Fungal Degradation of Plastics: A Review

P-ISSN: 1680-9300
E-ISSN: 2790-2129
Vol. (26), No. (2)
pp. 51-66

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Abstract:

Plastics have been increasingly used to supplement or partially replace natural and traditional materials including paper, wood and in some uses, even metals because they are inexpensive, highly flexible, strong, and non-biodegradable. Increased production of plastic, worldwide distribution, and the lack of degradability resulted in plastic accumulations in the environment and pose serious environmental and biological health risks. Therefore, creating appropriate measures for the cleanup environment may be a top priority in our attention. Recently, breakdown of polymers by biological systems has attracted the interest of Numbers of researchers. Different fungal species are shown to be able to break down plastic polymers and use them as a carbon source. This feature is exploited as an environmentally friendly approach to manage plastic waste. Various fungal strains have been shown to be effective in this field, including Aspergillus flavus, Phanerochaete chrysosporium, Aspergillus niger, Fusarium sp., Mucor sp., Cephalosporium sp., and others. Biodegradation mechanisms of polymers include biodeterioration, followed by polymer fragmentation, microbial assimilation, and ultimately mineralization. This review highlights the type of plastics, the fungal role in degradation of plastic, the biodegradation process of plastic polymers, the environmental conditions that influence the biodegradation process of plastic polymers as well as the enzymes used by fungi in the biodegradation process of plastic polymers and other methods of measuring and analyzing the biodegradation process of plastic polymers.

Keywords: Plastic Polymer, Biodegradation, Fungal Species, Fungal Enzymes, Assessment Techniques.

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1. Introduction

Plastics are a wide range of synthetic and semi-synthetic materials which simplify our life, make it easier, cleaner and less dangerous (Andrady & Neal, 2009). They are produced from repeating chemical units consisting of hydrocarbons to produce synthetic polymers which represent the primary units of plastic production (Napper & Thompson, 2020). The sources of make plastic include cellulose, salt materials, natural gas and crude oil (Höfer & Selig, 2012).

The basic dependence on a broad range of plastic materials has become essential to modern civilization and our lifestyle. Plastic usage and production have grown exponentially in the past 40 years since they find application in the broadest variety of products: agriculture, food packaging, transportation and electronic sectors, and even in the building industry (Larue et al., 2021). The extensive use of plastic in most industries has resulted in the manufacture of different kinds of plastics such

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Journal of Prospective Researches
Vol. (26), No. (2)
The paper was received on March 2, 2026; accepted on April 22, 2026; and published on April 29, 2026.

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10.61704/pr.606

as polyethylene terephthalate (PET), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), polypropylene (PP), polystyrene (PS), polycarbonate (PC), and polyurethane (PUR) (Geyer et al., 2017; Proshad et al., 2018) (Figure 1). The massive manufacturing of plastic led to the entrance of these long-chain polymers into all ecosystems and made them a serious environmental problem because waste management methods were unable to keep pace with the increasing rate of plastic consumption (Lau et al., 2020; Borrelle et al., 2020).

Research showed that between the year 1950 and 2015, only 9 percent of plastic waste was recycled and 12 percent was incinerated, and 60 percent found their way to the landfills or into the ocean waters of the world (Jambeck et al., 2015; Geyer et al., 2017; Vince & Stoett, 2018). Approximately 90% of plastic products produced globally are recalcitrant to degradation and are still present in the ecosystems (Galloway et al., 2020). Plastic can also become a significant risk to both the biotic and abiotic communities of the land and water (Stapleton, 2019; Mercogliano et al., 2020). Plastic waste management can either be done by burning the waste in the incinerator or disposing of it in landfills, which adds to global warming by releasing quantities of CO2 to the atmosphere (Gurgacz et al., 2023). High volumes of plastic dumping in natural environments resulting in soil, water, and air pollution (Wiedinmyer et al., 2014; Velis & Cook, 2021).

However, studies have proven that the cause of environmental pollution problems is megaplastic, macroplastic, mesoplastic, microplastic, and nanoplastic (Debroy et al., 2022). Plastic materials can be divided into smaller sizes such as mesoplastics (5mm-25mm), microplastics (less than 5mm), and nanoplastics (1 µm or 1000 nm) through environmental processes (Hartmann et al., 2019). Microplastics (MPs) and nanoplastics (NPs) are currently became as new pollutants that pollute the environment in diverse ways (Liu et al., 2024).

