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Review

Biodegradation of plastics by white-rot fungi: A review

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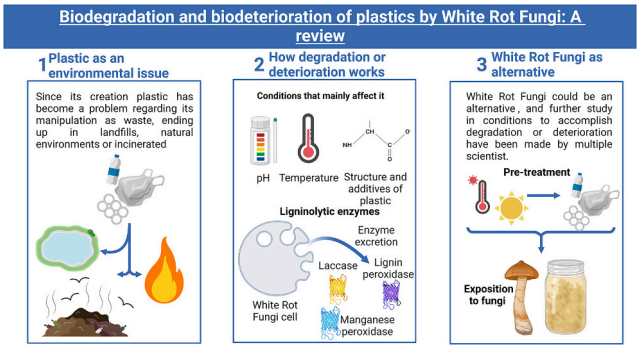
HIGHLIGHTS

- Recent progress in the biodegradation of plastics by white-rot-fungi is summarized.
- The effects of different types of plastics in the environment pollution are summarized.
- Biodegradations processes, advantages and disadvantages are approached.
- The roles of fungi and its enzymes are discussed.
- Ligninolytic enzymes have an important role in biodegradation process.

GRAPHICAL ABSTRACT



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ABSTRACT

Plastic pollution is one of the most environmental problems in the last two centuries, because of their excessive usage and their rapidly increasing production, which overcome the ability of natural degradation. Moreover, this problem become an escalating environmental issue caused by inadequate disposal, ineffective or nonexistent waste collection methods, and a lack of appropriate measures to deal with the problem, such as incineration and landfilling. Consequently, plastic wastes have become so ubiquitous and have accumulated in the environment impacting ecosystems and wildlife. The above, enhances the urgent need to explore alternative approaches that can effectively reduce waste without causing harsh environmental consequences. For example, white-rot fungi are a promising alternative to deal with the problem. These fungi produce ligninolytic enzymes able to break down the molecular structures of plastics, making them more bioavailable and allowing their degradation process, thereby mitigating waste accumulation.

Over the years, several research studies have focused on the utilization of white-rot fungi to degrade plastics. This review presents a summary of plastic degradation biochemistry by white-rot fungi and the function of their ligninolytic enzymes. It also includes a collection of different research studies involving white-rot fungi to degrade plastic, their enzymes, the techniques used and the obtained results. Also, this highlights the significance of pre-treatments and the study of plastic blends with natural fibers or metallic ions, which have shown higher levels of degradation. Finally, it raises the limitations of the biotechnological processes and the prospects for future studies.

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1. Introduction

Plastics are synthetic polymers with a high molecular weight, consisting of long carbonated chains typically derived from petroleum, natural gas, and coal (Jin et al., 2023; Loredo Treviño et al., 2012). Over the past few decades, these materials have become an integral part of our daily lives, to the extent that it is now unimaginable to envision life without them. Plastics find applications in various industries, including food, household appliances, construction, transportation, healthcare, and recreation. Their widespread use can be attributed to the specific characteristics that make them better than other materials, such as their strength, lightweight nature, durability, ease of manufacturing, affordability, and resistance to microbial degradation (Jin et al., 2023; Kumar et al., 2013; Mathur et al., 2011).

These versatile polymers offer a range of advantages in all industries due to their efficient structure. They can help in various ways, such as reducing food waste, saving energy, and decreasing CO_2 emissions (Plastics Europe, 2018; Shah et al., 2008). The most produced and marketed plastics include high-density polyethylene (HDPE), medium-density polyethylene (MDPE), low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), polyurethane (PUR), and terephthalate polybutylene (PBT), among others (Bhardwaj et al., 2012; Catto et al., 2014; Mahajan and Gupta, 2015).

Nowadays, approximately 367 million tons of plastics are produced worldwide each year (Li et al., 2023; Plastics Europe, 2020). To provide a broader perspective, since their creation around 1950, a staggering 9.2 billion tons of plastics have been synthesized, of which over 6.9 billion tons have turned into waste. Many of them are disposable plastics, and while their lifespan ranges from minutes to hours, their persistent in the environment ranges from decades to hundreds of years. Common disposal methods include landfilling (65 %), incineration (25 %), recycling (10 %), as well as their utilization in road construction, fuel production, degradation, and biodegradation (Parker, 2018; Sangale et al., 2019; Sivan, 2011).

While plastics offer benefits to industries, they pose challenges in terms of biodegradation due to the absence of recognizable enzyme functional groups, their hydrophobic nature (Sowmya et al., 2015), and their molecular stability. When disposed of in landfills, plastics can occupy 20 to 30 % of the space, reducing the life of landfills and forcing the creation of new ones. The above, leads to various issues, including soil disturbance from different wastes and disruption of the ecological balance in those areas (Mahajan and Gupta, 2015).

When plastics are not properly discharged, they cause harm to terrestrial and marine wildlife. Reports, indicate that every year 1 million birds and 10 million marine animals die due to plastics released into the environment. Furthermore, most of the plastic trash is moving around the world from the land to the oceans and vice versa, causing pollution into the environment, and therefore its bioaugmentation in the food web (Matjašič et al., 2021). In addition, if plastics are incinerated, they release toxic gasses that contribute to health problems and air pollution. Recycling is another alternative, but the efforts are not enough, and there is a lack of awareness and participation among the general population (Gajendiran et al., 2016; Kumar Gupta et al., 2016).

Recognizing the challenges associated with plastic disposal and its excessive production, new alternatives that enable the safe elimination of these polymers are needed. Some strategies could be a higher reusability rate, the production of biodegradable plastics and the biodegradation of existing ones. Moreover, these alternatives should be economically feasible and environmentally friendly (Gajendiran et al., 2016; Kumar Gupta et al., 2016).

The degradation of polymers refers to any physical or chemical disturbance that leads to change or loss of their original properties (Matjašič et al., 2021). Physical alterations can manifest as disruptions in the mechanical, optical, or electrical characteristics of the polymers, resulting in some phenomena such as crazing, cracking, erosion, discoloration, phase separation, or delamination. Chemical changes occur when the macromolecules undergo cleavage into smaller fragments, through in-bond scission triggered by factors such as light, heat, moisture, chemical conditions, or biological activity (Shah et al., 2008; Vohlidal, 2021). Despite this, degradation through chemical and physical methods is often expensive and can give rise to additional issues, such as the generation of toxic organic pollutants that hinder the degradation of natural substances in the soil (Ojha et al., 2017). In contrast, the biodegradation of plastics offers a more economical solution, as polymers can undergo complete mineralization through four main stages: biodeterioration, biofragmentation, bioassimilation, and ultimately, mineralization (Perera et al., 2021).

Even so, this process has its drawbacks and limitations. During the metabolic process, it can lead to the release of greenhouse gasses and other products that could have a negative impact on the environment. Also, if the biodegradation process is incomplete, metabolic intermediates could generate and release molecules with higher toxicity to the environment (Ammar, 2022; Atiwesh et al., 2021; Filiciotto and Rothenberg, 2021; Kida et al., 2022). Furthermore, biodegradation is often slower than other processes and requires appropriate conditions, such as temperature, moisture levels, and the presence of certain microorganisms (Filiciotto and Rothenberg, 2021). For instance, a better understanding of the process and conditions is indispensable to avoid these disadvantages and could achieve the desired complete mineralization. Nonetheless, the metabolites released during biodegradation are generally expected to be non-toxic and can undergo natural redistribution through the carbon, nitrogen, and sulfur cycles. Thus, studying the components generated during biodegradation, particularly in the context of polymers, is really important (Flury and Narayan, 2021). Some studies have shown that a certain amount of plastics and bioplastics could release toxic compounds like bisphenol A (BPA) and phthalates into the environment (Kyrila et al., 2021; Luzia et al., 2020). These chemical compounds could have negative effects on human health and the environment (Filiciotto and Rothenberg, 2021; Kubowicz and Booth, 2017; Singh and Sharma, 2008).

Studies on biodegradation of plastics have shown that the primary organisms involved are predominantly bacteria and fungi. These organisms produce various enzymes, including hydrolases, peroxidases, oxidases, and oxidoreductases (Martin Clavijo, 2012; Paço et al., 2017; Shah et al., 2008). These enzymes can be extracellular, intracellular, or membrane-bound, with the ability to break down polymers into small monomers. These monomers can then pass through microbial membranes and be utilized as carbon and energy sources, ultimately resulting in mineralization (Ghatge et al., 2020; Sangale et al., 2019; Shah et al., 2008). Alternatively, the biodegradation process can lead to the generation of other byproducts, which could be more susceptible to natural degradation (M. I. Ali et al., 2013a; Bhardwaj et al., 2012).

Most studies indicate that fungi are highly effective in the degradation of polymers due to their significant involvement in the decomposition of organic matter in soil and their metabolic versatility (Kim and Rhee, 2003; Zeghal et al., 2021). Among these fungi, a group known as white-rot fungi (WRF) stands out. It is important to note that white-rot fungi are not a taxonomic group but rather a collection of fungal species belonging to the basidiomycetes class that are able to degrade lignin. Some noteworthy species within this group include *Phanerochaete*, *Pleurotus*, *Ganoderma*, *Bjerkandera*, *Dichomitus*, and *Trametes* (Li et al., 2023; Mir-Tutusaus et al., 2018; Voběrková et al., 2018).

These fungi have demonstrated remarkable bioremediation capabilities, primarily attributed to their ligninolytic enzymatic system. This system comprises enzymes such as laccase (Lac), manganese peroxidase (MnP), and lignin peroxidase (LiP). These enzymes are non-specific in their substrate preference, and their ability to degrade lignin suggests a good potential for the degradation of synthetic polymers like plastics. Hence, white-rot fungi are a promising and viable alternative for the biodegradation of plastics, including biodegradable plastics (Catto et al., 2014; Manavalan et al., 2014).

Last decades, research about white-rot fungi in the bioremediation of plastics pollution have been growing. This review aims to provide a comprehensive overview of recent findings concerning the biodegradation of plastics using white-rot fungi. It will cover topics such as employed mechanisms by these fungi, the enzymes involved in the process, the byproducts generated, and the laboratory techniques used to assess biodegradation, including pre-treatments and other strategies.

