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# Potential of Bioremediation for Plastic Waste: Bacteria and Fungi: a Review

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**ABSTRACT**

The widespread use of plastic products across all industrial sectors continue to increase at a steady rate, contributing considerably to the accumulation of pollutants in aquatic and terrestrial environments. The pervasive presence of these synthetic compounds in ecosystems poses considerable risks to human health. Hence, plastic waste has consequently become a global environmental concern. Biodegradation utilizes different forms of organisms, such as bacteria and fungi, which are highly efficient in degrading different forms of plastic. Several genera of bacteria, such as *Pseudomonas*, *Ideonella*, and *Rhodococcus*, have demonstrated the ability to metabolize plastic materials by employing specific enzymes that convert plastic into simpler molecules that can be used as carbon sources. Similarly, fungal species, such as *Pestalotiopsis microspora*, *Schizophyllum*, *Fusarium*, *Penicillium*, and *Trichoderma*, degrade plastic and use it as a carbon source, exhibiting potential as effective agents in plastic waste management. Biodegradation relies on the enzymatic activity of microorganisms and their enzymes to break down plastic polymers. The metabolic enzymes offer a biological alternative for the removal of synthetic polymers. Consequently, bioremediation is considered a more environmentally friendly and safer approach than chemical treatment. However, this approach faces limitations, including the challenge of selecting appropriate microorganisms and the generally slower degradation rates compared with chemical methods.

## Introduction

Plastics are synthetic polymers widely recognized for their hardness, flexibility, strength, and cost-effectiveness [1]. These materials are composed primarily of carbon and hydrogen and may include organic and inorganic elements derived from fossil fuel by-products. Plastics can be classified based on their source or method of production, including natural, semisynthetic, synthetic, thermoplastic, and thermosetting polymers [3]. Broadly, plastics are classified into two main types: thermoplastics and thermosets. Thermoplastics are materials that melt when heated and harden when cooled, including polyethylene (PE), PE terephthalate (PET), low-density PE (LDPE), high-density PE (HDPE), polystyrene (PS), expanded PS (EPS), polyvinyl chloride (PVC), polycarbonate, polypropylene (PP), polylactic acid (PLA), and polyhydroxyalkanoate (PHA). Meanwhile, thermosets are plastics whose chemical structures undergo irreversible changes when heated and hence cannot be remelted. They include polyurethane (PUR), phenolic resins, epoxy resins, silicone, vinyl ester, acrylic resins, and urea formaldehyde resins (Fig. 1) [4]. As a class of organic polymers, plastics have extremely large molecular weights. They can be synthesized through the polycondensation or polymerization of raw materials, such as crude oil, coal, and cellulose. These components incorporate structural elements, such as carbon, hydrogen, nitrogen, oxygen, chlorine, sulfur, and silicon. PET is petroleum-derived polymer synthesized from the monomeric residues of terephthalic acid (TPA) and ethylene glycol (EG), through ester connections. These components contribute to its enhanced stability. It is widely used in single-use disposable plastic products because of its low production cost and relatively simple manufacturing process [3]. Plastics are widely used in

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everyday life because of its low cost, durability, and versatility [5]. Plastic consumption has increased globally, particularly during the COVID-19 pandemic, leading to a substantial increase in medical waste and single-use plastics [6]. The persistence of nonbiodegradable polymer–based plastic products poses a major environmental challenge. The combination of increased plastic use and inadequate waste disposal has placed considerable strain on ecosystems. This issue is further exacerbated by poor plastic waste management and a general lack of public awareness [7]. Plasticizers, which are incorporated to plastics to enhance flexibility, are not chemically bonded to the polymer matrix and leak over time, posing potential health risks [8]. PET is a unique petroleum-based plastic produced through the polycondensation of TPA and EG monomeric residues or transesterification of EG–DMT. Owing to its desirable properties, such as chemically inertness, stability at high temperatures, crystallinity, non-porosity, and mechanical strength, it has been widely used in the manufacturing of everyday products, such as bottles, containers, and textiles [22]. PET plastics account for more than 70% of global plastic usage, along with other polymers, such as polyesters, polysulfates, and polyamides. However, they contribute to approximately 12% of the total solid waste generated worldwide, posing a substantial risk to ecological systems [10]. Nevertheless, PET plastics exhibit exceptional durability because of their restricted molecular mobility, high hydrophobicity on surfaces, and crystalline structures, which enhance their chemical stability and resistance to degradation by water and microorganisms [11].

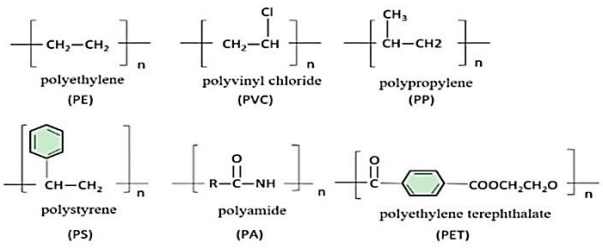


Figure 1. Chemical formulas of plastic types.