Jiang et al., (2019) documented the existence of micro and nanoplastics (MNPs) in rivers on the Tibetan Plateau, showing the impact of human practices even in isolated areas. Dube & Okuthe (2023) demonstrated that micro- and nanoplastics (MNPs) can be used in a wide range of sectors like textiles, packaging, agriculture, construction, and pharmaceuticals thereby contributes to the rapid diffusion of MNPs in the atmosphere, lithosphere, hydrosphere, and biosphere. Micro- and nanoplastics (MNPs) severely cause health effects for life forms; various forms of biota can mistakenly consume microplastics and nanoplastics as food. Once ingested, these particles can accumulate in their bodies and move up the food chain through bioaccumulation, eventually reaching higher trophic levels. This process poses risks to living organisms' health, as well as to microorganisms. (Chatterjee & Sharma, 2019).

In the same manner, the micro- and nanoplastics (MNPs) affect the growth of plants by affecting nitrogen delivery to plants in the agroecosystem of soil (Iqbal et al., 2020). Exposure of humans to MNPs through inhalation, ingestion, or dermal penetration can cause aberrant development of organs, inflammation, immune dysfunction, and tumorigenicity (Sun & Wang, 2023) Many studies have been done to see if bacteria may make use of polluted polymers in efforts to create new methods for handling plastic waste. By doing this, they may offer a sustainable and eco-friendly substitute for handling plastic waste (Cowan et al., 2022).

The most promising approach for dealing with plastic substances is biodegradation compared to other traditional methods such as incineration or dumping in landfills because it is eco-friendly in nature, and the end product of the process is harmless substances for the environment (Srikanth et al., 2022). Biodegradation involve numerous microbial strains able to degrade plastic substance under multiple environmental parameters (Srikanth et al., 2022). Bioremediation is an effective approach which employs biological agents, including bacteria, fungi, and algae for reducing plastic waste to acceptable levels in an environmentally acceptable way (Pathak & Navneet, 2017).

Fungi are living organisms belonging to their own kingdom within eukaryotic organisms. They inhabit a wide variety of terrestrial and aquatic environments. Most of the fungi are aerobic and they should have oxygen to survive though some can also survive under low oxygen levels such as in the oxygen minimum layers of the oceans or in the digestive system of animals. Fungi have some enzymatic systems that are capable of degrading complex organic matter and use them as sources of carbon and energy (El-gendi et al., 2021).

Fungi are key agents in the biodegradation of plastic polymers. It has been noted that fungi are effective in degrading materials through the production of enzymes such as lipases, cutinases, proteases, laccases, esterases and peroxidases that help in the degradation process of plastic under the influence of pro-oxidant ions like Fe^{2+}, Cu^{2+}, and Mn2+. Enzymes have the ability to break down larger molecular weights of chemicals and transform them into smaller ones that reach the nano scale by producing functional groups that oxidize or hydrolyze polymers and make them more hydrophilic (Srikanth et al., 2022).

Many studies indicated that significant numbers of fungal strains that are capable of breaking down long chains of polymers formed plastic material, like Alternaria sp., Aspergillus sp., Fusarium sp., etc. (Munir et al., 2018; Ekanayaka et al., 2022).

Another eco-friendly approach that can be used to control plastic waste in the world is mycoremediation of plastic which means the biodegradation of plastic waste by fungi. This review will attempt to identify the importance of fungi in the degradation of plastic classes, emphasize biodegradation as a mechanism that is used in the bioremediation process for plastic waste, identify the prevalent fungal strains and enzymatic systems that are involved in the plastic degradation, and assess of the remediation process.

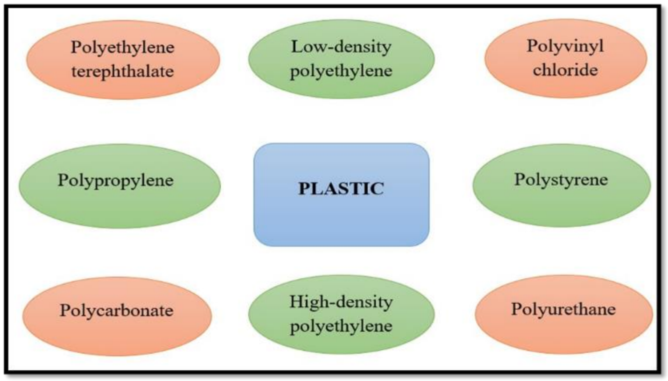

Figure 1. Classification of Plastics According to Chemical Structures.

