The Research of Medical Science Review

Received: 02 Decmber, 2024
Accepted: 02 January, 2025
Published: 09 January, 2025

ISSN: 3007-1208 | 3007-1216
Volume 3, Issue 1, 2025

BIODEGRADATION OF MICROPLASTIC: THE ROLE OF ASPERGILLUS SPECIES IN SUSTAINABLE PLASTIC WASTE MANAGEMENT

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ABSTRACT

Microplastic pollution has emerged as a significant environmental challenge due to its persistence, widespread distribution, and detrimental impacts on ecosystems and human health. Conventional plastic waste management strategies often fail to address the complexities of microplastic degradation, necessitating innovative and sustainable approaches. Among various biological solutions, fungal species, particularly Aspergillus, have demonstrated promising potential in microplastic biodegradation. This review explores the role of Aspergillus species in sustainable plastic waste management, focusing on their enzymatic capabilities, degradation mechanisms, and applications in reducing microplastic pollution.The ability of Aspergillus to produce a diverse range of enzymes, such as esterases, lipases, and oxidases, enables the breakdown of complex plastic polymers into simpler compounds. Key species, including A. niger and A. flavus, have shown significant potential in degrading microplastics under controlled environmental conditions. Factors such as temperature, pH, plastic properties, and co-metabolism with other microorganisms influence the efficiency of Aspergillus-mediated degradation. Furthermore, integrating Aspergillus into bioreactors, composting systems, and bioaugmentation strategies presents practical applications for large-scale waste management.Despite these advancements, challenges remain, including slow degradation rates, potential toxicity of byproducts, and scalability issues. Future research should focus on genetic engineering, omics technologies, and the development of integrated systems to enhance degradation efficiency and address current limitations. By leveraging the enzymatic and ecological versatility of Aspergillus, this review highlights its potential as a cornerstone in sustainable plastic waste management and emphasizes the need for continued innovation in combating microplastic pollution.

Keywords: *Aspergillus Species, Enzymatic Degradation, Sustainable Plastic Waste Management, Microplastic Biodegradation*

INTRODUCTION

Chemicals that are harmful to human health and have gotten into the environment due to human activity are called environmental pollutants. Additionally, environmental pollution is caused by natural events like volcanic eruptions. Human activities introduce pollutants by polluting the water, air, and soil. Inhalation, oral

absorption, and ingestion are the three main ways that contaminants reach the human body. To indicate the amount of a specific pollutant that is consumed, the word "dose" is frequently employed. The dose is dependent on exposure duration and intensity. Depending on the exposure level, different health effects may result. Although Industrialization develops a country, it introduces a large number of pollutants into the environment, which harms the health of those exposed [1].Exposure to environmental pollution is a significant source of health risks all over the world. In general, hazardous substances from both natural and man-made sources pollute the air. The main sources of contaminants include automobile emissions, power plants, burning garbage, chemical companies, and volcanic eruptions contaminants like sulfurdioxide (SO2), carbon monoxide (CO), nitrogen oxides (NOx), heavy metals, biological contaminants, ozone, tobacco smoke, etc. are all released into the air that is inhaled When these pollutants are ingested, they interfere with the body's internal functioning, causing diseases like cancer, cardiovascular, reproductive, prenatal central nervous system, and respiratory health issue. Tobacco smoke, which consists of harmful chemicals like benzene, cadmium, arsenic, formaldehyde, and nicotine is responsible for health illnesses. It will cause cancer, not only to the smoker but also affect passive smokers (who are exposed to tobacco smoke and is not a smoker). A person may develop asthma, bronchitis, throat infection, and a burning sensation in the eyes. Exposure to biological pollutants like bacteria, viruses, house dust, mites, cockroaches, and pollen can cause asthma, hay fever, and other allergic diseases, and volatile
organic compounds cause eye, nose, and throat irritation, headaches, nausea, and loss of coordination. Prolonged exposure may cause damage to the parts of the body, mainly the liver. Lead exposure can harm the brain and digestive systems, and in certain circumstances, it can result in cancer. Exposure to ozone causes itching in the eyes, burns may develop respiratory disorders like asthma, and our resistance to colds and pneumonia will be lowered. In winter, children may suffer from respiratory problems from exposure to nitrogen oxides. Depending on the exposure's type and intensity, the effect may be either short- or long-term. Short-term effects range from eye, skin, nose, and throat irritation, coughing, headaches, nausea, and dizziness to severe conditions like asthma, bronchitis, and lung and heart problems. Long-term effects will be neurological, reproductive, respiratory, and cancer [2].Mismanagement of plastic waste is a critical challenge, particularly in developing countries (Case A). For instance, China generated 14 million tonnes of plastic waste in 2010, with 75% mismanaged. Similarly, other Asian nations mismanage 50–75% of their plastic waste. Effective waste collection schemes are essential to reduce open burning and environmental leakage. Utilizing collected plastic-rich waste as an alternative fuel could address waste quantity while harnessing its energy potential. However, modern recycling systems remain unfeasible due to high investment costs. Recycling options, such as using plastics for construction, should be evaluated for sustainability to prevent microplastic leakage. Import restrictions on low-quality plastic waste can alleviate stress on underdeveloped local waste management systems. In developed countries (Case B), plastic waste management faces challenges due to reliance on exporting waste to Asia, which has now imposed strict import restrictions. The closure of such markets has exposed the inadequacy of domestic recycling infrastructure. Policies like the Basel Convention and the Circular Economy Package advocate for regionalized waste management solutions. Technologies such as near-infra-red sorting and feedstock recycling enable high-quality plastic recovery, but challenges persist with non-recyclable rejects. To address this, designing products for recycling and considering bans on hard-to-recycle materials may be necessary. Implementing these strategies can foster sustainable plastic waste management globally [3].Bioremediation employs microorganisms like bacteria, fungi, and yeast to clean contaminated soil and water by eliminating or transforming pollutants. Aquatic ecosystems are often the first affected by point sources, such as industrial discharges, and nonpoint sources, like agricultural runoff [4]. Contaminated water harms aquatic life, reduces reproduction, and poses risks to human health, necessitating the treatment of effluents [5]. Bioremediation, a cost-effective and eco-friendly method, uses microbes capable of degrading hazardous materials [5]. Microbial inoculums, prepared in laboratories or naturally occurring, enhance degradation by utilizing pollutants as nutrients and energy sources. External nutrients like carbon, nitrogen, and electron acceptors optimize microbial activity. Common microbes include *Pseudomonas*, *Rhodococcus*, *Lactobacillus*, and photosynthetic bacteria like *Rhodobacter* Cyanobacteria, such as *Nodularia* and *Oscillatoria*, exhibit