**Plastic waste**

Single-use plastic waste is a well-documented global concern, with approximately 79% ultimately ending up in natural environments [12]. Plastic waste has disrupted environmental balance, compromised public health, and negatively affected communities worldwide owing improper disposal methods and inadequate recycling systems. This issue is exacerbated by the nonbiodegradable nature of plastics [13]. When exposed to sunlight, plastic waste can quickly disintegrate into small particles and contaminate soil and water sources. These toxic particles pose severe risk to various organisms in the food chain and are particularly hazardous to marine organisms, such as mammals, turtles, and water birds [14]. The combustion of plastic waste presents environmental and health threats, especially in developing regions. This activity releases aerosols and poisonous compounds, such as dioxins, furans, and polycyclic aromatic hydrocarbons, reducing fresh air quality and increasing health risks [15]. Additionally, it contributes to the emission of $CO_2$ in the atmosphere, exacerbating global warming. $CO_2$ can trap solar heat, increasing the Earth's surface temperature [16]. Moreover, the persistence of accumulated plastics in terrestrial environments presents ecological challenges, impairing soil's physical structure and thereby leading to reduced water infiltration, hindered aeration, and decline in soil vitality [17]. The accumulation of plastic waste in soil decreases oxygen availability and diminishes the population of microorganisms that decompose organic and inorganic matter. This decline in microbial activity may affect soil fertility and hamper plant growth [18]. Hence, some measures to avoid these risks have been proposed, such as encouraging the use of alternatives to plastics and plastic products and discouraging the improper disposal of plastics [19]. According to data from World Count (2020), approximately 8,798,208 tons of plastic waste is found in the ocean. The regular dispersion of floating plastics has led to the formation of "floating plastic islands," which covers an area of up to 2,531,819,106 $km^2$. These figure continues to rise daily, highlighting the escalating severity of global plastic pollution. Most plastics are resistant to biodegradation and fragment into microplastics, which poses threats to ecosystems [20]. Plastics have permeated various environments, water bodies, terrestrial ecosystems, and the food chain [20]. In 2017, nearly 0.8 million tons of microplastics contributed to global plastic emissions, accounting for 80% of solid waste (macroplastics) in

global water systems. In 2050, the volume of these emissions may reach 2.2–3 gigatonnes [22]. These alarming trends highlight the urgent need to develop safe, fast, and efficient plastic remediation techniques [23].

**Plastic health risk**

Plastic pollution is a major threat to environmental and human health. Inhalation, ingestion and dermal uptake of micro- and nanoplastics (MNPs) may lead to respiratory disorders, neurological manifestations, and inflammatory bowel disease [24]. The microparticles of PP cause inflammation through several pathways depending on the size of the particles, and exposure to PP can cause the infiltration of inflammatory cells [1], elevated ROS and inflammatory cytokine and chemokine levels, lung damage, and mitochondrial impairment [25]. Furthermore, a systematic review that examined the role of microplastics in inflammation highlighted the types and sizes of microplastics inducing inflammation in in vivo and in vitro models and the influence of exposure time on these effects. The global concern concerning plastic pollution stems from the environment persistence and potential health hazards of plastics. The ingestion or inhalation of MNPs through various pathways may compromise immune function and increase susceptibility to diseases [27]. Some additives used in plastics, such as bisphenol A (BPA) and phthalates, are recognized for their carcinogenic and genotoxic effects on human health [28]. MNPs have been shown to inhibit cellular processes by disrupting membrane function and inducing ROS production and DNA damage [29]. Furthermore, these particles can serve as carriers for other toxins, enhancing their virulence through a “Trojan Horse” mechanism [30]. Plastic additives and non-polymerized monomers emitted throughout the lifecycle of plastics increase these risks [31]. Although the toxicity of MNPs are currently under extensive investigation, more comprehensive analysis is needed to elucidate the long-term impacts of MNP on human health and the environment [29], [30]. Emerging evidence suggests that MNPs exert carcinogenic and mutagenic effects, which contribute to DNA damage and development of several types of cancer, including biliary tract cancer, pancreatic cancer, and hepatocellular carcinoma [32].

Plastics themselves are not inherently carcinogenic, but some by-products associated with plastics, such as parabens and retinol, have been identified as potential contributors to the risk of developing cancer, especially breast cancer [33]. In fact, materials historically used in plastic manufacturing, , once considered inert and harmless, have since been found to induce diseases and genetic alterations over time [34]. Individual susceptibility to cancer is influenced by various factors [35]. Thus, although plastic may not be directly associated with cancer, the chemicals additives they contain and their potential interactions with genetic markers may contribute to carcinogenic effects over prolonged exposure. Some substances used in plastics, including BPA, phthalates, and brominated flame retardants, which are found in most consumer products, exhibit genotoxic properties that pose risk to human health [28].

**Bioremediation**

Bioremediation is an environmentally sustainable and cost-effective method that employs biological factors, particularly microorganisms, to mitigate environmental pollution [36]. This process can be applied across various polluted media, including soil, water, and air, and has been proven effective in degrading a wide range of pollutants, such as heavy metals, petroleum hydrocarbons, and pesticides [38] [39]. In response to growing prevalence of environmental contamination, bioremediation has emerged as a promising alternative to conventional chemicals treatments. It leverages the natural capabilities of microorganisms, fungi, insects, and plants to detoxify polluted environments. Bioremediation encompasses two primary approaches: in situ and ex situ. The in situ method treats pollutants at a contamination site without the need for excavation Ex situ techniques involve the removal of contaminated material for treatment elsewhere. This paper advocates the adoption of green technologies, such as bioremediation, as viable solutions to address the urgent need for environmental conservation and restoration of ecosystems degraded by human activities, industrialization, and agricultural practices [38], [39]. However, bioremediation presents some challenges, including the selection of appropriate microorganisms, the potential toxicity of biodegradation

by-products, and generally slower rates of reactions as compared with the physico-chemical techniques [40].