2. Characteristics and Categories of Plastic

2.1 Polyethylene (PE)

One of the common types of plastic is made from synthetic petroleum-based polymers and is the most prevalent and extensively marketed (Montazer et al., 2020). Polyethylene is made up extended linear chains of ethylene (C_2H_4) monomers and can be divided into either low-density polyethylene (LDPE) or high-density polyethylene (HDPE) based on the molecular weight and number of carbon atoms forming it (Mierzwa-Hersztek et al., 2019).

HDPE is used in producing detergent bottles, milk and juice bottles, waste containers, toys, and others, while LDPE is used in shopping and garbage bags, irrigation tubes, and others (Chen & Lin, 2021). The molecular weight of HDPE ranged from 100000 to 250000 Daltons, whereas that of LDPE was 40000 Daltons (Kurtz & Manley, 2009).

Because products made from PE are only used for a short time, they gradually accumulate in significant amounts in the environment. These significant quantities of PE waste prompted researchers and scientists to find appropriate alternative methods, such as microbial biodegradation, to face this emerging problem (Ragaert et al., 2017).

2.2 Polyethylene terephthalate (PET)

One of the most common plastics which is utilized in daily life and consists of thermoplastic polymers based on petroleum (Sang et al., 2020). PET is a linear polyester polymer produced from ethylene glycol $(C10H8O4)n$ and terephthalic acid (TPA) (Raheem et al., 2019).

Based on the intended application of PET products, the molecular weight ranged between 20000 and 50000 Daltons (Pang et al., 2016). PET is used in producing water and juice bottles and food containers, as well as in the textile sector to make polyester fibers for the clothing industry (Zimmermann & Billig, 2010).

PET is also utilized in industrial fields, such as producing electronic components (Zimmermann & Billig, 2010). PET can convert to various polymer degradation products like aromatic acids and low- molecular weight oligomers by chemical, physical, or biological depolymerization (Malafatti-Picca et al., 2019).

2.3 Polyurethane (PUR)

Synthetic thermoset polymer is a compound of ethyl carbamate ($H_2NCO_2C_2H_5$) and urethane which is combined with aromatic groups, ester, ether, and urea in repeated units. Polyurethane is divided into polyester (ester groups forming its structure) and polyether (ether groups forming its structure) (Álvarez-Barragán et al., 2016).

These groups are based on a condensation reaction that uses polyols to produce polyurethane (Álvarez - Barragán et al., 2016).

PUR is a multilateral substance that may be utilized as an elastomer, as a textile fiber, in paints, in pillows, and as foam for building insulation. Nowadays, the issue of the disposal of polyurethane into the environment represents a major challenge because it needs hundreds of years to decompose, and incineration measures release toxic emissions from PUR waste (Mahajan & Gupta, 2015).

2.4 Polyvinyl chloride (PVC)

PVC is a synthetic, thermoplastic, and petroleum-based substance that is widely utilized. The chlorine element (C_2H_3Cl) contributes 56.77% (w/w) of the long chains of ethylene monomers that make up pure PVC (Yang et al., 2013).

It is characterized as a solid, white, and harsh polymer that is resistant to chemical abrasion as well as extremely hydrophobic (Peng et al., 2020). It is utilized in producing pipes, electrical wires, profiles of doors and windows, walls and floor covers, credit cards, and textile goods (Peng et al., 2020).

PVC products gained particular interest because they have a long lifespan in the environment, and their management ways, whether disposing of them in landfills or incineration, causing the release of large amounts of tetrachlorodibenzo-p-dioxin and hydrogen chloride (Peng et al., 2020).

2.5 Polypropylene (PP)

PP is a thermoplastic, linear hydrocarbon synthetic polymer whereby one of the methyl groups replaces one hydrogen atom in the PP structure (Sheik et al., 2015). Compared to PE, PP is a semicrystalline, inert substance that is somewhat stronger and more resistant to chemical reactions and heat. The molecular weight of PP is 10,000 to 40,000 Daltons and it is highly hydrophobic (Mohanan et al., 2020).