potential in industrial effluent degradation and ecosystem detoxification. Industrialization and urbanization have increased global organic and inorganic contaminants. Research continues on genetically engineered microbes to optimize bioremediation, which depends on microbial ecology, contaminants, and environmental conditions. Bioremediation effectively mitigates pollution, protecting ecosystems and human health [6]. Among the various fungal species that can biodegrade plastic, Aspergillus sp. is a prominent and widely studied decomposer. Aspergillus sp. is a filamentous fungus known for its adaptability and wide distribution in various environments. In addition, this fungus produces a wide range of extracellular enzymes that are involved in the biodegradation of plastic polymers [7]. Using the potential of Aspergillus sp. to biodegrade plastic is a promising avenue for environmentally friendly waste management strategies. Further research is needed to optimize conditions for enhancing plastic biodegradation, understand ing the genetic basis of Aspergillus sp. in plastic biodegradation, and investigate the potential environmental effects of fungal plastic biodegradation. There are several obstacles to microbial bioremediation research, such as our incomplete knowledge of how adaptable microorganisms are to various environmental settings and complicated contaminants like microplastics and industrial effluents. The potential of novel microbial strains from understudied ecosystems is still unrealized, and safety and scalability concerns have limited the use of genetically engineered microbes (GEMs) on a large scale. Additionally, integrating bioremediation into waste management systems lacks practical frameworks, and its long-term environmental impacts require further study. This research aims to address these gaps by identifying novel microbial strains, optimizing biodegradation processes, and developing scalable, sustainable models for integrating bioremediation into existing waste management systems while ensuring safety and regulatory compliance.

2 Methods for the degradation of microplastic:

Advanced oxidation processes (AOPs) and biological degradation are two proposals that are currently being applied for MP decomposition. MPs can be degraded by these two processes that break the chemical bonds of polymer MPs into small molecules, which can be further converted into useful products and even completely mineralized into CO2 and H2O [8]. The breaking of the polymer chain is irregular and can occur at any monomer of polymer, eventually decomposing MPs into organic or inorganic products available. For some MPs, the chain fracture occurs at the end of the monomer repeating unit, and the remaining monomer breaks in succession through the chain depolymerization [9]. The formed products and degradation mechanism vary with the types of polymers, which is, to a great degree, influenced by environmental factors. Based on these current studies on the degradation of MPs by AOPs (direct photodegradation, photocatalytic oxidation, electrochemical oxidation) and microbial, we will review these two processes separately in the sections below.

Photocatalytic oxidation

Photocatalysis is also regarded to be an AOP for contamination elimination [10]. It is a mature green technology whose main feature is the utilization of infinite and free solar energy, meaning that it exhibits promising potential as an eco-friendly and low-cost treatment technique. Photocatalytic degradation of organic pollutants is mainly based on the semiconductor materials. As observed in Fig. 1, when the absorbed photon energy (E) is higher than the band gap energy (Eg) of the semiconductor ($E \geq Eg$), the electrons ($e¡$) in the valence band (VB) will be transferred to the conduction band (CB) and thus the positive holes (h+) are produced in the VB [11], leading to the separation of electron-hole pairs. Both species ($e¡$ and h+) react with $OH¡$, O2 or H2O to produce highly ROS, which initiated directly the degradation processes of organic pollutions and plastic products [12]. A large number of works have previously exhibited that large plastic film/particles can be decomposed by ROS [13]. Moreover, Zhang et al. (2020a) summarized the plastic photo-degradation mech anisms in detail, as observed in Fig. 2. Table 1 listed the recent de velopments on the degradation of large plastics such as PP, PE and PS based on various photocatalysts. As observed, most of plastic film s/particles can only be degraded partially under UV illumination, sug gesting the generated active oxygen species under visible light were not capable of inducing the chains cleavage and subsequent oxidation re actions. Given this, it is necessary to further study its application in MPs degradation. As

reviewed, there are also several works (Table 2) reporting the photodegradation of MPs with semiconductor materials as photocatalysts in aquatic environments. We found that TiO2-based nanomaterials were extensively utilized as model photocatalysts for the decomposition of MPs/large plastics under visible light in both Tables 1 and 2, which was most likely attributed to its superior oxidation ability of organic pollutants [14]. Additionally, a few studies reported that ZnO-based materials were applied for the MPs/plastics degradation because of its excellent catalytic activity and high redox potential [15]. Although these designed photocatalytic sys tems exhibited partial degradation, most of them did not investigated the final degradation products utilizing LC-MS or other detection tech niques. Additionally, these processes may release VOCs. Moreover, a further concern must be fully taken account into. Namely, it is difficult to recycle the catalyst because it is suspended in water, thus resulting in secondary pollution to some extent. These problems can be avoided if the catalyst is immobilized on the conductive substrate surface.

Figure 1: The proposed photocatalytic degradation mechanism of pollutants over TiO2. ENM: Engineered nanomaterial. (Reproduced with permission from Ref. [16]. Copyright 2018, Nature Publishing Group).

Electrochemical oxidation

Electrochemical oxidation is divided into anodic oxidation and in direct cathode oxidation. Of which the most common method is anodic oxidation (AO), referring to the direct oxidation of organic pollutants on the anode surface through charge transfer or indirect oxidation of pol lutants by •OH or reagents (active chlorine species, H2O2, O3, and per oxymonosulfate) in aqueous solution, as illustrated in Fig. 3. Indirect cathode oxidation is considered to be an electro-Fenton (EF) technology. In EF, •OH or other reactive oxygen radicals from the decomposition of H2O2 by the catalytic action of Fe2+ were generated through the Fen ton's reaction, and the produced free radicals were responsible for the oxidation of organic pollutants. Therefore, this technique has wide application prospect in the treatment of refractory organics. As mentioned in the former section, [17] have demonstrated that SR-AOPs showed a superior decomposition perfor mance of MPs being mainly composed of polyethylene through catalytic activation of peroxymonosulfate to produce active radicals, and the toxicity assessment suggested that the organic products originated from the degradation of MPs were friendly to the aquatic microorganisms. But this work did not identify the types of intermediate products. Due to strong controllability, easy operation, and less secondary pollution, electro-Fenton like (EF-like) process with the assistance of high-efficiency heterogeneous catalysts has been intensively used to generate strong oxidizing •OH for the elimination of organic contami nations [18]. The nature of the cathode materials greatly determined the overall degradation performance because EF-like system is dominated by the cathodic processes. Therefore, selecting highly efficient catalyst materials is extremely crucial. Based on above analysis, it seems to be very meaningful to study the elimination of MPs pollution with EF-like method. However, so far, there are few reports on the application of electrochemical method for the treatment of MPs pollu tion in aquatic environment. Last year saw a study on the decomposition of PVC MPs via an EF-like system based on a TiO2/graphite cathode [19]. This system displayed an outstanding activity for PVC decomposition by •OH oxidation and cathodic reduction dechlo

