetic tree showing relationships among diverse phyla of plastic degrading microbes.

innovative biotechnological processes. These extremophiles have been known though for more than 40 years but the research has increased in the last two decades as the conditions under which they survive have now become much broader than it was previously thought which has led to exposure of many unexplored habitats. Second, the increasing research and screening of extremophiles have unlocked various novel potential features of these organisms which can be utilized in diverse industrial sectors [27]. The role of the archaea in the biodegradation of the plastics is scarce and needs to be explored. The study of Jin *et al.* [28] recently reported the biodegradation of biodegradable plastics by species of *Methanothermobacter*.

4.2. Bacteria

Plastic wastes are dangerous for the natural environment as they accumulate in the rivers and oceans [23,29,30]. Fishing, industries, and coastal tourism are the major sources of plastics into the marine environment and pose a direct impact on seas and oceans [31]. The released plastics in the marine environment are colonized by the microbes [32-34]. It has been known fact that in sea water, colonization of the plastics by the bacterial communities starts immediately as they are introduced. Within a few hours, microbial assemblages are formed and surface of the plastics is covered in a step called as attachment. Microbial assemblages during this step may catalyze series of metabolic reactions that lead to the adsorption, desorption, and fragmentation of micro plastic-associated compounds [35].

Bacteria are emerging as an excellent agent for degradation of the plastics. Studies have reported that bacteria with capability to degrade plastics such as *Moritella* sp., *Pseudomonas* sp., *Psychrobacter* sp., and *Shewanella* sp. have been reported to degrade PCL [36]. *Vibrio alginolyticus* and *Vibrio parahemolyticus* have been reported for PVA-LLDPE degradation [37]. Singh *et al.* [38] reported *Bacillus* sp., *Pseudomonas* sp., and *Staphylococcus* sp. for polythene degradation. *Bacillus* sp., *Klebsiella* sp., and *Pseudomonas* sp. have been reported to degrade polyethylene synthetic plastic. *Clonostachys rosea, Pseudomonas* sp., *Rhodococcus* sp., and *Trichoderma* sp. from the arctic soil have been reported for degradation of PCL and commercial available bag based on potato and corn starch [39].

The use of the thermophiles for degradation of the plastics in the biological treatment of polluted thermal habitats is highly beneficial. The thermophilic microbes greatly improve the substrate bioavailability and solubility due to the changes in polymer properties including physical and optical [40]. PET majorly used in textile industry is available for hydrolysis by the activity of enzymes at about 65–75°C temperature due to the enhanced mobility of the amorphous sectors of the polymer chains [41,42]. The degradation of PET by *Thermobifida alba*, *Thermomonospora curvata* and *Thermobifida halotolerans* has been reported [43-45]. Recently, Jin *et al.* [28] reported *Coprothermobacter* sp. belonging to new phylum of anaerobic and thermophilic bacteria, Coprothermobacterota as degrader of biodegradable plastics.

4.3. Fungi

With the increasing research on the sustainable environment, fungal communities are getting greater attention as a potential bioresource in biodegradation of the plastics. Usman *et al.* [46] *Alternaria alternate, Aspergillus candidus, Aspergillus flavus, Aspergillus nidulans, Aspergillus niger, Aspergillus ornatus, Aspergillus terreus,* and *Rhizopus stolonifera* as potential degraders of polythene bags and bottom of plastic bottle. Cosgrove *et al.* [47] for the first time reported fungal communities from the surface of plastics such as polyester polyurethane during burial in situ in soil. In the study, *Geomyces pannorum* and *Phoma* sp. were reported as the potential candidates for PU degradation. Many studies have focused on plastic degradation by mushroom species. Da Luz *et al.* [48] reported the oxobiodegradable plastic biodegrading ability of *Pleurotus ostreatus*. Hock *et al.* [49] reported *Agaricus bisporus, Lentinula edodes, Pleurotus eryngii,* and *Pleurotus ostreatus* as di(2- ethylhexyl) phthalate degraders [Table 1].