2. Biochemistry of plastic degradation

The biodegradation of polymers is a slow process influenced by various factors. Some factors are related to the polymer itself, such as its composition, structural arrangement, carbon content, chain mobility, crystallinity, molecular weight, and plasticizers or additives presence. Other factors depend on the environmental conditions, like the degradation yield by microorganisms, and optimal enzymatic activity. These could be affected by some variables like humidity, temperature, pH, salinity, oxygen, sunlight, water, copolymers, and media composition. By optimizing these conditions, it is possible to improve the yield and speed of biodegradation, and ideally achieving the mineralization of persistent pollutants (Li et al., 2023; Priya et al., 2022; Siracusa, 2019; Stoleru et al., 2017).

pH and temperature are crucial environmental factors that can impact biodegradation. pH directly influences microbial development and enzymatic activity by inhibiting microbial growth and enzyme action. In the case of white-rot fungi, acidic pH creates optimal conditions for ligninolytic activity (Kale et al., 2015). Temperature also plays a significant role in biodegradation, determining the occurrence and speed of reactions. White-rot fungi are considered mesophiles (Ordaz et al., 2012), meaning they thrive within moderate temperature ranges. Their optimal temperatures typically range from 25 to 30 °C (Priya et al., 2022).

By carefully considering and controlling pH and temperature within appropriate ranges, favorable conditions can be created for biodegradation processes, especially in the case of white-rot fungi. Likewise, other environmental factors have notable influences on the biodegradation process.

Molecular weight is a physicochemical characteristic that can significantly influence biodegradation; polymers with lower molecular weight are generally easier to degrade. Additionally, microorganisms initiate degradation by attacking the ends of the polymer structure, making the number of ends present an important factor to consider. It is worth noting that molecular weight and the number of ends are inversely related. Crystallinity is another crucial factor to consider. The degree of crystallinity in a polymer is inversely proportional to its biodegradability. Enzymes find the amorphous regions easier to attack rather than crystalline areas. Besides, compounds added to polymers during manufacturing, such as additives, antioxidants, and stabilizers, could reduce the degradation yield and be toxic to microorganisms (Bacha et al., 2023; Kale et al., 2015; Priya et al., 2022; Siracusa, 2019). Fortunately, white-rot fungi have shown promising abilities in degrading certain compounds found in plastics, including bisphenol A and nonylphenol. This transformation makes the plastics more bioavailable to other microorganisms and to the fungi themselves (Kijpornyongpan et al., 2022).

Considering the factors mentioned above and previous studies on the interaction of enzymes with plastics, researchers have developed a new class of polymers known as biodegradable plastics. These plastics are designed to break down into CO_2, methane, and other compounds, within a timeframe of 6 months to 5 years, depending on their structure and thickness (Khoramejadian, 2013; Liu et al., 2010). Biodegradation time of these biodegradable plastics could be accelerated by incorporating components that facilitate oxidation or degradation. These types of polymers are referred to as oxo-biodegradable plastics (Rodrigues et al., 2013). Another approach to enhance biodegradability is by incorporating natural fibers into the polymer matrix. For example, cellulosic plastics, polylactic acid (PLA), starch-based plastics, and soy-based plastics (Catto et al., 2014; Wang et al., 2008). However, although these polymers are more environmentally friendly than synthetic ones, they also have disadvantages such as higher costs of production, higher permeability to gases, major fragility, low thermal resistance, low mechanical properties, vulnerability to degradation, and low processability (Abe et al., 2021).

The speed and efficiency of degradation are closely related to the degradation mechanism, which can occur under aerobic, anaerobic, or partially aerobic/anaerobic conditions. For complete biodegradation, also known as mineralization, microorganisms must be capable of breaking down the polymer and utilizing the resulting small molecules as an energy source. Typically, degradation systems involve several key steps. Firstly, the microorganisms attach to the polymer surface, followed by colonization. This attachment is mediated by the production of hydrophobic proteins that allow fungal structures to adhere to the hydrophobic surfaces of most plastics. Once colonization occurs, the microorganisms begin secreting extracellular enzymes. These enzymes bind to the polymer and catalyze its breakdown through hydrolysis and oxidation, leading to multiple ruptures and erosion of the polymer sheet. When the polymer is converted into smaller molecules, these molecules can either be released into the environment or enter to the microorganism's cell for mineralization through β-oxidation, and finally, they result in carbon dioxide and water, as shown in Fig. 1 (Bhardwaj et al., 2012; Devi et al., 2015; Kale et al., 2015; Kumar Sen and Raut, 2015; Priya et al., 2022; Siracusa, 2019; Wu et al., 2023).

3. Enzymatic biodegradation of polymers by white-rot fungi

White-rot fungi strains have the remarkable ability to break down lignin, a resilient and challenging-to-degrade heteropolymer, with a structural complexity found in plant cell walls. This degradation is carried out in order to access the carbohydrates like cellulose and hemicellulose found within the lignin layer. These fungi produce a combination of extracellular ligninolytic enzymes, organic acids, mediators, and accessory enzymes to accomplish the degradation of lignin. This enzymatic machinery lets them transform a wide range of molecules in a non-specific way, taking advantage of free radicals generation during the catalytic cycles, enabling the degradation process (Mir-Tutusaus et al., 2018).

Enzymes serve as catalysts for specific reactions or a series of reactions, including oxidation, reduction, hydrolysis, esterification, synthesis, and molecular inter-conversions (Singh and Sharma, 2008). Among the various methods for treating plastic waste, enzymatic degradation is considered particularly promising (Bhardwaj et al., 2012).

The ligninolytic system in white-rot fungi comprises four main enzymes: lignin peroxidases (LiP), manganese-dependent peroxidases (MnP), laccases (Lac), and versatile peroxidase (VP) (Bhardwaj et al., 2012). This enzymatic complex is notable for its high oxidizing power and lack of specificity. Below are brief descriptions of the most recognized enzymes.

3.1. Laccases (Lac)

Laccases (Lac; EC 1.10.3.2) are extracellular glycoproteins with multi-copper oxidase activity. The first report of laccase was by Yoshida (1883), and its characterization as a metal-containing oxidase was by Bertrand (1985). This makes it one of the oldest enzymes ever described. They typically consist of around 500 amino acids, have a molecular weight ranging from 50 to 130 kDa, and contain up to 25 % carbohydrate content. Laccases are versatile oxidoreductases known for their low specificity. They function optimally at temperatures between 40 and 65 °C, and their isoelectric point varies from 3 to 7 depending on the organism that produces them (Afreen et al., 2018; Alvarado-Ramírez et al., 2021; Deska and Kończak, 2019; Kunamneni et al., 2008; Naghdi

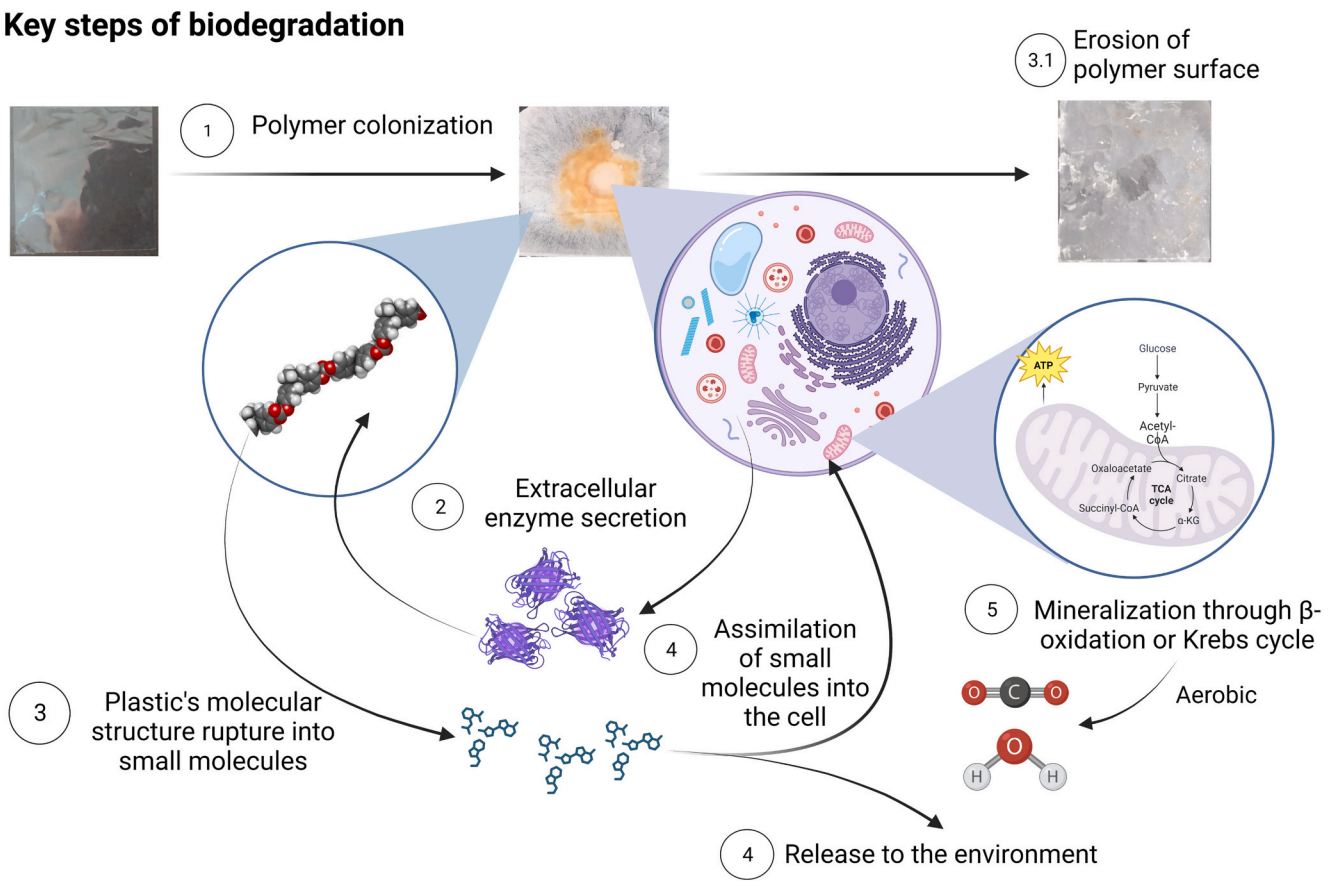

Fig. 1. Steps involved in biodegradation process performed by white-rot fungi.

et al., 2018).