rination, and some desirable and useful products were produced in the degradation process of PVC. Nonetheless, we do not know whether this developed system is suitable for other types of MPs. Despite this, in my opinion, this work still gives a direction to explore an efficient electro chemical oxidation method for MPs degradation to desirable products.

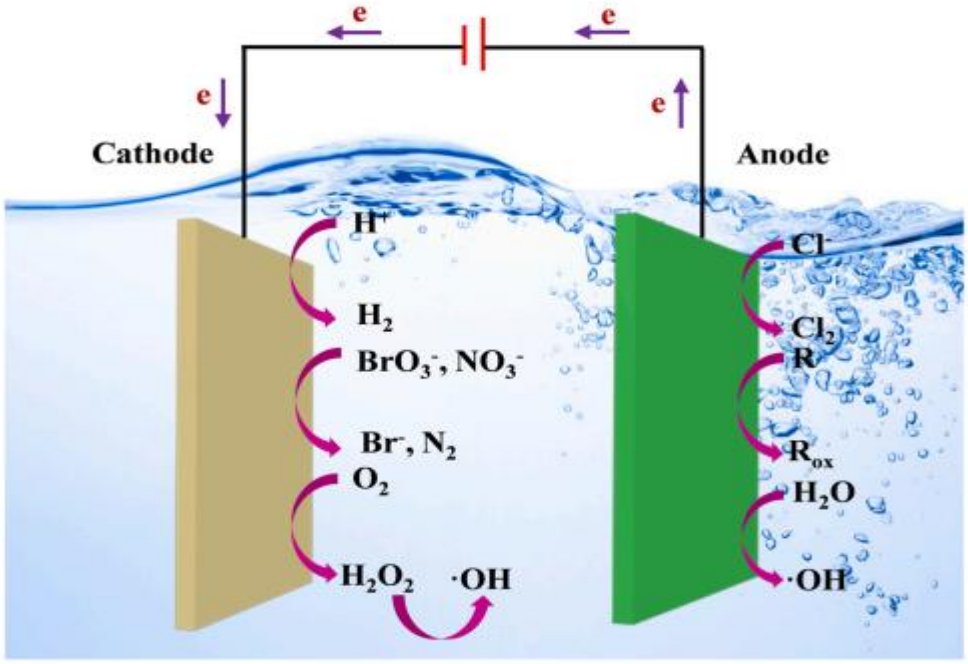

Figure 2: The removal mechanism of contaminants through redox reactions at the electrode surface or through the production of radicals. (Reproduced with permission from Ref. [16] Copyright 2018, Nature Publishing Group).

Enzymatic mechanisms involved in plastic biodegradation by fungi

The mechanism of biodegradation involves the action of microbial enzymes on the surface of the plastics. Microbes such as bacteria and fungi attach to the plastic film inert the enzymes and grow on it by utilizing it as a substrate and source of nutrition. Therefore, the polymers slowly get depolymerized and degradation will be compiled by the mineralization process, where H2O (water), CO2 (carbon dioxide), and CH2 (methane) are end products [20]. The ability of fungi was they invade substrates using enzymes that can detoxify pollutants. Fungi can also produce some surface-active proteins, i.e., hydrophobins to coat hyphae to hydrophobic substrates. The growth of many fungi can also cause small-scale swelling and bursting, as the fungi penetrate the polymer solids [21]. The degradation of plastics by some fungi occurs through the intracellular and extracellular enzymatic systems. The intracellular enzymatic system acts as an internal mechanism for detoxification and plays a major role in fungal adaption [22]. Tis system is mediated by the cytochrome P450 family (CYP), Phase I enzyme epoxidase and, Phase II enzyme transferases which involve oxidation and conjugation reactions. Cytochrome P450 family are heme-containing mono-oxygenases that are involved in catalyzing various enzymatic reactions [23].Cytochrome P450 enzymes are important for primary metabolism, enabling protection of the hyphal wall integrity and the formation of the spore outer wall . CYP isoforms are anchored in the membrane of the endoplasmic reticulum, having their active sites connected to both the cytosolic and membrane environments so they can uptake substrate from both surroundings. CYP contains three cofactors (NADPH+, H+, FAD, and Heme) and two enzymes (NADPH: CYP reductase and cytochrome P-450 hydrolase). Te extracellular enzymatic system consists of a hydrolytic system that produces hydrolases that are involved in polysaccharide degradation and the unspecifc oxidative system involved in breaking down complex structures, such as lignin degradation.Te unspecifc oxidative system can oxidize a wide range of substrates. It is formed mainly by nonspecifc oxidoreductases, including

enzymes, such as class II peroxidases (manganese peroxidase, lignin peroxidase, and versatile peroxidase), laccases, and unspecifc peroxygenases. These enzymes transfer electrons from organic substrates to molecular oxygen (laccases) by oxidation–reduction reactions using H2O2 as an electron-accepting co-substrate or by epoxidation, aromatic preoxygenation, and sulfoxidation [24]. Tis enzymatic complex is produced mainly by wooddegrading fungi, such as basidiomycetes [25]. Te action of fungi on the surface of plastics can be afected by environmental factors such as moisture, pH, temperature, etc. sufcient moisture is required for activation of fungi, appropriate pH environment is required for the action of enzymes on plastic polymer and equally, temperature plays a vital role in this biodegradation process, polymers of high melting point take more time to degrade than polymers of low melting point (Figure 3).