5. FACTORS AFFECTING PLASTIC DEGRADATION

The properties of polymers, as well as their response to diverse biotic and abiotic stimuli, influence synthetic plastic degradation [50]. The physicochemical properties influence breakdown as its susceptibility to biotic or abiotic degradation is determined by their backbone composition and chain length. Polymeric materials possess long carbon chains such as those found in polypropylene which make them resistant to biodegradation. However, the insertion of heteroatoms in the carbon chain, as in the case of oxygen-containing polymers, renders them prone to heat and biodegradation. Furthermore, hydrophobicity is another factor which affects the efficiency of breakdown of these polymers. The rate of degradation rises as hydrophilicity rises [51].

The crystallinity impacts rate of plastic degradation. The more the crystallinity of the polymer, the greater is the need for oxygen and water, which may trigger the degradation process. The amorphous portions of the polymers are also known to have some role in degradation process as they are thought to be more sensitive to thermal oxidation. Furthermore, the molecular weight of a polymer might also impact its breakdown rate. Polymers with a high MW, according to this idea, degrade more slowly due to their smaller relative surface area [19].

Plastic polymer manufacturing involves additives that might affect the rate of degradation. Nanoadditives, for instance, can improve the polymeric properties for industrial applications. Nanoscale reinforcements increase the surface area of the interface for improved performance. The integration of these nanoparticles into the polymers

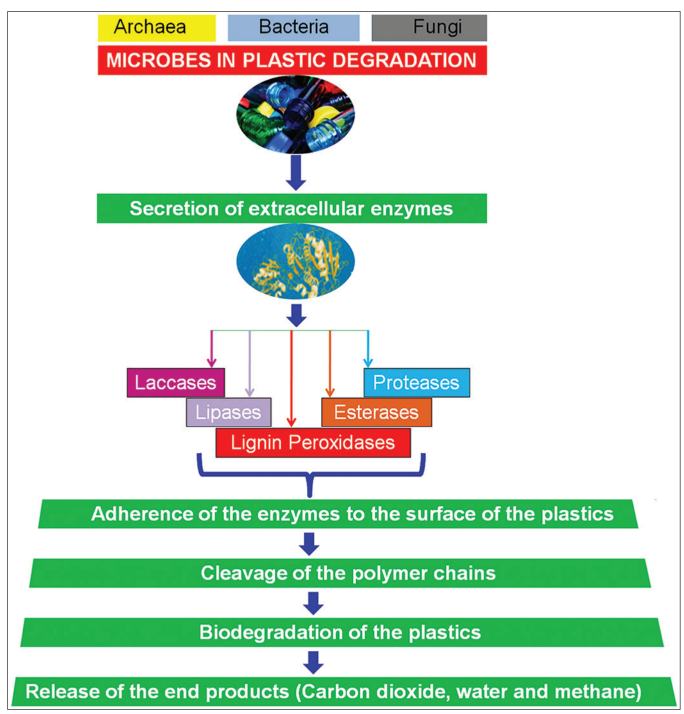

Figure 2: Mechanism of biodegradation of plastics through microbial enzymes.

Table 1: Diversity of plastic degrading microbes.