These enzymes play various biological roles, including lignin degradation in nature, pathogenicity, detoxification, morphogenesis, and sporulation. Their primary function is the oxidation of phenols and aromatic amines, although they can also degrade diphenols, aliphatic amines, and even non-phenolic compounds with the assistance of mediators. Mediators are small, low molecular weight compounds that act as intermediaries between the enzyme and non-phenolic compounds. They are constantly oxidized by the enzyme and reduced by the substrate. Examples of mediators include TEMPO (2,2,6,6-tetramethyl-1-piperidinyloxy), HBT (1-hydroxy-benzotriazole), and ABTS (2,2′-azino-bis-(3-ethylbenzothiazoline-6-sulphonic acid)) (Kumar and Chandra, 2020; Morosova et al., 2007; Rodríguez Sánchez, 2006; Singh and Gupta, 2020).

Laccases are highly regarded as ideal catalysts in bioremediation due to their ability to oxidize a wide range of compounds using O_2 and producing H_2O as a byproduct. This makes them particularly valuable for the oxidation of persistent pollutants such as pesticides, herbicides, pharmaceutical compounds, dyes, and plastics. Their versatility and potential in remediation efforts have attracted significant interest (Kumar and Chandra, 2020; Singh and Gupta, 2020; Sivan, 2011).

3.2. Lignin peroxidase (LiP)

Peroxidases are a type of catalyst proteins that belong to the oxidoreductases group of enzymes. One of their key characteristics is the ability to break down hydrogen peroxide to oxidize various types of compounds (Águila Puentes, 2010). Lignin peroxidase (LiP; EC 1.11.1.14) is one of the most important extracellular and monomeric heme glycoproteins, involved in lignin degradation. This enzyme has been widely described and characterized in *Phanerochaete chrysosporium* (Hammel and Moen, 1991; Harvey et al., 1986; Kersten et al., 1985). It has a molecular weight ranging from 37 to 50 kDa, functions optimally at temperatures between 35 and 55 °C, and has an optimum pH range of 2–5 (Naghdi et al., 2018; Voběrková et al., 2018).

LiP exhibits a remarkable ability to oxidize non-phenolic aromatic compounds. This oxidation process involves an oxidation-reduction reaction, wherein hydrogen peroxide serves as an electron donor, enabling the extraction of an electron from the aromatic ring and leading to the formation of unstable free radicals. Subsequently, through non-enzymatic reactions, a second molecule of the substrate acts as the reducing agent, completing the catalytic cycle of the enzyme and releasing the initial molecules of the substrate (Kumar and Chandra, 2020; Rodríguez Sánchez, 2006; Singh et al., 2021).

When hydrogen peroxide (H_2O_2) is present as a co-mediator, LiP exhibits the capability to oxidize a broad spectrum of compounds by catalyzing their one-electron oxidation via redox-active mediators. Veratryl alcohol is a fungal secondary metabolite, with the ability to enhance the enzyme action and therefore is one of the most important mediators for the enzymatic activity (Candeias and Harvey, 1995; Harvey et al., 1986; Zacchi et al., 2000). This is possible thanks to its low substrate specificity, nonspecific redox potential, and free form. These characteristics enable the enzyme to efficiently degrade emerging contaminants that are released into the environment, particularly from the cosmetic, pharmaceutical, biomedical, personal care products, wastewater, and plastics industries (Kumar and Chandra, 2020; Singh et al., 2021).

3.3. Manganese peroxidase (MnP)

Manganese peroxidase (MnP; EC 1.11.1.13) is an extracellular heme glycoprotein enzyme involved in lignin degradation. It is an isoenzyme

secreted by white-rot fungi and widely studied in *Phanerochaete crhysosporium*, the model fungus for lignin and xenobiotic biodegradation studies (Holzbaur et al., 1991; Palma et al., 2000). Its molecular weight ranges from 32 to 62.5 kDa, functions optimally at temperatures between 40 and 60 °C, and has an optimum pH range of 4–7 (Naghdi et al., 2018; Voběrková et al., 2018).

MnP is dependent on Mn^{2+} ions to finish the catalytic cycle (Bermek et al., 2004). The action of this enzyme is like lignin peroxidase, the difference being the oxidation of Mn^{2+} to Mn^{3+} during the substrate oxidation. The incorporation of Mn ions enables the enzyme to have a diverse range of substrates, phenolic and non-phenolic (Chowdhary et al., 2018; Kumar and Chandra, 2020; Rodríguez Sánchez, 2006).

MnP could be regarded as one of the most potent ligninolytic enzymes. It has been extensively studied and is recognized for its diverse enzymatic activities and the ability to oxidize various types of compounds. As a result, the interest in MnP has been growing, particularly in applications such as wastewater treatment, and degradation of dyes, resins, wood, and plastics (Chowdhary et al., 2018; Kumar and Chandra, 2020).

3.4. Versatile peroxidase (VP)

In addition to laccase, lignin peroxidase, and manganese peroxidase, white-rot fungi have been found to produce another important enzyme named versatile peroxidase (VP). VP has been described mainly in *Pleurotus* and *Bjerkandera* species (Pozdnyakova et al., 2013). Its ability to oxidize both Mn^{2+} and aromatic compounds was first reported in *Pleurotus eryngii* (Martínez et al., 1996). This enzymatic complex, comprising multiple enzymes, plays a crucial role in the recycling of organic material in ecosystems, making it one of the most significant catalysts in this process (Voběrková et al., 2018). Versatile peroxidase (VP; EC 1.11.1.16), also known as hybrid peroxidase or manganese-lignin peroxidase, exhibits characteristics of both LiP and MnP enzymes, combining their functionalities (Biko et al., 2020; Gonzalez-Perez and Alcalde, 2018; Kumar and Chandra, 2020).

Due to its hybrid nature, VP possesses a unique dual oxidative capability. This allows the enzyme to effectively oxidize compounds with both high and low redox potentials, including phenolic, non-phenolic, and diazo compounds, in a nonspecific manner, using H_2O_2 as an oxidant (Rodríguez et al., 2004). These remarkable characteristics have sparked significant biotechnological interest in VP, particularly in applications such as biosensor design, analytic kits, paper and pulp biobleaching, the textile industry, and bioremediation. In the field of bioremediation, VP has shown promising potential for the biodegradation of recalcitrant contaminants, including plastics (Biko et al., 2020; Gonzalez-Perez and Alcalde, 2018; Kumar and Chandra, 2020).

4. Biodegradation of plastics by white-rot fungi

Related to the degradation of plastics using white-rot fungi, two main methods have been developed: enzymatic treatment and direct degradation by fungi. In the enzymatic treatment method, plastics can be treated with purified enzymes or enzyme broths obtained from fungal cultures. On the other hand, the direct degradation method involves the use of active fungal cultures to directly degrade the pollutants. One of the major advantages of employing fungi in the degradation process is their ability to produce a wide range of enzymes, aside from ligninolytic enzymes, along with the subsequent production and transformation of intermediaries (Sumathi et al., 2016). Fig. 2 provides an overview of plastic biodegradation by white-rot fungi. Additionally, Table 1 summarizes recent reports of plastic degradation using white-rot fungi. The information is categorized by the types of plastics studied and includes details about the methods, environmental conditions, culture media, and other relevant information related to the degradation of these polymers.

4.1. Polyethylene or polythene

Polythene, also known as polyethylene, is a widely used thermoplastic in various consumer products. It holds great significance as a plastic due to its durability, water resistance, and lightweight nature. Polythene finds applications in the production of thin carry bags, milk bags, food wrappers, laminates, and more. It is a polymer composed of long chains of ethane monomers (Aswale, 2011). The degradation of polythene can be quantified by measuring the weight loss of the polymer after treatment with white-rot fungi such as *P. chrysosporium*, *T. versicolor*, and *P. ostreatus*. In a study performed by Aswale (2011). *P. chrysosporium* demonstrated a maximum polymer weight loss of 50 %, and *T. versicolor* exhibited maximum degradation at pH 8, while *P. ostreatus* showed the highest degradation at pH 4. Additionally, the effect of pre-photo degradation of polythene was investigated in an experiment that lasted 24 days. The degradation capability of pre-light exposed polythene was assessed, and *P. chrysosporium* displayed the highest degradation, achieving almost 100 % biodegradation after 30 days of treatment (Aswale, 2011).

In a study conducted by Mukherjee and Kundu (2014), *P. chrysosporium* was used to assess the degradation of polyethylene (PE) sheets. The 5 × 5 cm PE sheets were pre-treated with potassium dichromate ($K_2Cr_2O_7$) and sulfuric acid. The treated polymer was exposed to the fungi in various culture media. There were four cases in which diluted black liquor served as a lignin source, with two cases having an excess of nitrogen (N) and both cases being nitrogen-limited. Similarly, two cases had an excess of manganese (Mn) while two cases were manganese-limited. One case included five times the amount of black liquor compared to the other cases. The test samples were incubated for 15 days at a temperature of 37 °C.

The results showed a weight loss of 70 % within the 15-day incubation period. However, no further weight loss was observed beyond this point. Fourier-transform infrared spectroscopy (FITR) analysis revealed an increase in carbonyl peaks, indicating oxidation of the plastic by the fungi. The study also demonstrated that *P. chrysosporium* could only degrade low-density polyethylene (LDPE) when both Manganese peroxidase and Lignin peroxidase enzymes were present. This condition was met in the assays that had an excess of N and a deficiency of Mn (Mukherjee and Kundu, 2014).

In another assay, the authors (Hock et al., 2019) tested the ability of 3 fungi to use polyethylene (PE) or polystyrene (PS) as a carbon source for *Pleurotus abalones* and *Pleurotus ostreatus*. The PE was cut into pieces measuring 0.5 mm and mixed with Bushnell Haas Broth, a culture media lacking a carbon source. Different salt concentrations (0, 0.01, 0.05, and 0.10 M NaCl) and incubation temperatures (4 °C, 25 °C, 37 °C, and 60 °C) were tested. The fungi were inoculated for 7 days. After the incubation period, the results suggest that *Pleurotus abalones* and *Pleurotus ostreatus* can degrade and utilize PE or PS as a carbon source, as evidenced by their growth in the culture media (Hock et al., 2019).

4.1.1. Green polyethylene

Green plastics, also known as bio-based plastics, are a category of plastics produced from renewable raw materials such as vegetable fats and oils, instead of non-renewable sources like petroleum or natural gas. The development of these plastics, aims to achieve several important objectives, including the reduction of greenhouse gas emissions, minimizing the accumulation of waste in landfills, and decreasing the dependence on petrochemical derivatives (Rosenboom et al., 2022).

By using renewable resources, green plastics contribute to a more sustainable and environmentally friendly approach to plastic production. They offer potential benefits in terms of mitigating climate change, promoting resource conservation, and fostering a circular economy. The shift towards green plastics aligns with global efforts to reduce carbon footprints and transition to a more sustainable future (da Luz et al., 2015; Rosenboom et al., 2022).