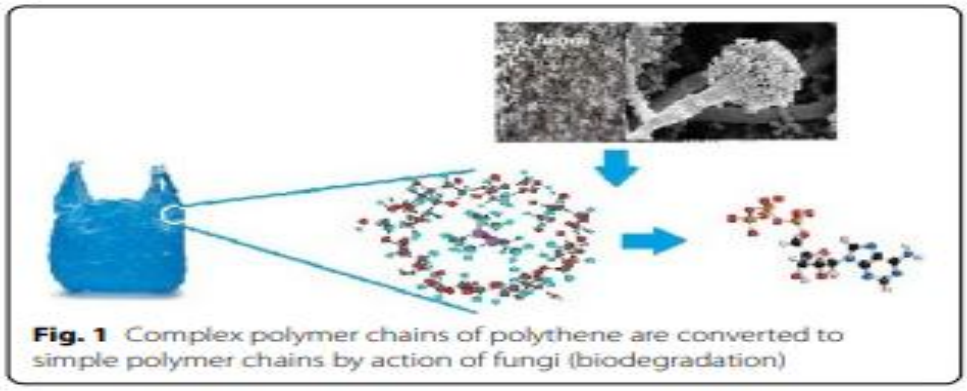

Fig. 1 Complex polymer chains of polythene are converted to simple polymer chains by action of fungi (biodegradation)

Figure 3: conversion of complex chain into the simple polymer by biodegradation

Biodegradation of various plastics

Polythene is mostly used in plastics in daily life due to its easy processing for products, such as plastic bags, plastic films, packing food materials, and textiles [26]. Polyethylene is chemically represented as (C2H4) n. PE is a combination of polymers of ethylene with different values of n. They are low-density polyethylene and high-density polyethylene. Low-density polyethylene is processed by applying high pressure (1000–5000 atm) and high temperature (520 kelvins), whereas high-density polyethylene requires low pressure (6–7 atm) and low temperature (333–343 K) [27]. It is reported that Polyethylene constitutes 64% of total synthetic plastics as it is being used for manufacturing bottles, carry bags, disposable articles, garbage containers, margarine tubs, milk jugs, and water pipes. Annually 500 billion to 1 trillion polythene bags are being used daily all over the world. The usage of polythene is increased at a rate of 12% per annum and approximately 140 million tonnes of synthetic plastic polymers are produced worldwide annually [28]. Phanerochaete chrysosporium is a fungal species that degrades high molecular weight polyethylene under nitrogen-limited and carbon-limited conditions [29]. Aspergillus, Cladosporium, Fusarium, Penicillium, and Phanerochaete have been reported for polyethylene degradation. Additives-free Polyethylene degradation was identified in Penicillium. simplicissimum Aspergillus niger, Aspergillus japonicas and Fusarium. sp .Penicillium chrysogenum NS10 (KU559907), and Penicillium oxalicum NS4 (KU559906) were identified for degrading HDPE and LDPE [30].

Importance of Aspergillus tubigensis Species in Sustainable Plastic Waste Management:

Aspergillus tubingensis has gained significant attention in sustainable plastic waste management due to its remarkable ability to degrade synthetic plastics, particularly polyurethane. This fungus secretes enzymes that catalyze the breakdown of plastic polymers into simpler molecules, offering an eco-friendly alternative to conventional chemical and mechanical recycling methods [31]. Unlike natural degradation processes that are slow and inefficient, *A. tubingensis* can degrade plastics at a much faster rate, even in challenging environmental conditions. Its adaptability to diverse habitats, such as soil and waste sites, highlights its potential for large-scale application. The fungus can grow directly on plastic surfaces, utilizing them as a

carbon source, making it an effective candidate for integration into industrial waste management systems, such as bioreactors or composting facilities [32]. Moreover, ongoing research focuses on optimizing its growth conditions and enzyme production to enhance its efficiency and scalability. However, challenges such as cost-effectiveness, containment, and ensuring no unintended ecological impacts must be addressed before large-scale implementation. Despite these hurdles, *Aspergillus tubingensis* represents a promising solution to mitigate plastic pollution, contributing significantly to a sustainable and greener future [33].

Enzymatic mechanisms

Enzymes are biological catalysts that accelerate chemical reactions in living organisms.Fig. 5 illustrates the reaction schemes of the fungal enzymes involved in plastic biodegradation. In addition, enzymes are widely used in industries such as food, pharmaceuticals, textiles, biofuel production, and bioremediation [34]. According to Table 2, the main enzymes involved in the biodegradation of plastic polymers by Aspergillus sp. include esterase, laccase, laccase-like multi copper oxidases (LMCOs), peroxidase, manganese peroxidase, lignase, cellulase, cellobiohydrolase, lipase, and urease. These enzymes play a crucial role in the biological degradation of plastic polymers. Recent research has identified several enzymes that can biologically degrade various plastic materials. For example, a study illustrated that the en zymes esterases and lipases can break down PET into smaller pieces [35]. Table 2 presents the effect of Aspergillus sp. enzymes on the biodegradation of different polymers.

Laccase

From Table 2, laccase is an enzyme found in various species of Aspergillus. Laccase is a copper-containing oxidase enzyme that catalyzes multiple substrates, such as phenols, amines, and cyclic compounds. It is found in many fungi, bacteria, and plants. In addition, this enzyme plays a role in biological purification, pulp production, dyeing, and paper production [36]. Sharma et al. (2022) stated that during the biodegradation process, enzymes such as laccase break down plastic polymers and convert them into biomass and microbial gases. Laccases can affect the plastic's chemical bonds, leading to the poly mer's structural degradation. This degradation process involves breaking the polymer chains into smaller pieces that microorganisms can further absorb and mineralize. It is important to note that while laccase has shown the potential to degrade certain plastics, its effectiveness may vary depending on the specific type of plastic and environmental conditions. Laccase enzyme has essential functions such as lignin degradation, detoxification, pigment production, and fungal growth [37]. Laccase requires molecular oxygen to facili tate biological decomposition reactions. It enables the execution of oxidative reactions, such as the degradation of polymers. By utilizing oxygen as an electron acceptor, laccase generates reactive oxygen species, including hydroxyl radicals, which enables it to break down polymer chains [38]. Xueqi Li et al. (2020) stated that laccase can generate free radicals during its catalytic cycle. These free radicals can then attack the polymer's structure by breaking its carbon chain, ultimately deleting the polymer into smaller fragments [39]. In addition, it has been found that laccase often exhibits a synergistic relationship with other enzymes, such as peroxidase, which results in the degradation of polymers. This enzyme exhibits stability and enzymatic solid activity across various temperatures and pH levels. This feature enables the laccase to function effectively under diverse environmental conditions, making it highly adaptable and suitable for various work environments [40].