Plastic degrading microbes	Type of plastic degraded	References
Achromobacter sp.	Low-density Polyethylene	Dey *et al.* [81]
Acinetobacter ursingii	Low-density polyethylene	Hussein *et al.* [82]
Agaricus bisporus	di (2-ethylhexyl) phthalate	Hock *et al.* [49]
Aspergillus flavus	Polyethylene	Deepika and Jaya [83]
Aspergillus fumigatus	Polypropylene	OLIYA *et al.* [84]
Aspergillus niger	Polyethylene	Deepika and Jaya [83]
Aspergillus niger	Low-density Polyethylene	Ogunbayo *et al.* [85]
Aspergillus niger	Low-density Polyethylene	Mohamad [86]
Aspergillus nomius	Low-density polyethylene	Munir *et al.* [87]
Bacillus licheniformis	Polyethylene	Ibrahim *et al.* [88]
Bacillus sp.	Low-density polyethylene	Gupta *et al.* [89]
Bacillus sp.	Low-density polyethylene	Joshi *et al.* [90]
Bacillus sp.	Polyethylene	Biki *et al.* [91]
Bacillus subtilis	Polycaprolactone	Widyananto *et al.* [92]
Bacillus subtilis	Polyethylene	Ibrahim *et al.* [88]
Bacillus subtilis	High-density polyethylene	Tadimeti [93]
Bacillus subtilis	Low-density polyethylene	Tadimeti [93]
Coriolopsis byrsina	Synthetic plastic	Kuswytasari *et al.* [94]
Enterobacter sp.	Polyethylene	Ren *et al.* [95]
Geomyces pannorum	Polyester polyurethane	Cosgrove *et al.* [47]
Ideonella sakaiensis	Polyethylene terephathalate	Juliana *et al.* [96]
Lentinula edodes	di (2-ethylhexyl) phthalate	Hock *et al.* [49]
Micrococcus sp.	Low-density polyethylene	Gupta *et al.* [89]
Oceanimonas sp.	Low-density polyethylene	Joshi *et al.* [90]
Paenibacillus sp.	Low-density polyethylene	Bardají *et al.* [97]
Paenibacillus sp.	Low-density polyethylene	Joshi *et al.* [90]
Penicillium citrinum	Low-density polyethylene	Khan *et al.* [98]
Phoma sp.	Polyester polyurethane	Cosgrove *et al.* [47]
Pleurotus eryngii	di (2-ethylhexyl) phthalate	Hock *et al.* [49]
Pleurotus ostreatus	Oxo-biodegradable (D_2W) plastic	da Luz *et al.* [48]
Pleurotus ostreatus	di (2-ethylhexyl) phthalate	Hock *et al.* [49]

(*Contd*...)

Table 1: (*Continued*).

Plastic degrading microbes	Type of plastic degraded	References
Pseudomonas aeruginosa	Low-density polyethylene	Hussein *et al.* [82]
Pseudomonas aeruginosa	Polyethylene	Hou *et al.* [99]
Pseudomonas aeruginosa	Polyethylene	Shahreza *et al.* [100]
Pseudomonas fluorescens	Low-density polyethylene	Hussein *et al.* [82]
Pseudomonas knackmussii	Polyethylene	Hou *et al.* [99]
Pseudomonas putida	Polyethylene	Ibrahim *et al.* [88]
Pseudomonas sp.	Polyethylene	Deepika and Jaya [83]
Pseudomonas sp.	Low-density polyethylene	Gupta *et al.* [89]
Pseudomonas sp.	Low-density Polyethylene	Ogunbayo *et al.* [85]
Pseudoxanthomonas sp.	Bisphenol-A polycarbonate	Yue *et al.* [101]
Ralstonia sp.	Polyethylene	Biki *et al.* [91]
Rheinheimera sp.	Low-density polyethylene	Joshi *et al.* [90]
Rhizopus oryzae	Low-density Polyethylene	Mohamad [86]
Shewanella sp.	Low-density polyethylene	Joshi *et al.* [90]
Staphylococcus sp.	Polypropylene	OLIYA *et al.* [84]
Stenotrophomonas pavanii	Polyethylene terephathalate	Huang *et al.* [102]
Stenotrophomonas sp.	Low-density Polyethylene	Dey *et al.* [81]
Streptomyces sp.	Polyethylene	Deepika and Jaya [83]
Streptomyces sp.	Low-density Polyethylene	Soud [103]
Thermobifida fusca	Polyethylene terephathalate	Huang *et al.* [102]
Trichoderma viride	Low-density polyethylene	Munir *et al.* [87]
Trichoderma sp.	Low-density Polyethylene	Hikmah *et al.* [104]
Vibrio sp.	Low-density polyethylene	Joshi *et al.* [90]

intends to improve mechanical, rheological, electrical, and thermal properties. This further makes the recycling and degradation process easier. The use of nanoparticle additions in polymer manufacturing may potentially help to overcome biodegradation issues [52]. The degradability of the polymer may be influenced by the fabrication process. Copolymerized PP (polypropylene), for example, is less photodegradable than PP made by bulk (mass) polymerization or using the ZieglerNatta catalyst.

Stabilizers are frequently employed as additives in plastic manufacture to reduce the rate of deterioration. The chemical functionalization type in a polymeric structure irreversibly modifies the physicochemical

Table 2: Microbial enzymes involved in the degradation of different types of plastics.