Although the production of these kinds of plastics provides

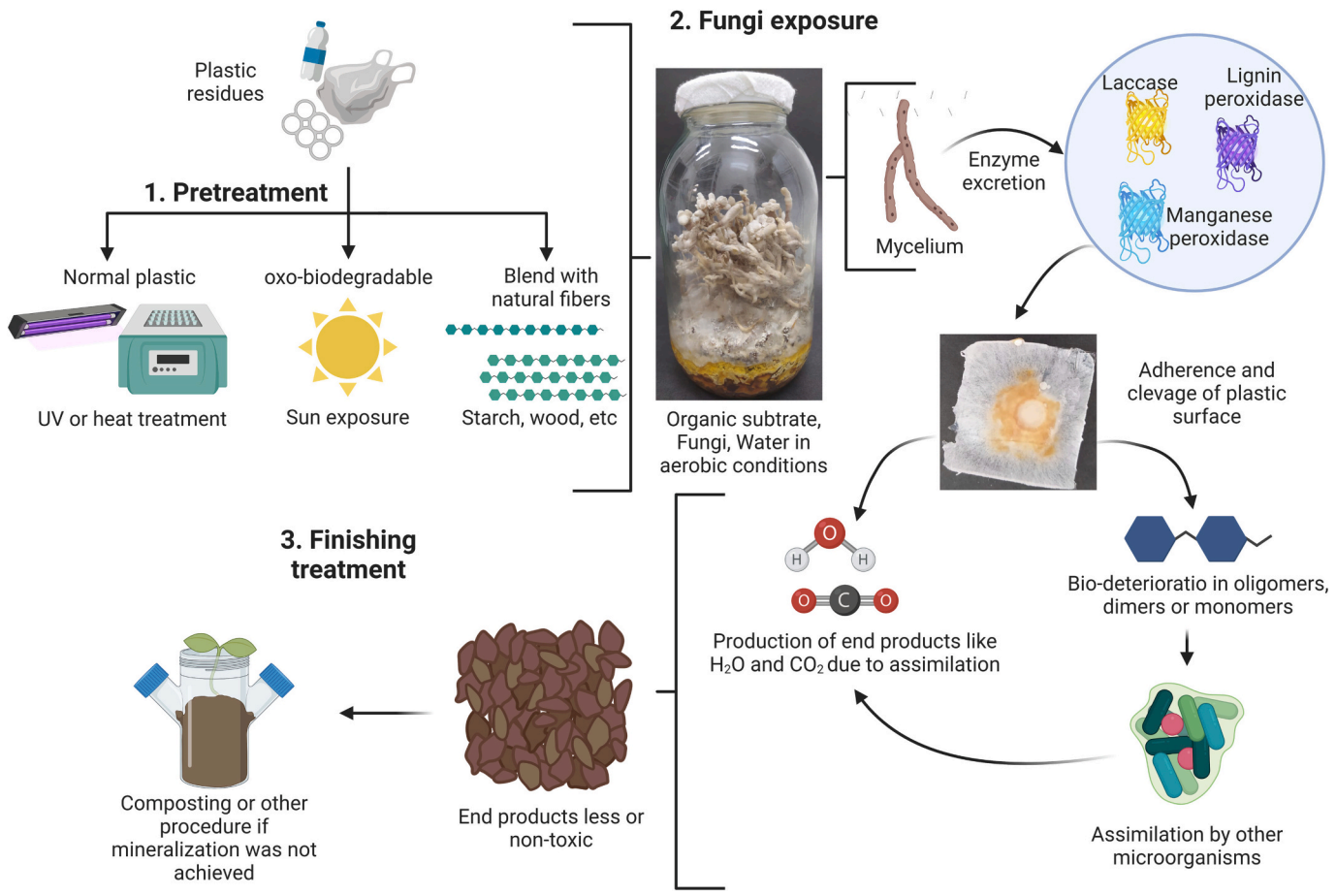

Fig. 2. Systematic overview of plastics biodegradation by white-rot fungi.

environmental benefits and can be recycled, there is little information about their degradability rate when are discarded into the environment. That is the purpose of the study made by da Luz et al. (2015), where the degradability of green plastics was investigated using the fungus *Pleurotus ostreatus* PLO6. The experimental approach involved subjecting the plastic to an abiotic degradation process through exposure to sunlight for varying durations of 30, 60, 90, and 120 days. After the abiotic degradation, the plastic was cut into fragments measuring 5 × 1 cm. These fragments were then mixed with 0.1 g of paper towel and 5 mL of mineral medium. *P. ostreatus* was inoculated into the mixture, and the incubation was carried out at a temperature of 25 °C for 30, 60, and 90 days.

The results of the study indicated that *P. ostreatus* could degrade the green plastic, both with and without the prior abiotic degradation treatment. However, it was not only the effect of fungus but also the combination with the sunlight pre-treatment which facilitate the degradation process. This suggests that the combination of abiotic degradation through sunlight exposure and subsequent incubation with *P. ostreatus* could be an effective approach to reducing the lifespan of plastic waste, potentially enhancing its biodegradability (da Luz et al., 2015).

4.2. High-Density Polyethylene (HDPE)

High-density polyethylene (HDPE) is a type of thermoplastic, derived from petrochemicals. Its dense structure enhanced its strength and durability. As a result, HDPE is extensively used across various industries, including textiles, food packaging, automotive manufacturing, and laboratory equipment. One of the key characteristics of HDPE is its resistance to microbial degradation. This is primarily attributed to its chemical composition, which makes it highly resistant to attack by microorganisms. Consequently, HDPE tends to accumulate in waste disposal sites, as it is not easily broken down by natural processes (Chaudhary and Vijayakumar, 2020).

To address the accumulation of HDPE and enhance its biodegradation, some researchers (Kang et al., 2019) have explored the use of extracellular enzymes produced by microorganisms like fungi. In their study, they focused on the production of laccase from *Bjerkandera adusta* TBB-03 using ash wood chips as a lignocellulosic substrate.

Different culture conditions were tested, this included the use of malt extract as a medium, a modified version of malt extract with ash wood replacing the carbon source, and solid-state fermentation (SSF). Strips of HDPE of 5 × 5 cm were prepared and added to each experimental unit. The incubation period lasted for 90 days at 25 °C and 120 rpm, except for SSF, which did not involve agitation.

At the end of the incubation period, the HDPE strips were analyzed using Raman Spectroscopy and scanning electron microscopy (SEM). The results indicated that the addition of a lignocellulosic substrate facilitated structural changes in HDPE. Furthermore, the study found that there were negligible differences between the modified malt extract agar assay and SSF. Lastly, it was exhibited that the crystallinity of HDPE increased while the amorphous structure decreased, suggesting that *B. adusta* TBB-03 had the ability to modify the structure of HDPE (Kang et al., 2019).

In another study conducted by Hassinger (2018), hardwood chippings were used as a lignocellulosic substrate, along with five different fungi: *Pleurotus ostreatus*, *Pleurotus ostreatus* var. *columbinus*, *Lentinula edodes*, *Ganoderma lucidum*, and *Trametes versicolor*. The study aimed to

Table 1
Overview of plastics biodegradation studies by white-rot fungi.

Polymer	Fungal strain	Pre-treatment and cultivation media	Conditions	Results	Reference
Polyethylene (PE)	*Phanerochaete chrysosporium* and *Trametes versicolor*	Petri dishes containing basal media, with varying concentration of glucose and nitrogen source	30 °C for 8 months	Results showed 50 % of weight loss	(Aswale, 2011)
Polyethylene (PE)	*Phanerochaete chrysosporium*	Pre-treatment with $K_2Cr_2O_7$ and sulfuric acid. 4 different media with differences in N and C concentrations and black liquor	37 °C for 15 days	70 % of weight loss, changes in chemical structure	(Mukherjee and Kundu, 2014)
Polyethylene (PE)	*Pleurotus abalones and Pleurotus ostreatus*	Bushnell Haas Broth, with different salt concentrations and temperatures, and PE as sole carbon source	7 days	Ability of the fungi to grow in the media	(Hock et al., 2019)
Polyethylene (PE)	*Pleurotus ostreatus* PLO6	Plastic exposed to sunlight for 30, 60, 90 and 120 days. Pieces of paper towel as lignocellulosic substrate, and mineral media	30, 60 and 90 days at 25 °C	Degradation was observed in the plastic with or without pre-treatment	(da Luz et al., 2015)
High density polyethylene (HDPE)	*Bjerkandera adusta TBB-03*	Malt extract, modified malt extract (ash wood as carbon source) and SSF with ash wood as substrate.	90 days, at 25 °C and 120 rpm (except for SSF)	Changes in HDPE structure, that made the polymer weaker	(Kang et al., 2019)
High density polyethylene (HDPE)	*Pleurotus ostreatus*, *Pleurotus ostreatus var. columbinus*, *Lentinula edodes*, *Ganoderma lucidum* and *Trametes versicolor*	Petri dishes with malt extract agar, including 25 % of hardwood chipping	4 months	Significant mass loss, and ability of all fungi to degrade except for *Ganoderma lucidum*	(Hassinger, 2018)
Low density polyethylene (LDPE)	Genus not identified	Minimal salt media broth and the plastic as sole carbon source	30 days at 28 °C and 150 rpm	18,40 % of degradation	(Hyder et al., 2021)
Low density polyethylene (LDPE)	*Schizophyllum commune* and *Phanerodontia chrysosporium*	Czapek-Dox Broth	60 days at room temperature	Both fungi showed ability to degrade the polymer	(Perera et al., 2021)
Low density polyethylene (LDPE)	*Pleurotus ostreatus*, *Pleurotus ostreatus* var. *columbinus*, *Lentinula edodes*, *Ganoderma lucidum* and *Trametes versicolor*	Petri dishes with malt extract agar, including 25 % of hardwood chipping	4 months	Significant mass loss, and ability of all fungi to degrade except for *Trametes versicolor*	(Hassinger, 2018)
Low density polyethylene (LDPE)	*Pleurotus ostreatus*	Pre-treatment with plasma discharge. Degradation in a wet chamber with semi solid Radha agar, glucose, copper and ABTS	150 days	Modification in the surface, increase of hydrophilicity and roughness, being 27 % of changes in the mechanical properties of LDPE	(Gómez-Méndez et al., 2018)
Low density polyethylene (LDPE)	*Agrocybe aegerita* and *Ganoderma lucidum*	Pre-treatment by blending the plastic with fatty acids. Degradation in Petri dishes with PDA and modified Czapeck-Dox Broth	26 °C and 70–80 % RH	Evidence of mycelium penetrating the polymer and evidence of oxidation	(Bertolacci et al., 2022)
Liner low density polyethylene (LLDPE) oxo Biodegradable plastic	*Phanerochaete chrysosporium*	Degradation in Petri dishes	180 days	Weight loss and Increased production of CO_2 indicating degradation	(Corti et al., 2012)
Polypropylene (PP), starch polypropylene blend and polypropylene + metallic ions	*Phanerochaete chrysosporium*	20 mg plastic in 100 mL of liquid media MSM	30 °C, 120 rpm for 12 months	Polypropylene, starch polypropylene blend and polypropylene + metallic ions pre-treated with UV radiation, showed higher oxidation and weight loss	(Jeyakumar et al., 2013)
Polyvinyl chloride (PVC)	*Pleurotus* sp. - *Phanerochaete chrysosporium* - *Poliporus versicolor*	50 mL of liquid media with veratryl alcohol and PVC as sole carbon source, high oxygenation	30 °C, 150 rpm, pH 4.5 for 30 days	Reduction of the percentage of C-H linkage, small weight loss and thickness. Best results obtain with this fungal strain	(Kirbaş et al., 1999)
Polyvinyl chloride (PVC)	*Phanerochaete chrysosporium* - *Lentinus tigrinus*	MSM media with sheets of PVC	30 °C, 150 rpm for 7 weeks	Evidence of the use of PVC as carbon source and transformation of the surface of the plastic.	(Ali et al., 2013a)
Starch polyvinyl chloride (PVC) blend	*Phanerochaete chrysosporium*	100 mL de medium MSM with sheets of starch PVC blend as sole carbon source	30 °C, 155 rpm for 30 days	Altered physical characteristics of the plastic and in its structure	(Ali et al., 2013a)
Cellulose blended polyvinyl chloride (PVC)	*Phanerochaete chrysosporium*	Soil burial or in liquid or solid mineral salt media	4 months of soil burial and 2 months at 30 °C for mineral salt media	The fungus was able to use the plastic as a carbon source, films presented cracks, holes and erosion. Structural changes	(Hassan et al., 2014)
Polystyrene (PS)	*Pleurotus abalones* and *Pleurotus ostreatus*	Bushnell Haas Broth, with different salt concentrations and	7 days	Ability of the fungi to grow in the media	(Hock et al., 2019)