Esterase

Esterase is a type of hydrolase enzyme that catalyzes ester bonds. This enzyme is found in many organisms, including bacteria, fungi, plants, and animals. Esterase is commonly used in the food, pharmaceutical, and chemical industries. Puspitasari et al. (2020) found that esterase is involved in the biodegradation of plastic polymers. Esterase cleaves polymer chains into low molecular weight fragments, which are then adsorbed onto the microbial cell membrane. However, it is essential to note that the effectiveness of esterases and other enzymes may vary depending on the specific type of plastic and environmental conditions [41]. According to Table 2, the esterase enzyme significantly impacts all kinds of plastics, including PET, LDPE,

PB, and PU. This enzyme plays a crucial role in the breakdown and metabolism of ester compounds. Shah et al. (2008) show that some polymers, such as PET and polyurethane, contain ester bonds in their structure. These ester bonds can bind to the enzyme and increase the rate of hydrolysis [88]. The versatile nature of esterase enzymes enables them to effectively break down a wide range of substrates. Consequently, esterase can target and degrade various plastic polymers as substrates [42].

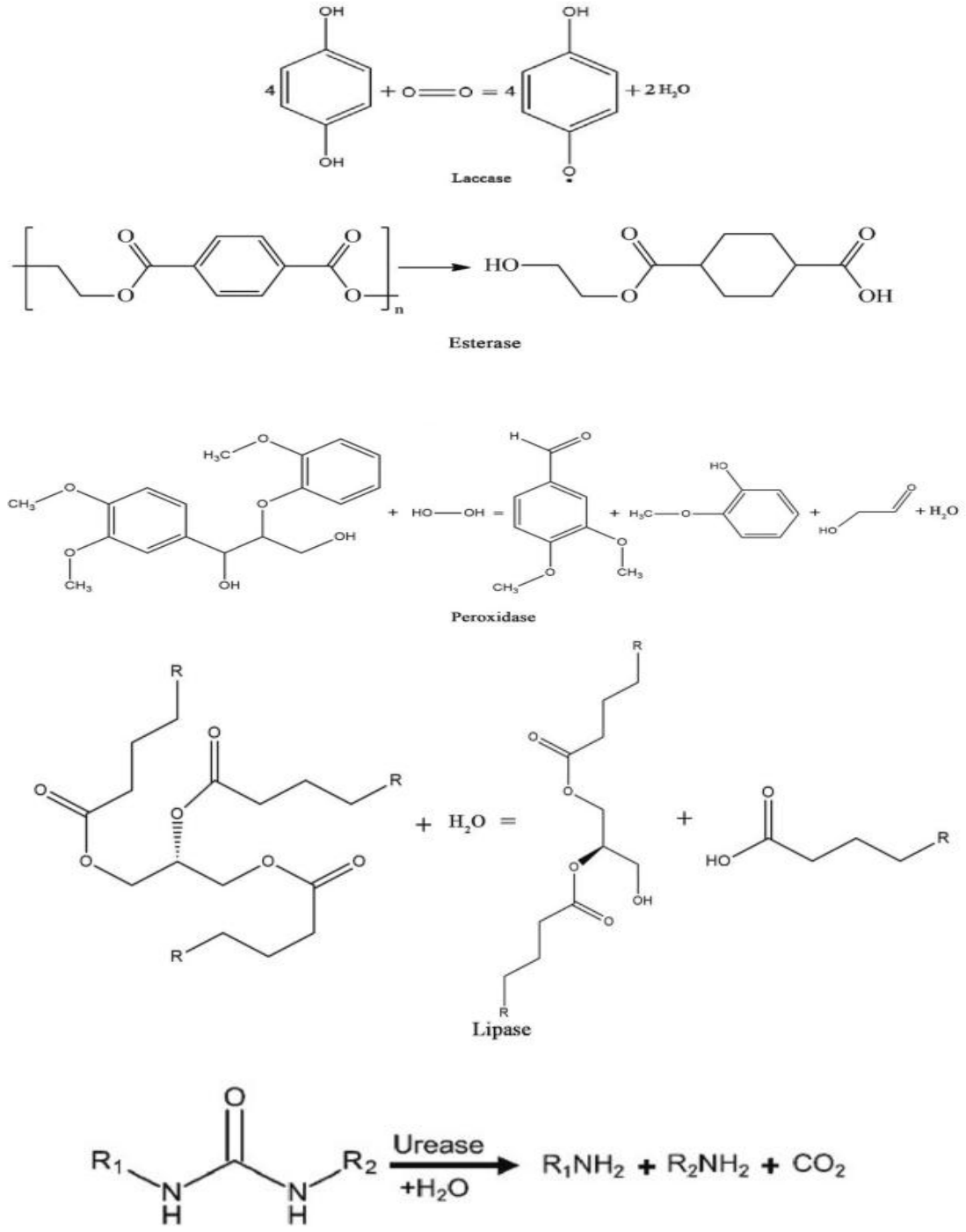

Figure 4: Reaction schemes of the fungal enzymes involved in plastic biodegradation [43].