Plastic degrading microbes	Plastic used	Enzyme	References
Acidovorax delafieldii	poly (tetramethylene succinate)-co-adipate	Lipase	Uchida *et al.* [105]
Acinetobacter gerneri	Polyurethane	Polyurethanase	Howard *et al.* [106]
Acinetobacter lwoffii	Polyhydroxyalkanoates	Lipase	Sharma *et al.* [107]
Actinomadura sp.	Polyester	Depolymerases	Sriyapai *et al.* [108]
Alcaligens faecalis	Polyethylene	Lipase	Nag *et al.* [109]
Alcaligens faecalis	Polyethylene	CMCase	Nag *et al.* [109]
Alcaligens faecalis	Polyethylene	Xylanases	Nag *et al.* [109]
Alcaligens faecalis	Polyethylene	Protease	Nag *et al.* [109]
Amycolatopsis mediterannei	Poly(ε-caprolactone)	Cutinase	Tan *et al.* [110]
Aspergillus melleus	Poly(ε-caprolactone)	Lipase	Amin *et al.* [111]
Aspergillus niger	Poly (lactic acid)	Lipase	Nakajima-Kambe *et al.* [112]
Aspergillus niger	Poly(ε-caprolactone)	Lipase	Nakajima-Kambe *et al.* [112]
Aspergillus tamarii	Polyethylene terephathalate	Lipase	Anbalagan *et al.* [113]
Aspergillus tamarii	Polyethylene terephathalate	Cutinase	Anbalagan *et al.* [113]
Bacillus pumilus	Polyurethane	Lipase	Nair and Kumar [114]
Bacillus sp.	Poly (butylene adipate co terephthalate)	Lipase	Zhang *et al.* [115]
Bacillus subtilis	Polyurethane	Polyurethanase-lipase	Rowe and Howard [66]
Bacillus sp.	Cellulose acetate plastic	Lipase	Ishigaki *et al.* [116]
Bacillus sp.	Cellulose acetate plastic	Cellulase	Ishigaki *et al.* [116]
Candida antarctica	Poly (butylene succinate)	Cutinase	Shi *et al.* [117]
Fusarium sp.	Poly (butylene succinate)	Lipase	Shi *et al.* [117]
Ideonella sakaiensis	Polyethylene terephthalate	PETase	Alfieri *et al.* [118]
Laceyella sp.	Polyester	Depolymerases	Sriyapai *et al.* [108]
Lactobacillus brevis	Poly(ε-caprolactone)	Lipase	Khan *et al.* [119]
Lactobacillus plantarum	Poly(ε-caprolactone)	Lipase	Khan *et al.* [119]
Moraxella sp.	Synthetic polymers	Esterase	Nikolaivits *et al.* [120]
Penicillium crustosum	Polyethylene terephathalate	Lipase	Anbalagan *et al.* [113]
Penicillium crustosum	Polyethylene terephathalate	Cutinase	Anbalagan *et al.* [113]
Pseudomonas chlororaphis	Polyhydroxyalkanoates	Lipase	Sharma *et al.* [107]
Pseudomonas chlororaphis	-	Lipase	Mohanan *et al.* [121]
Saccharothrix sp.	Poly (butylene succinate)	Depolymerases	Sriyapai *et al.* [122]
Stenotrophomonas sp.	Poly (butylene adipate-*co*-terephthalate)	Lipase	Jia *et al.* [123]
Streptomyces sp.	Polyester	Depolymerases	Sriyapai *et al.* [108]
Thermobifida alba	Aliphatic-aromatic copolyester film	Esterase	Hu *et al.* [43]

qualities and its degradation rate. The morphological properties of the polymer have an impact on its degradability. In reality, the rate of degradation will rise as the surface roughness increases, because greater surface area promotes biofilm growth more than smooth surfaces [53].

The plastic degradation process mechanisms and rate may be affected by geographical location, air pollution, and prevailing meteorological conditions. For example, PET bottles may survive on the seabed for more than 15 years [54]. Water availability is a key factor in the degradation process because hydrolytic cleavage of functional groups that are vulnerable to hydrolysis results in polymeric chain separation [55]. The rate of degradation of plastics is influenced by oxygen availability. The availability of high levels of oxygen leads to accelerated polymeric degradation due to reactivity of oxygen with carbon-centered radicals which are created during the early degradation steps [56].