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Table 1 (*continued*)

Polymer	Fungal strain	Pre-treatment and cultivation media	Conditions	Results	Reference
		temperatures, and PE as sole carbon source			
Polystyrene (PS)	*Ceriporia* sp. (BIOM3) and *Cymatoderma dentriticum* (WM01)	Pre-treatment mixing with dimethyl-formamide. Biodegradation in malt extract broth and nutrition broth media	30 days at 25 °C	Degradation of 19,44 % by Ceriporia sp. (BIOM3) and 15,70 % by *Cymatoderma dentriticum* (WM01)	(Yanto et al., 2019)
Polystyrene (PS)	*Phanerochaete chrysosporium*	Biodegradation in low carbon Potato Dextrose Agar	7, 14, 21. 28 and 35 days at 30 °C	Weight loss of 19.71 %, degradation rate of 1.25 %, changes on the surface, decrease of molecular weight by 31–33 %, formation of new functional groups.	(Wu et al., 2023)
Oxo-biodegradable plastic	*Pleurotus ostreatus*	10 g of plastic, 0,1 g of towel paper, 5 mL of mineral media	25 °C for 45 days	Evidence of plastic degradation with basidiocarp formations	(Rodrigues et al., 2013)
WPC – polypropylene (PP), ethylene vinyl acetate (EVA) and eucalyptus or pine	*Trametes villosa* - *Pycnoporus sanguineus* - *Coriolopsis rigida*	Solid media, composed by the mixture of PP, EVA and pine or eucalypt	30 °C, darkness for 60 days	Weight loss of the mixture plastic and wood, best results obtained with pine and eucalypt	(Catto et al., 2014)
WPC - 40 % polypropylene (PP) and 60 % pine, maple, or oak by weight	- *Trametes versicolor* -*Phanerochaete chrysosporium* - *Gloeophyllum trabeum* - *Postia placenta*	An agar test and a soil blocking test were carried out, using garden soil bottles that had a humidity of 70 %, supplemented with small WPC films.	27 °C for 10 to 12 weeks.	The soil block test was better than the agar method to evaluate the fungal attack of the WPCs. *G. trabeumand* and *P. placenta* fungi obtained better results and there was greater weight loss in the WPC made with maple and oak	(Lomelí-Ramírez et al., 2009)
WPC - 70 % of polypropylene (PP) and 30 % of *Eucalyptus globulus*, Pinecones or *Brassica rapa*	*Bjerkandera adusta*	Pre-treatment with Gamma irradiation. Degradation in Petri dishes with or without malt-glucose-agar extract	7 weeks at 28 °C	Physical changes in the WPC	(Butnaru et al., 2016)
WPC - maple 40-mesh wood flour at 49 % or 70 % and high-density polyethylene (HDPE) at 45 % or 30 %	*Trametes versicolor*	Degradation in Petri dishes	24 or 77 days at 25 °C	Increase in the stiffness of the WPC, 21 % of weight loss in the WPC with lower quantity of HDPE and 19 % in the higher	(Schirp and Wolcott, 2005).
WPC – polypropylene (PP) H-107 and *Eucalyptus* bark in 1:1 ratio	*Pycnoporus sanguineus*	Potato dextrose agar (PDA) with a substrate made with Eucalyptus spp. and WPC.	30 °C at 60 % humidity for 120 days	After 120 days of exposure, the fungus produced a biofilm under the WPC that led to deterioration of the mechanical properties and minor changes in the thermochemical stability of the WPC.	(Cesarino et al., 2019)
WPC - bamboo flour at 60 %, 50 % and 40 % with HDPE, LDPE, PVC, and PP	*Trametes versicolor*	Degradation performed in decay chambers, with moist forest loam and alder	12 or 16 weeks at 28 °C	Minimal weight loss registered	(Bari et al., 2017)
Aliphatic polyamides	*Phanerochaete chrysosporium* and *Bjerkandera adusta*	100 mL of modified glucose-mineral media, fragments of 2 cm of nylon as sole nitrogen source to complete a concentration 200 mg of nylon in 100 mL of media	30 °C, 90 rpm for 60 days	It was determined that part of the polymer was solubilized and metabolized by the fungi, specially by *Bjerkandera adusta*	(Friedrich et al., 2007)
Etilen vinyl alcohol (EVOH)	*Phanerochaete chrysosporium*	A mixture of equal amounts of corn husk and corncob adjusted with basal media in static bed reactor	24 °C, 60 % of humidity for 36 days	It was determined that the crystalline structure of EVOH was changed to PVOH, a more disorganized structure	(Arboleda et al., 2007)
Starch-based plastic polymer	*Phanerochaete chrysosporium*	Glass column of 20 cm height and 4 cm of diameter packed with 45 g of sugarcane bagasse and 3 g of starch-based polymer	60 % of humidity, 39 °C, 0,5 mL of air/min for 45 days	70 % and 74 % fungal starch degradation	(Roldán-Carrillo et al., 2003)
Used disposable diapers containing polyethylene (PE), polypropylene (PP), and a super absorbent polymer	*Pleurotus ostreatus*	The fungus was inoculated with the diapers in the following way (a) with or without plastic (b) manually crushed or mechanically ground (c) with or without grape marc supplement and a control with wheat straw.	During the invasion stage, the temperature was kept between 25 and 29 °C for 21 days under dark conditions, and in the fruiting period it was in the range of 22–25 °C. for 47 days under natural light conditions	The weight and volume of degradable materials were reduced by up to 90 %. The cellulose content decreased by 50 % and the lignin content by 47 %. The harvested mushrooms had good appearance and protein content and were free of human disease pathogens.	(Espinosa-Valdemar et al., 2011)
Polylactide (PLA)	*Phanerochaete chrysosporium*	Gamma-irradiated or activated by nitrogen plasma and grafted onto the chitosan surface. Then inoculated in Sabouraud solid medium with PLA as carbon source	28 °C for 14 days	The specific activities of the catalase and superoxide dismutase enzymes increased and peaked after 14 days of incubation. A significant decrease in molecular weight and an	(Stoleru et al., 2017)

(*continued on next page*)

Table 1 (*continued*)

Polymer	Fungal strain	Pre-treatment and cultivation media	Conditions	Results	Reference
				increase in the roughness of the polymer surface were observed.	

assess the degradation of five types of plastics, including HDPE.

The experimental setup involved placing 1 × 1 cm pieces of HDPE bags into Petri dishes containing malt dextrose agar supplemented with 25 % hardwood chippings and distilled water (with a lignin content of 2.5 g per 12.5 mL). The incubation lasted for three months.

At the end of the assay, a significant mass loss percentage was observed. *P. ostreatus* var. *columbinus*, *L. edodes* and *T. versicolor* exhibited higher levels of HDPE degradation. However, *G. lucidum* did not demonstrate the ability to degrade HDPE under the given conditions (Hassinger, 2018).

4.3. Low-density polyethylene (LDPE)

Low-density polyethylene (LDPE) is a thermoplastic that belongs to the polyolefin family and is derived from petrochemicals. It is known for its high flexibility, which sets it apart from other plastics like HDPE. LDPE finds extensive applications in the packaging industry, particularly for items like plastic bags, wrapping foils, and trash bags. Consequently, the abundance of LDPE in solid waste is higher compared to other types of plastics (Gamage and Uthpalani, 2022). As a result, LDPE has received significant attention in research studies focused on degradation processes.

In a study conducted by Ali Hyder et al. (2021), the biodegradation of LDPE was investigated using a fungus isolated from waste disposal. While genetic identification was not possible, morphological identification indicated that the isolated fungus belonged to the white-rot fungi group. The fungus was inoculated in a minimal salt medium along with a pre-weighed LDPE disc measuring 2 × 2 cm. The incubation period lasted for 30 days at a temperature of 28 °C and agitation of 150 rpm. After incubation, the LDPE discs were retrieved, rinsed, and weighed. The results revealed a weight loss percentage of 18.40 %, ranking it as the third most effective strain out of the four strains tested (Ali Hyder et al., 2021). Although these conditions were not optimal, this particular strain showed promise for further studies on degradation.