Mechanisms of microbial-mediated microplastic/plastic degradation

The microbial degradation process of MPs involves multiple biochemical reactions, and there are some differences in the degradation of different MPs. Numerous MP degradation mechanisms remain that have yet to be fully elucidated [44]. Microbe-mediated MP degradation is governed by different factors, including the MP chemical structure and molecular weight as well as the type of microorganisms present and other environmental conditions. The various characteristics of MPs, such as mobility, crystallinity, molecular weight, types of functional groups and substituents present, and the plasticizers or additives added to MPs, all play important roles in their degradation. In general, the mechanisms of MP degradation are complicated. At present, the mechanisms associated with polymer degradation are relatively well understood, but those involved in MP degradation have yet to be studied in depth, and the relevant degradation pathways have not been elucidated. Because MPs are polymers, the pathways associated with their degradation are similar to those of other polymers. During the degradation process, both must first be converted to monomers before they can be mineralized. The particle size of MPs is relatively large compared to the pore size in the cell membrane. Thus, MPs are too large to pass through cellular membranes and must first be depolymerized to smaller monomers before they can be absorbed and biodegraded within microbial cells. MPs are depolymerized by microbial enzymes as well as by microorganisms, in a process that typically involves hydrolysis, which is the most important reaction for the degradation of MPs. As shown in Fig. 3, MP hydrolysis is contrasted with oxidative degradation, which can transform both hydrolyzable and nonhydrolyzable polymers. During the hydrolysis process, the enzyme binds to the MPs and subsequently catalyzes hydrolytic cleavage. MPs can be degraded by the action of either intracellular or extracellular depolymerase in different microorganisms. Intracellular degradation involves the hydrolysis of an endogenous carbon reservoir by the accumulating microbes themselves. In contrast, extracellular degradation involves the utilization of an exogenous carbon source that is not necessarily performed by the accumulating microorganisms, since extracellular enzymes from microorganisms break down MPs into short chains or smaller molecules (e.g., oligomers, dimers, and monomers) that are small enough to pass through semipermeable membranes. This process is referred to as depolymerization. These short-chain molecules are then mineralized into end products (e.g., CO2, H2O, or CH4) through a process called mineralization, and these products can then be utilized as carbon and energy sources [45]. The microbial-mediated degradation of MPs is initiated by the secretion of enzymes that catalyze the cleavage of MP chains into monomers. Microbial enzymes are important in the microbial-mediated degradation of MPs. To study the mechanisms associated with the microbial-mediated degradation of MPs, many studies involving the separation and identification of enzymes in microorganisms have been performed in recent years. Yoshida et al. [46] isolated a novel bacterium, Ideonella sakaiensis 201-F6, that can use PET as its major energy and carbon source. When grown on PET, this strain produces two enzymes (ISF6-4831 and ISF6-0224) that are capable of hydrolyzing PET and the reaction intermediate, mono(2- hydroxyethyl) terephthalic acid. Both enzymes are required for the efficient enzymatic conversion of PET into its two environmentally benign monomers, terephthalic acid and ethylene glycol. In another study, Yoon et al. [47] isolated an AlkB family alkane hydroxylase that was active toward PE samples with molecular weights of up to 27,000 Da. It is interesting to note that the enzymes of this family have been described in microorganisms that can degrade hydrocarbons. The results of these studies indicate that enzymes are important in the MP degradation process and should be further studied. The enzymes involved in the microbial-mediated degradation of plastics are not completely understood at present, since different microorganisms encode different enzymes, and different types of plastics require different enzymes for degradation.

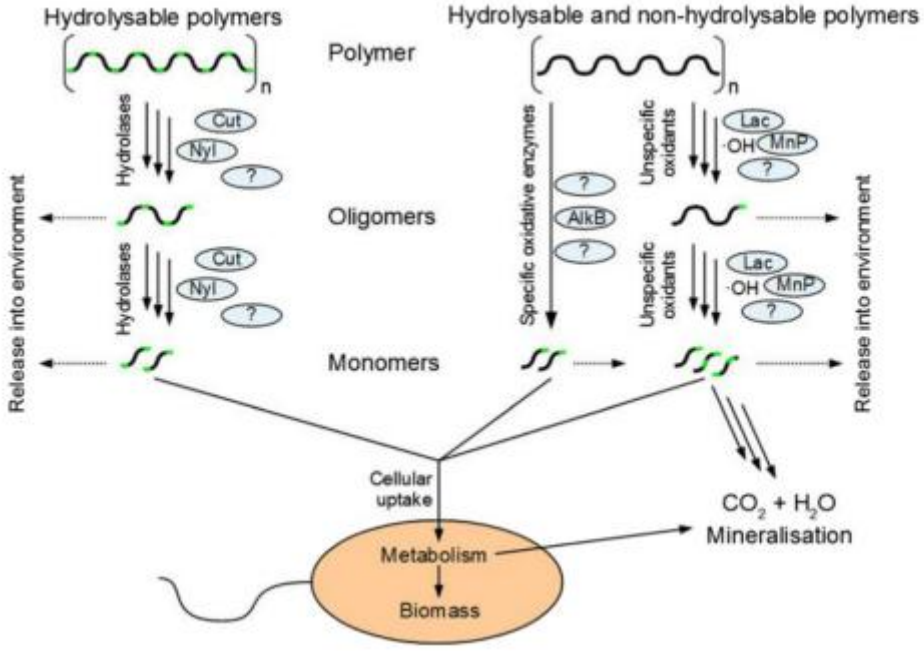

Figure 5: Pathways of polymer biodegradation. Polymer hydrolysis is contrasted with oxidative degradation, which can transform both hydrolyzable and nonhydrolyzable polymers. Green lines indicate functional groups, including hydrolyzable bonds inside hydrolyzable polymers. Question marks indicate enzymes that have yet to be identified. Abbreviations: Cut, cutinase; Nyl, nylon hydrolase; AlkB, alkane hydroxylase; Lac, laccase; MnP, manganese peroxidase. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.) [48].

Factors affecting MPs' biodegradation

Aspergillus sp.

According to Fig. 4a, the initial review of various articles showed that different species of microplastics-degrading fungi, including Aspergillus, Penicillium, Trichoderma, Cladosporium, and Mucor, accounted for 41.55%, 15.58%, 7.8%, 6.5%, and 3.9% of the studies, respectively. In addition, other fungal species that decompose microplastics, such as Zalerion, Curvularia Cephalosporium, Fusarium, Cochliobolus, Phanerochaete, Trametes, Alternaria, Chaetomium, Filamentous, Phoma, Geomyces, and Paecilomyces, accounted for 24.67% of the studies. Gong et al. (2023) used the fungal strain Cladosporium sp. to biodegradate LDPE. The results showed that this fungal strain could reduce 0.3% of the initial weight of the polymer [49]. Malachova et al. (2020) showed that Trichoderma sp. could degrade LDPE and PS by 0.5 ± 0.4% and 0.9 ± 0.4%, respectively. Pardo-Rodriguez et al. (2021) used Peni cillium and Mucor sp. to biodegradate PVC. Based on the results of their study, changes in the level and initial weight of microplastics were observed in both strains [50]. As can be seen from Fig. 4a, Aspergillus sp. has received more attention from researchers than other fungal species in biodegradation studies due to its advantages, such as its wide distribution in nature and ease of isolation from sources like soil and waste. Furthermore, the genetics of Aspergillus sp. are well understood, enabling researchers to manipulate its metabolic pathways to enhance its ability to degrade pollutants. According to the study by Amo bonye et al. (2021), Aspergillus sp. can decompose polymers and plastic materials by producing various enzymes [51]. This fungal species has hydrophobins, which are small fungal proteins that can also enhance the biodegradation capacity of plastics. From Fig. 4b, various Asper gillus sp. involved in the biodegradation of MPs were identified, including A. niger, A. flavus, A. oryzae, A. glaucus, A. fumigatus, A. terreus, and A. tubingensis. The percentages of studies reporting these species were 29.3%, 24.13%, 6.9%, 5.17%, 5.17%, 3.44%, and 3.44% respec tively. In addition, other Aspergillus sp. that decompose MPs include A. tubingensis, A. japonicus, A. nidulans, A.