To date, the management of environmental plastics involves chemical remediation and bioremediation strategies. However, the use of chemical methods often poses risk to the natural environment. In contrast, bioremediation utilize bacteria, fungi, algae, insects, or other microorganisms to degrade, absorb, alter, immobilize, or metabolize pollutants in the environment, offering an environmentally sustainable alternative [41]. The efficiency of bioremediation depends on plastics' crystalline structure, molecular size, functional groups, and additives. The biodegradation of plastics requires microorganisms to adhere to the plastic matrix, form a biofilm, degrade polymers into manageable forms, and convert these fragments into basic components, such as $CO_2$, water, and EG [42]. Numerous species of microorganisms have demonstrated the ability to degrade plastics, including the bacterial genera *Acinetobacteria*, *Bacillus*, *Pseudomonas*, and *Proteus* and fungus *Pleurotus ostreatus* [43], [44]. These microorganisms facilitate the degradation plastics by secreting various enzymes, such as proteases, esterases, lipases, and glycosidases, which catalyze the breakdown of plastic polymers [45]. Biodegradation can occur under aerobic or anaerobic conditions, generating distinct products. Under aerobic conditions, the primary degradation products are $CO_2$, and $H_2O$, and anaerobic degradation typically yields $CO_2$, $H_2O$, and $CH_4$ [46]. The biodegradation rate is generally higher under aerobic conditions because $O_2$ is more effective electron receptor than $CO_2$ and $SO_4$. The choice between aerobic and anaerobic conditions depends on the specific microbial species involved. Fungal biodegradation requires aerobic conditions, whereas bacterial degradation can occur under both conditions [47]. Photodegradation is a process initiated by UV radiation from sunlight or UV bulbs, which involves photochemical reactions that degrade polymer bonds into smaller fragments. These degradation products are then subjected to microbial degradation, wherein microorganisms further metabolize the products into end products commonly found in the environment [48], [49].

Plastic degradation can occur through two primary pathways: microbial and enzymatic degradation. In both types, involve the interactions of microorganisms with plastic materials. In microbial degradation, microbes implant themselves on the outermost layers of plastics. In enzymatic degradation, enzymes catalyze the degradation of plastics into water and $CO_2$,often in conjunction with microbial activity. Enzymes facilitate the degradation of polymers by inducing hydrogenation the polymers' surfaces and convert them into simpler compounds, such as monomers, dimers, and trimers, which are nutrition sources for microorganisms [46], [50]. The degradation of polymers alter the physical and chemical characteristics of polymers, particularly tensile strength, color, appearance, and shape, and induces cracking, erosion, separation, delamination, shifts in chemical composition, facilitating the production of functional groups [51]. Chemical degradation employs various chemical agents, such as acid bases and alkalis. Various biodegradation methods employ specific microorganisms and enzymes [51]. Biodegradation or enzymatic degradation are widely used, catalyzing plastic degradation by microbial enzymes without polluting the environment [52].

Microbial depolymerization and biodegradation are the alternative modes of plastic recycling and plastic waste treatment. The microbial degradation of plastics involves biodeterioration, biofragmentation, assimilation, and mineralization. Hence, biodegradation is widely regarded as the most economically viable and ecologically sustainable approaches to plastic degradation [53]. In contrast to other degradation methods, biodegradation offers financial and environmental advantages. This review focuses on the biodegradation of synthesized polymers by bacterial and fungal species.

## Microbial degradation of plastics

### Bacteria

Numerous studies have recognized bacteria as vital and diverse organisms with the capacity to degrade plastics. In recent years, plastic-degrading bacteria have been identified in numerous environments, including marine environments, landfills, soils, and composting environments [54]. The bacterial degradation of plastic waste is regarded as one of the most promising approaches for managing plastic pollution.

***Pseudomonas* species**

*Pseudomonas* spp. account for 21% of diverse bacterial genera linked to plastic degradation [56]. Early research on microbial plastic biodegradation primarily focused on *Pseudomonas* spp. [57]. Several *Pseudomonas* strains have been used to degrade plastics, with *Pseudomonas aeruginosa* receiving considerable interest because of its efficiency in degrading various types of plastics. *P. aeruginosa* isolated from the large intestines has attracted considerable interest. Notably, *Pseudomonas citronellolis* [58], *Pseudomonas putida* [59], *Pseudomonas alcaligenes* [60], and *Pseudomonas fluorescens* [61] have shown potential in the degradation of plastics. Several studies have indicated that *Pseudomonas* spp. are capable to degrade plastic materials by utilizing them as a carbon source, facilitating fungal growth and reducing polymers into the monomers and oligomers within few months [62]. Additionally, *Pseudomonas* spp. isolated from landfill soil samples have shown notable plastic degradation rates varying from approximately 76.4% to 85%within three weeks. These findings highlight the potential of microbial strains in effectively decomposing plastic materials, such as plastic bags [63].

Moreover, *P. aeruginosa* strains have been shown to effectively utilize plastics as a carbon source, achieving high percentages within 60 days of cultivation in modified Winogradsky columns [64]. Microbial communities, including *Pseudomonas* spp. have been reported to colonize microplastics, excrete enzymes, and reduce plastic molecular chains, elevating the high biodegradation rates of several kinds of plastics [65].

*Pseudomonas* spp. are thus recognized as durable and reliable agents for plastic biodegradation through enzymatic processes. In carbon metabolism, these bacteria secrete enzymes, such as esterase, serine hydrolase, and lipase, which degrade plastics into short-chain molecules, such as monomers and oligomers [63], [66]. Furthermore, *Pseudomonas* spp. have shown potential when used in combination with other microbial strains, such as *Pandoraea* sp. and *Dyella* sp. These organisms adhere to plastic surfaces, form biofilms, and secrete enzymes that degrade the molecular chains of plastics. This synergistic biodegradation has been associated with weight loss in various plastics, including PEF, PET, PVC LDPE, PP, and PS [67].