6. ROLE OF MICROBIAL ENZYMES IN PLASTIC DEGRADATION

Microbial enzymes are the most important environmental agents contributing to the biodegradation process. The process of biodegradation results in the conversion of the carbon in the polymer chains into smaller biomolecules or into carbon dioxide and water [57]. Thus, adding to the soil fertility and decreased accumulation of the plastics in turn reducing the cost of the waste management. The biodegradation of polyethylene through microbial enzymes consists of two steps. In the first step, there is adhesion of enzyme to the polyethylene substrate followed by the hydrolytic cleavage. Intracellular and extracellular depolymerases produced by fungi and bacteria are involved in the biodegradation of the polyethylene [58]. Microbial enzymes involved in lignin degradation have been reported to play a role in the biodegradation of polyethylene [59-62]. These include laccases, lignin peroxidases, and manganese peroxidases. Manganese peroxidase from *Phanerochaete chrysosporium* has been reported to play a chief role in degradation of a high molecular weight PE membrane [63]. The purified protease from *Pseudomonas fluorescens*, an esterase from *Comamonas acidovorans,* three esterases from *Pseudomonas chlororaphis,* and a lipase from *Bacillus subtilis* have been shown to exhibit hydrolytic capacity to emulsify polyester PUR [64-68]. Lipase and polyurethane esterase from *Rhizopus delemer* and *Comamonas acidovorans* have been reported to degrade PLA of low molecular weight and *Amycalotopsis* sp. has been reported for degradation of high molecular weight PLA [69]. *Pestalotiopsis microspora* containing serine hydrolase has been revealed to utilize the PU as a substrate, carbon source, and degrade it [70]. A thermostable laccase from *Rhodococcus ruber* has been investigated to degrade UV-irradiated films of PE [71]. Carboxylesterases from *Thermobifida fusca, Bacillus subtilis,* and *Bacillus licheniformis* have been shown to hydrolyze PET fibers partially as well as demonstrated a high activity against PET oligomers [72-76]. Thus, microbial enzymes play an important role in plastic waste management. Novel strategies and innovative solutions are important for reducing the production of non-biodegradable and non-reusable plastics and improvement of target enzymes or microbiomes in plastic biodegradation as tools for plastic management [77] [Table 2, Figures 2 and 3].

7. DRAFT GENOME

The role of the microbes in the environmental cleaning especially the degradation of the plastics is an emerging field. The studies of the genomes of plastic degrading microbes are limited. To understand the metabolic pathways and genes associated with biodegradation is of

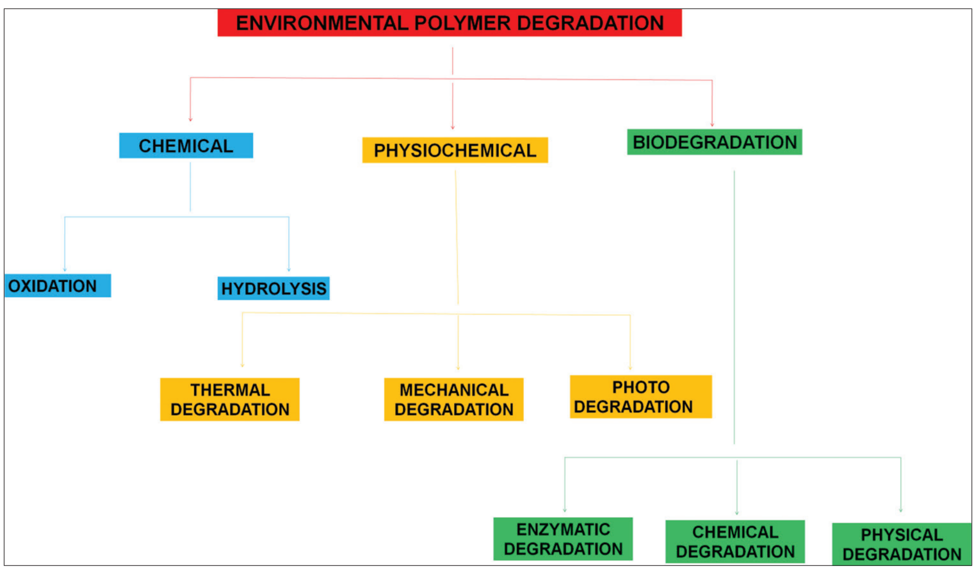

Figure 3: Different methods used for polymer degradation.