Another example of biodegradation of LDPE by fungi was performed by Perera et al. (2021). Initially, 33 strains of fungi were isolated and screened for their ability to produce laccase. From these, three strains were selected, including two white-rot fungi: *Schizophyllum commune* and *Phanerodontia chrysosporium*. The selected fungi were then inoculated with LDPE sheets measuring 2 × 10 cm in Czapek-Dox Broth and incubated for 60 days at room temperature.

At the conclusion of the assay, it was observed that both white-rot fungi were able to induce a degree of biodegradation in the LDPE sheets. This was evident through changes in weight loss, as well as structural and compositional modifications observed through FTIR analysis and SEM imaging. Additionally, there was a reduction in the tensile properties, indicating the impact of fungal activity on the material (Perera et al., 2021).

As mentioned before, Hassinger (2018) did various assays using 5 different species of white-rot fungi and 5 types of plastics, including LDPE. Similar to the findings for HDPE, all fungi, except *Trametes versicolor*, exhibited the capability to degrade LDPE. Among the tested fungi, *Pleurotus ostreatus* demonstrated the highest rate of biodegradation after one and three months. These results indicate the potential of *Pleurotus ostreatus* and other white-rot fungi in the biodegradation of LDPE (Hassinger, 2018). However, further research is necessary to optimize the degradation process and explore its applicability in real-world scenarios.

In another study (Gómez-Méndez et al., 2018), plasma discharge was used as a pre-treatment method to enhance the degradation of LDPE by *Pleurotus ostreatus*. The plasma oxygen luminescent discharge altered the hydrophobicity of the plastic surface, allowing microorganisms to adhere more effectively. After the pre-treatment, 3 cm^2 piece of LDPE was exposed to *P. ostreatus* for 150 days, in a wet chamber containing semi-solid Radha agar supplemented with glucose, copper, and ABTS as a redox mediator.

The results indicated physical modifications in the surface of the plastic, including increased hydrophilicity and surface roughness. These modifications were accompanied by a 27 % change in the mechanical properties of LDPE, indicating clear signs of biodeterioration. The study suggests that the combination of plasma discharge pre-treatment and subsequent exposure to *P. ostreatus* can enhance the degradation of LDPE and promote its biodeterioration (Gómez-Méndez et al., 2018).

Another option to pre-treat plastics before exposing them to fungi is by blending them with fatty acids through melting/solidification cycles, transforming the polymer into a substrate that can be degraded by microorganisms. The research made by Bertolacci et al. (2022) did the melting/solidification cycles to LDPE sheets. Following the pre-treatment, the plastic was cut into squares of 2 × 2 cm and placed in Petri dishes containing Potato Dextrose Agar (PDA) or modified Czapek-Dox Broth without a carbon source.

Two fungal strains, *Agrocybe aegerita* and *Ganoderma lucidum*, were selected. A plug from each fungus was inoculated with the plastic pieces in Petri dishes, then incubated at 26 °C and 70–80 % relative humidity for one month. The results showed that the mycelium of the fungi was able to penetrate the plastic, indicating the colonization of LDPE. Chemical analyses revealed the ability of *Agrocybe aegerita* to oxidize LDPE chains, indicating the degradation of the plastic. These findings suggest that the pre-treatment involving melting/solidification cycles enabled the colonization and subsequent degradation of LDPE by the selected fungal strains (Bertolacci et al., 2022).

4.4. Oxo-biodegradable linear low-density polyethylene

Linear low-density polyethylene (LLDPE) is a widely used type of polyethylene known for its ease and cost-effectiveness of production. It is a thermoplastic polymer with good mechanical and optical properties, thanks to the presence of olefins in its structure. LLDPE finds applications in various industries, including food packaging and agriculture, where its ability to retain moisture and maintain stable temperatures is beneficial (Alshabanat, 2019).

LLDPE oxo-biodegradable, on the other hand, is a modified form of LLDPE. It contains metallic ions in its structure, typically introduced through the addition of transition metal salts. These metallic ions act as catalysts, promoting the breakdown of the polymer chains when exposed to sunlight or heat, generating free radicals, which initiate oxidative degradation of the polymer. It is important to note that the oxo-biodegradability of LLDPE is a subject of debate and ongoing research. The effectiveness and environmental implications of this technology are still being evaluated and vary depending on factors such as formulation, exposure conditions, and waste management practices (Corti et al., 2012).

Corti et al. (2012) attempted to verify if the incorporation of these metallic ions enabled the degradation of the polymer with *P. chrysosporium*. The researchers exposed some sheets of LLDPE oxo-biodegradable to sunlight, while others were kept in the dark. Subsequently, the sheets were placed on agar plates inoculated with *P. chrysosporium*, with the cultivation media containing a low

concentration of glucose to stimulate co-metabolism.

The results of the study indicated that the sheets exposed to sunlight were more susceptible to colonization by the fungus compared to those that were not exposed to sunlight. This suggests that the incorporation of metal ions in the LLDPE oxo-biodegradable facilitated microbial degradation. However, it is important to note that further research is needed to fully understand the degradation mechanisms and the overall environmental impact of oxo-biodegradable plastics (Corti et al., 2012).

4.5. Polypropylene

Polypropylene (PP) is a cost-effective polymer derived from propylene, a byproduct of petroleum refining. It has extensive applications in various industries, including automotive, pipelines, food, and textiles, among others. However, the degradation of PP poses challenges due to its impermeable structure, the tightly packed and hydrophobic nature of PP, along with its high crystallinity, contribute to its resistance to microbial attack, since it is less accessible to the enzymes produced by microorganisms. As a result, PP is considered to have low biodegradability and can persist in the environment for extended periods, contributing to the accumulation of plastic waste (Jeyakumar et al., 2013).

To address the challenge of PP degradation, researchers have explored structural modifications by incorporating other compounds and subjecting the polymer to pre-treatments. In a study conducted by Jeyakumar et al. (2013), sheets of unmodified PP, PP blended with starch, and PP with metal ions were used to investigate their biodegradability. The sheets were subjected to different pretreatment conditions, including heating at 100 °C for 10 days, exposure to UV radiation for 10 days, or no pre-treatment.

After the pre-treatment, the polymers were mixed in a liquid medium and exposed to *P. chrysosporium* for degradation. The results revealed that sheets containing metallic ions and exposed to UV radiation exhibited the highest level of degradation. Furthermore, the pre-treated sheets were more susceptible to fungal colonization and degradation compared to the untreated sheets, particularly when exposed to UV radiation. These findings are consistent with the study by Corti et al. (2012), which also demonstrated the influence of pre-treatments, such as UV exposure, on the degradation of PP.

4.6. Polyvinyl chloride

Polyvinyl chloride (PVC) is one of the most widely produced plastics globally. It is favored for its excellent resistance and flexibility, making it a popular choice in various industries such as packaging, toys, furniture, pipelines, and construction materials. The structure of PVC consists of a carbonated chain made up of repeating vinyl chloride monomer units ($CH2 = CHCl$). This chain gives PVC its unique properties and versatility. The presence of chlorine atoms in the polymer structure contributes to its flame-retardant properties, chemical stability, and durability. While PVC is widely used and has many desirable properties, its disposal and environmental impact have raised concerns. When PVC products are incinerated or poorly managed, they can release toxic chlorine-based compounds and contribute to the generation of hazardous byproducts (Ali et al., 2013b; Bolívar, 2021).

In a study conducted by Kirbaş et al. (1999), the biodegradation of PVC by three species of white-rot fungi was investigated. The fungi included *Pleurotus* sp., *Phanerochaete chrysosporium*, and *Polyporus versicolor*. Each fungus was inoculated into a liquid medium with high oxygenation. The PVC plastic served as the sole source of carbon in this environment. The results revealed that all three species of white-rot fungi were indeed capable of breaking down and degrading PVC under the given conditions. Indicating that the fungi possessed the necessary enzymes to dismantle the complex structure of PVC and utilize it as a carbon source for their own growth (Kirbaş et al., 1999).

Another study regarding the degradation of PVC was conducted by Ali et al. (2013b), using microorganisms obtained through bioprospecting. The study involved burying sheets of PVC in sterile soil with residual water. Subsequently, a degradation test was performed in which PVC served as the sole carbon source for the microorganisms present.

At the end of the test, the microorganisms with higher biomass were selected and analyzed. Among these microorganisms, two species of white-rot fungi were identified: *Phanerochaete chrysosporium* and *Lentinus tigrinus*. Results suggested that both fungi were found to be capable of utilizing PVC as a carbon source and were able to induce physical changes in the polymer sheets. To assess the degradation level, the PVC sheets were subjected to gel permeation chromatography analysis, where a decrease in the molecular weight of the treated films was found, indicating that the fungi could break down the polymer chains of PVC (Ali et al., 2013b).

4.6.1. Starch PVC blend

In order to enhance the bioavailability of PVC and facilitate its degradation, various strategies have been explored, including blending the polymer with natural fibers such as starch. Blending PVC with starch allows easy incorporation of the polymer without compromising its efficiency as a packaging material. However, it is important to determine whether the inclusion of starch facilitates faster degradation of the PVC blend. A study conducted by Ali et al. (2013a) focused on this issue. In this study, sheets of PVC blended with starch were buried in garden soil along with residual water. From the PVC blend sheets, a strain of *P. chrysosporium* PV1 was isolated as it demonstrated better growth capabilities under these conditions. Subsequently, a degradation test was carried out, where the PVC blend sheets served as the sole carbon source in a liquid medium. Following the incubation period, the PVC blend sheets exhibited weight loss and physical changes, including a roughened surface. These observations indicated that the PVC blend was undergoing degradation. The results suggest that blending PVC with starch enhances its bioavailability and promotes degradation (Ali et al., 2013a).

4.6.2. Cellulose blended PVC

As mentioned before, to enable PVC degradation, blending it with natural fibers such as cellulose could be an option, as demonstrated by the study conducted by Hassan et al. (2014). The study aimed to investigate the ability of *P. chrysosporium* to degrade PVC films blended with cellulose.

Several treatment methods were employed in the study. A soil burial test, where PVC films were buried in garden soil and inoculated with 15 mL of spore suspension. The films were left in the soil for a period of four months. Similarly, a shake flask test was made, three PVC films measuring 1 × 1 cm were added to a flask containing a spore suspension and mineral salt media. The flask was then incubated for three months at a temperature of 30 °C. Lastly, the solid mineral salt media test, three pieces of PVC were placed in a solid mineral salt media and inoculated with a spore suspension. The incubation period for this test was two months at a temperature of 30 °C.