Research has demonstrated the capacity of *Pseudomonas* sp. to degrade PET plastics. Twenty-four-hour-old and fresh working cultures of *Pseudomonas* isolates from soil contaminated with petroleum showed lipase activity and ability to form biofilms on PET surfaces. However, PET seemed to be at a nascent stage of degradation, as indicated by molecular changes [68]. *Pseudomonas* has been known to have synergistic effects when used with *Bacillus* species in consortia in PET degradation, indicating a solution to the management of plastic waste. Degradation involves the secretion of enzymes that degrade PET into TPA and EG, which can be metabolically used for the production of monomers (Fig. 2) [69]. Some of the mechanisms by which *Pseudomonas* degrade plastics include cell surface attachment, enzymatic catalysis, specific pathways, and interactions with various chemical factors [70].

***Ideonella sakaiensis***

*Ideonella sakaiensis* is a recently identified bacterium notable for its ability to degradate PET, showing potential of plastic recycling [66]. This unusual bacterium was isolated from a sediment sample collected near a recycling facility in Osaka, Japan. This bacterium, a member of the genus *Ideonella*, within the family Comamonadaceae and class Betaproteobacteria, has attracted considerable attention for its unique enzymatic capabilities [71].

*I. sakaiensis* has demonstrated a remarkable ability to utilize PET as a carbon and energy source, facilitating chemical processes. This bacterium hydrolyzes PET into its constituent monomers, which can be repurposed for the production of new plastic products. Central to this process are IsPETase and MHETase, which catalyze the breakdown of PET into mono hydroxyethyl terephthalate (MHET) and dimeric bis 2-hydroxyethyl terephthalate (BHET), the latter of which can be further converted into monomeric MHET. Once these components are enzymatically disassembled into their fundamental constituents, they undergo further biodegradation, allowing cells to metabolize them as energy sources. Following as purification and recycling, these monomers can be repurposed for recycling applications. In contrast

to PET, which poses persistent threat to the environment, monomers pose minimal ecological risk [72].

IsPETase, also known as PET hydrolase, and MHETase, which is referred to as MHET hydrolase, are the two enzymes responsible for the enzymatic breakdown of PET. Upon contact with a PET surface, *I. sakaiensis* establishes a firm attachment, which subsequently triggers the release of the enzymes. The bacterium's extracellular structure facilitates the transport of IsPETase to the PET surface, thereby initiating the enzymatic degradation [73]. IsPETase functions as a hydrolytic catalyst that facilitates the breakdown of PET by utilizing a reactant ternary system consisting of Ser–His–Asp residues. The Ser residue serves as the nucleophile, attacking the ester bond on the acyl side. This reaction leads to the formation of a covalent intermediate (Fig. 1), with the assistance of solvents, such as EG [74]. MHET (major) and BHET (minor) are the resulting intermediates. With the assistance of porin proteins, the degradation products are transported to the periplasm, where further enzymatic processing occurs. MHETase, an outer membrane-anchored lipoprotein [73], plays a central role in this phase. This tetrahedral intermediate is stabilized by an oxyanion hole, which is shaped through covalent catalysis involving Try87 and Met160 residues [75]. The second step involves the hydrolysis of the major intermediate MHET by MHETase, which is a hydrolytic enzyme that hydrolyzes MHET, yielding the monomeric components TPA and EG. The TPA transporter and TPA-binding protein facilitate the uptake of TPA, which is then incorporated into the tricarboxylic acid (TCA) cycle through protocatechuic acid following its translocation across the membrane into the cytosol. Glyoxylic acid breaks down the other product, EG, in the TCA cycle [74]. As a result, this two-step hydrolytic reaction generates major products, such as TPA and EG, which can be further processed in plastic recycling plants into new plastic polymers.

### ***Rhodococcus* spp.**

*Rhodococcus* species exhibit exceptionally high potential for the degradation of different forms of plastics with the aid of specific enzymes. Core enzymes, such as PET esterases and PE oxidation enzymes, have been identified, which are crucial to the breakdown of plastics and causes weight loss, changes in molecular structure, and production of by-products, such as palmitic acid and TPA. These microbes degrade materials by forming biofilms, which ensure the efficient utilisation of plastic components. Different *Rhodococcus* species, including *R. pyridinovorans*, *R. erythropolis*, and *R. opacus* have demonstrated excellent plastic degradation ability [76], [77].

The ability of *Rhodococcus* species to degrade different types of plastics is attributed to the specific enzymes they produce. Among various plastic degrading enzymes, multicopper oxidases, alkane monooxygenases, cytochrome P450 hydroxylases, para-nitrobenzyl esterase, and carboxylesterase, are prominent plastic-degrading enzymes with distinct chemical structures, which are composed of C−C backbones, heteroatoms, and polyesters [77], [78]. However, the ability of *Rhodococcus* strains to generate biofilms on plastic surfaces enhance their biodegradation performance by providing structural support and facilitating the retention of nutrients [79]. An understanding of the enzymatic systems and metabolic routes in *Rhodococcus* species entails the effective use of these bacteria in biotechnological processes for mitigating plastic pollution [80], [81]. *R. ruber* C208 utilizes PE as the sole carbon source and forms a mud-like biofilm. A study utilizing weight loss analysis revealed a weight reduction of up to 8% in a polymer after 30 days of incubation; moreover, it was found to degrade polyolefins. The first developmental phase involves the formation of cellular clumps containing microcolonies in biofilms. *Rhodococcus* sp. is characterized by unique traits related to polymer degradation, although the efficiency of this process is influenced by isolation site. For instance, *Rhodococcus* sp 36 from soil sediments exhibited higher efficiency in degrading PP than *Bacillus* sp. Both bacterial strains demonstrated the capacity to utilize PP microplastics as growth substrates. *Rhodococcus* sp. 36 degraded PP by 6.4% after 40 days of cultivation, whereas Bacillus sp. achieved a degradation rate of up to 4.0% [82].