Table 3: Genome sequencing of plastic degrading microbes.

Plastic degraders	Size (Mb)	GC%	Protein	Gene	References
Azoarcus sp. PA01T	3.9	66.08	3625	3712	Junghare *et al.* [124]
Bacillus albus PFYN01	6.4	34.90	6566	-	León-Zayas *et al.* [78]
Bacillus sp. AIIW2	4.4	45.70	-	4714	Kumari *et al.* [125]
Bacillus thuringiensis C15	5.2	35.0	5275	-	León-Zayas *et al.* [78]
Bacillus sp. Y-01	5.8	38.24	4996	-	Wang *et al.* [126]
Paenibacillus aquistagni DK1	5.4	47.40	4754	4950	Furlan *et al.* [127]
Pseudomonas aeruginosa S3	6.6	66.17	6437		Satti *et al.* [79]
Pseudomonas putida CA-3	6.1	61.89	5608	-	Almeida *et al.* [128]
Pseudomonas sp. B10	6.2	60.70	5565	-	León-Zayas *et al.* [78]
Pseudomonas sp. SWI36	5.7	61.90	5186	-	León-Zayas *et al.* [78]
Pseudomonas sp. SWI36	5.7	61.90	5193	-	León-Zayas *et al.* [78]
Sphinogobacterium sp. S2	5.6	43.50	5385	-	Satti *et al.* [79]
Stenotrophomonas maltophilia PE591	4.7	66.50		4432	Frederico *et al.* [80]

major importance. A few researchers have reported the draft genomes of the plastic degrading microbes [78-80] [Table 3].

8. CONCLUSION AND FUTURE PERSPECTIVES

Plastic is the most utile fabricated polymer that has become an imminent part of human life, spanning countless sectors, all with inimitable attributes. However, unpredicted use of synthetic polymers, our throw-away culture, and widespread mismanagement has become ubiquitous in all the natural habitats, leading to rampant ingress of plastics into the environment and has become a global disquiet. The pernicious effects of plastics are apparent and intimidate food safety and quality, human, and wildlife health and contribute to climate change. Given the overwhelming impediment of dealing with worldwide plastic pollution, the novel microbial approach could be a pivotal component of the solution. Microbial communities are proficient in degrading inorganic and organic materials. The interest has aroused to study microbiomes for their capability to degrade plastic polymers. However, the multeity of known enzymes and microbes acting on synthetic polymers is still rather restricted. Hence, further exploration and screening of effectual microbial strains, suitable *in-situ* and *ex-situ* remediation techniques, and apposite maintenance of microbial growth and physicochemical conditions are imperative to curtail polymer hazards for the surroundings. Besides, at molecular level, identification of genes accountable for producing enzymes with potential of plastic degradation and recombinant DNA technology can perk up and expedite remediation of plastic waste. Another bonafide, effectual, and sustainable approach is to bolster the use of bio-based and biodegradable plastics. In fact, the replacing conventional plastics with bioplastics can lead to considerable energy and GHGs emissions savings. Furthermore, plastic pollution being a serious issue across the globe solicits a clamant and international rejoinder involving all germane participants at different levels. Unless waste management practices are revitalized, the flux of plastics to the oceans could amplify by an order of magnitude in the ensuing decade. Hence, awareness about plastic pollution and its negative and undesirable effects on living organisms and environment is important. The awareness should be spawned at the school level. Furthermore, students must be guided on biodegradable and non-biodegradable plastic waste and their separation before disposal. To knuckle down, the predicament of plastic debris in the oceans is a herculean task and a catholic approach and collated action is urgently obligated that combines technology, public/policy initiatives and advocacy to circumvent further plastic pollution, and the subsequent affliction to aquatic ecosystems and human health.

9. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work.

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11. CONFLICTS OF INTEREST

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12. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

13. DATA AVAILABILITY

All data generated and analyzed are included within this research article.

14. PUBLISHER'S NOTE

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