There are many sectors in which PP can be used, including diapers, pipes, automobile parts, and food and material packaging (Tokiwa et al., 2009). The short lifespan of materials that are packaged by PP resulted in the entrance of enormous quantities of PP into environmental systems; therefore, there is a need to find alternate, environmentally appropriate techniques such as fungal or bacterial biodegradation instead of disposal in the environment (Mohanan et al., 2020).

The process by which PP becomes resistant against biodegradation includes its hydrophobicity characteristic, high-molecular-weight, and chemical additives that preserve PP from atmospheric oxidation.

2.6 Polystyrene (PS)

PS is a highly stable, synthetic, thermoplastic polymer that consists of aromatic styrene monomer $(C_8H_8)_n$. PS is hard and rigid because of its strong hydrophobicity and huge molecular weight (Chaudhary & Vijayakumar, 2020; Othman et al., 2021). Because of its cost- effectiveness, easy production, hardness, and light weight in transport, PS is appropriate in the packaging industry (Ho et al., 2018; Chaudhary & Vijayakumar, 2020).

It is used in producing electrical and electronic devices as well as products related to construction (Krueger et al., 2017). There are a few studies that have been done on the biodegradation of PS by fungi because of its resistance to the breakdown process of the carbon backbone (Goldman, 2010).

3. Biodegradation

Biodegradation is an effective process for degradation of plastic since its final products do not pollute the environment, it is an eco-friendly mechanism, and it is carried out with fewer requirements by organisms present in the natural environment, thereby being cost-effective (Srikanth et al., 2022). Microorganisms, in particular, fungi are critical in the decomposition of complex organic matter by the use of physicochemical processes into simple components (Radhi & Zaaen, 2025). Biodegradation of plastic occurs in several steps based on biochemical routes encompassing biodeterioration, biofragmentation, assimilation, and mineralization (Heris, 2024) (Figure 2).

Biodeterioration in this stage, the microbe binds to the plastic surface and forms microcracks, which alter the physicochemical and mechanical values of the plastic including color, brightness, and flexibility, thereby accelerating the biodeterioration process of plastic polymers (Kumar et al., 2017). Biofragmentation, or depolymerization, is the significant stage involved in biodegradation of plastic whereby polymer chains are cleaved into smaller components (oligomers, dimers, and monomers) using extracellular enzymes secreted by microorganisms, where chemical bonds are broken by different mechanisms, mostly through the hydrolysis pathway using hydrolases such as cutinase, esterases, and lipases, as well as oxidation catalyzed by oxidative enzymes such as laccase, manganese peroxidase, and lignin peroxidase. Introducing polar functional groups (–OH and –COOH) along the polymer chains breaks down the chemical bonds formed; consequently, the plastic is degraded into compounds with low molecular weight (Abdullah et al., 2020; Asiandu et al., 2021).

The purpose of microbial adhesion on the substrate (plastic polymers) and secreting extracellular enzymes is to obtain a source of plastic-derived carbon, which can be utilized as energy source and biomass synthesis (Jenkins et al., 2019; Anjana et al., 2020). Assimilation, also known as the uptake stage in which the molecules resulting from polymer biodegradation enter the microbial biomass across the cellular membranes by transport proteins to reach the cytoplasm and are converted into intermediate compounds within energy-generating pathways (Asiandu et al., 2021).

Mineralization is the last stage in the biodegradation of plastic; the monomers are converted to smaller molecules in both aerobic and anaerobic conditions to give CO_2 and H_2O under aerobic conditions, whereas they release CH_4, N_2 and H_2 in anaerobic conditions. Mineralization levels determine the rate of plastic biodegradation (Ho et al., 2018; Anjana et al., 2020).