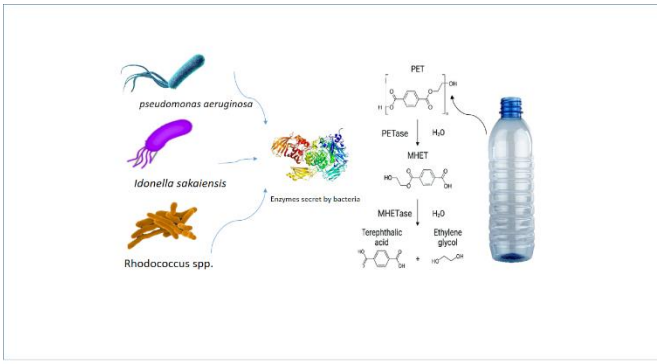


Figure 2. PET biodegradation by bacteria to

**Fungi**

Fungal communities, as integral components of the soil microbiota, play an important role in regulating ecosystem functions and soil biochemistry [83]. Although bacteria and fungi can decompose organic matter, fungi are largely and primarily responsible for decomposing resistant organic matter [84]. Fungi can utilize and partially degrade many plastic polymers, although the process is slow. The rapid biodegradation of plastics often involves fungal growth on plastic surfaces, and despite the high resistance of plastic polymers to degradation, they are often susceptible to fungal degradation, either independently or in conjunction with bacterial communities. Some fungi are capable of consuming plastic polymers as a food source [84]. Refrigerator insulation materials and artificial leather can be biodegraded within weeks through the application of fungi, which serve as effective agents for plastic degradation. Numerous fungal species are capable of utilizing plastic as a carbon source. For instance, the common edible oyster mushroom, found in the Amazon rainforest, has demonstrated such capabilities. *Pestalotiopsis microspore* can survive solely on plastic substrates because it can utilize PUR, which the main component of plastics and degraded into organic materials [84].

*Schisophyllum commune*, characterized by its split gill structures, has potential medicinal properties and has demonstrated potential in supporting cancer treatment. It absorbs excess plastics through biodegradation. PUR is more susceptible to fungal degradation than other types of plastic polymers [86], [87].

Soil fungi are involved in the decomposition of PUR [87]. Esterase and urethane hydrolase, which are secreted by fungi, such as *Aspergillus terrus* [89], [90], and xolipase, play an essential role in decomposing plastic waste [87]. The abundance of Ascomycota fungi in substrates with elevated concentrations of plastic polymers exceeds that in substrates with low concentrations of the same type of polymers [3], [91]. The biodegradation of plastics by fungal strains is a potentially cost-effective and environmentally advantageous approach for plastic waste treatmentc [91], [6]. Various Ascomycota fungal genera, such as *Aspergillus*, *Candida*, *Fusarium*, *Cladosporium*, *Paecilomyces*, and *Penicillium*, have been acknowledged as effective decomposers of a vast variety of plastics. However, research has mainly focused on the degradation of PE polymers by fungi, encompassing other forms of polymers and micro- and nanostructures [91], [72].

Fungi exhibit an ability to colonize various plastic polymers without pretreatment or supplementation with a carbon source and crucial to the initiation of plastic degradation. Alterations in fungal morphology serve as markers of fungal adjustment and proliferation on plastic polymers, such as PUR. Utilizing scanning electron microscopy (SEM), researchers observed that several fungal strains undergo morphological transformations and distortions when colonizing PUR and utilizing it for cellular proliferation. *Fusarium*, *Penicillium*, and *Trichoderma* have demonstrated considerably potential in breaking down polymers, such as PUR, rubber, and PE. Over 90% of the fungi thrive on PUR [92].

***Aspergillus* spp.**

A study demonstrated that *Aspergillus niger*, *Aspergillus terreus*, *Aspergillus fructus*, and *Aspergillus flavus* degraded HDPE heat treated at 70 °C for two weeks. The fungi grew densely, and fungal filaments penetrated the film and decreased the polymer mass and tensile strength of HDPE. Further analyses showed cracks on the polymer surface and decreased the amount of carbonyl residue, indicating a high fungal degradation potential for HDPE. By contrast, some studies have shown that fungi can degrade HDPE without any polymer pretreatment. *Aspergillus tubingensis* and *A. flavus* showed considerably high efficiency for HDPE

degradation. Moreover, changes in film surface topography and chemical changes, such as decreased carbonyl index, were observed. Light white oil stimulates hydrophobic interactions between species and polymer surfaces, enhancing biodegradation rate [93]. *A. flavus* has been reported to degrade HDPE into particle with low molecular weight, and the process may be driven by multiple laccase-like copper oxidases [93]. *Aspergillus japonicus* has the ability to degrade commercial LDPE over a period of two to four weeks. The degradation capacity of *A. japonicus* is twice that of *A. niger*, that is, *A. japonicus* degrades 11.11%, whereas *A. niger* degrades 5.8% in a month [88].