clavatus, A. calidoustus, A. flavipes, A. fructus, A. versicolor, A. sydowii, A. parasiticus, A. ornatus, A. nidulans, and A. cremeus. Together, these species accounted for 22.41% of the studies. According to Fig. 4b, A. niger and A. flavus have accounted for a higher percentage of investigations. By producing different enzymes, these two species can break down the polymer chains of microplastics and facilitate their biodegradation [52]. Raman et al. (2012) reported that A. niger reduced the weight of LDPE by 5.8% over 30 days [53]. Mathur et al. (2011) attributed the destruction of the polyethylene surface to the formation of a biofilm by A. niger. Raaman et al. (2012) also discovered that A. niger and A. flavus can degrade polyethylene and reduce its weight by approximately 19–24% within 2–4 months [54].

MPs' size

As shown in Fig. 4c, biodegradable polymers with sizes ranging from 20 to 100 µm, 100 to 1000 µm, and 1000 to 2000 µm accounted for 60%, 30%, and 10% of the studies, respectively. According to Fig. 4c, fungi can more effectively biodegrade polymers within a 20–100 µm size range. As the size increases, the surface-to-volume ratio decreases; therefore, the access of enzymes to the carbon chain is limited. This limitation can potentially slow down the biodegradation process. Miri et al. (2022) show that the smaller size of the polymer allows more access of fungal enzymes to the carbon chain of the polymer and makes it easier to degrade. The findings of the study of Ghosh et al. (2013) show that the size of polymers plays a vital role in their degra dation by fungi [55]. Plastic polymers within the 1000 to 2000 µm size may pose more significant challenges for fungi regarding biodegrada tion. The larger size can further limit the accessibility of enzymes to the polymer chains, potentially slowing down the biodegradation process. However, fungi are known for their ability to produce a wide range of enzymes with different substrate specificities, which can assist in the biodegradation of various types of plastic polymers. Some fungi can break down larger plastic polymers. For example, Altammar et al. (2022) showed that A. niger can efficiently degrade PET-based materials through lipase production. It is essential to mention that the ability of fungi to decompose polymers is not limited only to the size of the polymer. Other parameters, such as the chemical composition and structure of the polymer, are also crucial in this process [56].

Polymer type

Studies on the biodegradation of polymers by *Aspergillus* species are primarily focused on low-density polyethylene (LDPE), constituting 44% of research, followed by high-density polyethylene (HDPE) at 11.76%, polyurethane (PU) at 11.76%, and other microplastics at 5.88%. LDPE and HDPE are significant environmental concerns due to their widespread use, and enzymes such as esterase, laccase, and peroxidase play key roles in their degradation . *A. niger* and *A. terreus* have demonstrated a 30% weight reduction of LDPE, while *A. tubingensis* and *A. flavus* reduced HDPE weight by 6.88% and 9.34%, respectively [56,61]. PU's complex structure poses challenges, but fungal enzymes like esterase, lipase, and urease hydrolyze its ester and urethane bonds, enabling degradation into smaller molecules. *A. fumigatus* degraded PU ether foams by 65% Polyvinyl chloride (PVC), though less biodegradable, can be broken down by *A. glaucus*, *A. niger*, and *A. parasiticus* by 32%, 17%, and 67%, respectively, through esterase and lipase activity. Polyethylene terephthalate (PET) degradation by *Aspergillus* involves enzymatic actions that fragment polymer chains, forming biofilms and surface erosion. PETases, a class of esterase enzymes, degrade PET into oligomers like MHET and TPA, showcasing the potential of *Aspergillus* in polymer biodegradation [56].