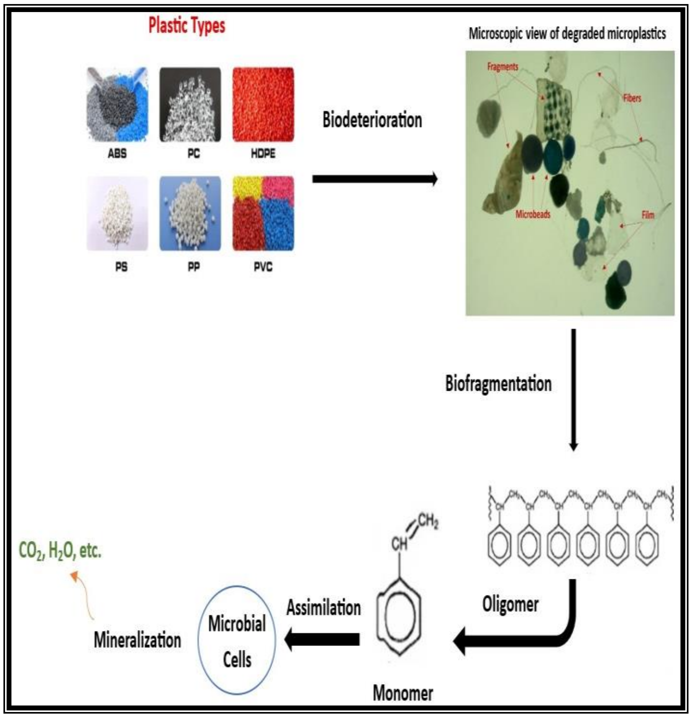

Figure 2. Biodegradation Steps of Plastic Polymers.

4. Role of Fungal Species Involved in Biodegradation

Two The fungi are widespread organisms in the world, and the number of fungal species is estimated to be from 1.5 to 12 million, including parasitic, saprotrophic, and mutualistic fungi that survive in the variety of niches and host environments located in soil, water, and living bodies (Bhunjun et al., 2022). Fungi can have unicellular, filamentous, or dimorphic morphologies. Various types of fungi are important to the biodegradation strategy of plastic polymers due to their potential to secrete enzymes such as cutinase, laccase, esterases, and lipases, which are able to cleave chemical bonds of complex polymers and use them as a carbon source extracted from plastic polymers (Raghukumar, 2017; Gladfelter et al., 2019).

Fungal degrading potential of plastic polymers makes it one of the key strategies for managing the plastic waste issue (Ojha et al., 2017). Biological degradation of plastic by fungi involves alteration of physical and chemical properties of basic structures forming plastic by functional groups of fungal enzymatic secretion that change surface properties, reduce molecular weight, solubility, or cause loss of flexibility and mechanical strength of plastic (Krueger et al., 2015; Wei & Zimmermann, 2017).

Plastic biodegradation can be influenced by many agents for example the chemical structure of plastic polymers, elasticity, degree of crystallinity, plasticizers added, and melting temperature as well as the dimensions of molecules formed of plastic polymers (Vedrtnam et al., 2019). Environmental factors contribute to the biodegradability of plastic, such as exposure to temperature or ultraviolet radiation (UV), and introduce functional groups like carbonyl, carboxyl, and hydroxyl groups that lessen the hydrophobicity of plastic, thereby increasing the biodegradability level of plastic (Tokiwa et al., 2009; Jacquin et al., 2019; Taghavi et al., 2021).

Fungal exoenzyme secretion degrades plastic polymers in various forms; either the surface of plastic polymers is modified by hydrolase enzymes (cutinases, proteases, lipases, and carboxylesterases) to increase their hydrophilicity, or the degradation of polymers into smaller molecules is carried out by oxidoreductase enzymes (peroxidases and laccases) (da luz et al., 2019). Table 1. Summarizes many fungal species are able to secrete plastic polymer-degrading enzymes, such as Aspergillus sp., Penicillium sp., Mucor sp., etc. (Ekanayaka et al., 2022).

Table 1. **Major Fungal Enzymes Involved in Degradation of Plastics.**

Fungal species	Enzyme type	Degrading mechanism	References
Alternaria alternata *Ascocoryne* sp. *Aspergillus* sp. *Aspergillus caespitosus* *A. terreus* *Clavariopsis aquatica* *Cochliobolus* *Eupenicillium hirayamae* *Lesiodiplodia theobromae* *Paecilomyces lilacinus* *P. variotii* *Paradendriphiella arenariae* *Trichoderma harzianum* *Trametes versicolor* *Phialophora alba* *Phoma* sp. *Pleurotus ostreatus*	Laccase	Oxidoreductases	Sheik et al., 2015; Zhang et al., 2020
Aspergillus oryzae *Fusarium solani* *Amycolatopsis mediterannei* *Humicola insolens* *Moniliophthora roreri* *Thermobifida fusca* *Thermomyces lanuginosus*	Cutinases	Hydrolases	Ronkvist et al., 2009; Tan et al., 2021
Aspergillus fumigatus *A. flavus* *A. niger* *A. tubingensis* *Cladosporium* sp. *Cladosporium asperulatum* *C. montecillanum* *C. pseudocladosporioides*	Esterases	Hydrolases	Álvarez-Barragán et al., 2016; Khruengsai et al., 2022