After the incubation, PVC films exhibited several physical changes such as cracks, holes, pits, erosion, and structural alterations. These observations indicate the ability of *P. chrysosporium* to utilize PVC as a carbon source and degrade the blended films. The presence of cellulose in the PVC blend likely contributed to the enhanced degradation by providing an additional carbon source for the fungus and a site to attach and begin degradation (Hassan et al., 2014).

4.7. Polystyrene

Polystyrene (PS) is a type of thermoplastic that contains aromatic hydrocarbons in its structure. It is composed of monomers, such as styrene, and can be found in both solid and foamed forms. In various industries, PS is primarily used for protective packaging, especially for

food and jewel cases. Additionally, it finds applications in manufacturing CD and DVD cases, containers, lids, bottles, trays, tumblers, and more (Srikanth et al., 2022).

As mentioned before, Hock et al. (2019) did a test to assess if *P. ostreatus* or *P. abalones* could use PE or PS as a carbon source, and after a test of 7 days with different concentrations of salt and temperatures, growth was observed, showing that the fungi could use PS as a carbon source.

In another study conducted by Yanto et al. (2019) the biodegradation of polystyrene using white-rot fungi was explored. The researchers used three fungal isolates, including *Ceriporia* sp. (BIOM3) and *Cymatoderma dentriticum* (WM01), along with three bacterial isolates. The experiment involved using malt extract broth supplemented with a solution containing 990 mg of polystyrene, 49.5 mL of dimethyl-formamide, and 0.05 mL of tween 80. The mixture was then inoculated with the microorganisms and incubated at 25 °C for 30 days. After the incubation period, the results showed that *Ceriporia* sp. was able to degrade 19.44 % of the polystyrene, while *C. dentriticum* degraded 15.70 %. However, it's worth noting that these values were the lowest among the strains tested (Yanto et al., 2019).

In a separate study conducted by Wu et al. (2023), the researchers examined the degradation of polystyrene using various organisms, including *P. chrysosporium* (BKMF-1767, CCTCC, No. AF-96007). PS membranes were cut into 50 × 50 mm sheets and placed in a low carbon Potato Dextrose Agar medium, previously inoculated with *P. chrysosporium*. The Petri dishes were sealed and incubated at 30 °C for 7, 14, 21, 28, and 35 days. After incubation, the membranes were rinsed and dried for further quality analysis.

The results showed that polystyrene membranes exposed to *P. chrysosporium* for 35 days experienced a weight loss of 19.71 % and a degradation ratio of 1.25 %. These results were the most favorable among the organisms tested. *P. chrysosporium*, exhibited the fastest colonization of the membranes, leading to earlier biodeterioration. Additionally, the researchers observed damage and changes in surface morphology through scanning electron microscopy (SEM), along with evidence of reduced hydrophobicity. The molecular weight also decreased by 33–31 %, indicating depolymerization. ATR-FTIR spectra analysis revealed the formation of new functional groups, suggesting oxidation and the potential end of the polymer chain (Wu et al., 2023).

In this study, the resulting products from the degradation of polystyrene (PS) were determined using gas chromatography–mass spectrometry (GC–MS). Initially, the compounds present in early stages of degradation were styrene, phenylacetaldehyde, phenylethane, benzene, and m-Tolu aldehyde. As the degradation progressed, these compounds were broken down into lighter-weight molecular species that could enter the cells for further metabolism (Wu et al., 2023).

The researchers also developed a predictive model regarding the action of Lacasse and Lignin Peroxidase (LiP) on PS. Starting with LiP, two hydroxyl (OH) molecules are split, and hydrogen peroxide (H_2O_2) oxidizes the Fe^{3+} present in the enzyme's structure, converting it into Fe^{4+}. This process forms the oxygen ferry complex, which attacks PS and generates free radicals. On the other hand, lacasse has a trinuclear copper cluster free radical that oxidizes PS through the reoxidation of FAD (flavin adenine dinucleotide) with molecular oxygen. The generation of free radicals, including the trinuclear copper cluster, enables the attack on PS, leading to partial oxidation. Specifically, the PS-O chains are oxidized, resulting in the formation of aromatic oxygenates, which are smaller molecules of PS that can be easily further oxidized by active oxygen radicals until they enter the cells for metabolism (Wu et al., 2023).

4.8. Oxo-biodegradable plastics

As previously mentioned, oxo-biodegradable plastics contain metal ions or oxides in their structure, which facilitate photo or thermal oxidation. This oxidation process releases free radicals that weaken the main structure of the polymers, making them more vulnerable to microbial attack (Rodrigues et al., 2013). As a result, the degradation time of these plastics is reduced.

To support this statement, some researchers (Rodrigues et al., 2013) investigated the ability of *Pleurotus ostreatus* PLO6 to degrade oxo-biodegradable plastics. The experiment involved exposing the polymer to sunlight for 120 days to initiate the degradation process. Subsequently, the plastic was exposed to P. ostreatus PLO6 in a liquid medium, where the polymer served as the carbon source along with paper towels. At the conclusion of the study, it was observed that *P. ostreatus* PLO6 was able to utilize the plastic as a carbon and energy source. Fourier transform infrared spectroscopy (FTIR) analysis revealed that the polymer exposed to sunlight exhibited the highest degree of degradation. However, it is important to note that complete mineralization of the plastic was not achieved in either case. Therefore, waste management containing these polymers should involve additional treatments, such as composting (Bacha et al., 2023). Interestingly, the study also found that the plastic lacked sufficient nitrogen to support fungal growth. However, *P. ostreatus* PLO6 was able to grow due to the presence of nitrogen-fixing bacteria within its hyphae (Rodrigues et al., 2013).

4.9. Wood plastic composite

Wood plastic composite (WPC) is primarily composed of wood flour as the filler and thermoplastic resins, which are typically synthetic but can also include thermoset resins or naturally derived resin systems. These materials have been developed over the course of 40 years and find applications beyond construction. WPC is utilized in various industries, including automotive, indoor applications, and nonstructural building projects. Common uses include decks, fences, and exterior windows (Kord et al., 2021; Popescu, 2017). As previously mentioned, WPC is an intriguing material due to the incorporation of wood, which has the potential to enhance the biodegradation of the composite.

The inclusion of wood in wood plastic composites (WPC) makes them particularly interesting in research involving white-rot fungi. The presence of wood in WPC provides a potential pathway for the fungi to readily degrade the wood component and gain access to degrade the accompanying synthetic compounds present in the composite.

Catto et al. (2014) conducted a degradation test on wood plastic composite (WPC) to investigate whether the inclusion of natural fibers could facilitate the degradation of the compounds. The study utilized a polymer derived from bottle caps, composed of polypropylene (PP), ethylene vinyl acetate (EVA), and eucalyptus or pine flour. These WPC samples were exposed to three fungal species: *Trametes villosa*, *Pycnoporus sanguineus*, and *Coriolopsis rigida*.

The results indicated that WPC containing pine exhibited better degradation when exposed to *T. villosa*, followed by *P. sanguineus*. On the other hand, WPC with eucalyptus showed the most significant degradation with *P. sanguineus*. These findings suggest that the introduction of natural fibers may accelerate the degradation of the polymers. Furthermore, among the tested fungi, *T. villosa* demonstrated the most effective degradation capability (Catto et al., 2014).

In a study conducted by Lomelí-Ramírez et al. (2009) the resistance of wood plastic composites (WPC) made from oak, pine, and maple was examined against fungal attacks by *Trametes versicolor* and *Phanerochaete chrysosporium* over a period of 6 to 12 weeks. The biodegradation tests were carried out using both agar and soil blocking methods. The results of the study indicated that the blocking method was more effective in evaluating the biodegradation of WPC. It was also observed that WPC was susceptible to fungal attacks, with *Trametes versicolor* causing the most significant weight loss in the agar-based method (Lomelí-Ramírez et al., 2009).

In another example (Butnaru et al., 2016), the degradation of wood plastic composites (WPC) was investigated. The WPC used in this study consisted of a mixture of 70 % polypropylene and 30 % lignocellulosic biomass, which could be *Eucalyptus globulus*, Pinecones, or *Brassica rapa*.

The degradation test was performed using the fungus *Bjerkandera adusta*. The WPC samples underwent pre-treatment with Gamma irradiation before being placed in Petri dishes containing malt-glucose-agar extract and the fungus. The incubation was carried out at 28 °C for 7 weeks. Additionally, another test was conducted under the same conditions, but without the addition of culture media, only the WPC samples and the fungus.

The results showed the formation of cracks and structural changes in the WPC caused by the fungal activity. It was also observed that the WPC samples pre-treated with Gamma irradiation exhibited more pronounced variations in the external structure compared to the samples without pre-treatment (Butnaru et al., 2016).

In a similar way, (Schirp and Wolcott, 2005) other researchers made a study where wood plastic composites (WPC) were tested using maple 40-mesh wood flour and high-density polyethylene (HDPE) at two different concentrations. The first formulation consisted of 49 % wood filler and 45 % HDPE, while the second formulation had 70 % wood filler and 30 % HDPE. WPC pieces measuring 6 mm in width and 46 mm in length were prepared for each experimental unit.

The WPC samples were placed on agar plates containing a fully grown strain of *Trametes versicolor*. The incubation period lasted for either 24 days or 77 days at a temperature of 25 °C. The results indicated that the hyphae of *Trametes versicolor* increased the stiffness of the WPC samples. Additionally, there was a weight loss of 21 % in the formulation with 30 % HDPE and 19 % in the formulation with 45 % HDPE (Schirp and Wolcott, 2005).

In a study conducted by Cesarino et al. (2019), the degradation of a WPC composed of polypropylene H-107 and Eucalyptus bark in a 1:1 ratio was tested. The degradation process involved the use of the fungus *Pycnoporus sanguineus*. The WPC was added to Petri dishes containing fully grown *P. sanguineus* in ES-substrate, and the samples were incubated at 30 °C with 60 % humidity for a duration of 120 days. After this period, the WPC exhibited changes in its rheological characteristics, impact strength, hardness, and weight loss. However, the changes in weight loss were minimal, suggesting that *P. sanguineus* could degrade the WPC but not in the most efficient manner (Cesarino et al., 2019).

Since the mixture of wood and plastics can be an excellent opportunity to assess degradation using white-rot fungi, another example was made by Bari et al. (2017), the biodegradation of a wood plastic composite (WPC) composed of bamboo and four different plastics (HDPE, LDPE, PVC, and PP) was examined using the fungus *Trametes versicolor*. Three ratios of bamboo flour (60 %, 50 %, and 40 %) were tested, and each sample was prepared in dimensions of 30x10x5 mm.