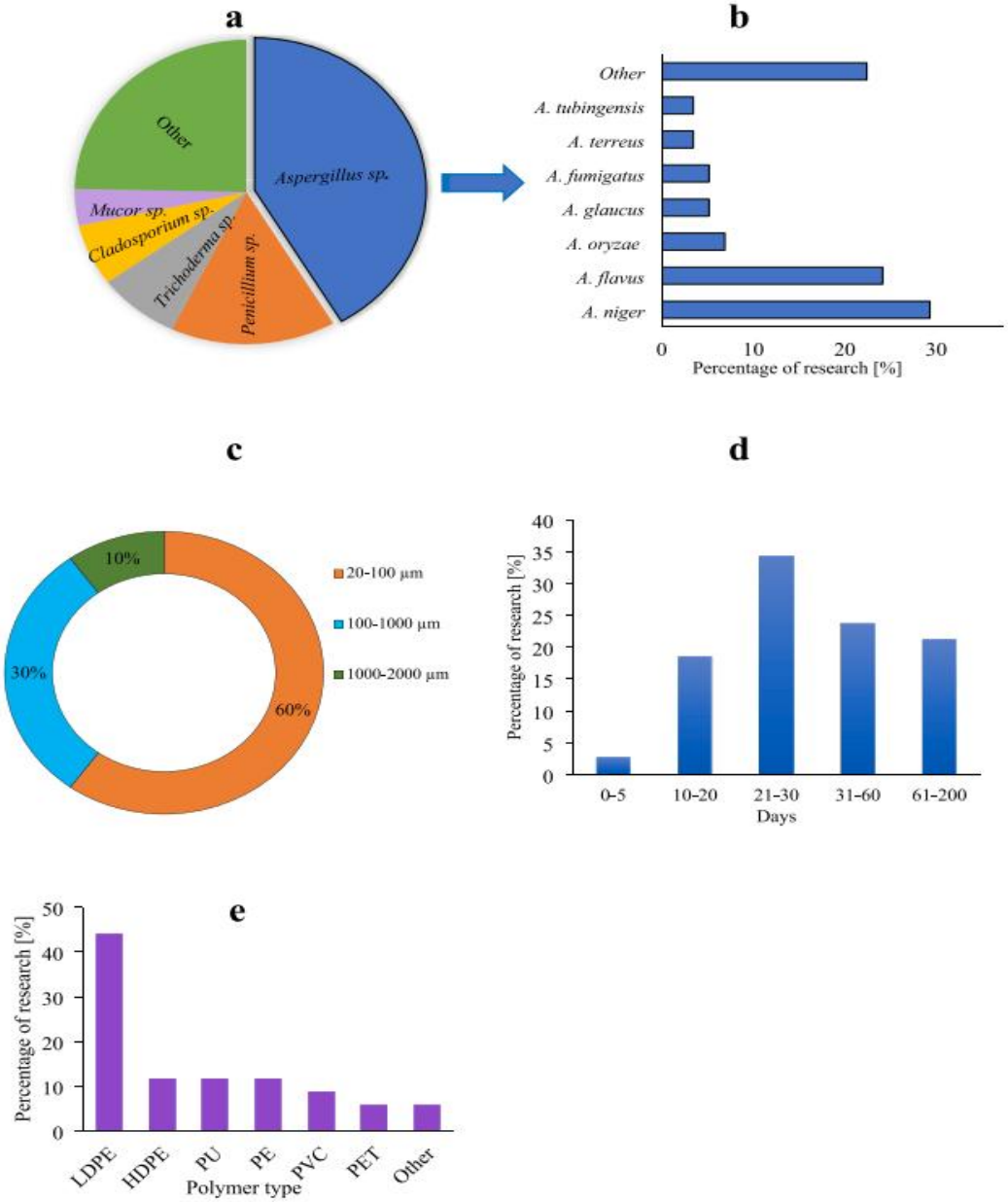

Figure 6: Classification studies based on: (a) fungi genera, (b) Aspergillus sp. (c) size, (d) exposure time, (e) polymers type [43].

Challenges in plastic biodegradation

One of the primary obstacles in contemporary research on the biodegradation of plastics is the lack of a standardized methodology for accurately assessing and comparing the plastic-degrading capabilities of isolated microbes and their corresponding enzymes. Various approaches such as loss of weight, formation of biofilm, and reduction of tensile strength, have been adopted for quantifying biodegradation. However, this diversity has led to the lack of a universally accepted framework for comparing findings across various studies on plastic biodegradation. Quantification approaches like the formation of biofilm and rate of mineralization apply only to studies involving whole-cell biocatalysts. The direct use of isolated enzymes does not induce biofilm formation on the surface of polymers or carbonization. Additionally, variations in procedural aspects, including the processing of plastic samples into various forms (films, pellets, and

powder), the duration of biodegradation, and pre-treatment methods complicate the comparison of plasticdegrading capabilities among isolated microbial species. The inclusion of additives, such as fillers, stabilizers, and plasticizers in commercial plastic products will impact overall biodegradability. Therefore, evaluating the abilities of microorganisms and enzymes to degrade commercial-grade plastics, which are major contributors to plastic pollution is crucial. Some studies have explored the use of benzene and alcohol as solvents to eliminate synthetic additives from commercial LDPE films before their exposure to biodegradation [57]. Exploring the potential of reusing these solvents to eliminate additives from commercial-grade plastics could lead to more economically viable plastic biodegradation processes. The lack of comprehensive characterization studies on plastic degrading enzymes at the molecular level hinders a thorough comprehension of the enzymatic biodegradation mechanism. This understanding is crucial for maximizing the practical applications of enzymes. Molecular profiling of plastic degrading enzymes can facilitate the implementation of protein engineering techniques to improve enzyme activities and stabilities for industrial applications. Although most enzyme characterization and protein engineering investigations have concentrated on PET-degrading enzymes, these methodologies can serve as references for future research efforts aimed at discovering and characterizing other plastic-degrading enzymes to accomplish effective biodegradation of conventional plastics.

Future Prospects

The unsystematic dumping of plastic waste into landfills and oceans poses a significant threat globally, leading to the release of microplastics and fragmented particles into the environment. This has resulted in various serious issues, causing harm to human health and adverse environmental impacts. Due to these concerns, it is crucial to exercise caution in the usage and disposal of plastics. Implementing sustainable strategies for institutional and industrial utilization and disposal of synthetic polymers is imperative. Additionally, there is a need to incorporate biomonitoring into human and animal systems to elucidate the lethal effects of plastic waste materials. Addressing the accumulation of plastic waste in the environment requires the development of eco-friendly solutions, moving beyond traditional methods. Several reports suggest the potential of microorganisms, such as Ideonella sp., Bacillus sp., Streptomyces sp., and Pseudomonas sp., in combating plastic waste at the laboratory scale. However, comprehensive studies are still essential to identify the pathways involved in the biodegradation of plastic wastes. Existing research in this area requires lakhs of descriptive details, and further extensive studies are necessary. Teacher efforts in plastic removal of biodegradation technology should aim to enhance existing approaches or develop new ones. Identifying highly efficient microbial consortia and exploring species and enzymes with multi-functionality on leading polymers are crucial areas for further investigation [58].

Conclusion:

One promising approach to managing plastic waste sustainably is the biodegradation of microplastics by Aspergillus species. Aspergillus species can break down a variety of polymers, such as LDPE, HDPE, PU, PVC, and PET, into smaller, environmentally safe pieces thanks to their enzymatic properties. In order to use complex polymer structures as carbon sources, these fungi employ enzymes such as esterase, laccase, and PETase. Aspergillus's biodegradation ability is not only efficient but also flexible enough to work with a variety of polymers, demonstrating their adaptability. By developing this biological approach, the environmental impact of plastic trash can be considerably decreased, providing a cost-effective and environmentally friendly substitute for traditional plastic disposal techniques. This emphasizes how important fungi are to finding long-term solutions to the world's plastic pollution problem.

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