C. tenuissimum *Aureobasidium pullulans* *Curvularia senegalensis* *Embarria clematidis*			
Acremonium sp. *Alternaria* sp. *Aspergillus flavus* *A. oryzae* *A. tubingensis* *Beauveria* sp. *Candida* sp. *Mucor* sp. *Fusarium* sp. *Penicillium citrinum* *Rhizopus* sp. *Fusarium solani* *Penicillium* sp. *Rhizomucor* sp. *Cryptococcus* sp. *Eremothecium* sp. *Geotrichum* sp. *Humicola* sp. *Ophiostoma* sp. *Thermomyces lanuginosus* *Trichoderma* sp.	Lipases	Hydrolases	Garrido et al., 2012; Thirunavukarasu et al., 2016; Khan et al., 2017; Tan et al., 2021; Khan et al., 2023
Aspergillus caespitosus *A. terreus* *Ascocoryne* sp. *Alternaria alternate Phialophora alba* *Ceriporiopsissubvermispora* *Clavariopsis aquatica* *Dichomitus squalens* *Paradendriphiella arenariae* *Phanerochaetechrysosporium* *Phlebia radiata* *Polyporus brumalis* *Trametes versicolor Bjerkandera adusta* *Eupenicillium hirayamae* *Paecilomyces variotii Trametes versicolor* *Phoma* sp.	Peroxidases Manganese peroxidases Lignin peroxidases Versatile peroxidase	Oxidoreductases	Ryu et al., 2014; Temporiti et al., 2022

5. Fungal Enzymatic Systems Involved in Plastic Degradation

Studies associated with the fungal capability of degrading plastic material discovered that there are many types of fungal enzymes involved in the biodegradation of plastic (Temporiti et al., 2022). Table 2. Categorizes these enzymes based on the enzyme's ability to degrade plastic types.

5.1 Cutinases

Cutinases are extracellular esterase enzymes that belong to the α/β-hydrolase classes and are secreted by fungal and bacterial groups, which exhibit differences in their primary structure based on whether they are eukaryotic or prokaryotic origin (Chen et al., 2008). The primary structure of cutinase consists of an α/β fold and a central β-sheet with five parallel strands (Gigli et al., 2019). They have an active site composed of a catalytic group of Ser-His-Asp/Glu (Gigli et al., 2019).

Catalyzing mechanisms include the removal of the hydroxyl group of serine by histidine, a nucleophilic attack the acyl carbonyl carbon on the substrate forming an acyl-enzyme intermediate that is subsequently hydrolyzed, and the negative charge formed by the oxyanion hole is stabilized. Many fungal species secrete cutinase enzymes, such as Aspergillus oryzae, Fusarium solani, Penicillium citrinum, and Humicola insolens (Liebminger et al., 2009; Gigli et al., 2019).

Cutinases contribute to the biodegradation of plastic polymers. Cutinase enzyme from Fusarium solani pisi degrades 97% of low-crystallinity PET film during 96 h (Ronkvist et al., 2009). Cutinase enzyme isolated from Cryptococcus sp. has effective degradation potential of polylactic acid (PLA) in plastic.

5.2 Lipases

Fungal lipases are extracellular enzymes belonging to the esterase class. The lipase enzyme exhibits optimal potential to degrade synthetic polymers, making it a promising way to remediate plastic waste. Lipase enzyme is produced by some fungal species such as Aspergillus oryzae, Candida antarctica, and Rhizopus delemer (de castro et al., 2017; Carniel et al., 2017).

Many studies related to the capability of lipase to degrade plastic compounds showed lipase secreted by Rhizopus delemer degraded 53% of the polyester -type polyurethanes (ES-PU) film in one day only (Tokiwa et al., 2009). Lipase extracted from Candida antarctica exhibited remarkable activity to degrade polyethylene terephthalate (PET) (Carniel et al., 2017). Lipase from Aspergillus niger has biocatalytic activity to degrade polyethylene (PE), polyethylene terephthalate (PET), and polystyrene (PS) (Safdar et al., 2024).