In the biodegradation of LDPE, the genus *Aspergillus* possess the capability to degrade PE. *Aspergillus oryzae* is more efficient in breaking down PE and synthesizing laccase and esterase than bacteria. A study utilizing electron microscopy to investige the surface morphology of PE films showed grooves and rough structures in plastic surfaces. *A. niger*, *A. terreus*, and *A. japonicus* exhibited degradation rates of 10% within one month, and scanning electron micrographs revealed brittle and porous PE surfaces. *Aspergillus clavatus* reduced the weight carrier capacity of PE by 35% in two months, producing 4 g/L CO2 after one month of incubation on the plastic surfaces. Similar effects were observed in LDPE films containing *Fusarium* fungi, which underwent considerable growth on the PE surfaces and induced the formation of pits and cracks and corrosion of PE, demonstrating its ability to utilize PE as a carbon and energy source [95], [96].

The ability of *Aspergillus* strains to degrade PVC is limited. A soil burial experiment using *Phanerochaete chrysosporium, L. tigrinus, A. niger* and *A. sydowii* thrived on PVC after 10 months of incubation [97]. Two different strains of *Aspergillus*, *A. terreus* and *A. fumigatus*, isolated from soil incubated in PBSA medium free of carbon source were able to degrade the PBSA polymer basic medium. *A. fumigatus* and *A. terreus* were found to degrade PBSA films at rates of over 80% within one month [98].

Various environmental factors affect the activity of esterase and lipase enzymes produced by *A. tubinggenesis*. Enzyme production is enhanced after the incorporation of different carbon sources to the PUR polymers [94], [46]. The optimum pH for maximum esterase activity was found to be at neutral pH, and lipase shows maximum activity at acidic pH. After two weeks, the enzyme activity began to decrease. The optimum temperature for both enzymes is 37 °C for *A. tubinggenesis*. Above and below this temperature, the production of both enzymes decreases [94].

Ten fungal strains belonging to the genera *Aspergillus and Penicillium*, from the Red Sea waters of Saudi Arabia, were found to be capable of degrading LDPE powder. *Penicillium* has a considerably high polymer adsorption rate. In another study on LDPE, 45 fungal isolates belonging to 13 fungal genera were found in tidal water and plastic waste collected from mangrove forests on the Red Sea coast of Saudi Arabia. In a similar study on LDPE, 12 different geophysical locations on the western coast of India were identified. A total of 109 fungal isolates were collected that were involved in LDPE degradation. Six robust LDPE-degrading fungal isolates were found in marine waters that grew abundantly on LDPE films, producing enzymes that degrade plastic polymers and releasing $CO_2$ [99], [100], [101].

***Myceliophthora* spp.**

*Myceliophthora* sp. is one of the most important fungi that degrade plastics by producing the enzyme laccase, which catalyzes the process of plastic degradation. The enzyme is produced at pH 5 and 30 °C [102].

***Pestalotiopsis microspora***

*P. microspora* is one of the important fungi in the decomposition of plastic waste, inducing changes in plastic samples, particularly in color [103], [104].

It is highly efficient in degrading plastics and capable of surviving solely in plastic substrates, converting PUR into organic matter even without oxygen [84], [88]. *Pestalotaibisis* has the ability to degrade plastic if PUR is used as a carbon source, and PUR degradation activity is linked to esterase activity. stimulates *P. microspora* produces esterase in a PUR medium and can degrade plastics under anaerobic and harsh conditions [104].

*P. microspora* uses plastics as a carbon and nitrogen source. PUR is completely degraded in a basal

medium after three weeks of incubation. The polymer degradation rate of the *P. microspora* is 71% under the same conditions [105]. In addition to degrading PUR in soil, this species can degrade PUR in aquatic environments [107]. It breaks down waste materials, such as PUR polyester and other polymers, and absorb them during fertilization, converting them into organic matter that can be safely consumed. In this process, the PUR is effectively reduced to energy for the fungus. This process completely reduces waste, rendering fungi as ideal agents for processing accumulated plastic waste [108].

**Enzymes involved in plastic degradation**

Biocatalysts include enzymes and major products from fungi and bacteria and play a role in increasing the rate of chemical reactions in living organisms. They are implicated in the biodegradation of plastics, modulating the physical structure of polymers and degrade them into oligomers, dimers, and monomers, which can be absorbed by the human body. Some enzymes are involved in the degradation of plastics on external interfaces, including peroxidases, lipases, esterases, amidases, oxidases, and laccases. Moreover, the enzymes are extensively used in various industries, such as pharmaceuticals, biofuel industries, and biodegradation [109].

These enzymes degrade PUR polymers by disrupting ester bonds [106], [110]. Lipase is produced by fungi, and one of the common genera is *Aspergillus* found in garbage, spoiled food, and soil. Lipase secreted by the extracellular part of fungi is capable of breaking down ester bonds. Apart from breaking down PUR, this enzyme can reduce fat waste [111], [112]. In addition, esterase has been applied to the food processing, pharmaceutical, and chemical industries, including plastic recycling. Esterase is a hydrolase enzyme that catalyzes the hydrolysis of ester linkage. It plays a role in the degradation of plastic polymers [113], such as PET, LDPE, and PB into PU. This enzyme is crucial to the breakdown and catabolism of ester substances in the human body. PET and PUR polymers contain ester bonds in their backbone structures. The enzyme considerably affects all types of plastic polymers, including PET, LDPE, PB, and PU. This enzyme plays a crucial role in the degradation and metabolism of ester compounds. Some polymers, such as PET and PUR, contain ester bonds in their structures. These ester bonds can bind to esterase enzymes and increase the efficiency of hydrolysis [90]. The multifactor nature of esterases enables them to efficiently degrade a wide range of substrates. Thus, esterases can target and degrade many plastic polymers [114], [115]. The production of enzymes depends on the type of plastic. For example, to degrade PUR, fungi secrete some enzymes that are important for degrading and disassembling plastic polymers [104]. *A. flavus* and *Fusarium graminearum* are some of the fungi known to produce enzymes, such as laccase amylase, lignin peroxidase, and manganese peroxidase. These enzymes are important and necessary for breaking carbon bonds in PE and other plastic polymers, and *Pastelotiobisis* produces serine hydrolase [103], [116].