The degradation test was performed in decay chambers consisting of French squares filled with moist forest loam and alder. The chambers were inoculated with *T. versicolor* and left until the mycelium covered the entire substrate. Subsequently, the WPC samples were added to the chambers, and the incubation was carried out at 28 °C for 12 or 16 weeks.

At the end of the incubation period, it was observed that the PVC composites were the most affected by the fungus. However, the weight loss in all the treatments was minimal. A significant challenge noted in the study was that the WPC composites were not moist enough to sustain fungal growth effectively (Bari et al., 2017).

4.10. Aliphatic polyamides

Aliphatic polyamides, such as nylon-66 and nylon-6, have been commercially produced since the late 1930s and remain significant materials in various industries. Nylon-66 is a polymer derived from the combination of adipic acid and hexamethylenediamine. On the other hand, nylon-6 is synthesized through ring-opening polymerization of e-caprolactam and is known by various commercial names such as Perlon, Nylon, and Steelon (Friedrich et al., 2007).

Friedrich et al. (2007) performed a study where the efficiency of nylon degradation was evaluated using agar as the growth medium. A total of 58 fungi were tested, and among them, 12 strains exhibited a clear zone formation around the aliphatic polyamides within the first 10 days. Two WRF were identified among the tested strains, namely, two strains of *P. chrysosporium* and one strain of *Bjerkandera adusta*.

The fungi that demonstrated potential for nylon degradation were further studied in a submerged culture using a modified glucose-mineral medium. The physical degradation of nylon-6 fibers was observed through Scanning Electron Microscopy (SEM). Interestingly, only the WRF, *B. adusta* and *P. chrysosporium*, were found to attack the nylon fibers. This degradation is likely facilitated by the action of the enzyme Manganese peroxidase (Friedrich et al., 2007).

4.11. Etilen-Vinil-Alcohol

Etilen-Vinil-Alcohol (EVOH) is a copolymer that combines polyethylene (PE) and polyvinyl alcohol (PVOH). It is commonly used in food packaging due to its excellent gas barrier properties, flavors permeability, and good mechanical properties. EVOH significantly extends the shelf life of packaged foods by providing an effective barrier against oxygen and moisture. However, like many other polymers, EVOH poses environmental challenges due to the large volume of solid waste generated once the packaged foods are consumed. Disposal of EVOH waste can contribute to the accumulation of non-biodegradable materials in landfills and the overall environmental impact (Arboleda et al., 2007).

In the study made by Arboleda et al. (2007), EVOH films were exposed to enzymes produced by the fungus *Phanerochaete chrysosporium*. After the exposure, the films were analyzed by Differential Scanning Calorimetry (DSC) and X-ray to assess the structural changes. The results of the analysis revealed that the enzymes could modify the crystalline structure of the EVOH polymer, leading to a more disordered structure.

The biodegradation primarily targeted the polyvinyl alcohol (PVOH) component of the EVOH, while the polyethylene (PE) component remained relatively unaffected. The presence of hydroxyl groups (OH) in the PVOH facilitated the initiation of oxidative reactions caused by the enzymes produced during the secondary metabolism of *P. chrysosporium*. These oxidative reactions likely contributed to the degradation and modification of the EVOH structure (Arboleda et al., 2007).

4.12. Starch blends with plastic

Starch-based polymers have gained significant attention as alternatives to synthetic polymers due to their comparable physical and structural properties, along with the added benefit of being more biodegradable, mainly in solid state culture accompanied with lignocellulosic materials (Roldán-Carrillo et al., 2003).

Some investigations have been testing the ability of *P. chrysosporium* to degrade a starch polymer, an example can be the one conducted by Roldán-Carrillo et al. (2003). The researchers observed an increase in enzymatic activity during the secondary metabolism of *P. chrysosporium* at the end of the incubation period. This suggests that the fungus exhibited enhanced production of enzymes capable of degrading starch-based polymers. Furthermore, a significant degradation of starch, ranging from 70 % to 74 %, was observed in all cases.

To further analyze the degradation process, high-performance liquid chromatography (HPLC) was employed. This analytical technique allowed the researchers to detect the production of low molecular weight molecules such as dextrin, maltotriose, maltose, and glucose. The presence of these molecules indicates the breakdown of starch into smaller, more easily metabolizable components.

The results of the study indicate that *P. chrysosporium* possesses the potential to efficiently degrade starch-based polymers. The combination of nitrogen-deficient culture conditions and the presence of starch or glucose as carbon sources stimulated the enzymatic activity of the fungus, leading to substantial degradation of the starch polymer. These

findings contribute to our understanding of microbial degradation processes and highlight the potential of utilizing P. chrysosporium for the biodegradation of starch-based polymers (Roldán-Carrillo et al., 2003).

4.13. Other polymers

Some researchers (Espinosa-Valdemar et al., 2011) evaluated the ability to degrade disposable diapers made of polyethylene, polypropylene, and an adsorbent, using *P. ostreatus*. At the end of the study, 85 % of weight and volume loss was reported. Stoleru et al. (2017) assessed the capacity of *P. chrysosporium* to degrade pre-treated sheets of polylactide (PLA). The sheets were exposed to nitrogen plasma or irradiated with gamma rays and then were covered with chitosan, reporting weight loss after the action of *P. chrysosporium*.

5. Conclusions

Nowadays, there has been a growing concern about the environmental impact of recalcitrant compounds, particularly single-use plastics. Facing this issue and finding effective solutions has become important. Extensive research has been conducted to explore biodegradation strategies for synthetic polymers and to identify alternative materials to replace them, with comparable mechanical properties but less harmful to the environment. One promising approach among the various biodegradation strategies is the utilization of white-rot fungi, which possess enzymes capable of modifying the structure of plastics. This enzymatic action enhances the bioavailability of plastics and facilitates their natural degradation. Recent studies have focused on pretreating plastics before exposing them to fungi, aiming to improve the degradation rate. The results from these pretreatment methods have consistently yielded positive outcomes, often surpassing those achieved without pretreatment. Therefore, it is highly recommended to accompany biodegradation processes with suitable pretreatments. In the studies conducted, *Phanerochaete chrysosporium* emerged as the most used strain and yielded the best results, followed by *Trametes versicolor*. Additionally, some research focused on bioprospecting microorganisms found in residual water or soil from landfills, which demonstrated the ability to degrade targeted polymers.

Both solid and liquid media were frequently utilized for cultivation, with many media lacking an external carbon source as the plastics themselves provided the required carbon. Moreover, ligninolytic materials were commonly added to the media to induce the production of ligninolytic enzymes. Solid-state fermentation has stand out promising outcomes in plastic degradation.

To evaluate changes in the surface and chemical properties of plastics, researchers predominantly employed analytical and instrumental techniques to assess surface alterations.

Furthermore, studies indicated the formation of new functional groups and a reduction in hydrophobicity, suggesting that the tested fungi could utilize the polymers as a carbon source.

Combining plastics with natural fibers, such as starch or metallic ions, yielded favorable outcomes in terms of degradation and deterioration. This suggests that blending these compounds with plastics can be an effective strategy to improve waste management and increase the chances of successful degradation processes. A proposed model depicted a series of key steps involved in the degradation of plastics by white-rot fungi. These steps include initial colonization, where hydrophobic proteins are produced to aid the fungi in attaching to the plastic surface, followed by the release of ligninolytic enzymes that attack the polymer and generate monomers. Finally, these monomers enter the fungal cells and are metabolized, primarily in the TCA cycle.

6. Future perspectives

Despite the progress made in the biodeterioration and biodegradation of plastics using white-rot fungi, further research is still needed to fully harness their potential. Although *Phanerochaete chrysosporium* has shown promising capabilities in degrading various polymers, it is crucial to evaluate the ability of microbial consortia to lead a complete biodegradation of these polymers and avoid the formation of toxic metabolic intermediates. This would allow for further enhancement of its effectiveness as a biodegradation agent. Additionally, continued bioprospecting efforts in landfills or residual water sources can be fruitful, as microorganisms in these environments may have already developed degradation pathways for different types of polymers, which can be further amplified under laboratory conditions.

Moreover, there is still limited information available regarding the specific metabolic pathways involved in the degradation of each plastic by fungi, as well as the compounds generated during the degradation process and the specific interactions between enzymes and plastics. Obtaining such information would be valuable for standardizing environmental conditions, culture media, pre-treatment methods, and incubation conditions, ultimately leading to the complete mineralization of polymers or increasing their bioavailability in conjunction with composting. In composting, a new microbial consortium could aid in the final mineralization of the polymers, ensuring the most efficient and cost-effective degradation process. Furthermore, it is essential to expand research efforts on a larger scale in order to translate the acquired knowledge into real-world scenarios.

Finally, one of the overarching challenges we face is reducing the consumption of synthetic plastics and promoting the use of bio-based products, thus facilitating the transition towards a greener and more circular economy.

List of abbreviations

DBP	Dibutyl Phthalate
DSC	Differential scanning calorimetry
EVOH	Etilen-Vinil-Alcohol
EVA	Ethylene vinyl acetate
FTIR	Fourier transform infrared spectroscopy.
HDPE	High-density polyethylene
HPLC	High performance liquid chromatography
Lac	Lacasse
LDPE	Low-density polyethylene
LiP	Lignin peroxidase
LLDPE	Linear low-density polyethylene
MDPE	Medium-density polyethylene
MnP	Manganese peroxidase
PBT	Terephthalate polybutylene
PDA	Potato dextrose agar
PE	Polyethylene
PET	Polyethylene terephthalate
PLA	Polylactic acid
PP	Polypropylene (PP)
PUR	Polyurethane (PUR)
PVC	Polyvinyl chloride (PVC)
PVOH	Polyvinyl alcohol
SEM	Scanning electron microscopy
VP	Versatile peroxidase
WPC	Wood plastic composite

CRediT authorship contribution statement

Paula Andrea Bautista-Zamudio: Writing – original draft, preparation of figures and tables, editing of the manuscript. **María Alejandra Flórez-Restrepo**: Writing – original draft, preparation of figures and tables, editing of the manuscript. **Leidy Carolina Monroy-Giraldo**: Writing – original draft, preparation of figures and tables, editing of the manuscript. **Xiomara López-Legarda**: Conceptualization, supervision, Writing - Review & Editing. **Freimar Segura-Sánchez**: Conceptualization, supervision, Review & Editing. All authors read and approved the

final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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