5.3 Esterases

Esterase enzymes are part of the hydrolase class that catalyze the cleavage of ester compounds into acids and alcohols. Esterases produced by bacteria and fungi are able to the decomposition of plastic (Khandare et al., 2022).

Some fungal species that secrete the esterase enzyme encompass Aspergillus flavus, Aspergillus tubingensis, Chaetomium globosum, and Aspergillus terreus (Khan et al., 2017). Esterase enzyme is able to degrade polycaprolactone (PCL) and poly (butylene succinate-co-adipate) (PBSA) film (Adigüzel et al., 2024).

5.4 Laccases

Laccase is a multi-copper oxidase enzyme that is responsible for catalyzing the oxidation process of phenolic substances. It generates water and byproducts while using molecular oxygen as a co-substrate (Nunes & Kunamneni, 2018). Laccase enzyme can be isolated from some fungal species such as Aspergillus terreus, Penicillium sp., Aspergillus flavus, Pleurotus ostreatus, and Trichoderma harzianum (Gómez-Méndez et al., 2018; Zhang et al., 2020; Eldin et al., 2022).

Laccases have the unique capacity to oxidize lignin, which helps them to achieve the degradation process of recalcitrant substances (Osma et al., 2010). Additionally, laccase may contribute to the oxidation of hydrocarbons that represent the primary chemical structure of polyethylene (PE).

Activity of both laccase and manganese peroxidase together proved their ability to degrade anthracene (Khajehzadeh et al., 2024). Laccase derived from Aspergillus terreus and Penicillium sp. demonstrated efficiency in degrading polyethylene (PE) (Eldin et al., 2022).

5.5 Peroxidases

Peroxidases are oxidoreductase enzymes catalyzing redox reactions by free radicals that insert or remove electrons of compounds during reactions, thereby forming oxidized-polymerized compounds. Peroxidases are classified into lignin peroxidases (LiP), manganese peroxidases (MnP), versatile peroxidases (VP), and generic peroxidase (Kellner et al., 2014).

Common fungal species that produce peroxidase enzyme include Trichoderma harzianum, Phanerochaete chrysosporium, Trametes versicolor, Pleurotus ostreatus, Aspergillus niger, Aspergillus flavus, and Fusarium graminearum (Ganesh et al., 2017).

Manganese peroxidase enzyme from Trichoderma harzianum and Phanerochaete chrysosporium exhibit outstanding potential to degrade polyethylene. Peroxidase produced by Fusarium graminearum showed polyethylene-degrading capacity (Ganesh et al., 2017).

Table 2. **Documented Fungal Enzymes for Degrading Plastic Types.**

Plastic type	Degradation enzyme	References
PE	Laccases Peroxidases Lignin peroxidases Manganese peroxidases	Gómez-Méndez et al., 2018; Malachová et al., 2020; Santacruz-Juárez et al., 2021
PET	Cutinases Lipases Esterases	Almansa et al., 2008; Danso et al., 2019; Carr et al., 2020
PUR	Cutinases Proteases Esterases Ureases Lipases	Yang et al., 2013; Khan et al., 2017; Osman et al., 2018; Temporiti et al., 2022
PVC	Laccases	Chaudhary; Vijayakumar, 2020
PS	Esterases	Tahir et al., 2013

6. Assessment of Remediation Mechanism

There are several techniques to assess the level of biodegraded plastic by fungi. Gravimetric assessment is the oldest and simplest method for calculating the biodegradable level of plastic. In this method, the plastic weight is measured before exposure to fungal degradation, then measured again after a period of time from fungal growth on the plastic polymers; loss in plastic weight indicates plastic biodegradation (Syranidou et al., 2017).

Nowadays, a number of novel assessment techniques are adopted to quantify the level of plastic biodegradation. Scanning electron microscopy (SEM) is employed to assess biodegradation of plastic by using a high-intensity electron beam to illuminate a surface and then scanning across it. Scanning Electron Microscopy (SEM) produces a surface image, offers high magnification, and thus provides high clarity at the nanoscale level (Baidurah, 2022).