Laccase and peroxidase introduce oxygen to the main chain of PE, triggering an electrical imbalance in the polymer structure. As a result, a carbonyl group is produced, and $CH_2$ becomes hydrophilic. These changes facilitate the enzymatic degradation of plastic polymers [106], [116]. Peroxidases have been found to catalyze the oxidation of a wide range of substrates by using hydrogen peroxide or other peroxides produced by many fungi as electron acceptors [118]. Fungal peroxidases are classified into several classes, including multipurpose peroxidases, manganese peroxidases, lignin peroxidases, and chromophore peroxidases [120]. These enzymes oxidize a variety of substrates with high oxidation and reduction potentials. They have various applications, particularly in the biodegradation of plastic polymers [120]. Peroxidase enzymes are mainly involved in the pre-degradation stage of plastics, allowing long carbon chains to be degraded into smaller molecules, which can be easily absorbed by fungi. Peroxidases, lipases, esterases, amidases, oxidases, and laccases have been found to be involved in extracellular plastic degradation [91]. Some extracellular enzymes secreted by pioneer bacteria and fungi can hydrolyze hydrophobic groups, thereby reducing the surface hydrophobicity of plastics and allowing the consumption of plastics. Plastics are then degraded into harmless substances, which are returned to the biochemical cycle, such as $H_2O$, $CO_2$, and N [139]. In addition, this enzyme exhibits stability and enzymatic activity at different temperatures and pH

levels. This enables laccases to work effectively in a variety of environmental conditions. Lactic acid was found to exhibit a synergistic relationship with other enzymes, such as peroxidase, leading to the degradation of polymers. [127] Laccase works at approximately 30 °C and acidic pH with a pH range of 2–5. It catalyzes a range of phenolic compounds and aromatic amines by withdrawing oxygen from $H_2O$ molecules. Peroxidase introduces oxygen into the PUR main chain, resulting in the formation of a carbonyl group, which renders the $CH_2$ chain hydrophilic and susceptible to enzymatic degradation [129], [130]. Some fungi produce other enzymes, such as cellulase pectinase, and glycosidase, which play an important role in decomposing polymers in soil into small, water-soluble, and insoluble components consisting of 10–50 carbon atoms and free radicals, which are then metabolized to fungi [85], [106]. The enzyme works protease hydrolyzes urethane bonds, making it effective on polymers including polyurethan and nylon. While urease works to degrade polyester PUR, one of the fungi that produce the urease enzyme is *Penicillium Fusarium* and *Trachoderma* [72], [131], [132]. Urease is involved in the biodegradation of PUR. The ester bonds present in PUR are targeted and cleaved by this enzyme and other related fungal enzymes. Urease also promotes the release of phenolic compounds into the culture medium [133]. Therefore, the enzymatic hydrolysis process is an ideal and important strategy for treating plastic waste [110].

To date, few studies have documented the involvement of fungal ligninase in the biodegradation of PVC by the fungus *P. chrysosporium*, especially in processes involving the attachment of fungal hyphae on the polymer surfaces by hydrophobin, formation of biofilms, and secretion of enzymes that can break down polymers into small fragments. PE, including HDPE and LDPE, and PVC, PS, and nylon can be degraded by laccases. PBS, PBSA, polycaprolactone (PCL), and PET can be degraded by lipases, esterases, and cutinases produced by fungi. Thus, the enzyme combination may help accelerate biodegradation. However, the overexpression of these enzymes in heterologous hosts and genetic modifications can improve their performance [92].

Esterases [134], lipases, proteases, and ureases can degrade PUR substrates through ester bond cleavage. Infrared analysis and molecular inhibition of PUR degradation by *P. microspora* have indicated that ester degradation by serine hydrolase is responsible for the biodegradation of PUR. PUR exhibits enhanced degradation activity under anaerobic conditions in synthetic polymers as the sole carbon source [94], [135].

The hydrolyzable ester of this aliphatic polyester is PCL, which makes it susceptible to microbial degradation by lipases and esterases. PCL is a synthetic thermoplastic polymer composed of the monomer caprolactone ($C_6H_{10}O_2$) and can be used in a wide range of applications [136], [137], [138]. PCL is biodegradable in many natural environments, such as soil and seawater [136], [139]. [137]. *Aspergillus fumigatus* has the highest degradation rate for PCL among known fungi [117]. Some microbial enzymes, such as laccases, ligninolytics, lipases, proteases, and ureases, can degrade plastic polymers exposed to biotic and abiotic factors [140]. In addition to enzymes, other compounds, such as acids and peroxides, alter the pH of the environment and facilitate biodegradation [139], [141].