SEM is used to monitor the colonization of microorganisms in plastic films and image the damage to plastic polymers resulting from cracks, pits, and deformation caused by microorganism growth in plastic particles (Vaksmaa et al., 2021). Many studies have used SEM in examinations related to fungus growth on polymers. SEM is a quick method for examining microstructures in fungi and surface attachments (Ojha et al., 2017).

The presence of these morphological damages (e.g., cracks, pits, and erosion) gives direct visual evidence of microbial activity and, therefore, the presence of biodegradation. Another technique for monitoring surface modification of polymers that undergo biodegradation process is Atomic Force Microscopy (AFM). Topographical changes occurring at the surface of polymer, including the formation of pits and crevices, microbial colonization as well as surface roughness can be directly seen in this technique.

These nanoscale topographical changes and enhanced roughness of the plastic surfaces are good evidence of gradual degradation of the polymers. To identify chemical changes for molecular structures of polymers, Fourier-Transform Infrared Spectroscopy (FTIR) can be used during and after exposure to biodegradation processes, such as monitoring functional groups in original polymer chains, detecting degradation products, and comparing samples before and after biodegradation processes by determining physical and chemical changes of plastic polymers (Xu et al., 2019; Almond et al., 2020). X-ray Diffractometer (XRD) used in the crystalline examination of biodegraded polymers. Differential Scanning Calorimetry (DSC) is utilized to detect thermal changes in polymers exposed to biodegradation that affect their properties, such as the glass transition temperature, melting temperature, crystallization temperature, percentage of polymer crystallinity, specific heat capacity, transformation enthalpy, and many more (Suresh et al., 2011).

Such modifications in functional groups, chemical bonds, crystallinity and thermal properties give a clear indication of the breakdown of a polymer chain during biodegradation. It is important to measure the CO_2 level released during each step of the degrading process. Obtained CO_2 concentration provides evidence of the breakdown of polymers, the rate and biodegradation efficiency, and biomineralization thereby, confirmation of the existence of biodegradation (Rauscher et al., 2023). To prove the biochemical change and degradation of polymer materials, both Gas Chromatography-Flame Ionization Detection (GC-FID) and Gas Chromatography-Mass Spectrometry (GC-MS) are used for analyzing secondary metabolites generated during biological break down of polymers (Eyheraguibel et al., 2017).

The presence of released monomers and oligomers also confirms the presence of polymer degradation thus, High-Performance Liquid Chromatography (HPLC) is also employed in biodegradation of polymers to detect monomers that are released during the process, especially non-volatile and polar degradation products (Przygoda-Kuś et al., 2025).

7. Conclusions

Several types of fungi can break down plastic-forming polymers under appropriate environmental circumstances. Different fungal species can alter the physicochemical properties of different plastic polymers, including polyethylene terephthalate (PET), low-density polyethylene (LDPE), high-density polyethylene (HDPE), polyvinyl chloride (PVC), and others.

There are four stages for plastic biodegradation by fungal species, including biodeterioration (adhesion, colonization, and biofilms of fungal microbes on the polymer surface), biofragmentation (fragmentation of plastic polymer into monomer), assimilation (transport into fungal cytoplasm), and mineralization (breakdown of polymers by enzymatic activities into different oxidized metabolites such as CO_2, N_2, CH_4, and H_2O).

Microbes secrete enzymes such as peroxidase, laccase, lipase, esterase, and cutinase to catalyze the breakdown of chemical bonds of plastic polymers, thereby becoming an environmentally promising way to remediate plastic waste instead of the physicochemical depolymerization way to degrade plastic. In the future, the researchers will focus on biodegradation pathways and biological systems that will lead to alteration of physical and chemical characteristics of biodegradable pollutants such as the polymers of plastics. Understanding and identifying the biological systems that cause apparent physical and chemical alterations will be the main objective of future research.

However, few fungal-derived enzymes have been attributed to polymer degradation. These enzymes have not received much attention regarding their biochemical and structural properties. knowledge the mechanisms of biodegradation helps in the design of new biodegradable plastic polymers, the creation of microbial biosynthetic systems with enhanced breakdown efficiency, and the genetic modification of enzymes via protein engineering.

The objective is to purify powerful microbial enzymes for commercial use, isolate and identify powerful microbial consortia directly from plastic contamination sites, and enhance catalytic activity through genetic engineering.

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