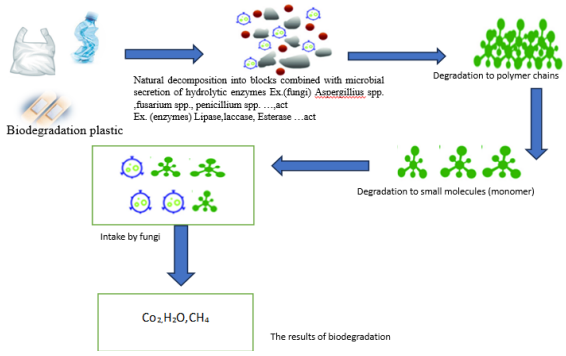


Figure 3. Effect of fungi on the decomposition of plastic

Table (1) lists a number of biodegradation enzymes that degrade plastic polymers.

| NO. | Enzymes | Fungi | Plastics polymers |
|---|---|---|---|
| 1 | Esterase | *Aspergillus oryzae* | |
| | | *Aspergillus calidoustus* | |
| | | *Aspergillus flavipes* | PET |
| | | *Aspergillus fructus* | LDPE |
| | | *Aspergillus pseudodeflectus* | PB |
| | | | PUR |
| | | *Aspergillus terreus* | PE |
| | | *Aspergillus tubingensis* | PP |
| | | *Aspergillus fumigatus* | PCL |

| | | | |
|---|---|---|---|
| | | *Aspergillus flavus*<br>*Aspergillus oryzae*<br>*Aspergillus niger*<br>*Chytridiomycota*<br>*Cryptomycota*<br>*Paramoeba permaquidensis*<br>*Embarria clematidis*<br>*pestalotiopsis microspora* | |
| **2** | Lipase | *Aspergillus tubingensis*<br>*Aspergillus oryzae*<br>*pestalotiopsis microspora* | PUR<br>PBSA<br>PCL |
| **3** | Laccase | *Myceliophthora* sp.<br>*Aspergillus terreus*<br>*Aspergillus calidoustus*<br>*Aspergillus flavipes*<br>*Aspergillus fructus*<br>*Aspergillus pseudodeflectus*<br>*Fusarium graminearum*<br>*Aspergillus japonicus* | <br>PE<br>HDPE<br>LDPE |
| **4** | Peroxidase | *Aspergillus pseudodeflectus*<br>*Aspergillus terreus*<br>*Aspergillus niger*<br>*Aspergillus calidoustus*<br>*Aspergillus flavipes*<br>*Fusarium graminearum*<br>*Chytridiomycota,*<br>*Cryptomycota ructus*<br>*Paramoeba permaquidensis*<br>*Phanerochaete(P.)chrysosporium*<br>*Trametes (T.) versicolor*<br>*Aspergillus graminearum* | <br>LDPE<br>PS<br>PE |
| **5** | Urease | *Aspergillus niger*<br>*Embarria clematidis*<br>*pestalotiopsis microspore*<br>*Penicillumbrevicompactum*<br>*Fusarium tricinctum*<br>*Trichoderma harzianum* | PU<br>PE |
| **6** | Protease | *pestalotiopsis microspora* | PU |
| **7** | Ligninase | *Phanerochaete chrysosporium* | PVC |

## Conclusions

Various forms of bacteria and fungi assist in the degradation of plastics. *Pseudomonas*, *Ideonella*, and *Rhodococcus* are the primary bacteria, whereas fungi, such as *Aspergillus*, *Myceliophthora*, and *Pestalotiopsis* have demonstrated effectiveness. Altering the controlling variables can boost the efficacy of plastic biodegradation by these microorganisms. This approach is promising for mitigating plastic pollution.

## Conflicts of Interest

The authors confirm that they have no known conflicts of interest associated with this publication and no significant financial source has been received that could have influenced the study's outcomes.

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# إمكانيات المعالجة الحيوية للنفايات البلاستيكية: البكتيريا والفطريات

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**الخلاصة:**

ان استخدام المنتجات البلاستيكية في جميع القطاعات الصناعية يتزايد بمعدل ثابت، مما يزيد من تراكم الملوثات في الماء والتربة. ويشكل انتشار هذه المركبات المصنعة في النظم البيئية الأرضية والمائية مخاطر كبيرة على صحة الإنسان. ان النفايات البلاستيكية اصبحت مصدر قلق عالمي في النظم البيئية المختلفة. تتضمن عملية التحلل الحيوي استخدام أشكال مختلفة من الكائنات الحية، مثل البكتيريا والفطريات وما إلى ذلك، والتي تتمتع بكفاءة عالية في تحلل أشكال مختلفة من البلاستيك. وقد أظهرت انواع عديدة من البكتيريا مثل ***Pseudomonas*** ،***Ideonella*** و***Rhodococcus*** قدرتها على تحلل البلاستيك واستخدامه كمصدر للكربون، حيث تقوم هذه البكتيريا بتحويل البلاستيك إلى جزيئات أبسط باستخدام الإنزيمات. وعلاوة على ذلك، أظهرت الفطريات مثل ***Pestalotiopsis microspora*** ،***Schizophyllum*** ،***Fusarium*** ،***Penicillium*** و***Trichoderma*** القدرة على تحلل البلاستيك واستخدامه كمصدر للكربون، مما يجعلها أدوات فعالة في معالجة النفايات البلاستيكية. تعتمد عملية التحلل الحيوي على الكائنات الحية الدقيقة وأنزيماتها لتفكيك البوليمرات البلاستيكية. ان الإنزيمات الأيضية التي تنتجها هذه الكائنات الحية الدقيقة وسيلة مفيدة لإزالة هذه البوليمرات. وهذا يجعل المعالجة الحيوية خيارًا صديقًا للبيئة وأكثر أماناً من المعالجة الكيميائية. ومع ذلك، يواجه هذا النهج تحديات تتعلق باختيار الكائنات الحية الدقيقة المناسبة ومعدلات التحلل االبطيئة مقارنة بالطرق الكيميائية.

**الكلمات المفتاحية:** البلاستيك، البكتريا، الفطريات، التحلل الحيوي، انزيمات التحلل